Highlights on top-quark properties, mass and cross-section measurements with the ATLAS detector

International Workshop on Deep Inelastic Scattering

L. Monsonis, on behalf of the ATLAS collaboration

IFIC, University of Valencia

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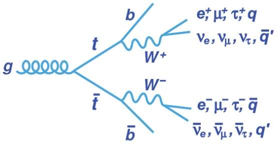
Top-quark properties, production and decay

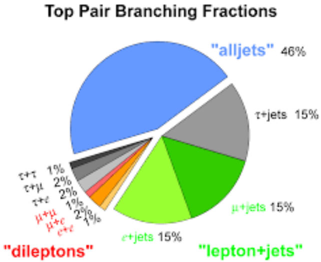
Top-quark properties (PDG-2012)

- Spin: $s = 1/2$
- Charge: $Q = +2/3$
- Mean lifetime: $\simeq 0.5 \;\; 10^{-24} s$

Top-quark production modes

- $t\bar{t}$ production
- Single top production
- Associated production

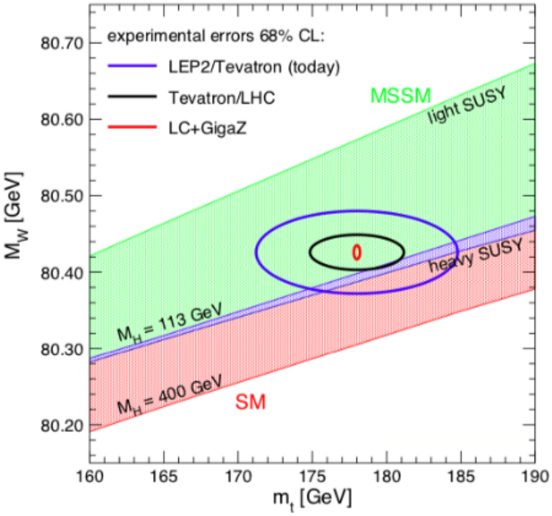




Top-quark is the unique quark which decays before hadronization due to its short lifetime. It allows the study of bare quarks

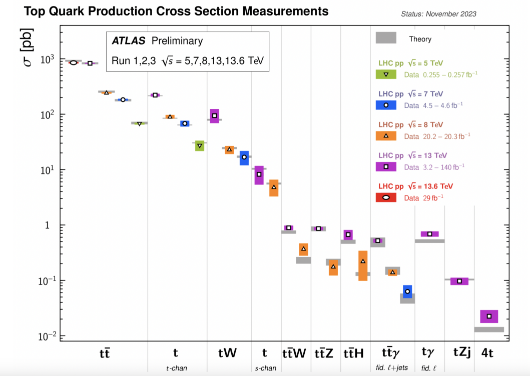
Top quark mass measurement

- Relations between top and Higgs masses change in new physics: mass measurements contribute to restrict the parameters space of BSM models.
- Yukawa coupling $\sim$ 1 to Higgs boson: the top and Higgs masses play a important role in the EW vacuum stability.



Top quark in LHC

- LHC is a **TOP QUARK FACTORY**.
- Large production cross sections provided by high center-of-mass energy.
- Allowing precision studies for:
  - Inclusive and differential cross-sections for various production processes.
  - Determination of top quark properties: mass, width, charge asymmetry, spin-correlation,...
  - Improving modeling of QCD and PDF.
- In this presentation a brief summary of the ATLAS recent properties top-quark properties measurements will be shown.



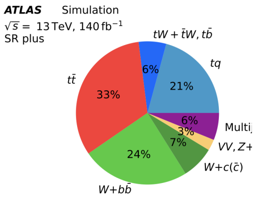
Single top t-channel total cross-section (arXiv:2403.02126)

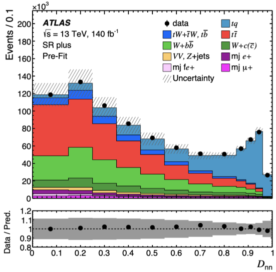
This analysis performs the measurement of the inclusive t-channel top and anti-top cross section and their ratio $R_t = \sigma_t/\sigma_{\bar{t}}$.

Motivation:

- Precision measurement of the largest single top production channel.
- To provide a measurement using the full Run 2 dataset (previous result uses 3.2 fb^{-1}).
- Testing pdfs (particularly for R_t).
- Extraction of $|V_{tb}|$ and also constraints on other CKM values.
- Search for new physics in the EFT framework.

A neural network has been used to separate t-channel single top-quark signal events from the expected background events.





Single top t-channel total cross-section (arXiv:2403.02126)

A binned profile maximum likelihood fit to neural network discriminant used to determine the cross-section.

$f_{lv}|V_{tb}| = 1.015 \pm 0.031$
30 % improvement respect combination ATLAS and CMS Run I measurement.

RESULTS:

σ_t	$\sigma_{\bar{t}}$	σ_{tch}	R_t
$137.0^{+8.1}_{-7.6}$	$83.8^{+5.5}_{-5.2}$	221^{13}_{-13}	$1.636^{+0.036}_{-0.034}$

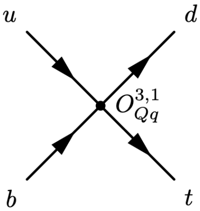
Relative uncertainties: ~ 6 % for each cross section.

PREDICTIONS:

σ_t	$\sigma_{\bar{t}}$
134.2 ± 2.2	80.0

EFT interpretation overview:

- Only the four-fermion operator $O^{3,1}_{Qq}$, constrain $C^{3,1}_{Qq}$, is consider.



- 95 % CL is extracted from a likelihood scan.
- Obtained confidence interval: $-0.272 < C^{3,1}_{Qq} < 0.206$.

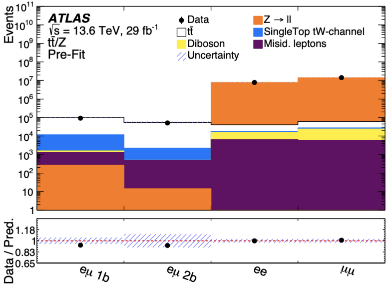
$t\bar{t}$ cross-section and $t\bar{t}/Z$ cross-section ratio using LHC Run 3 (Phys. Lett. B 848 (2024))

Motivation:

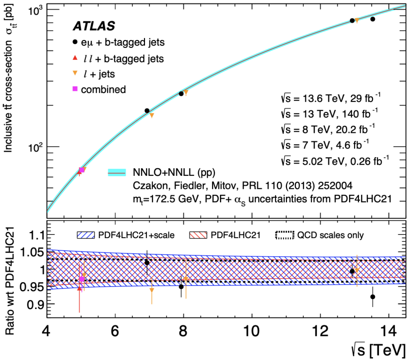
- Measure inclusive $t\bar{t}$ cross-section in dilepton channel only:
  - Smaller background.
  - Low dependence on jet uncertainties.
- Measure $t\bar{t}/Z$ cross-section ratio:
  - Lepton uncertainties are reduced somewhat.
  - Sensitive to gluon/quark PDFs.

$t\bar{t}$ cross section:

- A profile likelihood fit to the number of events with one b-tagged jet (N_1) and two b-tagged jets (N_2).



$t\bar{t}$ cross-section and $t\bar{t}/Z$ cross-section ratio using LHC Run 3 (Phys. Lett. B 848 (2024))



Expected values:

$$\sigma_{t\bar{t}}/\sigma_Z^{\rm SM} = 1.245 \pm 0.076(\text{scale} + \text{PDF}, \text{PDF4LHC21}),$$
$$\sigma_{t\bar{t}}^{\rm SM} = 924^{+32}_{-40}(\text{scale} + \text{PDF})\text{pb},$$
$$\sigma_Z^{\rm SM} = 741 \pm 15(\text{scale} + \text{PDF})\text{pb}$$

Fitted values:

$$\sigma_{t\bar{t}}/\sigma_Z = 1.145 \pm 0.003(\text{stat}) \pm 0.021(\text{syst}) \pm 0.002(\text{lumi}),$$
$$\sigma_{t\bar{t}} = 850 \pm 3(\text{stat}) \pm 18(\text{syst}) \pm 20(\text{lumi})\text{pb},$$
$$\sigma_Z = 743.6 \pm 0.2(\text{stat}) \pm 10.7(\text{syst}) \pm 16.9(\text{lumi})\text{pb},$$

- **Experimental uncertainties** for $\sigma_{t\bar{t}}$ and $\sigma_{t\bar{t}}/\sigma_Z$ are smaller than those of the theory predictions .
- Relative uncertainties around 2-3 % (limited by systematic uncertainties).

Differential cross section and large-R jet substructure measurement (arXiv:2312.03797)

This analysis performs the measurement of the substructure of top quark decays using the lepton+jets and all-hadronic final states in the boosted regime.

Motivation:

- Poor modelling of jet substructure in data by current MC generators.
- Effects beyond the SM can appear as modifications of the top-quark substructure.
- High sensitivity to some MC parameters.

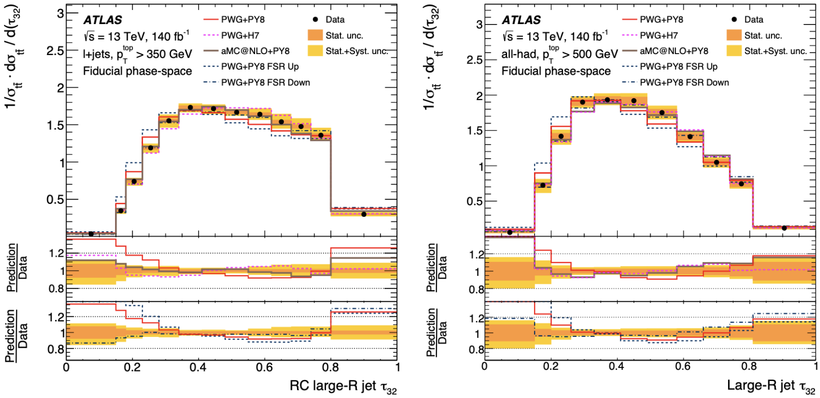
Unfolding is performed using Iterative Bayesian approach.

Substructure observables considered in the studies:

Variable	Motivation
N-Subjettiness Ratios	Tagging, sensitive to FSR/ISR variations, sensitive to generator variation
Energy-Correlation Functions	Tagging, sensitive to FSR variations, sensitive to generator variation
ECF Variables	Tagging, sensitive to FSR variations, sensitive to generator variation
k_t Splitting Functions	Sensitive to FSR/ISR variations, sensitive to generator variation
Eccentricity	Sensitive to FSR variations
Generalised Angularities	Sensitive to FSR/ISR variations, sensitive to generator variation
Q_W	Sensitive to FSR/ISR variations, sensitive to generator variation

Differential cross section and large-R jet substructure measurement (arXiv:2312.03797)

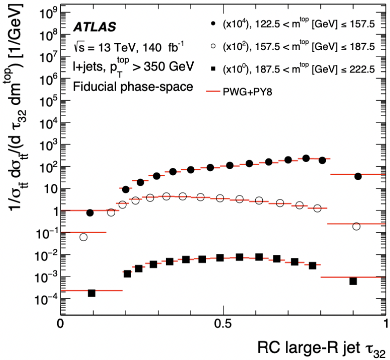
Results: Single Differential:

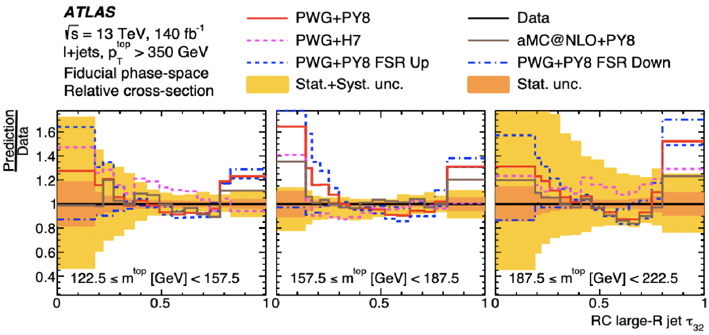


- τ_{32} is one of the variables with worst agreement with the data.
- In lepton+jets channel PWG+H7 and PWG+PY8 FSR down give the best agreement with data.

Differential cross section and large-R jet substructure measurement (arXiv:2312.03797)

Results: Double Differential:

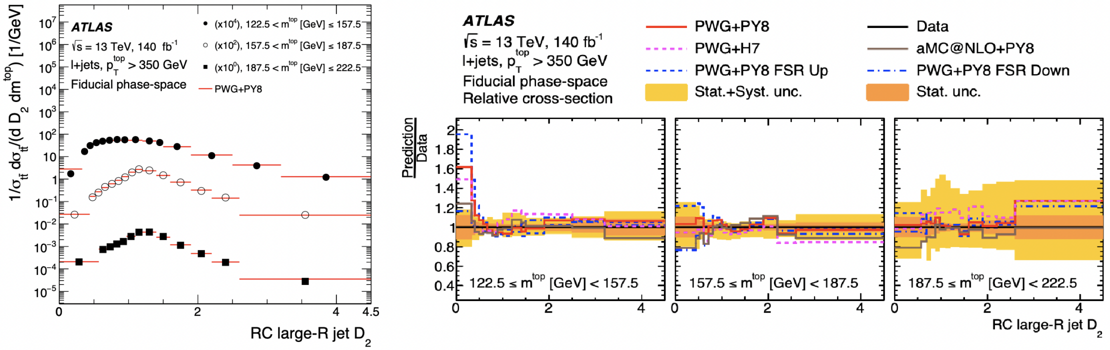




- The predictions of τ_{32} versus m_{top} show poor agreement in the central m_{top}.

Differential cross section and large-R jet substructure measurement (arXiv:2312.03797)

Results: Double Differential:



- The predictions of D_2 correlations with m_{top} and p_T^{top} are generally in better agreement with the unfolded data than τ_{32}

Top-quark mass combination ATLAS/CMS run I (arXiv:2402.08713)

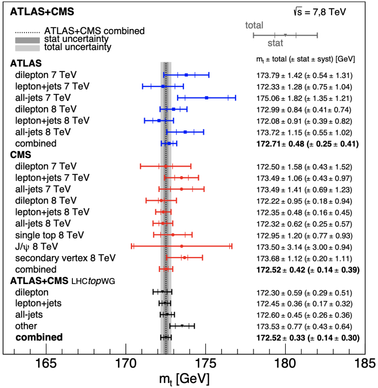
This analysis performs the combination of fifteen top-quark mass measurements performed by the ATLAS and CMS experiment at the LHC for 7, 8 TeV analysis in different final state channels.

Metodology:

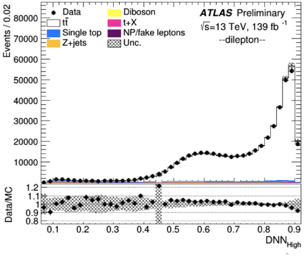
- Use Best Linear Unbiased Estimator method (BLUE).
- Must calculate/estimate the correlation between the measurements to get final covariance matrix.

Result:
$m_t = 172.52 \pm 0.14(\text{stat}) \pm 0.30(\text{syst})$ GeV (~ 0.2 % precision)

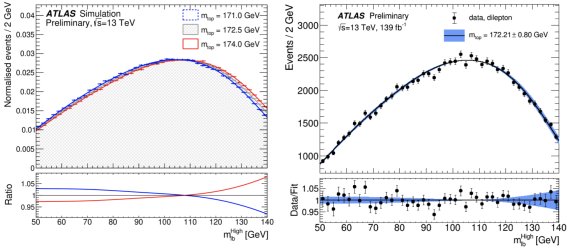
The combination achieves an improvement in the total uncertainty of 31% relative to the most precise input measurement.



Top-quark mass using dileptonic invariant mass(ATLAS-CONF-2022-058)



- Select top pairs dilepton channel
- Generate templates for m_{lb} distribution as a function of m_{top}.
- DNN for event reconstruction.
- Likelihood fit to find best value for m_{top}.



$$m_t = 172.21 \pm 0.20(stat) \pm 0.67(syst) \pm 0.39(recoil)GeV$$

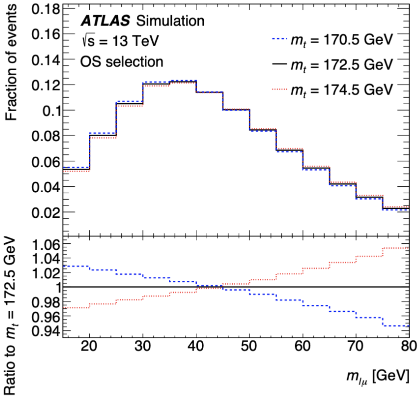
Leading systematic uncertainties: JES, recoil scheme, ME matching, color reconnection

Top-quark mass using a leptonic invariant mass(arXiv:2209.00583)

- Uses the semileptonic channel, data with 36.1^{-1} of luminosity.
- $m_{l\mu}$ is reconstructed with a lepton (e or μ) from W boson and a soft muon originating from a b-quark decays.
- Likelihood fit to find best value for m_{top}.

Motivation:

- Compared to the standard direct reconstruction methods:
  - Smaller sensitivity to the JES/JER.
  - Less sensitivity to top-quark production modelling.



Result:

$m_t = 174.41 \pm 0.39(\text{stat}) \pm 0.66(\text{syst}) \pm 0.25(\text{recoil})$ GeV

Quantum entanglement in events with top-quark pairs (arXiv:2311.07288)

Quantum Entanglement is the phenomena that the quantum state of each particle cannot be described independently of the state of other.

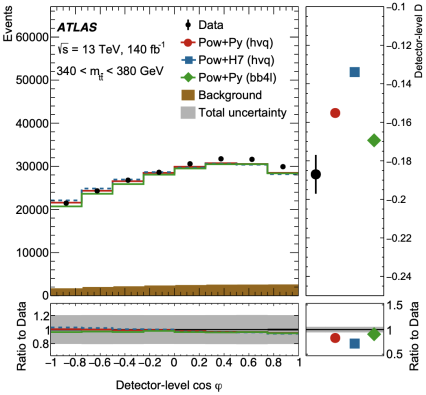
Motivation:

- Top quark properties allows us to test Quantum Entanglement.
- Not explicitly measured before between a pair of quarks.
- Use dilepton channel: leptons carry 100 % of the spin information of their parent top quark.

Condition for entanglement: $tr[C] + 1 < 0$, where C is the spin correlations matrix.

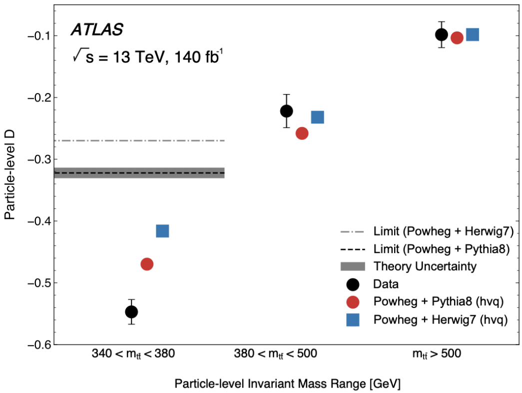
if $D = tr[C]/3$ where $D = -3 < cos\phi >$
$\rightarrow D < -1/3$

$cos(\phi)$ **detector distribution and D values:**



Quantum entanglement in events with top-quark pairs (arXiv:2311.07288)

- Select the most **sensitive kinematical region**: $m_{t\bar{t}} < 380$ GeV (Eur. Phys. J. Plus (2021)).
- Obtain the measured D from calibration curve.
- Measurement at particle level to reduce parton shower uncertainty.



Results:

$$D = -0.537 \pm 0.002[stat.] \pm 0.019[syst.] \text{ for } m_{t\bar{t}} < 380,$$

First observation of quantum entanglement in top quark events

Summary

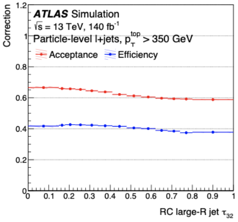
- LHC provided the largest top quark data sets ever.
- Many measurements with Run-2 data confirm good agreements with SM expectations.
- First Run-3 measurements are being published.
- Many precision measurements are limited by modelling uncertainties. Differential measurements improve them.
- Highlight selection of the latest ATLAS publications have presented in this talk (top public result webpage).
- Other interesting results:
  - t-channel production at 5 TeV (arXiv:2310.01518).
  - $t\bar{t}$ production at 8.16 TeV (ATLAS-CONF-2023-063).

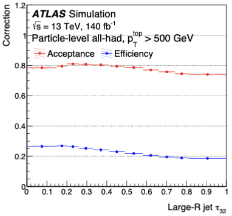
BACK UP

Differential cross section and large-R jet substructure measurement (arXiv:2312.03797)

Unfolding:

- Unfolding performed using Iterative Bayesian approach.
- Studying the average correlation factor, we have selected 6 as number of iterations for all observables.
- Unfolding Tests: Stress Test
  - Reweight the nominal prediction at both reco- and particle-level using the same stressing function f(x).
  - Calculate the ratio of the unfolded reweighted-reco to the reweighted-particle.
  - This ratio should be 1 if the unfolding is unbiased when subjected to the stress





$t\bar{t}$ cross-section and $t\bar{t}/Z$ cross-section ratio using LHC Run 3 (arXiv:2308.09529)

Observed impact of the different sources of uncertainty on the $t\bar{t}$ and Z-boson cross sections and their ratio R

	Category	Uncertainty [%]		
		$\sigma_{t\bar{t}}$	$\sigma^{\text{fid.}}_{Z\to\ell\ell}$	$R_{t\bar{t}/Z}$
$t\bar{t}$	$t\bar{t}$ parton shower/hadronisation	0.9	< 0.2	0.9
	$t\bar{t}$ scale variations	0.4	< 0.2	0.4
	$t\bar{t}$ normalisation	-	< 0.2	-
	Top quark p_{T} reweighting	0.6	< 0.2	0.6
Z	Z scale variations	< 0.2	0.4	0.3
Bkg.	Single top modelling	0.6	< 0.2	0.6
	Diboson modelling	< 0.2	< 0.2	0.2
	$t\bar{t}V$ modelling	< 0.2	< 0.2	< 0.2
	Fake and non-prompt leptons	0.6	< 0.2	0.6
Lept.	Electron reconstruction	1.2	1.0	0.4
	Muon reconstruction	1.4	1.4	0.3
	Lepton trigger	0.4	0.4	0.4
Jets/tagging	Jet reconstruction	0.4	-	0.4
	Flavour tagging	0.4	-	0.3
	PDFs	0.5	< 0.2	0.5
	Pileup	0.7	0.8	< 0.2
	Luminosity	2.3	2.2	0.3
	Systematic uncertainty	3.2	2.8	1.8
	Statistical uncertainty	0.3	0.02	0.3
	Total uncertainty	3.2	2.8	1.9

Top-quark mass combination ATLAS/CMS run I (arXiv:2402.08713)

Correlation strengths ρ of the systematic uncertainty categories between ATLAS and CMS, as used in the combination

Uncertainty category	ρ	Scan range	$\Delta m_t/2$ [MeV]	$\Delta\sigma_{m_t}/2$ [MeV]
JES 1	0	—	—	—
JES 2	0	$[-0.25, +0.25]$	8	7
JES 3	0.5	$[+0.25, +0.75]$	1	<1
b-JES	0.85	$[+0.5, +1]$	26	5
g-JES	0.85	$[+0.5, +1]$	2	<1
l-JES	0	$[-0.25, +0.25]$	1	<1
CMS JES 1	—	—	—	—
JER	0	$[-0.25, +0.25]$	5	1
Leptons	0	$[-0.25, +0.25]$	2	2
b tagging	0.5	$[+0.25, +0.75]$	1	1
p_T^{miss}	0	$[-0.25, +0.25]$	<1	<1
Pileup	0.85	$[+0.5, +1]$	2	<1
Trigger	0	$[-0.25, +0.25]$	<1	<1
ME generator	0.5	$[+0.25, +0.75]$	<1	4
QCD radiation	0.5	$[+0.25, +0.75]$	7	1
Hadronization	0.5	$[+0.25, +0.75]$	1	<1
CMS b hadron $\mathcal{B}$	—	—	—	—
Color reconnection	0.5	$[+0.25, +0.75]$	3	1
Underlying event	0.5	$[+0.25, +0.75]$	1	<1
PDF	0.85	$[+0.5, +1]$	1	<1
CMS top quark p_T	—	—	—	—
Background (data)	0	$[-0.25, +0.25]$	8	2
Background (MC)	0.85	$[+0.5, +1]$	2	<1
Method	0	—	—	—
Other	0	—	—	—

Top-quark mass combination ATLAS/CMS run I (arXiv:2402.08713)

The measured m_{top} is given together with the statistical top and systematic uncertainties in GeV for the m_{lb}^{High} observable

	m_{top} [GeV]
Result	172.21
Statistics	0.20
Method	0.05 ± 0.04
Matrix-element matching	0.40 ± 0.06
Parton shower and hadronisation	0.05 ± 0.05
Initial- and final-state QCD radiation	0.17 ± 0.02
Underlying event	0.02 ± 0.10
Colour reconnection	0.27 ± 0.07
Parton distribution function	0.03 ± 0.00
Single top modelling	0.01 ± 0.01
Background normalisation	0.03 ± 0.02
Jet energy scale	0.37 ± 0.02
b-jet energy scale	0.12 ± 0.02
Jet energy resolution	0.13 ± 0.02
Jet vertex tagging	0.01 ± 0.01
b-tagging	0.04 ± 0.01
Leptons	0.11 ± 0.02
Pile-up	0.06 ± 0.01
Recoil effect	0.39 ± 0.09
Total systematic uncertainty (without recoil)	0.67 ± 0.05
Total systematic uncertainty (with recoil)	0.77 ± 0.06
Total uncertainty (without recoil)	0.70 ± 0.05
Total uncertainty (with recoil)	0.80 ± 0.06