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Measurements of $t\bar{t}+X$ using the ATLAS detector



Marisa Sandhoff

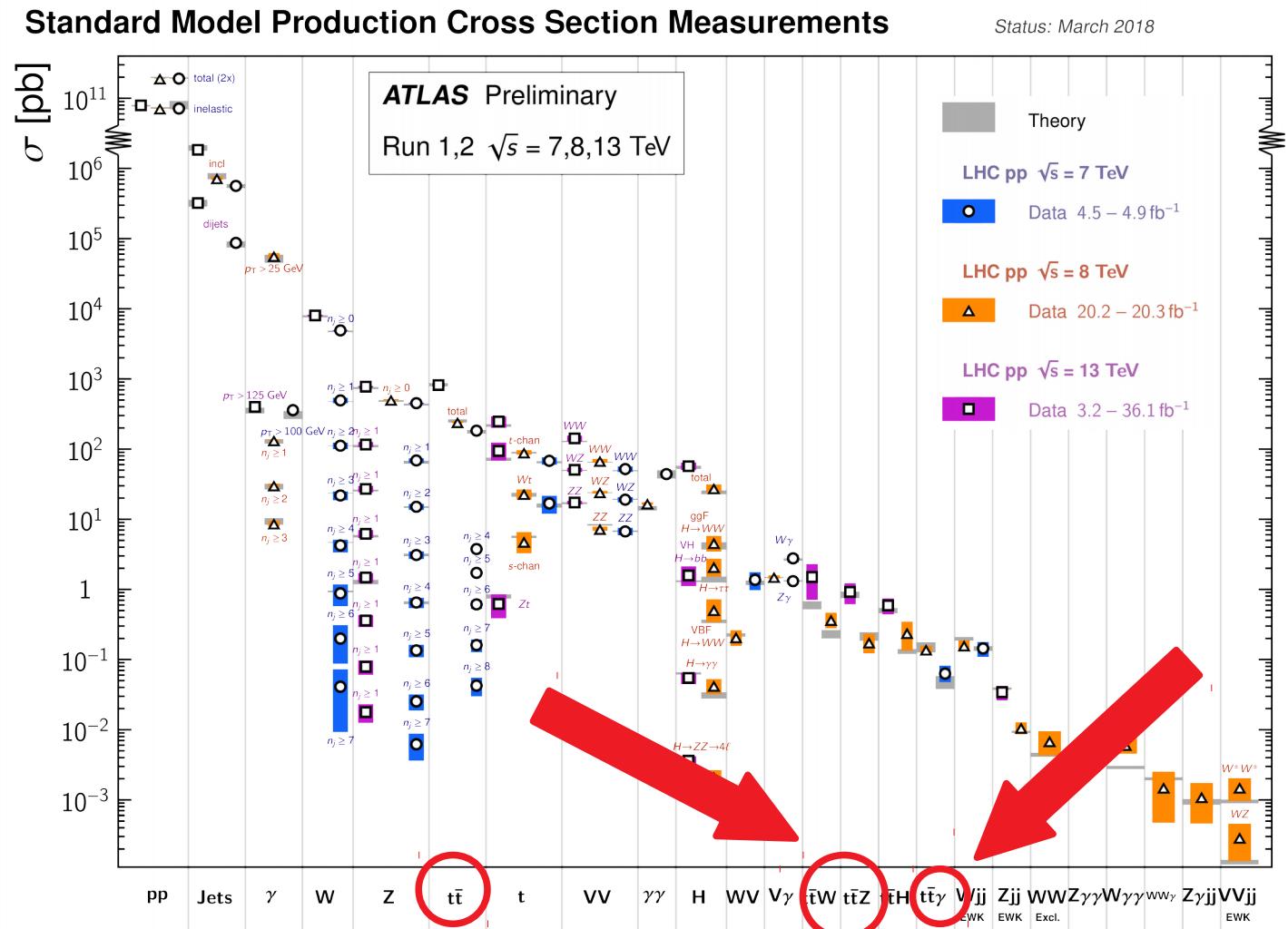
Bergische Universität Wuppertal

on behalf of the ATLAS Collaboration



Introduction

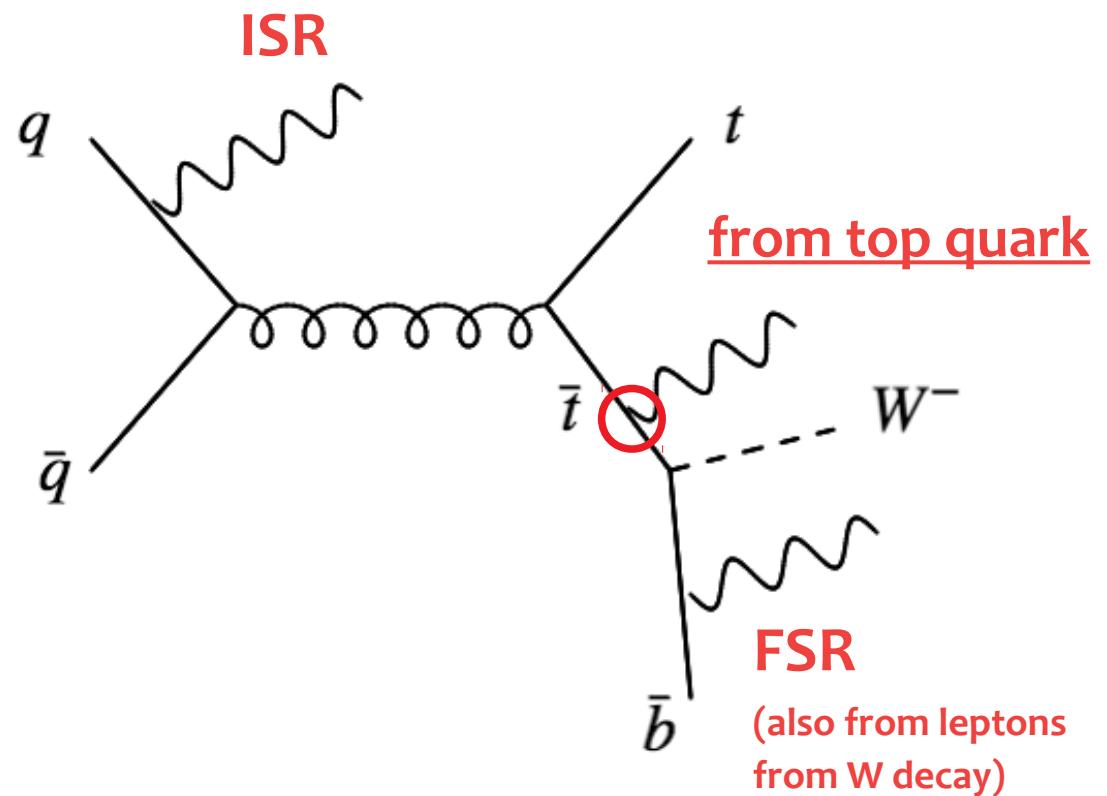
- due to large centre-of-mass energy of the LHC $t\bar{t}$ events copiously produced
- study $t\bar{t}$ associated production with vector bosons and jets
 - processes background to BSM physics
 - test standard model
 - tune MC generators
- today presenting 5 analyses covering: $t\bar{t}\gamma$, $t\bar{t}W$, $t\bar{t}Z$ and $t\bar{t}+(b)$ jets
- ATLAS data used:
 - 20.2fb @ 8TeV (2012)
 - 3.2fb @ 13TeV (2015)
 - 36.1fb @ 13 TeV (2015/16)



- ◆ Photons can be emitted as ISR, FSR + directly from the top quark
→ measure $t\gamma$ electroweak coupling!

- ◆ Event selection:
→ enhance event fraction of photons radiated from the top quark

- ◆ standard single lepton channel selection + ≥ 1 b-tag
- ◆ Photons from top quark:
 - ◆ one γ with $p_T(\gamma) > 15 \text{ GeV}$,
 - ◆ $\Delta R(\text{jet}, \gamma) > 0.5$,
 - ◆ $\Delta R(\text{lepton}, \gamma) > 0.7$



After event selection 3 classes of events:

Prompt photons

- ◆ **Signal** and backgrounds
(mostly $W\gamma/Z\gamma + \text{jets}$ (from MC);
multijet with γ)

$e \rightarrow \gamma$ fake

(template from data)

- ◆ e misidentified as γ
(dilepton $t\bar{t}$ events, $Z + \text{jets}$)

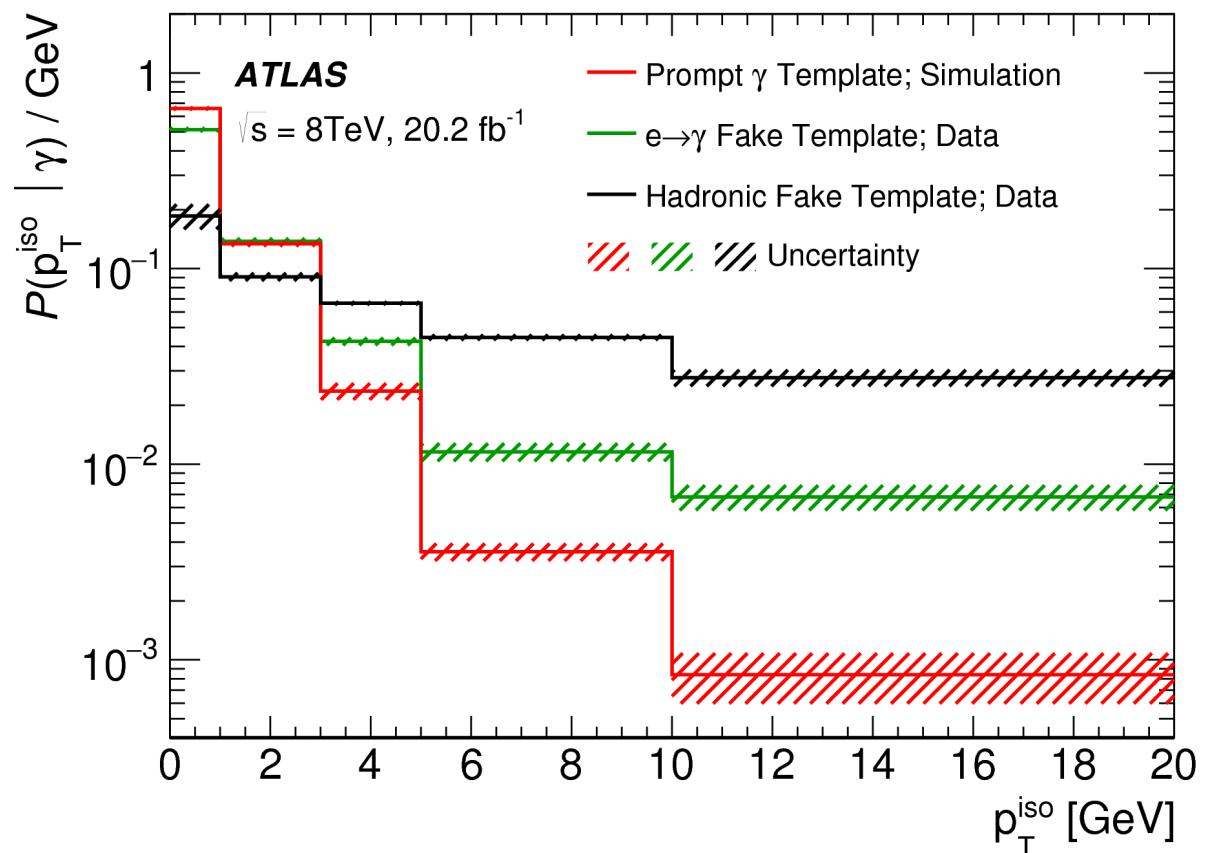
hadronic fake

(template from data)

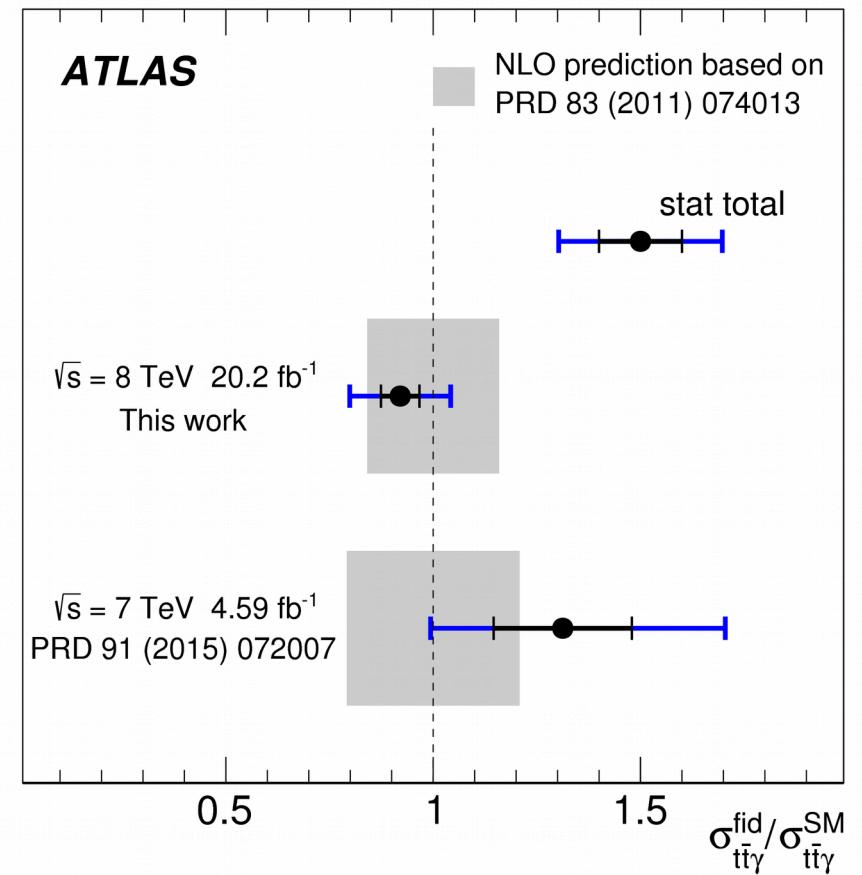
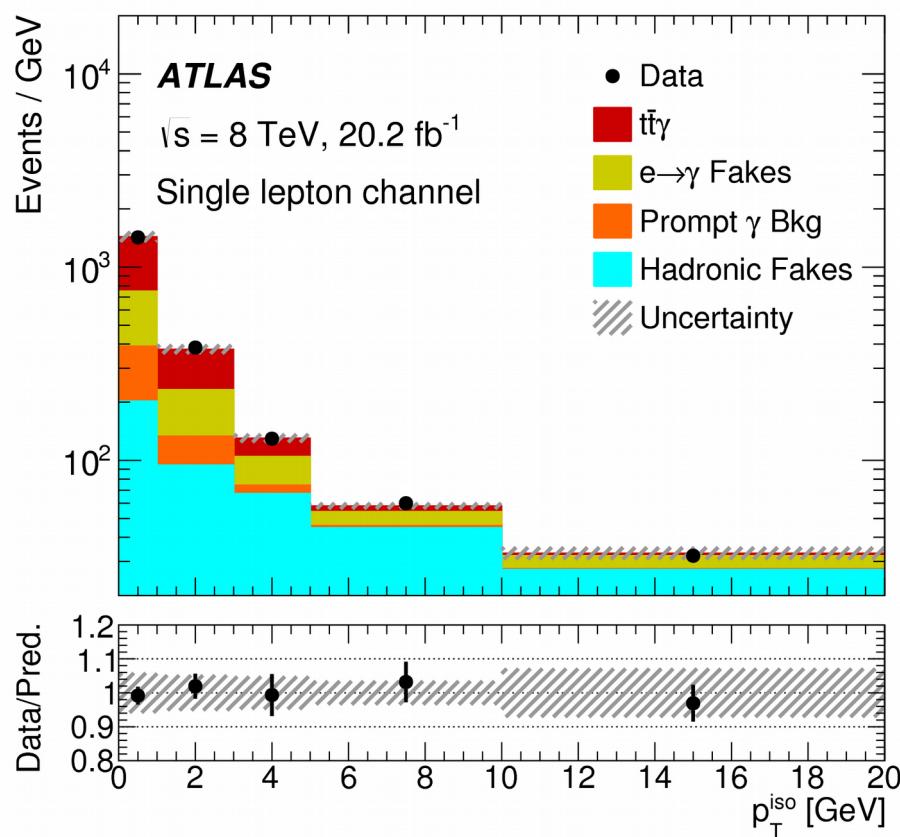
- ◆ γ from hadron decays
and hadrons identified as γ
($t\bar{t}$ events with fake γ)

→ template fit in the isolation
of the photon

(p_T^{iso} : sum of p_T of all tracks
within cone of 0.2 rad around the photon)

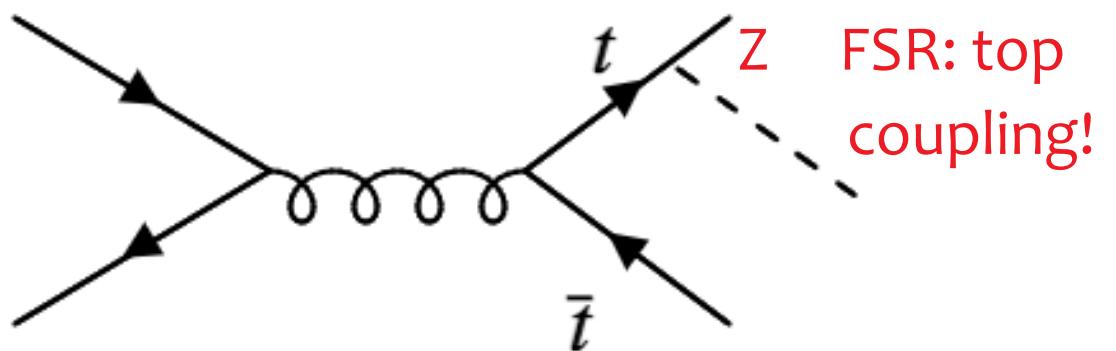
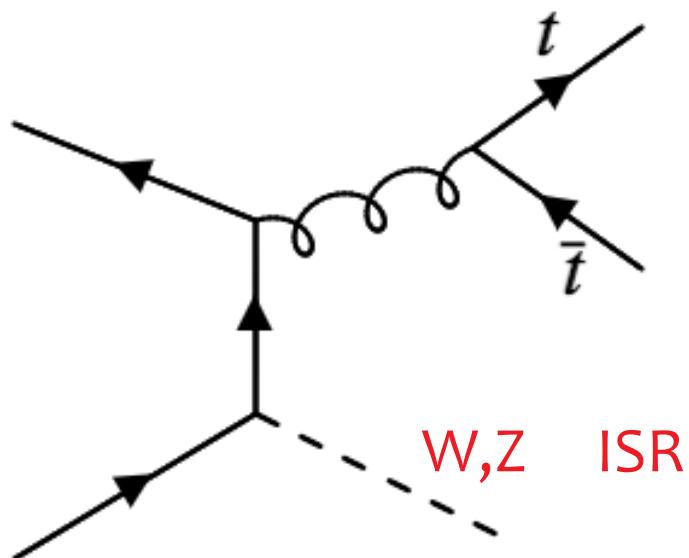


- ◆ p_T^{iso} distribution after likelihood fit
- ◆ $\sigma_{t\bar{t}\gamma} = 139 \pm 7 \text{ (stat)} \pm 17 \text{ (syst)} \text{ fb} (\pm 13\% \text{ total})$
- ◆ dominant syst. uncertainties: fake rates (6.3%)



- ◆ $\sigma_{t\bar{t}\gamma}$ (NLO pred.) = $151 \pm 24 \text{ fb}$
- ◆ Good agreement with NLO prediction!

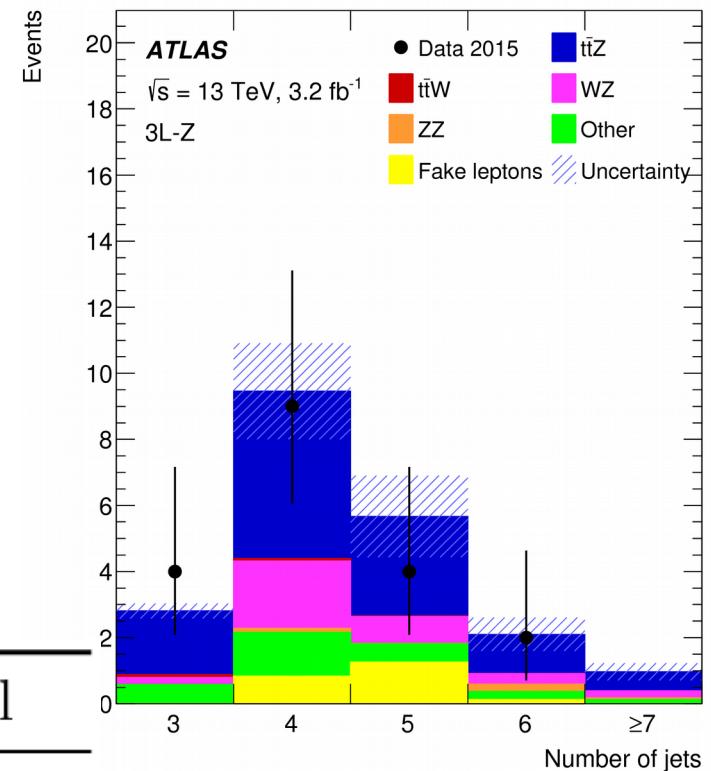
- ◆ Important background to $t\bar{t}H$ production
- ◆ BSM physics could affect $\sigma_{t\bar{t}W}$ and $\sigma_{t\bar{t}Z}$
 - ◆ important test of SM validity



- ◆ Measurement of the neutral-current tZ coupling in FSR

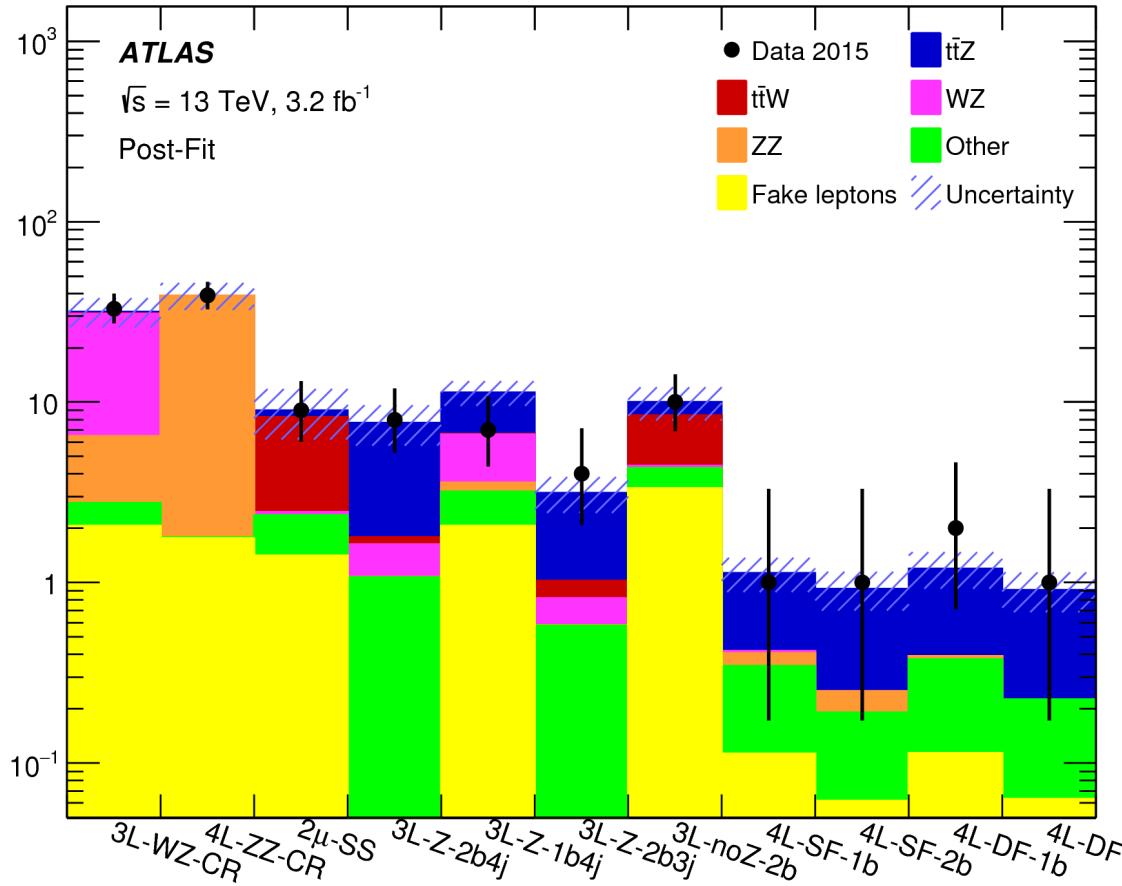
- ◆ 3 channels, characterized by $t\bar{t}$ and boson decay modes → **2, 3 and 4 leptons**
- ◆ multiple analysis regions in every channel
→ **enhance signal sensitivity**
 - ◆ standard dilepton and lepton+jets $t\bar{t}$ selection with 1 or 2 b-tags + selection of W and Z
 - **9 signal regions**
- ◆ Main backgrounds: WZ and ZZ, Z+jets, $t\bar{t}$ with fake leptons

Process	$t\bar{t}$ decay	Boson decay	Channel
$t\bar{t}W^\pm$	$(\mu^\pm \nu b)(q\bar{q}b)$ $(\ell^\pm \nu b)(\ell^\mp \nu b)$	$\mu^\pm \nu$ $\ell^\pm \nu$	SS dimuon Trilepton
$t\bar{t}Z$	$(\ell^\pm \nu b)(q\bar{q}b)$ $(\ell^\pm \nu b)(\ell^\mp \nu b)$	$\ell^+ \ell^-$ $\ell^+ \ell^-$	Trilepton Tetralepton



- ◆ Binned maximum likelihood fit in 9 signal + 2 control regions to N_{events}

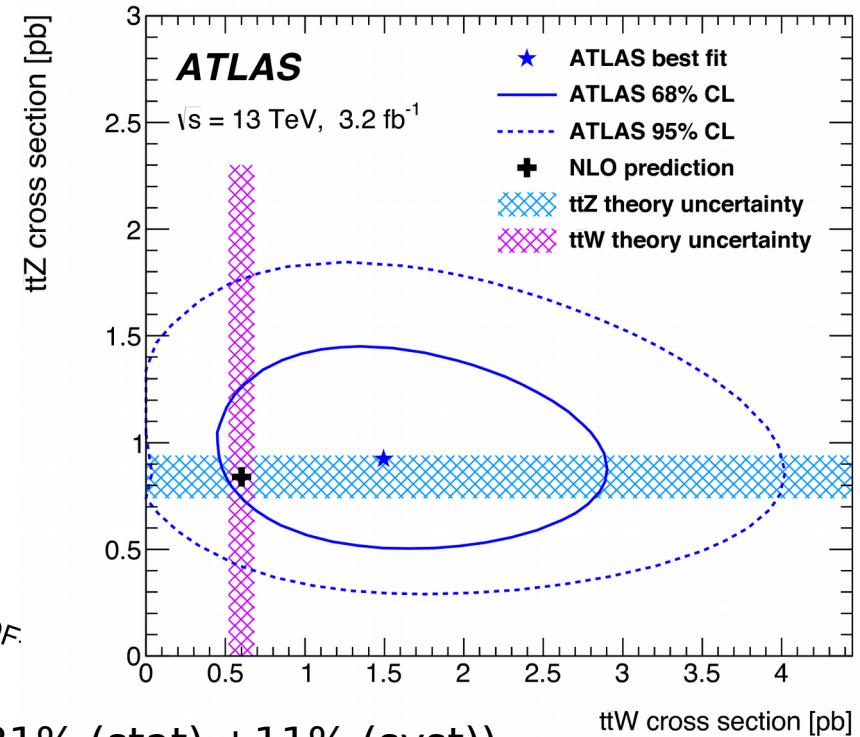
Events



$$\sigma_{t\bar{t}Z} = 0.92 \pm 0.29 \text{ (stat)} \pm 0.1 \text{ (syst)} \text{ pb } (\pm 31\% \text{ (stat)} \pm 11\% \text{ (syst)})$$

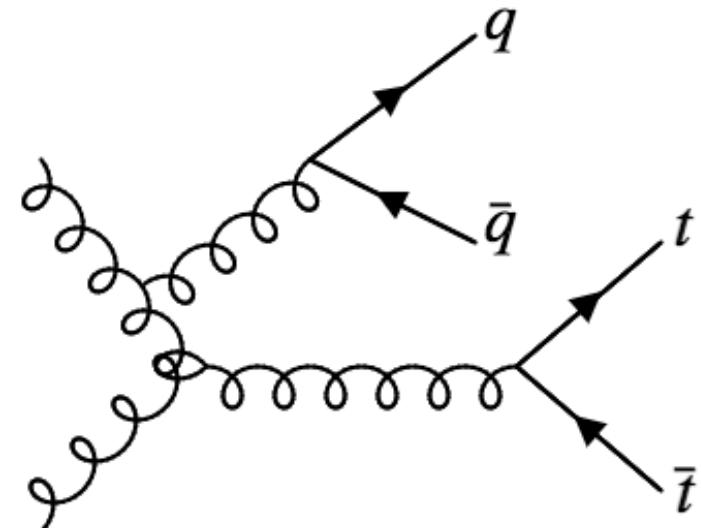
$$\sigma_{t\bar{t}W} = 1.50 \pm 0.72 \text{ (stat)} \pm 0.33 \text{ (syst)} \text{ pb } (\pm 48\% \text{ (stat)} \pm 22\% \text{ (syst)})$$

- Still dominated by statistics
- Dominant systematic uncertainty: reconstructed objects (8.3% (Z)), 9.3% (W))



$t\bar{t} + \text{jets}$ 3.2 fb^{-1} @ 13 TeV

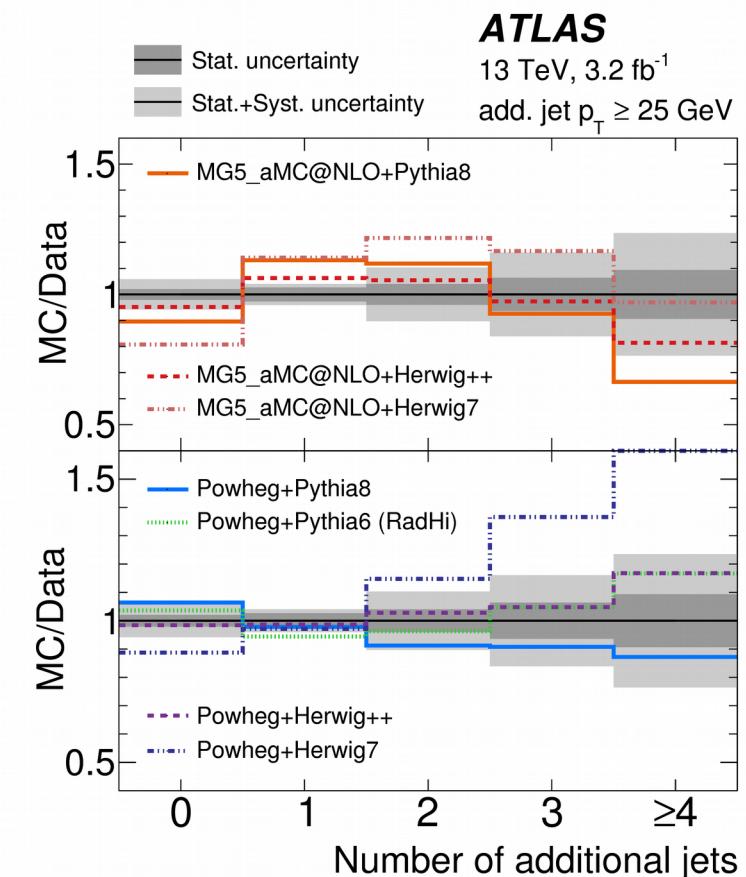
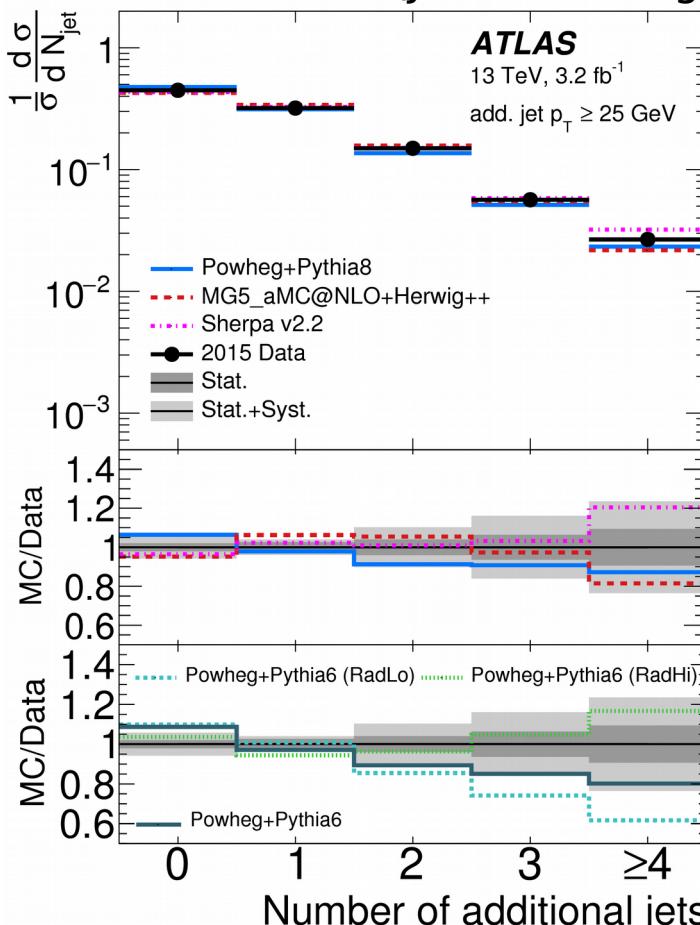
- ◆ kinematics of jets from top quark decay well described
- ◆ $t\bar{t}$ production often includes additional jets from gluon radiation
 - ◆ generators show differing levels of agreement in describing the kinematics
→ Significant uncertainties in precision measurements (e.g. m_{top} , $\sigma_{t\bar{t}}^{\text{incl}}$)
- ◆ Several models available to describe the production of these jets (incl. (NLO) QCD calculations, parton shower models)
 - Test and optimize these predictions!
(tune free model parameters)



$t\bar{t} + \text{jets}$ 3.2 fb^{-1} @ 13 TeV

- ◆ **Eur. Phys. J. C77 (2017) 220**
- ◆ Selection of dilepton $t\bar{t}$ events:
 - ◆ 1 e + 1 μ (opposite charge), 2 b-tags
 - ◆ Clean event selection, < 5% background events contamination
- ◆ **arXiv: 1802.06572 (submitted to JHEP)**
- ◆ Selection of lepton+jets $t\bar{t}$ events:
 - ◆ 1 e or 1 μ , ≥ 4 jets, ≥ 2 b-tags
 - ◆ 10%-15% background events contamination
- ◆ → additional jets: independent of jet flavour (mainly gluon and light jets)
- ◆ Correct distributions back to particle level and compare to theoretical predictions

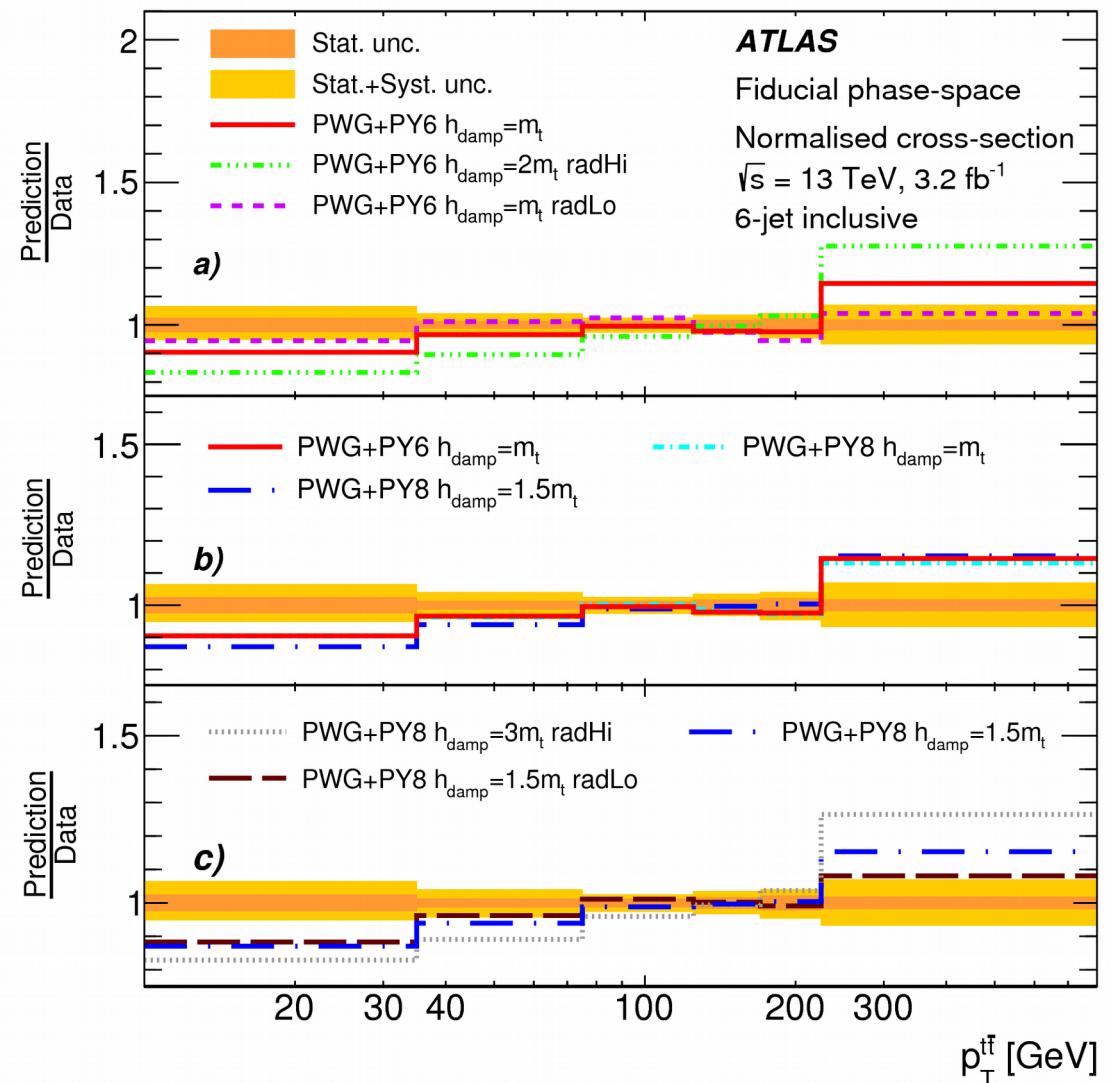
- ◆ N_{jets} compared to several predictions and different matched parton showers
 - ◆ dominated by systematic uncertainties (JES, modeling)
- ◆ Most predictions within uncertainties
- ◆ MG5_aMC@NLO agree within 5-10% with most matched parton showers
- ◆ Good agreement for new Powheg+Pythia8 setup
- ◆ Powheg+Pythia6: RadHi tune preferred* (Perugia2012)



*tune including h_{damp}

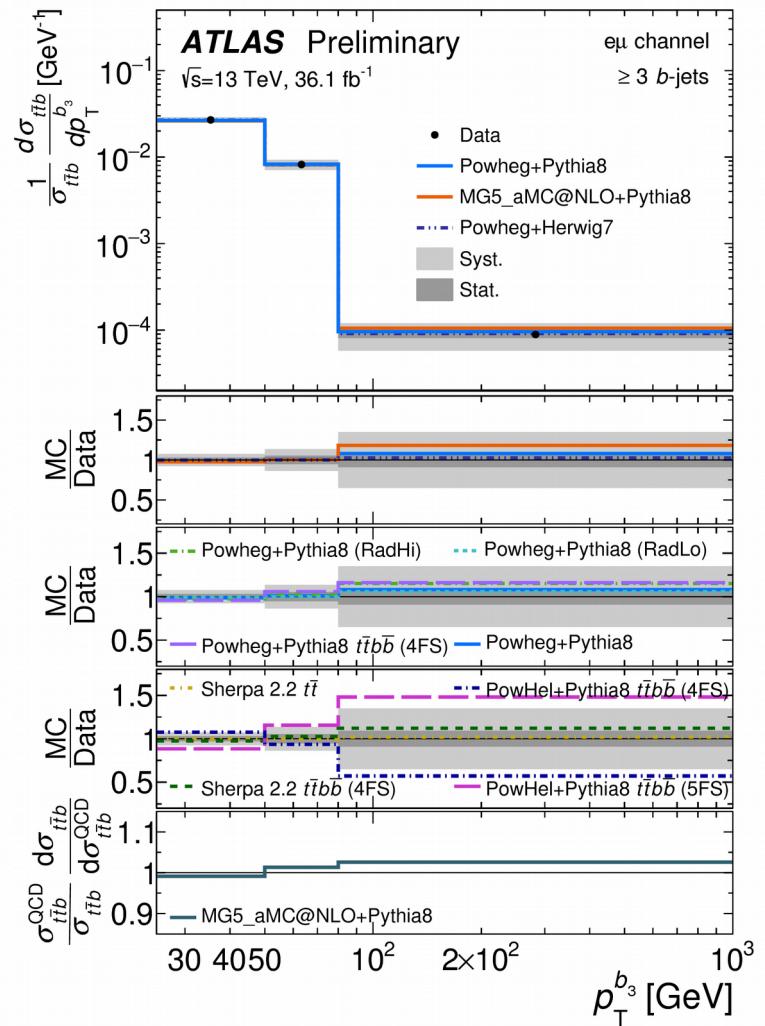
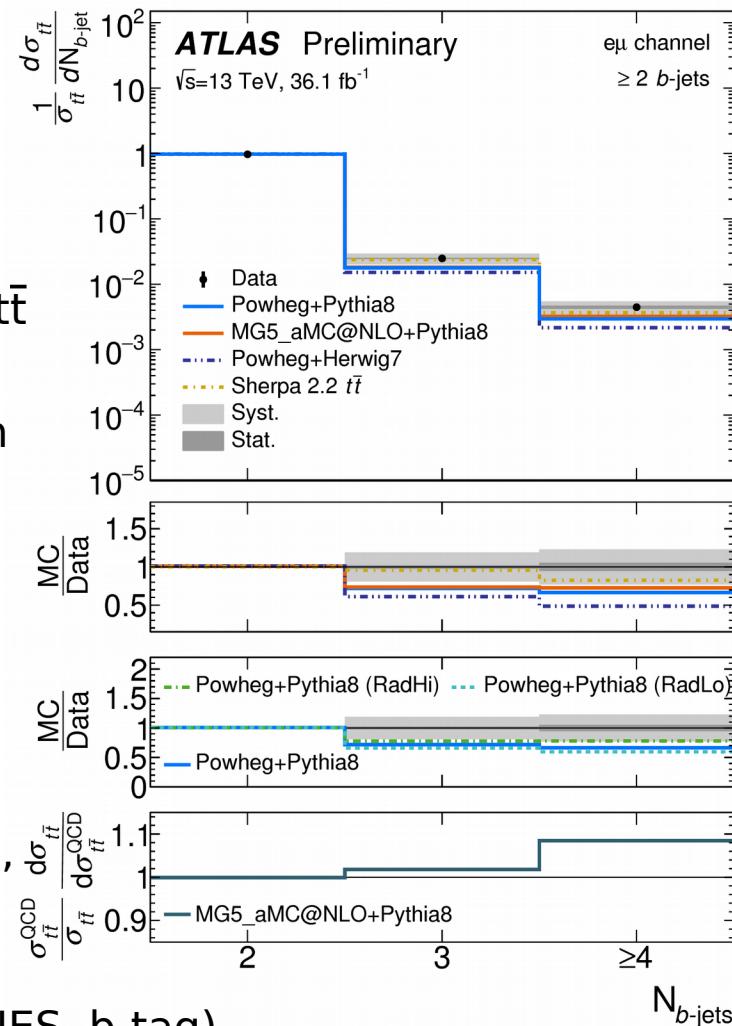
parameter: controls the p_T of the first gluon/quark emission beyond the $t\bar{t}$ production

- ◆ $p_t^{t\bar{t}}$: Comparison to several predictions and different values of the h_{damp} parameter
- ◆ Pythia6 predictions: radLo preferred (lower amount of gluon radiation)
 - ◆ In contrast to analysis presented on last slide
- ◆ For Powheg+Pythia8: smaller impact of h_{damp} choice
- ◆ Difficulties for MC models to describe variables like N_{jets} and $p_T^{t\bar{t}}$ simultaneously

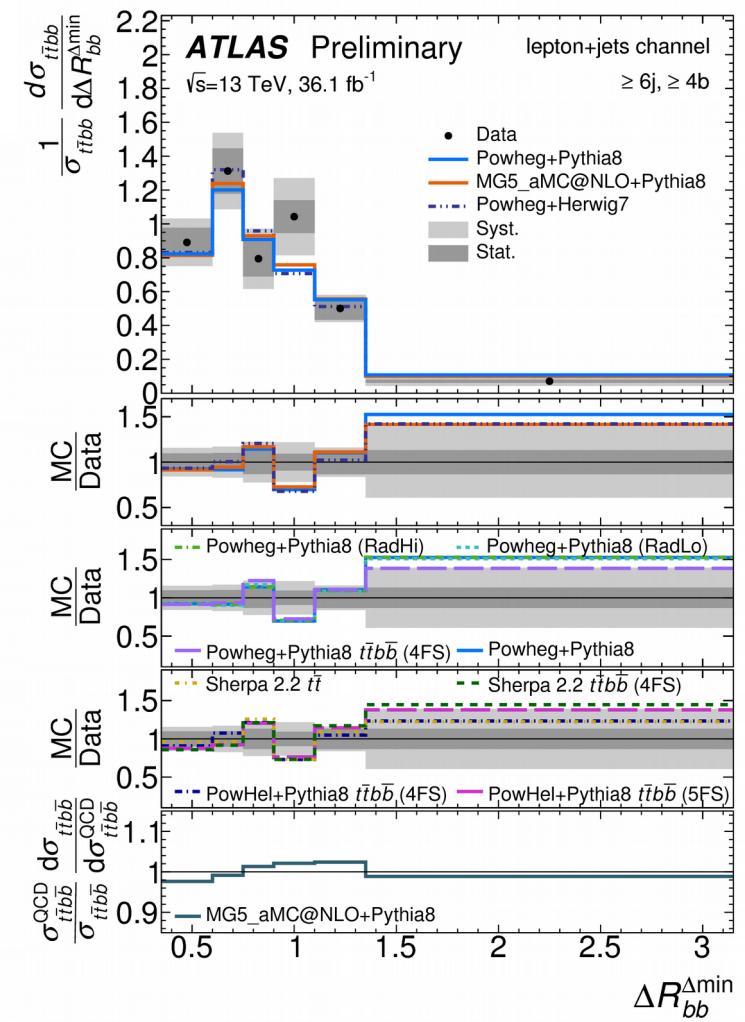
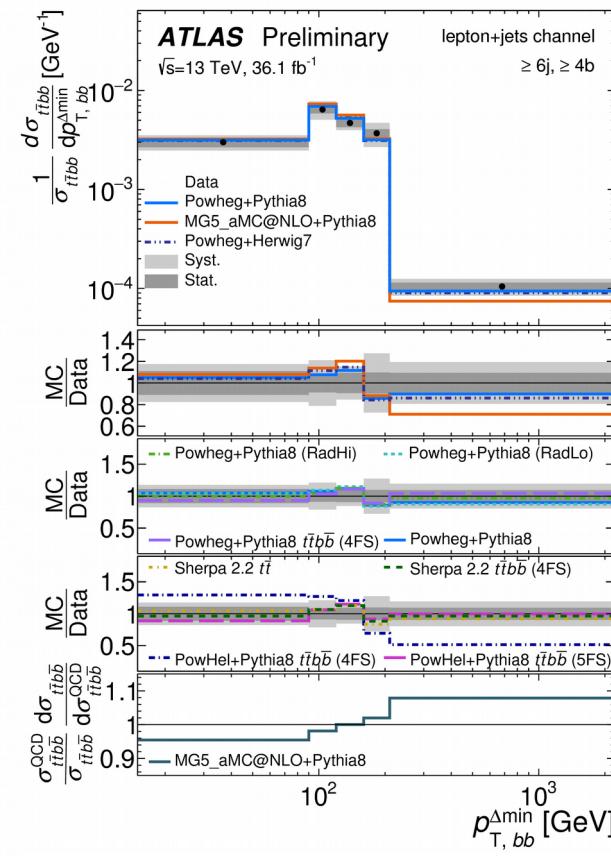
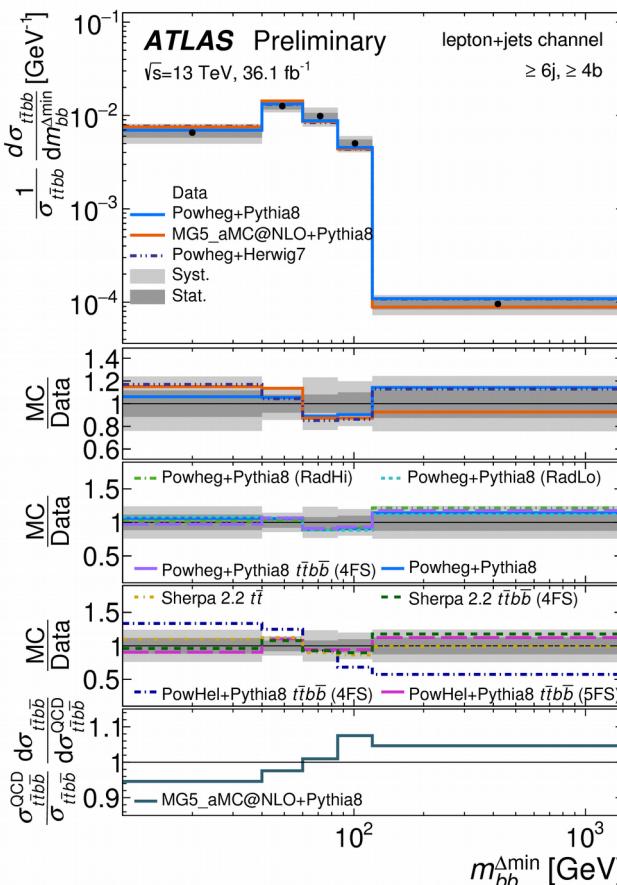


- ◆ Measurement of $t\bar{t}$ with additional **b** jets
 - ◆ challenge for QCD calculations because of $m_b \neq 0$ GeV
→ Important test of QCD predictions
- ◆ $t\bar{t}+b\bar{b}$ important background to $t\bar{t}H(H \rightarrow b\bar{b})$:
 - ◆ Better modeling of $t\bar{t}+b\bar{b}$ would directly improve $t\bar{t}H(H \rightarrow b\bar{b})$ measurement
- ◆ Measurement in both $e\mu$ and $l+jets$ channel ($p_T(\text{jet}) > 25$ GeV)
 - ◆ Selection $e\mu$:
 - ◆ $N_{\text{bjet}}: \geq 2$ jets, ≥ 2 b-tags; all other ≥ 3 jets, ≥ 3 b-tags
 - ◆ Selection $l+jets$:
 - ◆ For kinematic distributions: ≥ 6 jets with ≥ 4 b-tags
 - ◆ $<5\%$ bkg for $e\mu$, $<10\%$ bkg for $l+jets$ (much higher statistics for $l+jets$)
- ◆ → Correct for detector effects and compare to MC generator predictions

- ◆ Good agreement in 1st bin: jet from top decay
- ◆ too few events with ≥ 3 b-jets in all MC predictions (eμ channel)
 - ◆ Except SHERPA 2.2 $t\bar{t}$
- ◆ RadHi and RadLo tunes do not improve situation
- ◆ p_T 3rd b-jet (not from $t\bar{t}$) overestimated, but within uncertainties
- ◆ except for PowHel+Pythia8 $t\bar{t}bb$
(5FS: massless b quarks,
4FS: massive b quarks)
- ◆ syst. uncert. dominant (JES, b-tag)



- ◆ Pair of closest b-jets (in ΔR) (lepton+jets channel)
- ◆ Some discrepancies between data and MC for ΔR
(better agreement for p_T and mass of this b jet pair,
except for PowHel+Pythia8 (4FS) (massive b quark))



Conclusion and outlook

- ◆ high centre-of-mass energy of LHC allows for the copious production of top quark pairs in association with other final state particles
- ◆ presented ATLAS results on $t\bar{t}+\gamma$, $t\bar{t}+W/Z$:
 - ◆ $\sigma_{t\bar{t}\gamma} = 139 \pm 7 \text{ (stat)} \pm 17 \text{ (syst)} \text{ fb}$ (20.2 fb^{-1} @ 8TeV, JHEP 11 (2017) 086)
 - ◆ $\sigma_{t\bar{t}Z} = 0.92 \pm 0.29 \text{ (stat)} \pm 0.1 \text{ (syst)} \text{ pb}$
 - ◆ $\sigma_{t\bar{t}W} = 1.50 \pm 0.72 \text{ (stat)} \pm 0.33 \text{ (syst)} \text{ pb}$
(3.2 fb^{-1} @ 13 TeV, Eur. Phys. J. C77 (2017) 40)
- ◆ for $t\bar{t}+(b)$ jets kinematic distributions at particle level compared to MC predictions
 - ◆ some discrepancies in describing the data can be seen
→ valuable input for MC tuning
 - ◆ most observables relatively well described
 - ◆ difficulties for MC models to describe different variables using same setup

Additional Material

Process	$e + \text{jets}$	$\mu + \text{jets}$
Multijet + γ	7.5 ± 3.6	8.3 ± 5.2
$W\gamma + \text{jets}$	65 ± 25	97 ± 25
$Z\gamma + \text{jets}$	35 ± 19	38 ± 20
Single top + γ	13 ± 7	19 ± 10
Diboson + γ	2.6 ± 1.5	2.5 ± 1.4

Expected yields of background processes with a prompt photon. The uncertainties include all sources of systematic uncertainties.

Source	Relative uncertainty [%]
Hadron-fake template	6.3
$e \rightarrow \gamma$ fake	6.3
Jet energy scale	4.9
$W\gamma + \text{jets}$	4.0
$Z\gamma + \text{jets}$	2.8
Initial- and final-state radiation	2.2
Luminosity	2.1
Photon	1.4
Single top+ γ	1.2
Muon	1.2
Electron	1.0
Scale uncertainty	0.6
Parton shower	0.6
Statistical uncertainty	5.1
Total uncertainty	13

List of the most important systematic uncertainties and their effects on the measurement of the inclusive cross section. In addition, the statistical and total uncertainty are given. The total uncertainty is derived from the likelihood fit.

Range	$t\bar{t}\gamma$	Hadronic fake	$e \rightarrow \gamma$ fake	$W\gamma+\text{jets}$	$Z\gamma+\text{jets}$	Single top+ γ	Multijet+ γ	Diboson+ γ	Data
Total	1060 ± 130	1020 ± 90	710 ± 90	160 ± 40	73 ± 32	32 ± 15	16 ± 6	5.1 ± 2.4	3072
$15 \leq p_T < 25 \text{ GeV}$	280 ± 40	360 ± 40	240 ± 35	47 ± 13	23 ± 10	7 ± 4	4.4 ± 2.3	1.3 ± 0.7	966
$25 \leq p_T < 40 \text{ GeV}$	309 ± 34	233 ± 26	171 ± 7	37 ± 10	22 ± 10	6.4 ± 3.3	3.8 ± 2.4	1.8 ± 0.9	783
$40 \leq p_T < 60 \text{ GeV}$	220 ± 40	205 ± 21	111 ± 30	28 ± 8	13 ± 6	10 ± 5	1.6 ± 1.9	0.5 ± 0.3	589
$60 \leq p_T < 100 \text{ GeV}$	160 ± 40	116 ± 16	100 ± 40	24 ± 7	10 ± 5	8 ± 4	3.4 ± 2.1	1.0 ± 0.6	420
$100 \leq p_T < 300 \text{ GeV}$	150 ± 25	71 ± 10	50 ± 20	23 ± 7	4 ± 2	0.9 ± 0.7	0.8 ± 1.0	0.3 ± 0.2	298
$ \eta < 0.25$	246 ± 34	121 ± 21	93 ± 24	18 ± 6	9 ± 4	4.0 ± 2.2	5.2 ± 1.8	1.0 ± 0.6	497
$0.25 \leq \eta < 0.55$	260 ± 40	130 ± 20	116 ± 29	29 ± 8	11 ± 6	3.7 ± 2.1	0.0 ± 0.4	1.5 ± 0.8	552
$0.55 \leq \eta < 0.90$	180 ± 40	198 ± 27	150 ± 40	31 ± 9	16 ± 7	2.2 ± 1.3	4.0 ± 1.8	0.4 ± 0.2	578
$0.90 \leq \eta < 1.37$	200 ± 40	233 ± 33	169 ± 50	35 ± 10	17 ± 8	9 ± 5	5.7 ± 2.1	1.0 ± 0.5	663
$1.37 \leq \eta < 2.37$	150 ± 40	344 ± 33	200 ± 12	48 ± 13	19 ± 9	13 ± 6	5.4 ± 2.5	1.4 ± 0.7	782

Post-fit event yields for the signal and backgrounds for the inclusive cross-section measurement and for the different bins of reconstructed photon p_T and η for the differential cross-section measurement. The uncertainties include the statistical and systematic uncertainties.

Variable	3ℓ -Z-1b4j	3ℓ -Z-2b3j	3ℓ -Z-2b4j	3ℓ -noZ-2b
Leading lepton			$p_T > 25 \text{ GeV}$	
Other leptons			$p_T > 20 \text{ GeV}$	
Sum of lepton charges			± 1	
Z -like OSSF pair	$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$			$ m_{\ell\ell} - m_Z > 10 \text{ GeV}$
n_{jets}	≥ 4	3	≥ 4	≥ 2 and ≤ 4
$n_{b-\text{jets}}$	1	≥ 2	≥ 2	≥ 2

Summary of event selections in the trilepton signal regions.

Region	Z_2 leptons	p_{T34}	$ m_{Z_2} - m_Z $	E_T^{miss}	$n_{b\text{-tags}}$
4 ℓ -DF-1b	$e^\pm \mu^\mp$	$> 35 \text{ GeV}$	-	-	1
4 ℓ -DF-2b	$e^\pm \mu^\mp$	-	-	-	≥ 2
4 ℓ -SF-1b	$e^\pm e^\mp, \mu^\pm \mu^\mp$	$> 25 \text{ GeV}$	$\left\{ \begin{array}{ll} > 10 \text{ GeV} & > 40 \text{ GeV} \\ < 10 \text{ GeV} & > 80 \text{ GeV} \end{array} \right\}$	$\left\{ \begin{array}{ll} > 10 \text{ GeV} & - \\ < 10 \text{ GeV} & > 40 \text{ GeV} \end{array} \right\}$	1
4 ℓ -SF-2b	$e^\pm e^\mp, \mu^\pm \mu^\mp$	-	$\left\{ \begin{array}{ll} > 10 \text{ GeV} & - \\ < 10 \text{ GeV} & > 40 \text{ GeV} \end{array} \right\}$	$\left\{ \begin{array}{ll} > 10 \text{ GeV} & - \\ < 10 \text{ GeV} & > 40 \text{ GeV} \end{array} \right\}$	≥ 2

Definitions of the four signal regions in the tetralepton channel. All leptons are required to satisfy $pT > 7 \text{ GeV}$ and at least one lepton with $pT > 25 \text{ GeV}$ is required to be trigger matched. The invariant mass of any two reconstructed OS leptons is required to be larger than 10 GeV.

$t\bar{t}W$ and $t\bar{t}Z$ 3.2 fb^{-1} @ 13 TeV Eur. Phys. J. C77 (2017) 40

Region	$t + X$	Bosons	Fake leptons	Total bkg.	$t\bar{t}W$	$t\bar{t}Z$	Data
3 ℓ -WZ-CR	0.52 ± 0.13	26.9 ± 2.2	2.2 ± 1.8	29.5 ± 2.8	0.015 ± 0.004	0.80 ± 0.13	33
4 ℓ -ZZ-CR	< 0.001	39.5 ± 2.6	1.8 ± 0.6	41.2 ± 2.7	< 0.001	0.026 ± 0.007	39
2 μ -SS	0.94 ± 0.08	0.12 ± 0.05	1.5 ± 1.3	2.5 ± 1.3	2.32 ± 0.33	0.70 ± 0.10	9
3 ℓ -Z-2b4j	1.08 ± 0.25	0.5 ± 0.4	< 0.001	1.6 ± 0.5	0.065 ± 0.013	5.5 ± 0.7	8
3 ℓ -Z-1b4j	1.14 ± 0.24	3.3 ± 2.2	2.2 ± 1.7	6.7 ± 2.8	0.036 ± 0.011	4.3 ± 0.6	7
3 ℓ -Z-2b3j	0.58 ± 0.19	0.22 ± 0.18	< 0.001	0.80 ± 0.26	0.083 ± 0.014	1.93 ± 0.28	4
3 ℓ -noZ-2b	0.95 ± 0.11	0.14 ± 0.12	3.6 ± 2.2	4.7 ± 2.2	1.59 ± 0.28	1.45 ± 0.20	10
4 ℓ -SF-1b	0.212 ± 0.032	0.09 ± 0.07	0.113 ± 0.022	0.42 ± 0.08	< 0.001	0.66 ± 0.09	1
4 ℓ -SF-2b	0.121 ± 0.021	0.07 ± 0.06	0.062 ± 0.012	0.25 ± 0.07	< 0.001	0.63 ± 0.09	1
4 ℓ -DF-1b	0.25 ± 0.04	0.0131 ± 0.0032	0.114 ± 0.019	0.37 ± 0.04	< 0.001	0.75 ± 0.10	2
4 ℓ -DF-2b	0.16 ± 0.05	< 0.001	0.063 ± 0.013	0.23 ± 0.05	< 0.001	0.64 ± 0.09	1

Expected event yields for signal and backgrounds, and the observed data in all control and signal regions used in the fit to extract the $t\bar{t}Z$ and $t\bar{t}W$ cross sections. The quoted uncertainties in expected event yields represent systematic uncertainties including MC statistical uncertainties. The tZ , tWZ , $t\bar{t}H$, three- and four-top-quark processes are denoted $t+X$. The WZ , ZZ , $H \rightarrow ZZ$ (ggF and VBF), HW and HZ and VBS processes are denoted 'Bosons'.

Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	2.6%	3.1%
Reconstructed objects	8.3%	9.3%
Backgrounds from simulation	5.3%	3.1%
Fake leptons and charge misID	3.0%	19%
Signal modelling	2.3%	4.2%
Total systematic	11%	22%
Statistical	31%	48%
Total	32%	53%

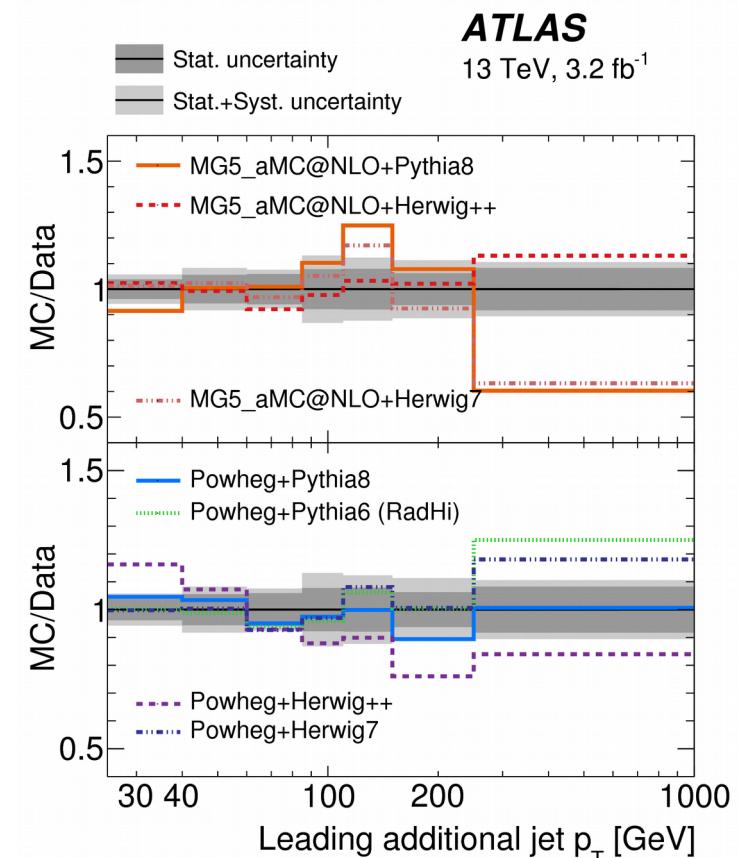
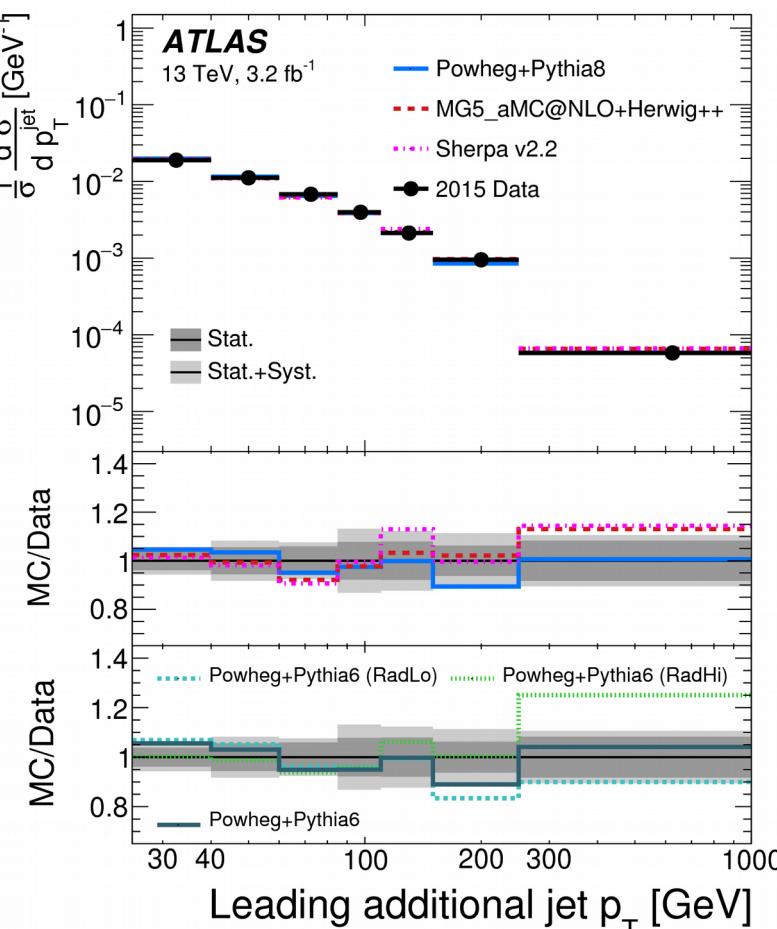
List of dominant and total uncertainties in the measured cross sections of the $t\bar{t}Z$ and $t\bar{t}W$ processes from the fit. All uncertainties are symmetrised.

- ◆ **p_T distributions** dominated by statistics, systematic uncertainties mostly from JES and modeling

- ◆ Best agreement for Powheg+Pythia8

- ◆ Some models show significant derivations from the data

- ◆ Measurement provides valuable input for MC tuning



- ◆ MG5_aMC@NLO and Powheg matched with different parton showers

$t\bar{t}$ + jets 3.2 fb^{-1} @ 13 TeV Eur. Phys. J. C77 (2017) 220

Process	Yield	
Single top (Wt)	236 ± 2 (stat.)	± 46 (syst.)
Fake leptons	117 ± 22 (stat.)	± 120 (syst.)
$Z+jets$	6 ± 3 (stat.)	± 1 (syst.)
Dibosons	3.1 ± 0.4 (stat.)	± 1.5 (syst.)
Total background	362 ± 22 (stat.)	± 130 (syst.)
$t\bar{t}$ (≥ 1 pile-up jet)	310 ± 2 (stat.)	± 88 (syst.)
$t\bar{t}$ (no pile-up jets)	6850 ± 11 (stat.)	± 940 (syst.)
Expected	7520 ± 25 (stat.)	
Observed	8050	

Yields of data and MC events fulfilling the selection criteria.

Sources	Relative uncertainty in [%] in additional jets multiplicity				
	0	1	2	3	≥ 4
Data statistics	2.1	2.7	4.0	6.0	9.0
JES/JER	5.0	1.8	7.0	12.0	16.0
<i>b</i> -tagging	0.5	0.2	0.7	1.4	2.0
ISR/FSR modelling	0.4	0.5	2.2	3.8	6.0
Signal modelling	1.9	2.0	5.6	6.0	11.0
Other	1.4	0.9	2.5	3.3	5.0
Total	6.0	4.0	10.0	16.0	24.0

Summary of relative uncertainties in [%] for the jet multiplicity measurement using a jet pT threshold of 25 GeV. "Signal modelling" sources of systematic uncertainty includes the hadronisation, parton shower and NLO modelling uncertainties. "Other" sources of systematic uncertainty refers to lepton and jet selection efficiencies, background (including pile-up jets) estimations, and the PDF.

$t\bar{t} + \text{jets}$ 3.2 fb $^{-1}$ @ 13 TeV Eur. Phys. J. C77 (2017) 220

Sources	Relative uncertainty in leading additional jet p_T [GeV] in [%]						
	25–40	40–60	60–85	85–110	110–150	150–250	> 250
Data statistics	3.8	6.0	6.0	8.0	8.0	6.0	8.0
JES/JER	2.9	3.3	2.1	2.7	3.8	3.8	4.2
b -tagging	0.3	0.2	0.6	0.4	0.6	0.4	1.3
ISR/FSR modelling	0.6	1.6	1.4	0.7	2.4	4.0	2.1
Signal modelling	2.5	4.0	3.6	10.0	8.0	8.0	4.0
Other	1.5	2.8	1.8	3.4	2.4	1.6	1.8
Total	6.0	8.0	8.0	13.0	12.0	11.0	11.0

Summary of relative measurement uncertainties in [%] for the leading additional jet p_T distribution. "Signal modelling" sources of systematic uncertainty includes the hadronisation, parton shower and NLO modelling uncertainties. "Other" sources of systematic uncertainty refers to lepton and jet selection efficiencies, background (including pile-up jets) estimations, and the PDF.