Measurements of associated top quark production and searches for new top quark phenomena with the ATLAS detector

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On behalf of the ATLAS Collaboration

Lake Louise Winter Institute 2022
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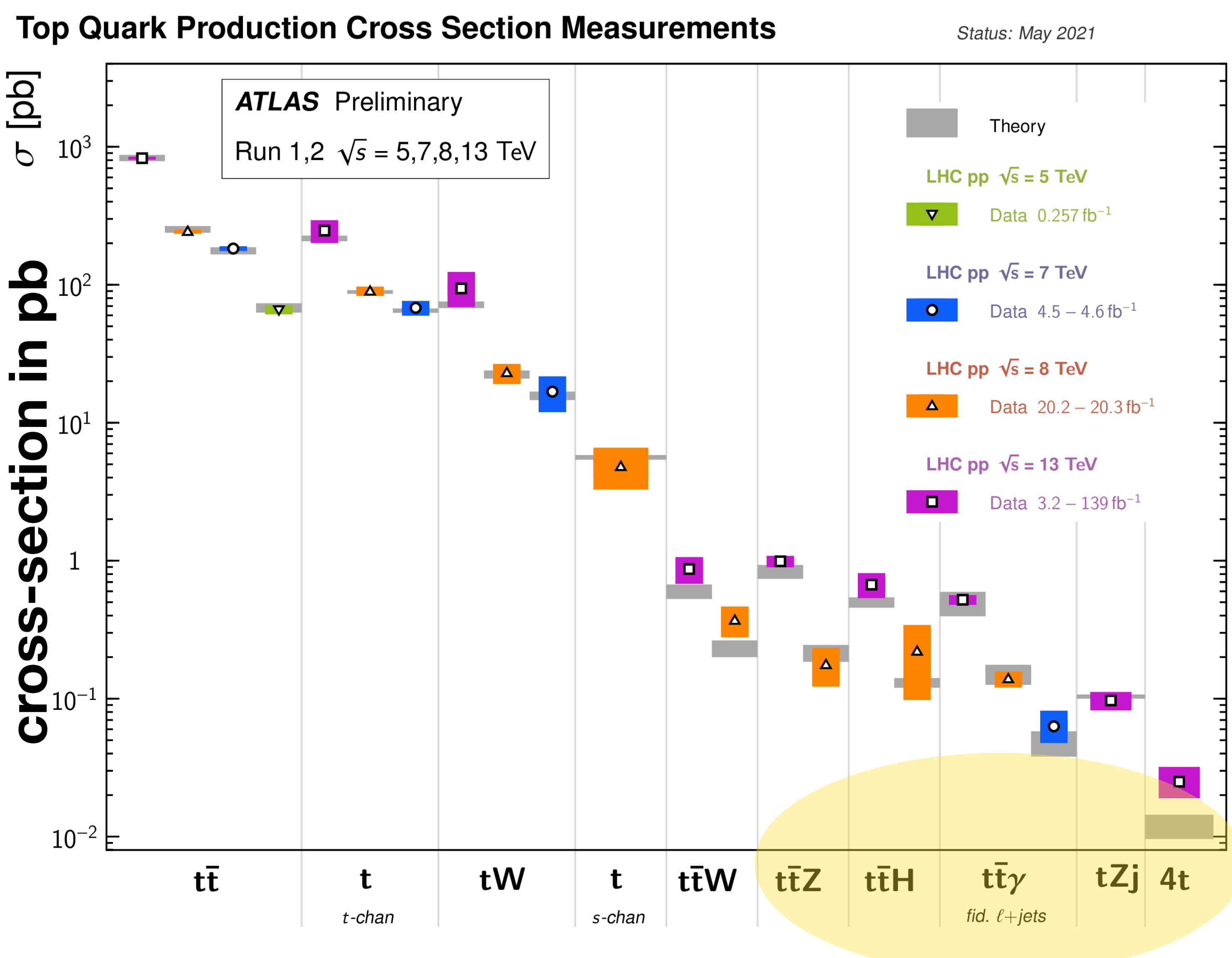
Introduction

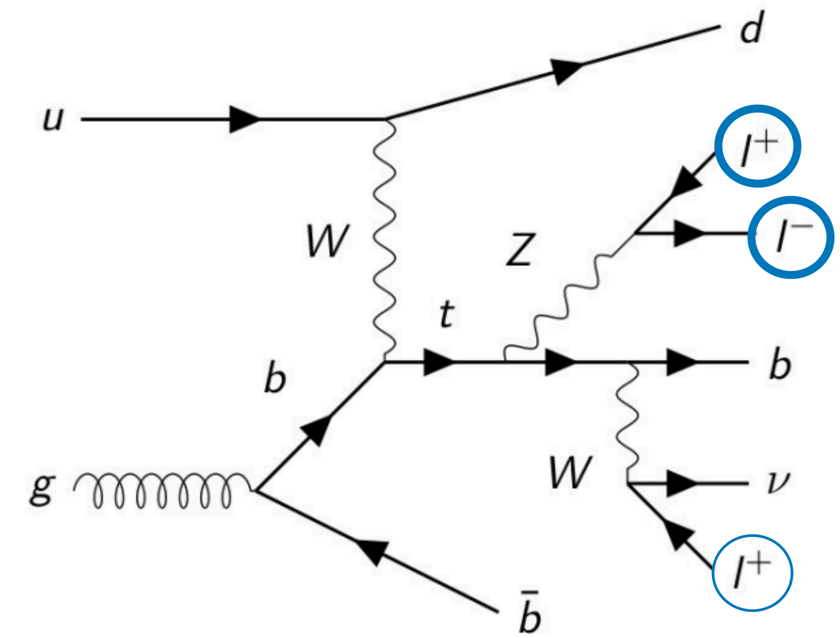
- Top quark is very special and produced at a very high rate at the LHC
- Run 2 of the LHC brought us to an unprecedented centre-of-mass energy of 13 TeV!
- Opened up measurements to new rare SM processes
  - Rare top production modes become fully accessible with Run 2 data
  - Results shown here use **139 fb^{-1}** of data
- **Rare top processes**:
  - Allow to probe top quark coupling to gauge bosons
    - tZq , $tq\gamma$, tWZ
  - Dominant and irreducible backgrounds to BSM searches
    - ttW, ttZ, $t\bar{t}t\bar{t}$
  - Sensitive to new physics effects (**FCNC** processes)



Different processes

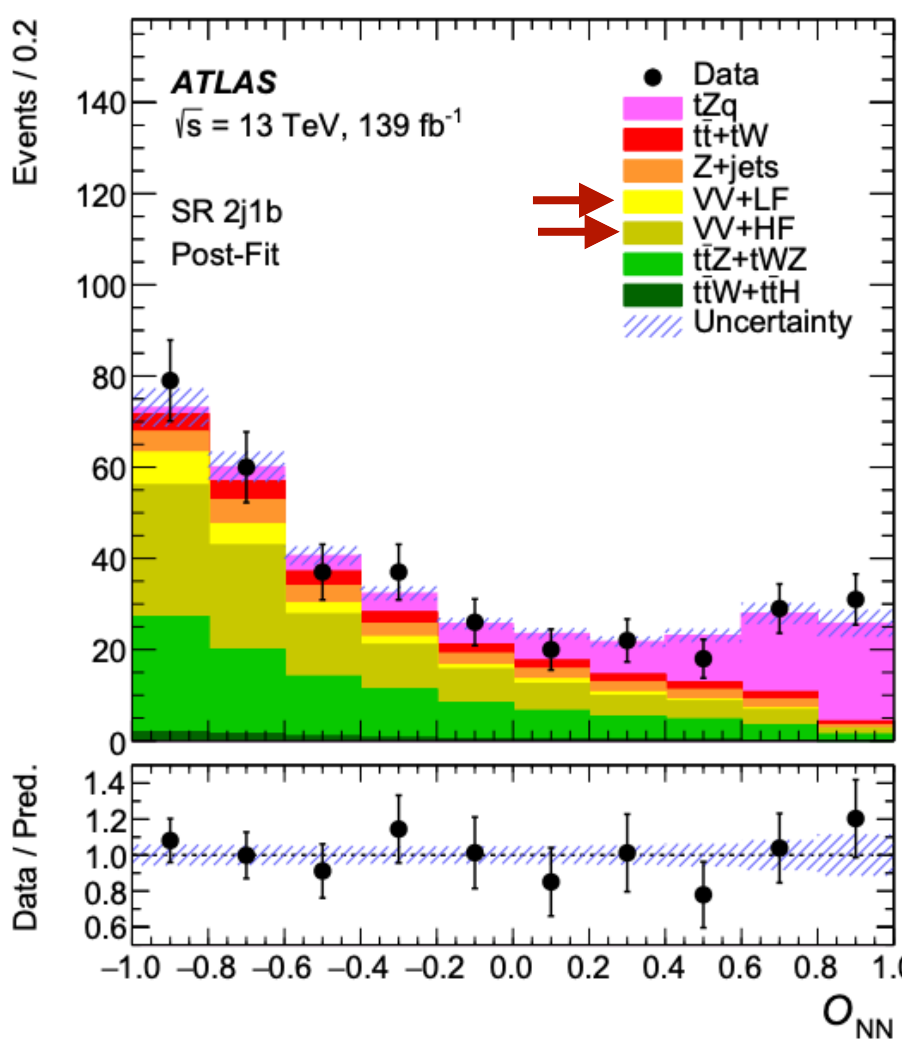
Observation of the electroweak production of tZq JHEP 07 (2020)

- **Strategy:**
- Events contain three isolated leptons (e/μ)
  - One pair should build a Z mass peak
- Two or three jets, one of which is identified as containing a b-hadron (b-tagged)
- Large background coming from diboson+Heavy Flavour jets (VV+HF)
- Signal and backgrounds are separated using a Neural Network
- Signal fraction is estimated using a profile-likelihood fit



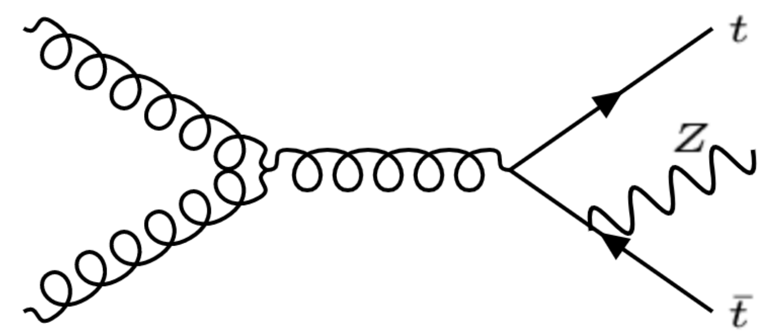
- **Results:**
- Yields a tZq production cross section of **97 ± 13 (stat.) ± 7 (syst.) fb** [SM cross section: 102^{+5}_{-2} fb]
- **Statistically limited**, systematics dominated by prompt lepton background
- **Observation with $> 5\sigma$**

Neural network output

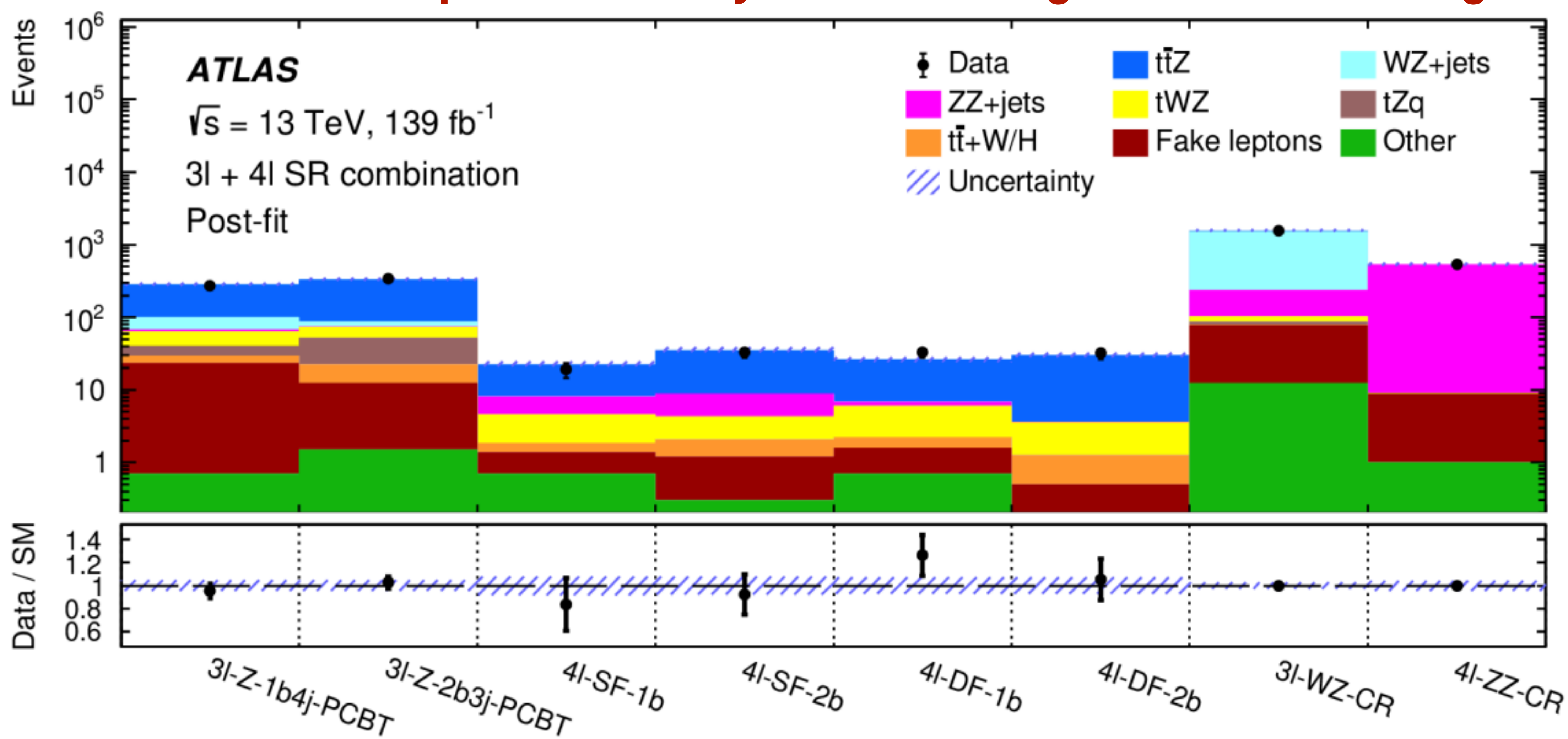


Inclusive & differential $t\bar{t}Z$ production [Eur. Phys. J. C 81 (2021) 737]

- Inclusive and differential measurement, targeting 3-lepton and 4-lepton channels (e/μ)
- ≥ 3 jets and ≥ 1 b-jet
- Control regions for WZ and ZZ backgrounds (free-floating)
- Expected cross section: $\sigma^{\text{exp}}_{t\bar{t}Z} = 0.84^{+0.09}_{-0.10}$ pb
- Measured cross-section: $\sigma_{t\bar{t}Z} = 0.99 \pm 0.05(\text{stat.}) \pm 0.08(\text{syst.})$ pb

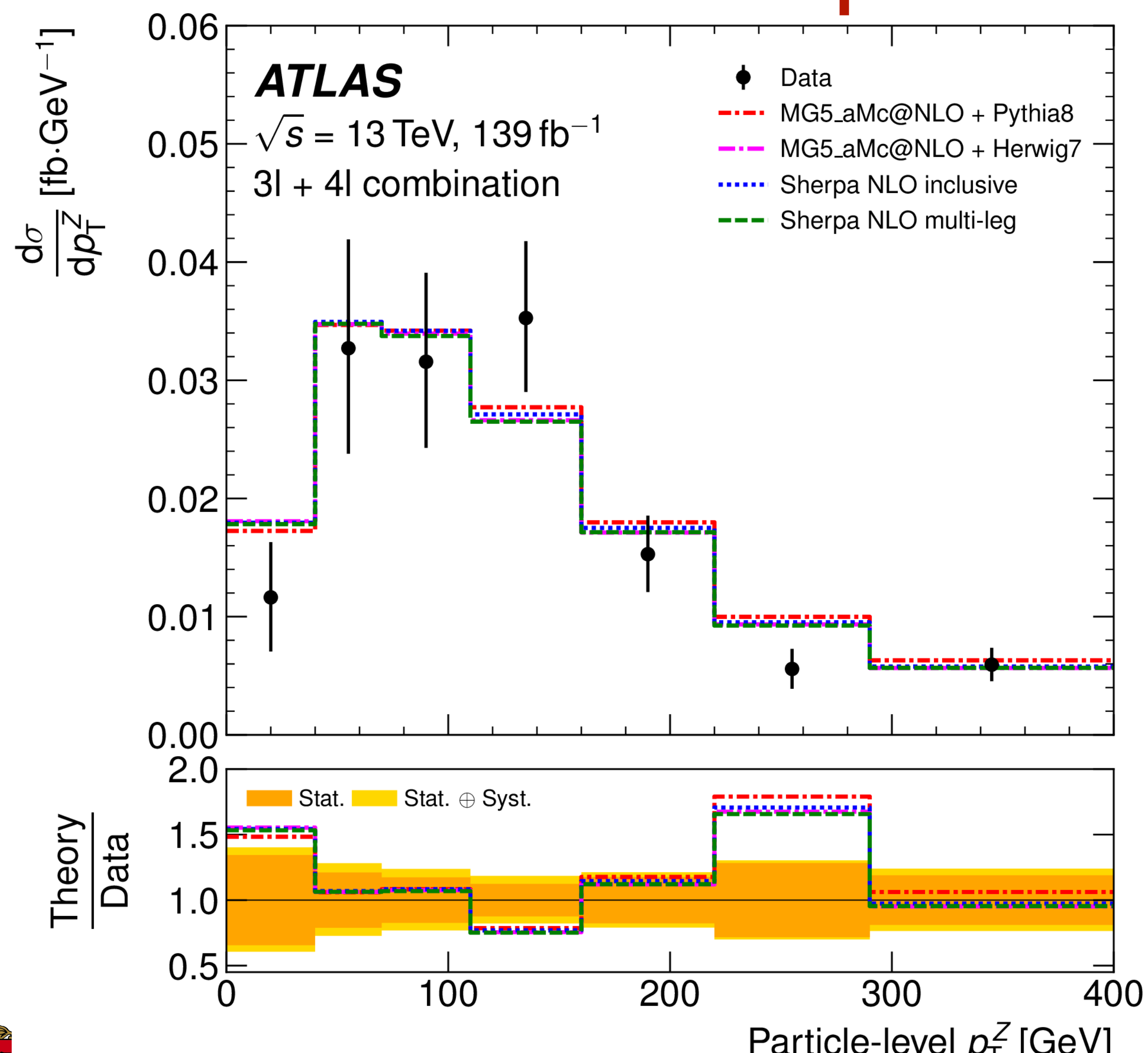


Observed and expected event yields in the Signal and Control regions

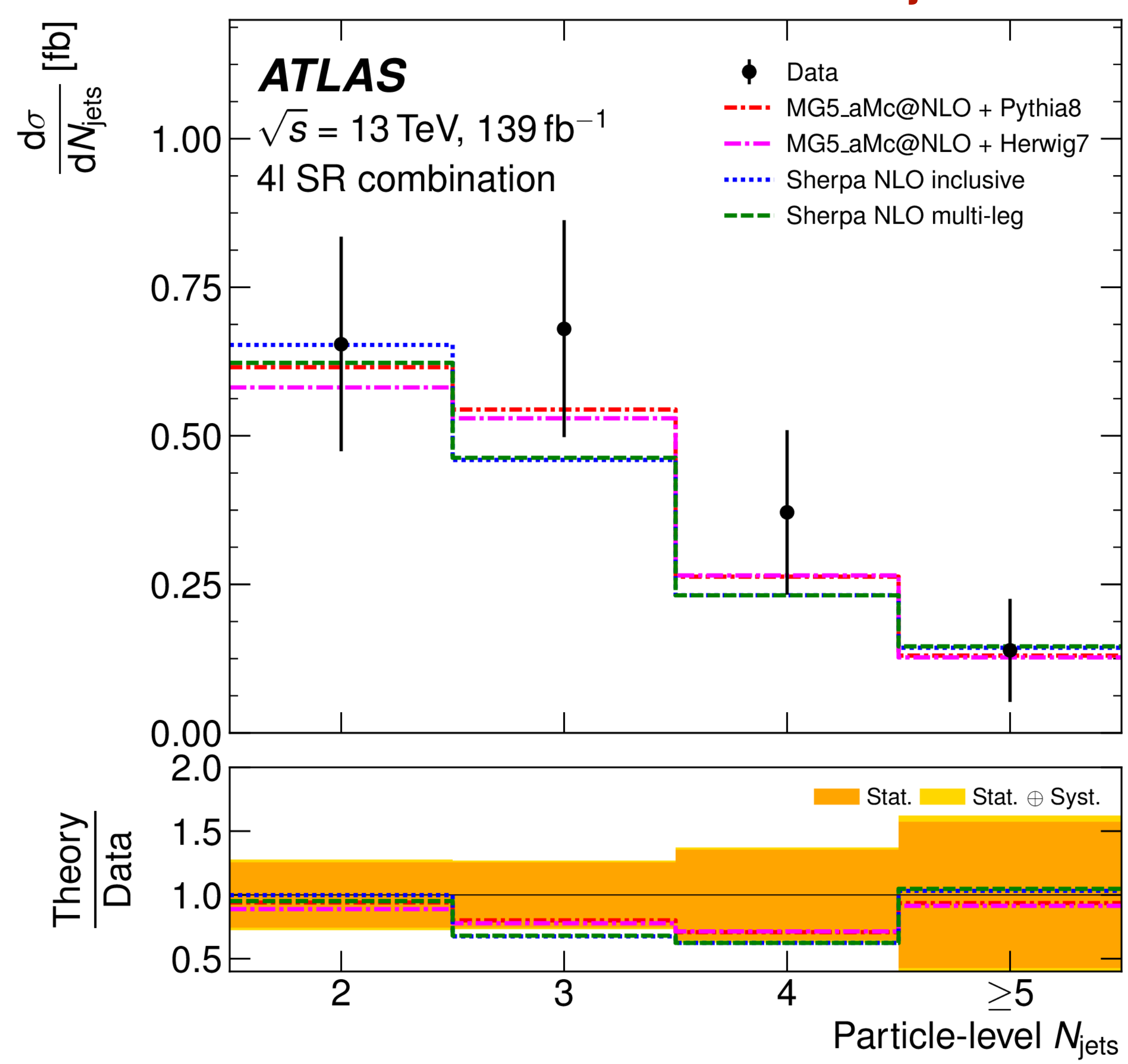


- 10 observables unfolded to parton and particle level
  - Sensitive to BSM effects and modeling
- Dominated by stat. uncertainty
- Main systematic uncertainties are: Fake leptons, WZ modeling, $t\bar{t}Z$ modeling, and b-tagging

Particle-level p_T^Z



Particle-level N_{jets}

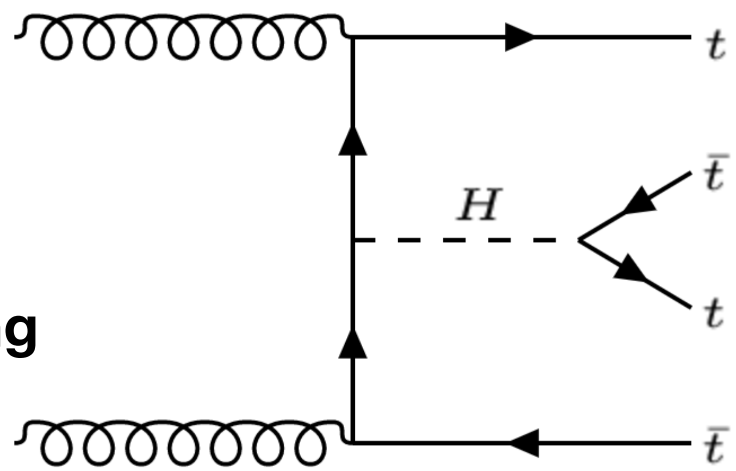


Good agreement with the prediction!

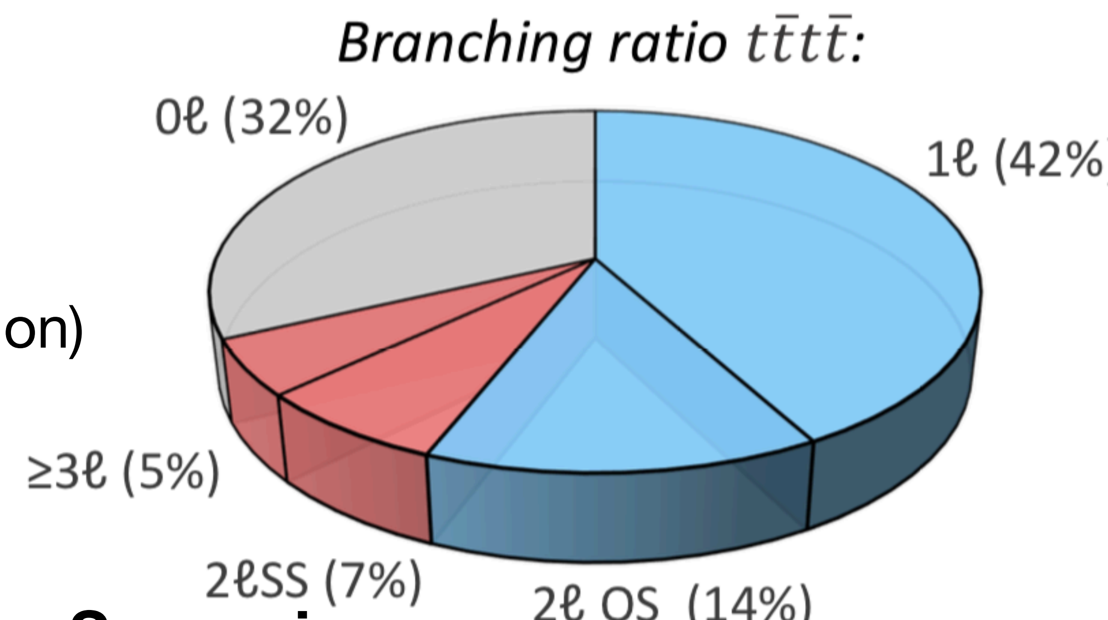
Production of four tops

Eur.Phys. J. C (2020)80:10985   JHEP 11 (2021)118

- **Rare process predicted by the SM and has never been observed**
  - $\sigma_{SM}(t\bar{t}t\bar{t})$ = 11.97 fb at NLO (QCD+QED) at **13 TeV**



- **Sensitive to the magnitude and CP properties of the Yukawa coupling of the top quark to the Higgs boson**
- **Sensitive to many BSM models** (EFT, 2HDM SUSY, …)
- Channels are split according to:
  - **2ℓSS** (7%) / **3ℓ** (5%)
    - Small branching fraction & Small background ($t\bar{t}W$, $t\bar{t}Z$, non-prompt leptons, charge misidentification)
    - Most sensitive channel
  - **1ℓ** (42%) / **2ℓOS** (14%)
    - Dominant branching fraction
    - Large irreducible background from **tt+jets** (tt+heavy flavour jets)



Same sign

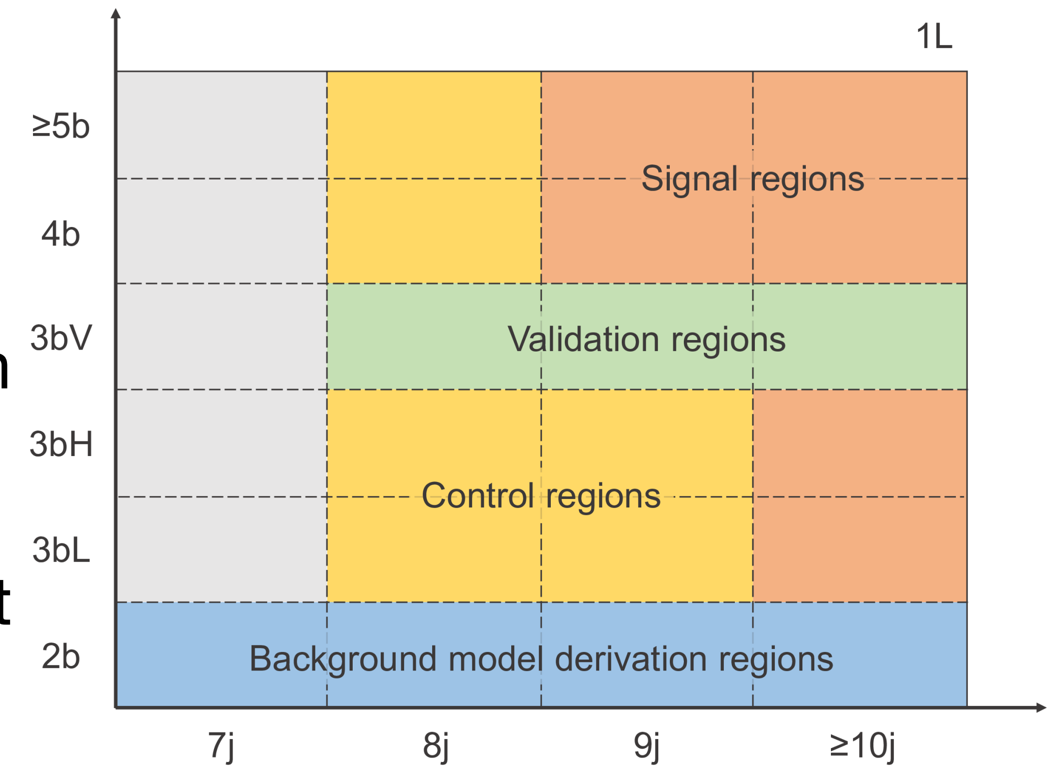
Opposite sign

Production of four tops

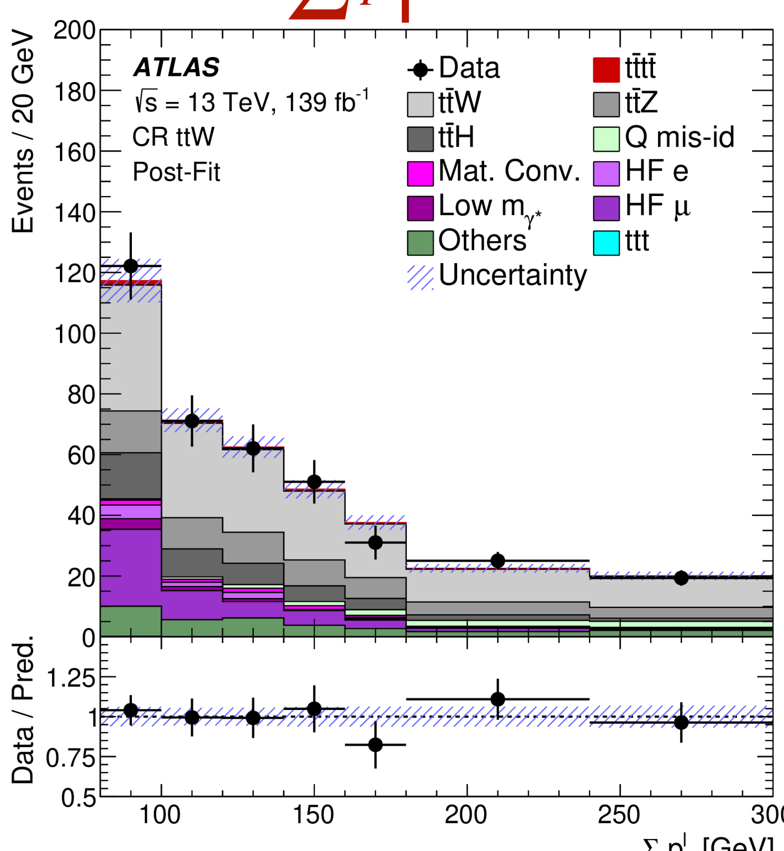
[Eur.Phys. J. C (2020)80:10985](#) [JHEP 11 (2021)118](#)

- Targeting events with high **jet** and **b-jet** multiplicities
- Split in multiple regions: Control (CR) signal (SR) and validation (VR) regions
  - Dedicated Control Regions are defined to constrain normalisation factors in **2ℓSS/3ℓ channel**
  - Designed a 3-step sequential re-weighting to target different type of mismodeling in the **1ℓ/2ℓOS**

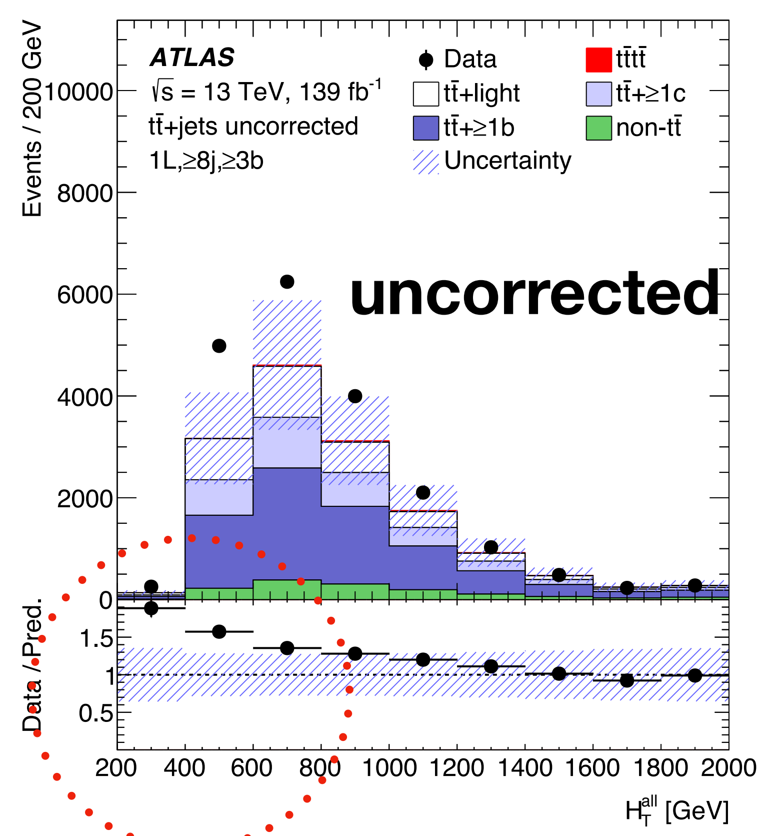
Regions in the 1l channel



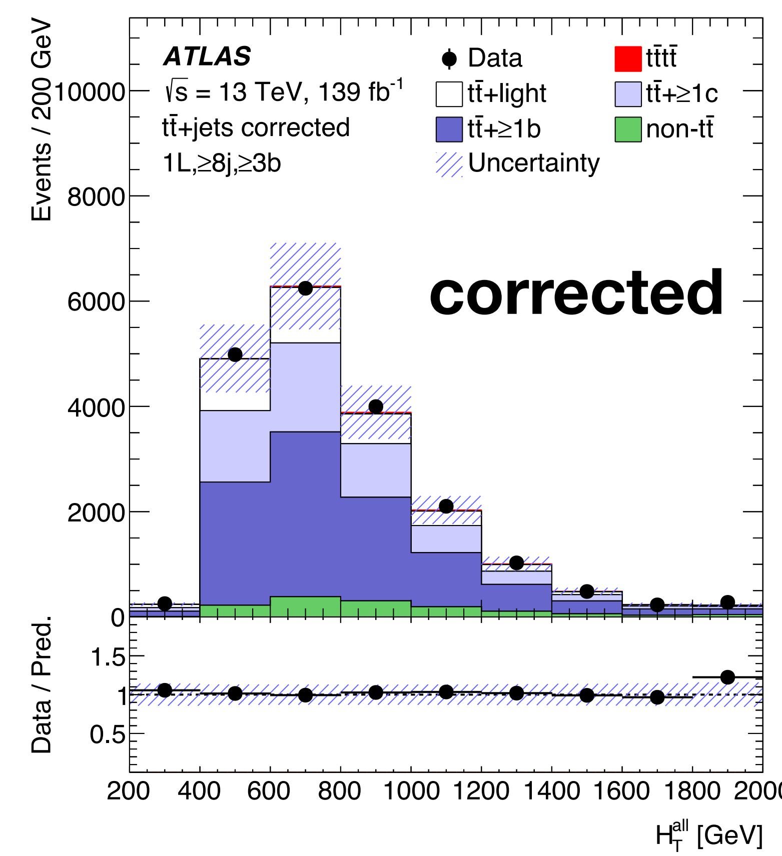
$\sum p_T^{\text{lepton}}$



H_T^{all}



H_T^{all}

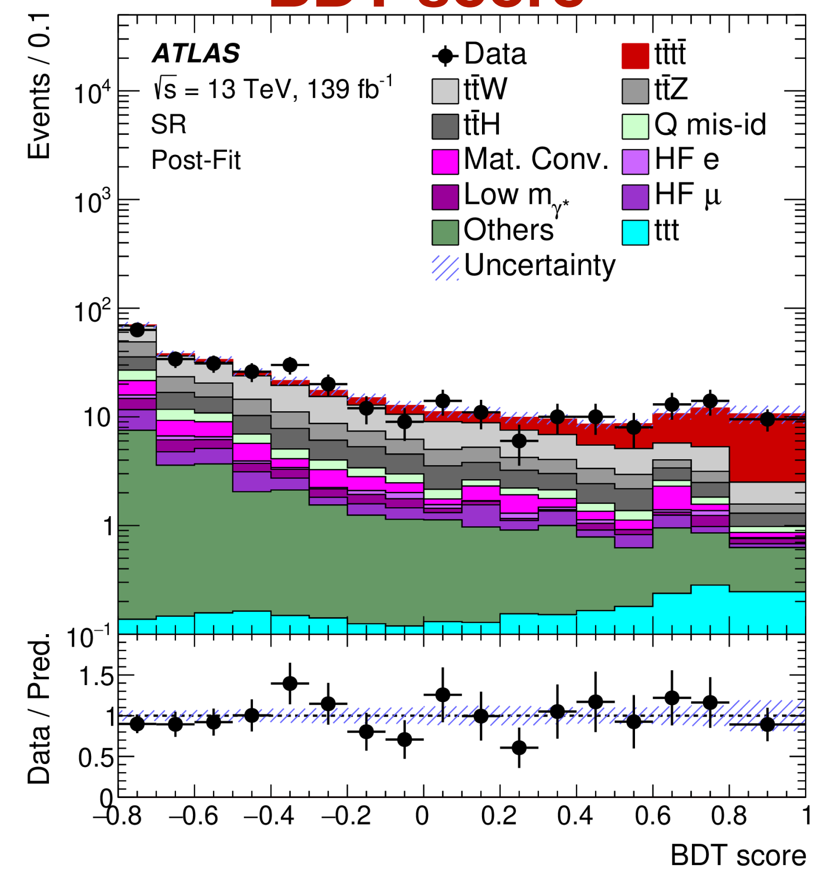


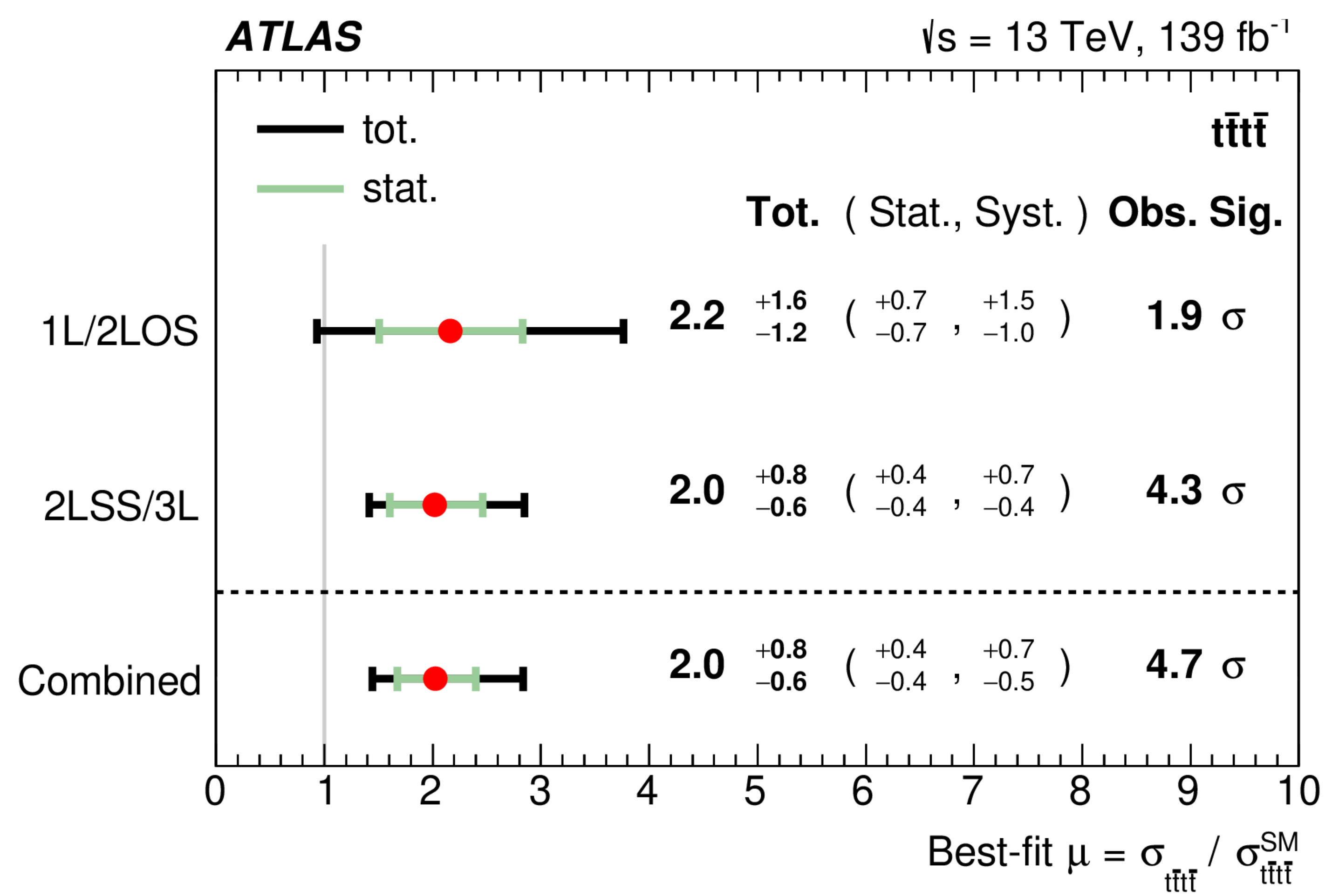
Production of four tops

Eur.Phys. J. C (2020)80:10985 JHEP 11 (2021)118

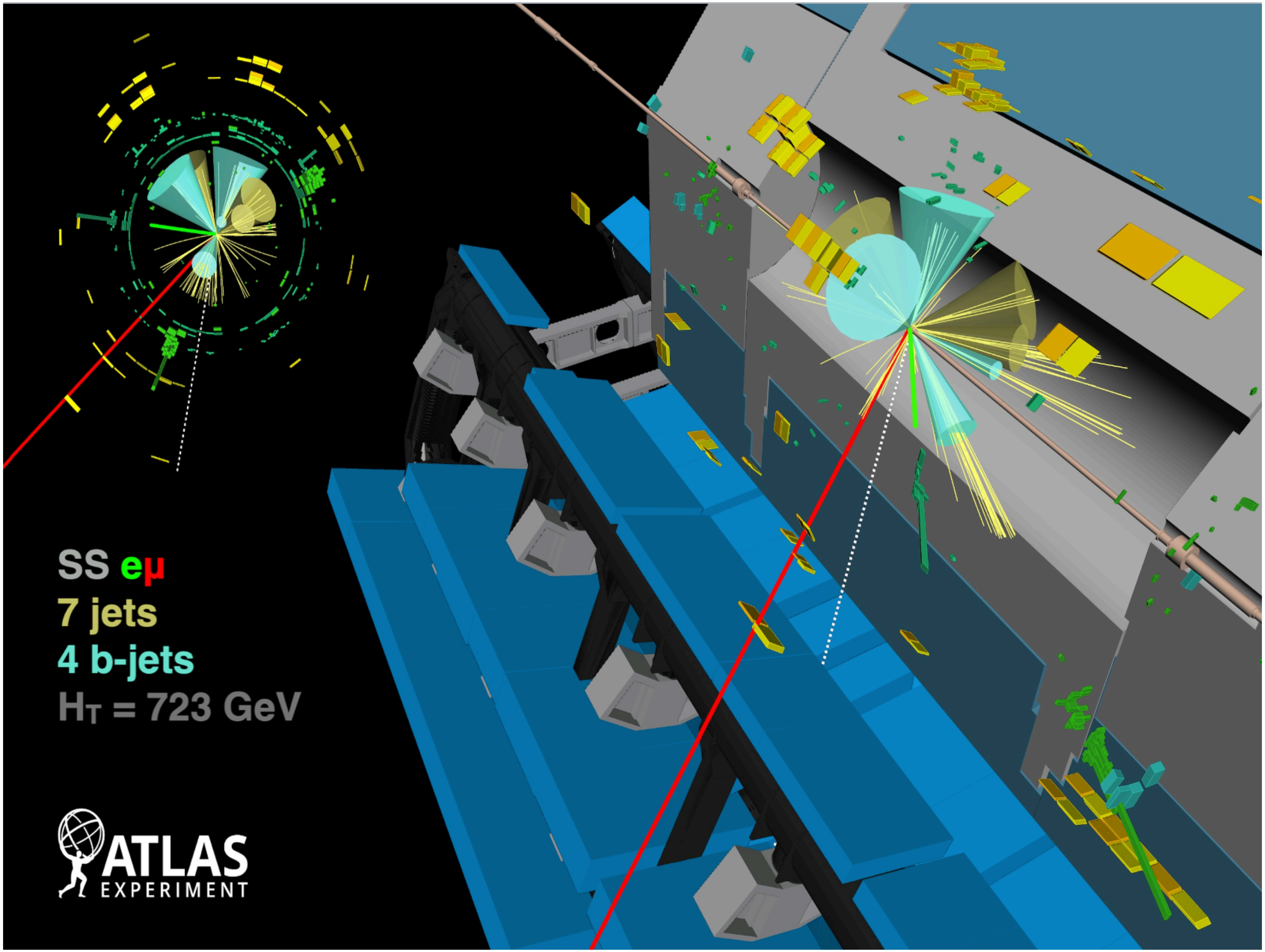
- Signal is separated from background based on a BDT in the SR
- A simultaneous profile likelihood fit is performed in the CR and SR
- The combined four-top cross-section: $\sigma(t\bar{t}t\bar{t}) = 25^{+7}_{-6}\ fb$
- To be compared to $\sigma(t\bar{t}t\bar{t}) = 12 \pm 2.4\ fb$
- Compatible with the SM prediction within 2.0 σ
- Observed (expected) significance: **4.7** (**2.6**) **σ**
- The dominant systematics uncertainties:
  - modeling of the four top signal
  - modeling of $t\bar{t}W$ and $t\bar{t}$+jets
  - b-tagging and Jet Energy Scale

BDT score



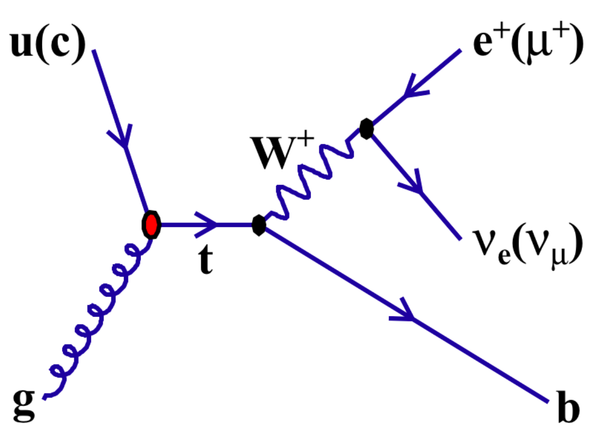


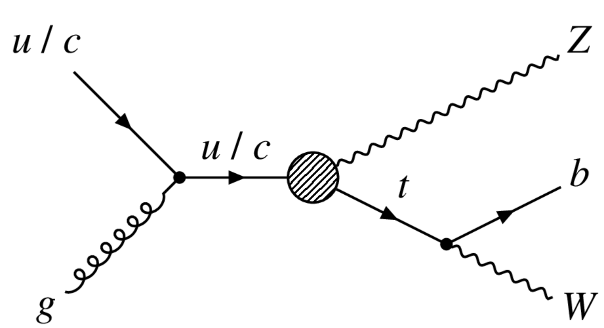
ATLAS finds first evidence the four top quark process!

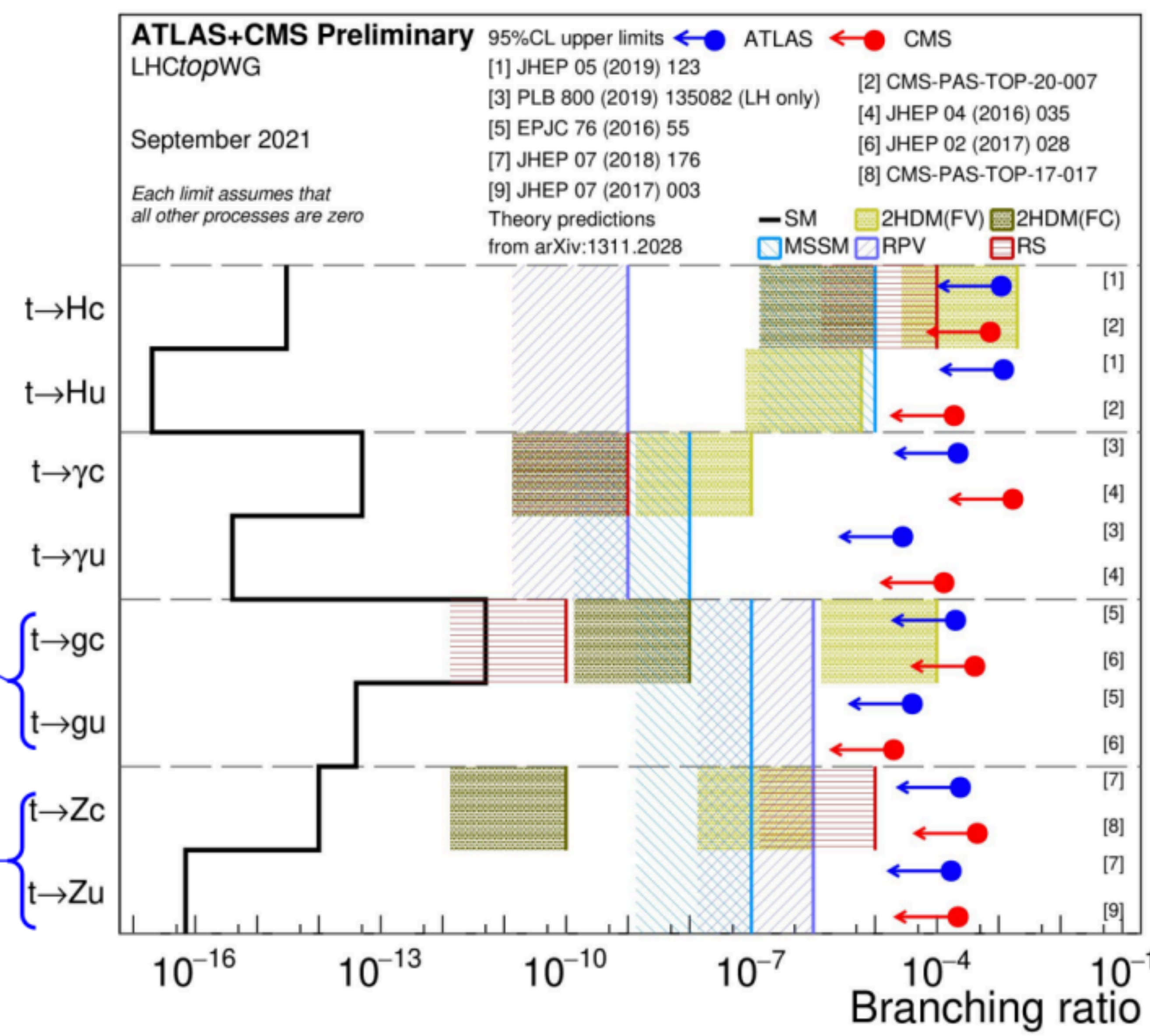


Searches for Flavour Changing Neutral Current (FCNC)

- FCNC in the SM is forbidden at tree-level: heavily suppressed in loops by GIM mechanism BRs ~10^{-14}
- BSM can enhance FCNC up to ~10^{-4}
  - Many potential models: 2HDM, MSSM, RPV SUSY, …
- Any observation of FCNC can hint to new physics
- FCNC probe can be done in both top quark **production**, and **decay**







FCNC Search for $t \to Zq$ ATLAS-CONF-2021-049

- **Strategy:**

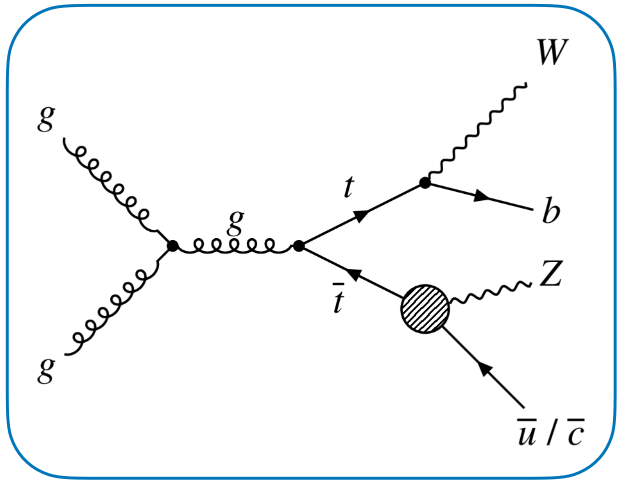
- Events contain three isolated leptons leptons (e, μ) ≥2 jets, (one b-tagged) and MET

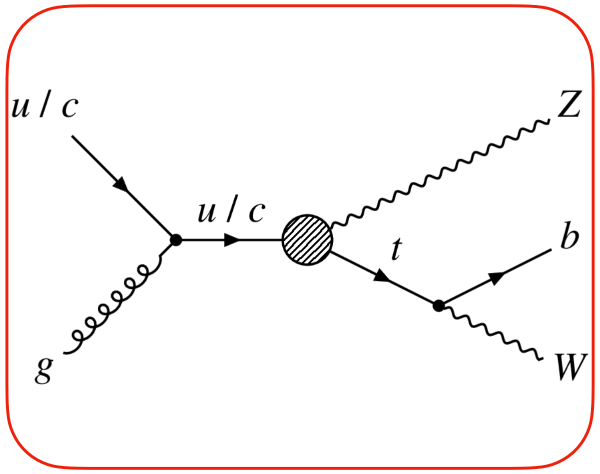
- Only Z boson decays into charged leptons and leptonic W boson decays are considered as signal

- 2 signal regions (SRs) considered targeting FCNC in production and decay:
  - SR1 (ttbar decay): ≥2 jets, 1 b-tag
  - SR2 (tZ production): 1& 2 jets, 1 b-tag

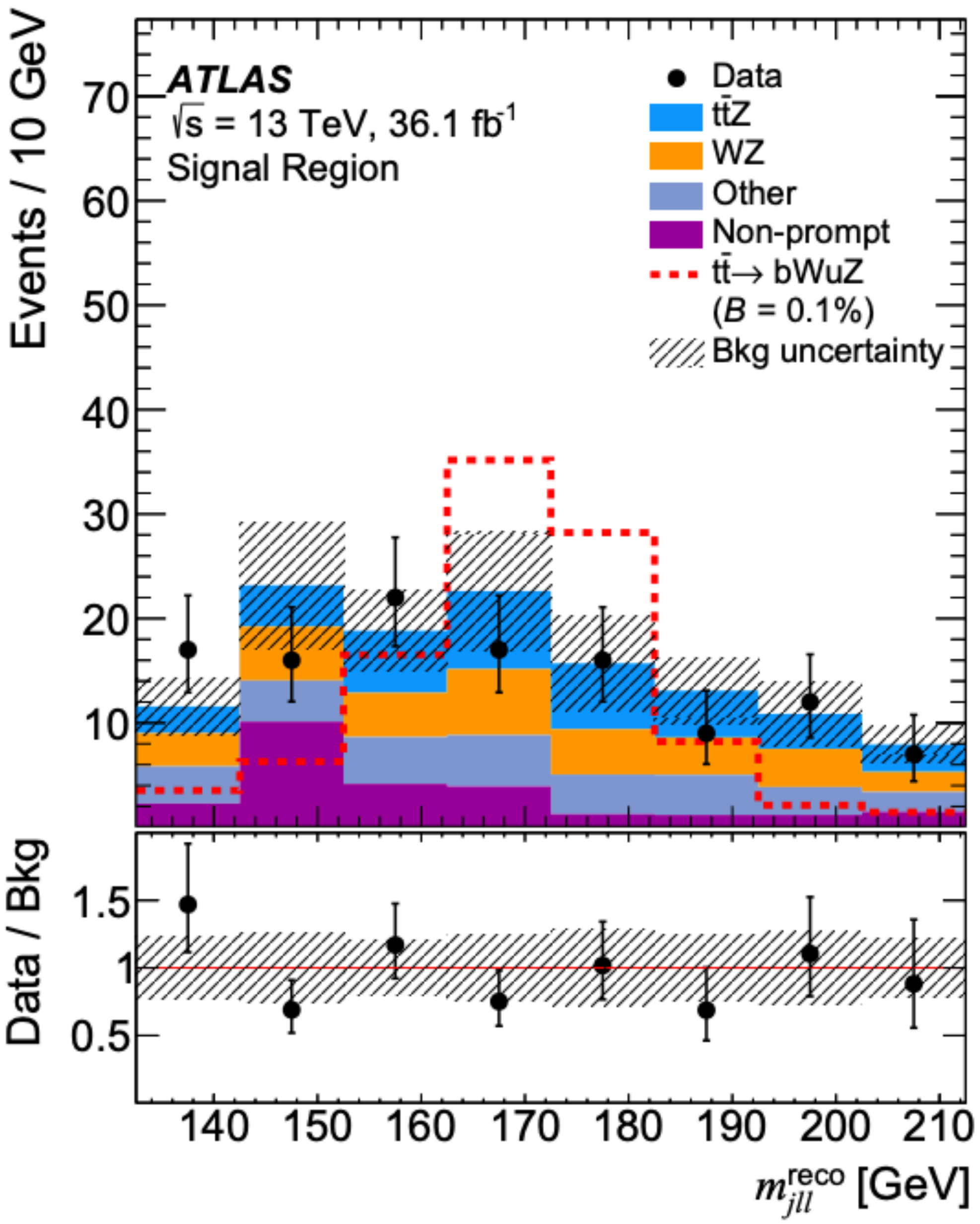
- Events reconstructed via minimisation of kinematic properties of the final state objects under the FCNC top hypothesis
  - Mass veto to ensure orthogonality in 2j events

- Largest background contributions from **Diboson** and $t\bar{t}Z$



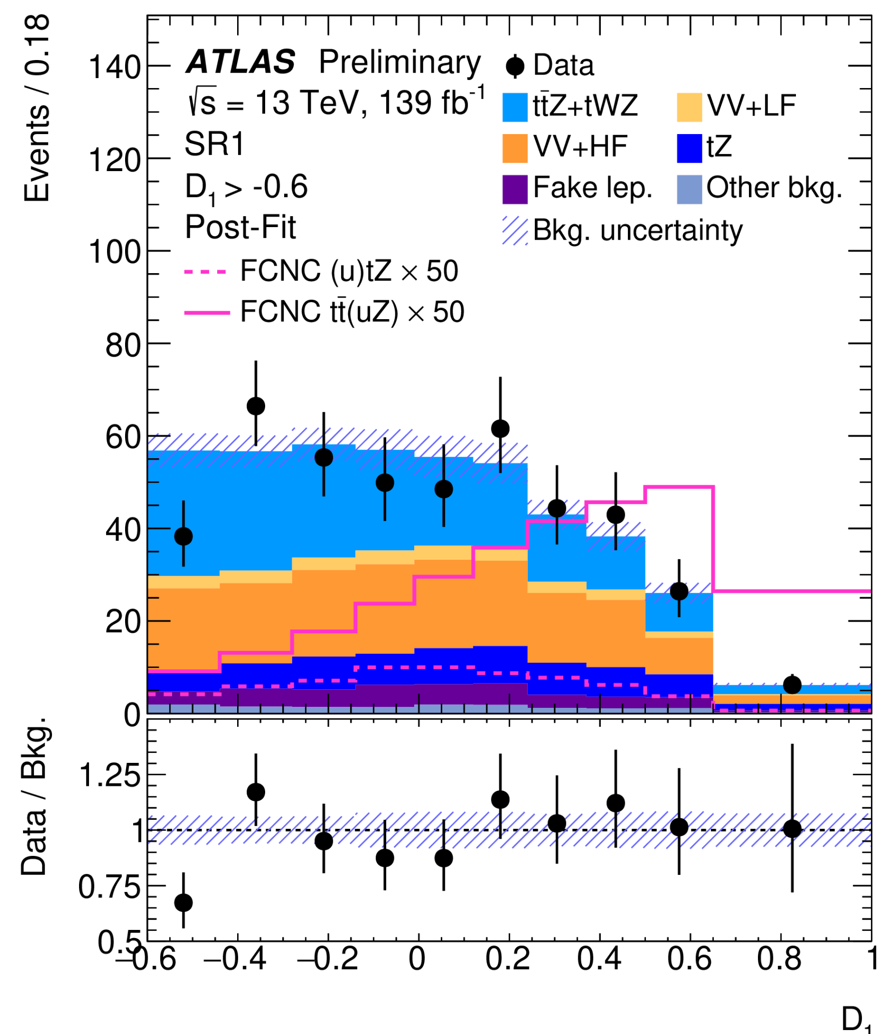


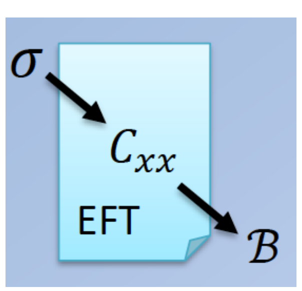
Mass of the FCNC top-quark candidate in SR1



- Gradient BDT used to better separate signal from backgrounds
- Four separate fits performed to extract **LH** and **RH** results for the FCNC **tZu** and **tZc** couplings
- Good agreement between MC predictions and data
- 95% CL upper limits set on branching ratios for both tZu and tZc vertices and for both RH/LH couplings
  - **Improved by a factor of 2-3 on previous limits**
- Limits on relevant EFT Wilson coefficients for vertices also set

D_1 discriminant in SR1

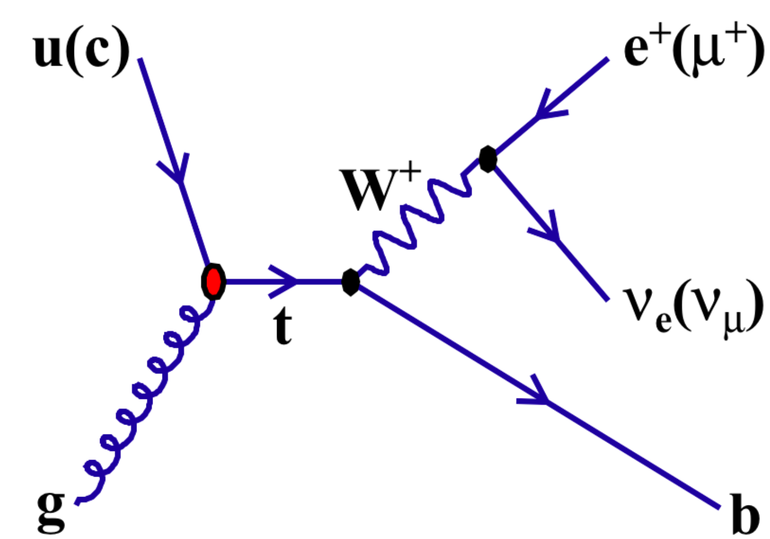




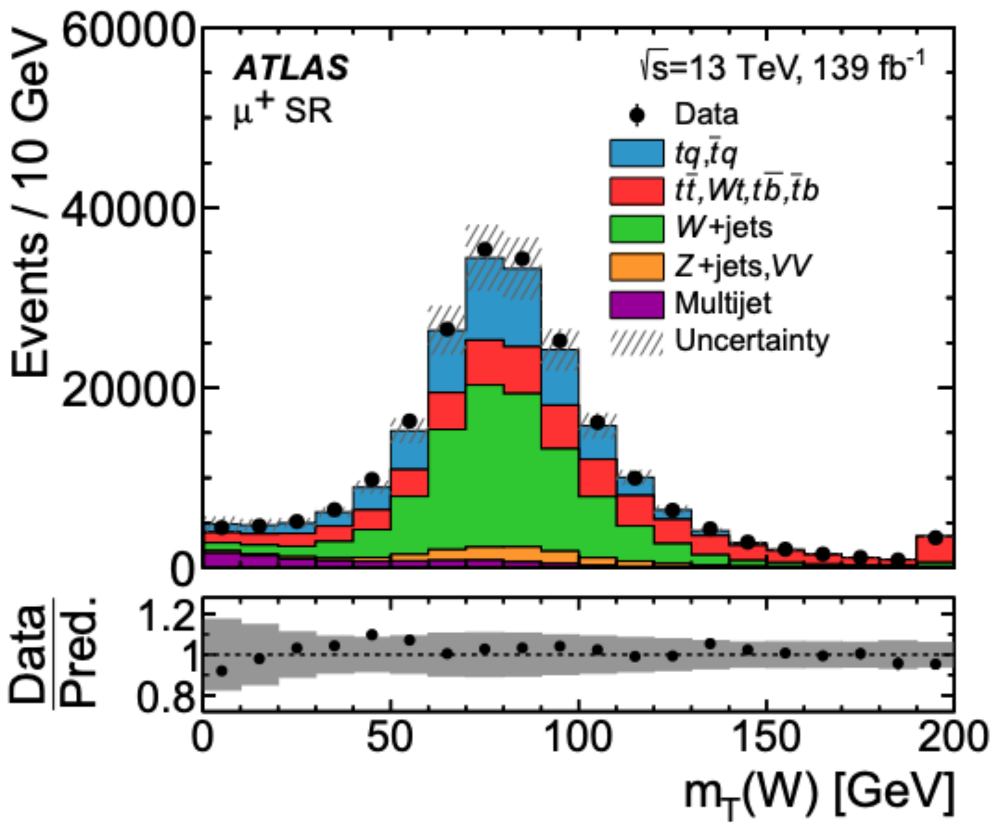
Observable	Vertex	Coupling	Observed	Expected
$\mathcal{B}(t \to Zq)\ [10^{-5}]$	tZu	LH	6.2	$4.9^{+2.1}_{-1.4}$
$\mathcal{B}(t \to Zq)\ [10^{-5}]$	tZu	RH	6.6	$5.1^{+2.1}_{-1.4}$
$\mathcal{B}(t \to Zq)\ [10^{-5}]$	tZc	LH	13	11^{+5}_{-3}
$\mathcal{B}(t \to Zq)\ [10^{-5}]$	tZc	RH	12	10^{+4}_{-3}
$\lvert C_{uW}^{(13)*}\rvert, \lvert C_{uB}^{(13)*}\rvert$	tZu	LH	0.15	$0.13^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(31)}\rvert, \lvert C_{uB}^{(31)}\rvert$	tZu	RH	0.16	$0.14^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(23)*}\rvert, \lvert C_{uB}^{(23)*}\rvert$	tZc	LH	0.22	$0.20^{+0.04}_{-0.03}$
$\lvert C_{uW}^{(32)}\rvert, \lvert C_{uB}^{(32)}\rvert$	tZc	RH	0.21	$0.19^{+0.04}_{-0.03}$

FCNC Search for top-gluon with $t \to l\nu b$ 2112.01302

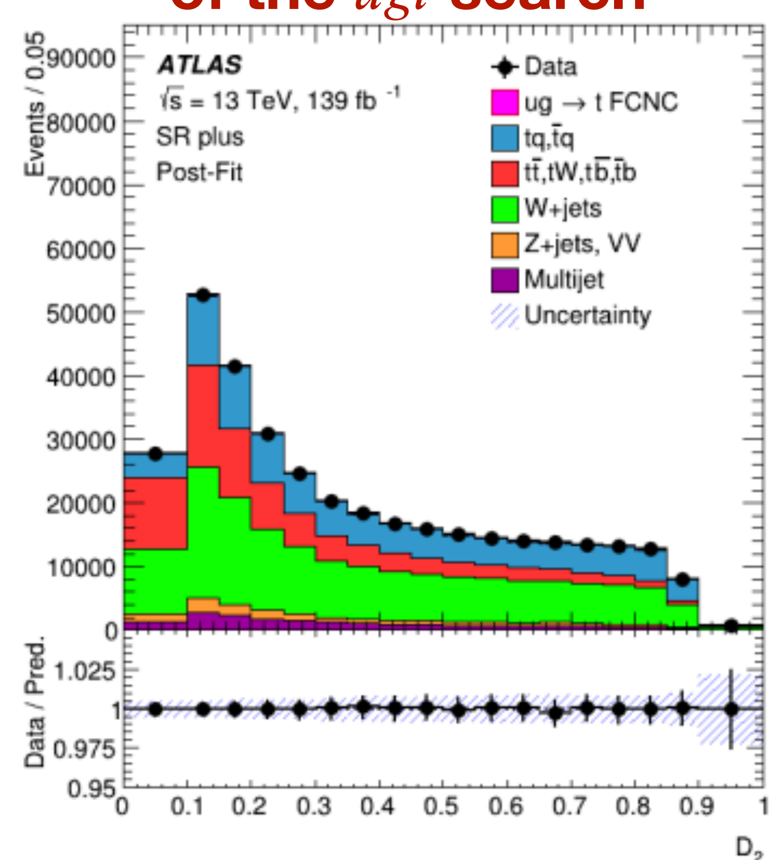
- Target $l + b$-tagged jet and E_T^{miss}
- Main backgrounds: $W + b\bar{b}$, t-channel single-top and $t\bar{t}$ production
  - Multijet contribution determined in a data-driven way by fitting E_T^{miss} and $m_T(W)$
- Neural Network (NN) used to construct two discriminants:
  - D1 targeting top antiquark production $\bar{u}/\bar{c} + g \to \bar{t}$: signal region for cgt and ugt in l^- channel
  - D2 aimed at direct top quark production $u + g \to t$: signal region for ugt in l^+ channel



$m_T(W)$



NN discriminant D_2 of the ugt search



FCNC Search for top-gluon with $t \to l\nu b$ 2112.01302

- Binned maximum-likehood fit performed separately to ugt and cgt FCNC processes
- Leading systematic uncertainties related to the W+jets process for the ugt fit and the modelling of the parton shower for the cgt fit
- Measured data consistent with background-only hypothesis
- Limits for FCNC tgq couplings set at the 95% CL for cross-sections, branching ratios and further interpreted in terms of EFT coefficients
  - **A factor of three more restrictive than the previous ATLAS results**

Coupling	$\sigma(q+g \to t)$	$\mathcal{B}(t \to gq)$	$\lvert C_{uG}^{qt}\rvert/\Lambda^2$
tgu	3.0 pb	$0.61\ (0.49) \times 10^{-4}$	0.057
tgc	4.7 pb	$3.7\ (2.0) \times 10^{-4}$	0.14

Conclusion

- Run 2 opened up measurements to **new rare SM processes**
- We've found **exciting results** using the full run 2 data-set
  - Processes with a top quark in association of boson(s) are searched for
    - Establishing SM processes (tZq)
    - Looking for new physics processes (**FCNC**)
  - A slight excess in the measured $t\bar{t}t\bar{t}$ cross section, but still compatible with the SM prediction within 2 σ

Complete list of ATLAS public top physics results


Thank you &
See you at the slopes!
VE RI TAS
HARVARD
ATLAS
EXPERIMENT

back-up (tZq)

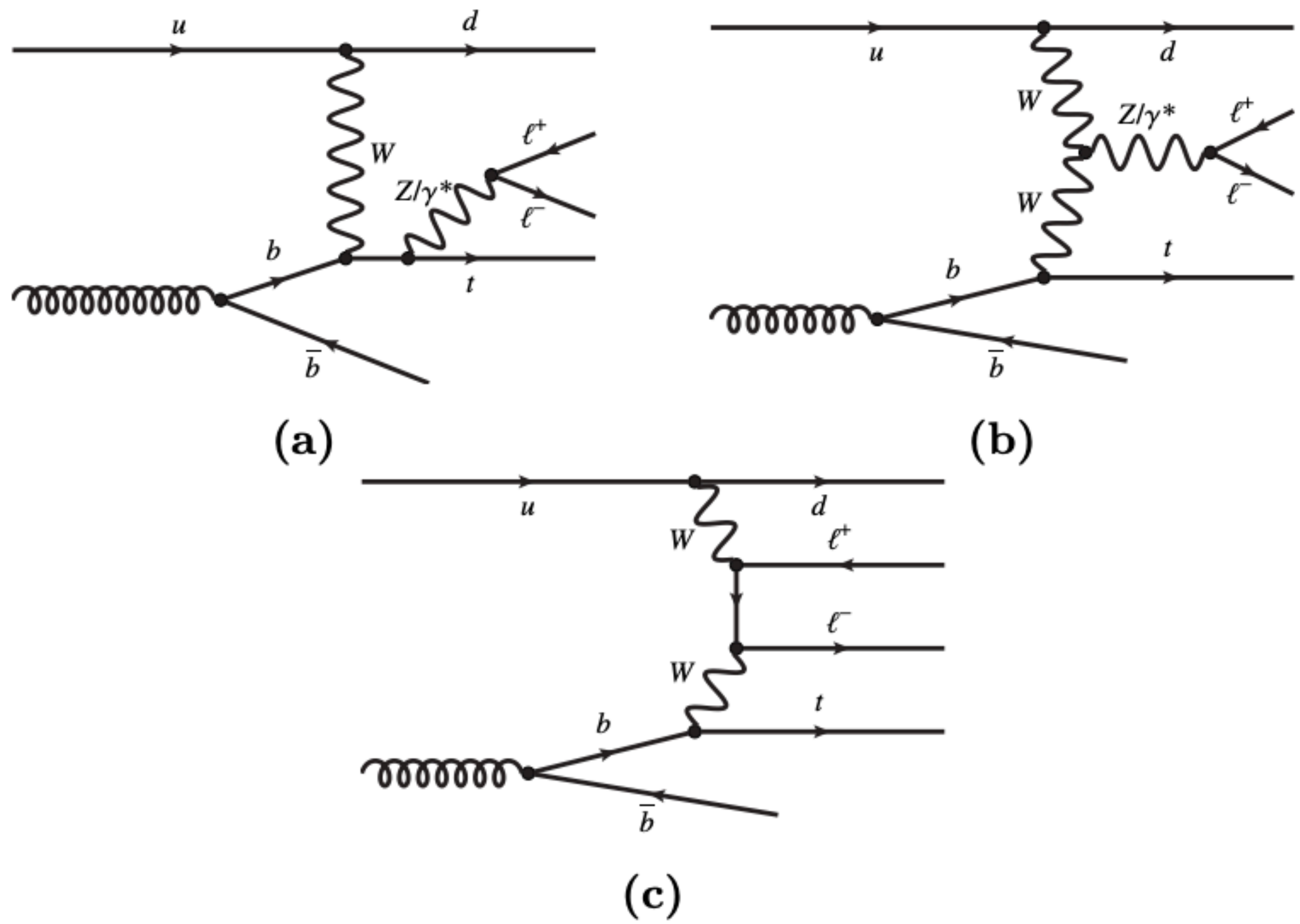


Figure 1. Example Feynman diagrams of the lowest-order amplitudes for the tZq process, corresponding to (a, b) resonant $\ell^+\ell^-$ production and (c) non-resonant $\ell^+\ell^-$ production. In the four-flavour scheme, the b-quark originates from gluon splitting.

back-up (tZq)

Common selections			
Exactly 3 leptons (e or μ) with $\lvert\eta\rvert < 2.5$ $p_T(\ell_1) > 28$ GeV, $p_T(\ell_2) > 20$ GeV, $p_T(\ell_3) > 20$ GeV $p_T(\text{jet}) > 35$ GeV			
SR 2j1b	CR diboson 2j0b	CR $t\bar{t}$ 2j1b	CR $t\bar{t}Z$ 3j2b
≥ 1 OSSF pair	≥ 1 OSSF pair	≥ 1 OSDF pair	≥ 1 OSSF pair
$\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV	$\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV	No OSSF pair	$\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV
2 jets, $\lvert\eta\rvert < 4.5$	2 jets, $\lvert\eta\rvert < 4.5$	2 jets, $\lvert\eta\rvert < 4.5$	3 jets, $\lvert\eta\rvert < 4.5$
1 b-jet, $\lvert\eta\rvert < 2.5$	0 b-jets	1 b-jet, $\lvert\eta\rvert < 2.5$	2 b-jets, $\lvert\eta\rvert < 2.5$
SR 3j1b	CR diboson 3j0b	CR $t\bar{t}$ 3j1b	CR $t\bar{t}Z$ 4j2b
≥ 1 OSSF pair	≥ 1 OSSF pair	≥ 1 OSDF pair	≥ 1 OSSF pair
$\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV	$\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV	No OSSF pair	$\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV
3 jets, $\lvert\eta\rvert < 4.5$	3 jets, $\lvert\eta\rvert < 4.5$	3 jets, $\lvert\eta\rvert < 4.5$	4 jets, $\lvert\eta\rvert < 4.5$
1 b-jet, $\lvert\eta\rvert < 2.5$	0 b-jets	1 b-jet, $\lvert\eta\rvert < 2.5$	2 b-jets, $\lvert\eta\rvert < 2.5$

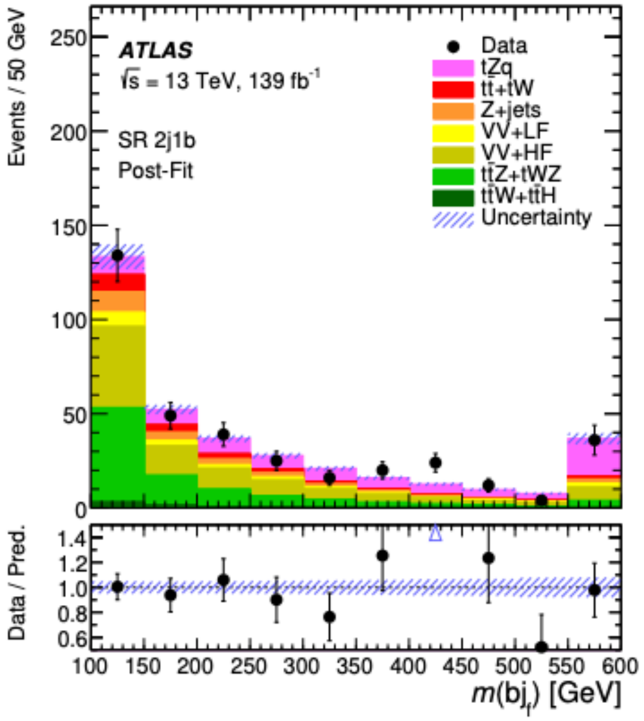
Table 1. Overview of the requirements applied when selecting events in the signal and control regions. OSSF is an opposite-sign same-flavour lepton pair. OSDF is an opposite-sign different-flavour lepton pair.

back-up (tZq)

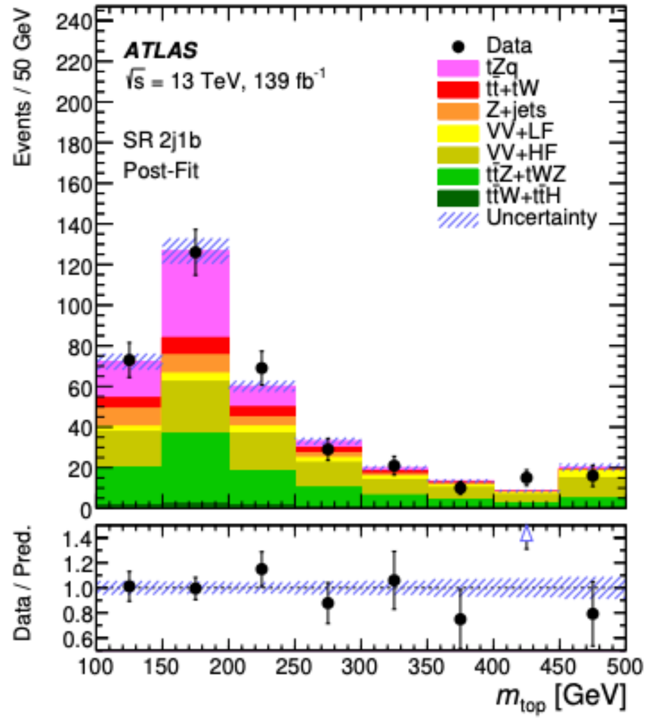
Variable	Rank		Definition
	SR 2j1b	SR 3j1b	
$m_{b\mathrm{j_f}}$	1	1	(Largest) invariant mass of the b-jet and the untagged jet(s)
m_{top}	2	2	Reconstructed top-quark mass
$\lvert\eta(\mathrm{j_f})\rvert$	3	3	Absolute value of the η of the $\mathrm{j_f}$ jet
$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$	4	4	Transverse mass of the W boson
b-tagging score	5	11	b-tagging score of the b-jet
H_{T}	6	–	Scalar sum of the p_{T} of the leptons and jets in the event
$q(\ell_W)$	7	8	Electric charge of the lepton from the W-boson decay
$\lvert\eta(\ell_W)\rvert$	8	12	Absolute value of the η of the lepton from the W-boson decay
$p_{\mathrm{T}}(W)$	9	15	p_{T} of the reconstructed W boson
$p_{\mathrm{T}}(\ell_W)$	10	14	p_{T} of the lepton from the W-boson decay
$m(\ell\ell)$	11	–	Mass of the reconstructed Z boson
$\lvert\eta(Z)\rvert$	12	13	Absolute value of the η of the reconstructed Z boson
$\Delta R(\mathrm{j_f}, Z)$	13	7	ΔR between the $\mathrm{j_f}$ jet and the reconstructed Z boson
$E_{\mathrm{T}}^{\mathrm{miss}}$	14	–	Missing transverse momentum
$p_{\mathrm{T}}(\mathrm{j_f})$	15	10	p_{T} of the $\mathrm{j_f}$ jet
$\lvert\eta(\mathrm{j_r})\rvert$	–	5	Absolute value of the η of the $\mathrm{j_r}$ jet
$p_{\mathrm{T}}(Z)$	–	6	p_{T} of the reconstructed Z boson
$p_{\mathrm{T}}(\mathrm{j_r})$	–	9	p_{T} of the $\mathrm{j_r}$ jet

Table 2. Variables used as input to the neural network in SR 2j1b and SR 3j1b. The ranking of the variables in each of the SRs is given in the 2$^{\mathrm{nd}}$ and 3$^{\mathrm{rd}}$ columns, respectively. The untagged jet is denoted $\mathrm{j_f}$. When two untagged jets are selected, $\mathrm{j_f}$ ($\mathrm{j_r}$) refers to the one for which the invariant mass of this untagged jet and the b-tagged jet is the largest (smallest). The b-tagging score indicates whether the b-jet would also satisfy a tighter b-tagging requirement corresponding to a working point with an efficiency of 60% instead of 70%.

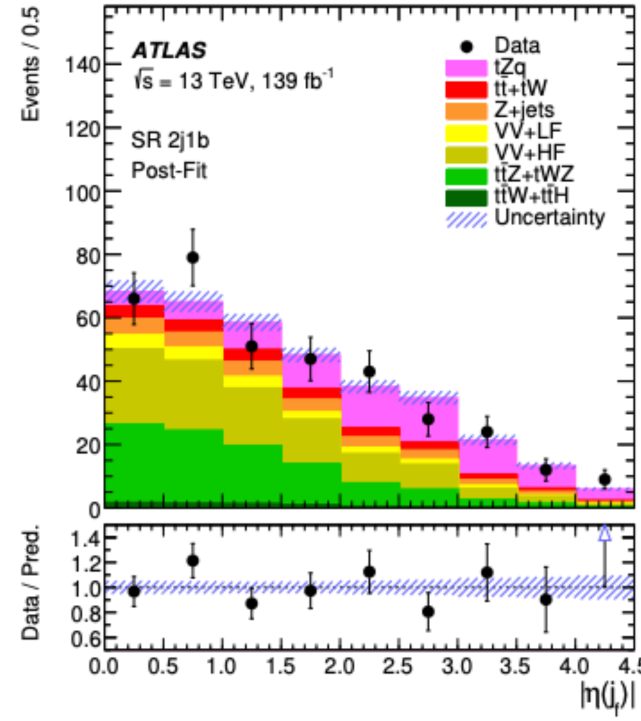
back-up (tZq)



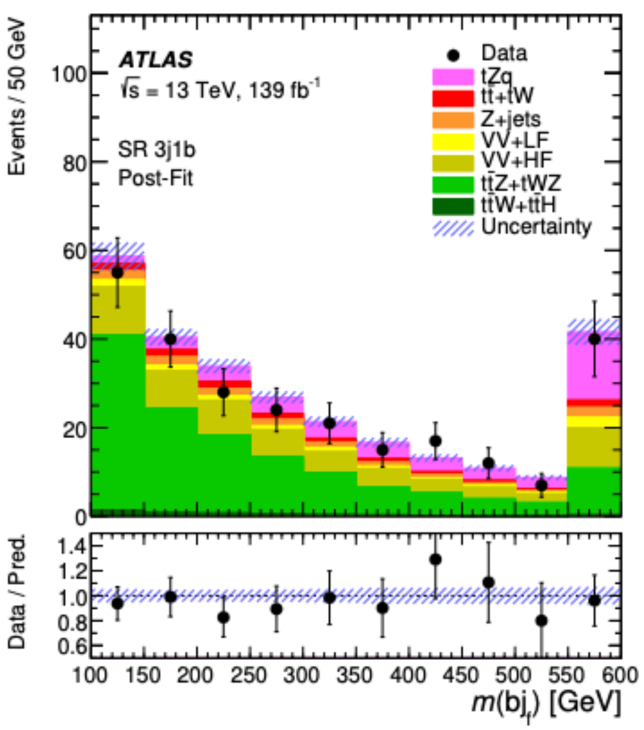
(a)



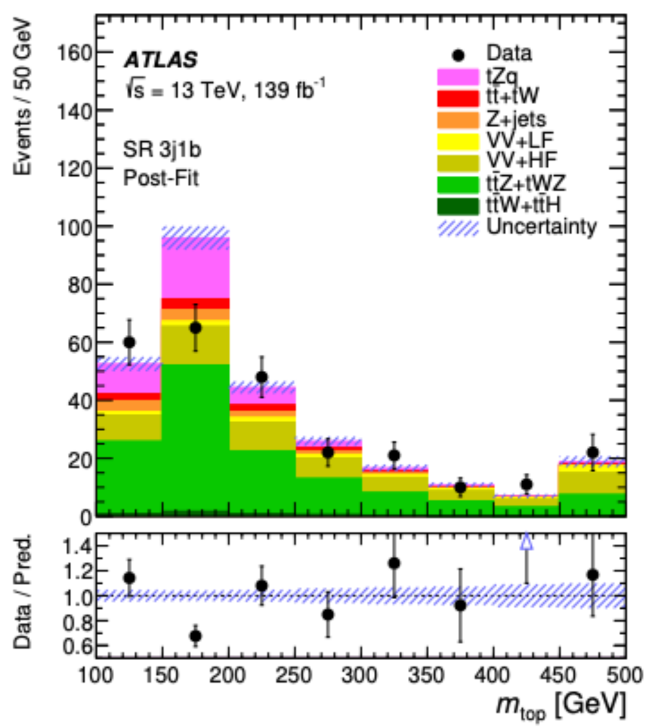
(b)



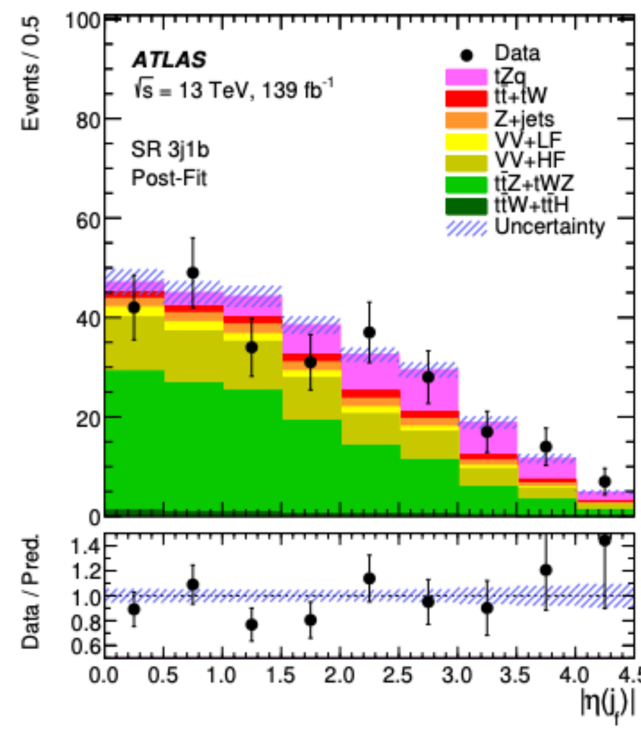
(c)



(d)



(e)



(f)

back-up (tZq)

Uncertainty source	$\Delta\sigma/\sigma$ [%]
Prompt-lepton background modelling and normalisation	3.3
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction and calibration	2.0
Lepton reconstruction and calibration	2.0
Luminosity	1.7
Non-prompt-lepton background modelling	1.6
Pileup modelling	1.2
MC statistics	1.0
tZq modelling (QCD radiation)	0.8
tZq modelling (PDF)	0.7
Jet flavour tagging	0.4
Total systematic uncertainty	7.0
Data statistics	12.6
$t\bar{t} + tW$ and $Z+$jets normalisation	2.1
Total statistical uncertainty	12.9

Table 4. Impact of systematic uncertainties on the tZq cross-section, broken down into major categories. For each category the impact is calculated by performing a fit where the nuisance parameters in the group are fixed to their best-fit values, and then subtracting the resulting uncertainty in the parameter of interest in quadrature from the uncertainty from the nominal fit. For simplicity, the impact is given as the average of the up and down variations. Details of the systematic uncertainties are provided in the text. MC statistics refers to the effect of the limited size of the MC samples. The total systematic uncertainty is a bit larger than the quadratic sum of the individual contributions due to correlations.

back-up (ttZ)

Table 1 The definitions of the trilepton signal regions: for the inclusive measurement, a combination of the regions with pseudo-continuous b-tagging 3ℓ-Z-$1b4j$-PCBT and 3ℓ-Z-$2b3j$-PCBT is used, whereas for the differential measurement only the region 3ℓ-Z-$2b3j$ with a fixed b-tagging WP is employed

Variable	3ℓ-Z-$1b4j$-PCBT inclusive	3ℓ-Z-$2b3j$-PCBT inclusive	3ℓ-Z-$2b3j$ differential
N_ℓ ($\ell = e, \mu$)	$= 3$		
	$\geq$1 OSSF lepton pair with $\lvert m_{\ell\ell}^{Z} - m_Z \rvert < 10$ GeV		
	for all OSSF combinations: $m_{\text{OSSF}} > 10$ GeV		
p_{T} (ℓ_1, ℓ_2, ℓ_3)	> 27, 20, 20 GeV		
N_{jets}	≥ 4	≥ 3	≥ 3
$N_{b\text{-jets}}$	$= 1$@60%	≥ 2@70%	≥ 2@85%
	veto add. b-jets@70%		

Table 2 The definitions of the four tetralepton signal regions. The regions are defined to target different b-jet multiplicities and flavour combinations of the non-Z leptons ($\ell\ell^{\text{non-}Z}$)

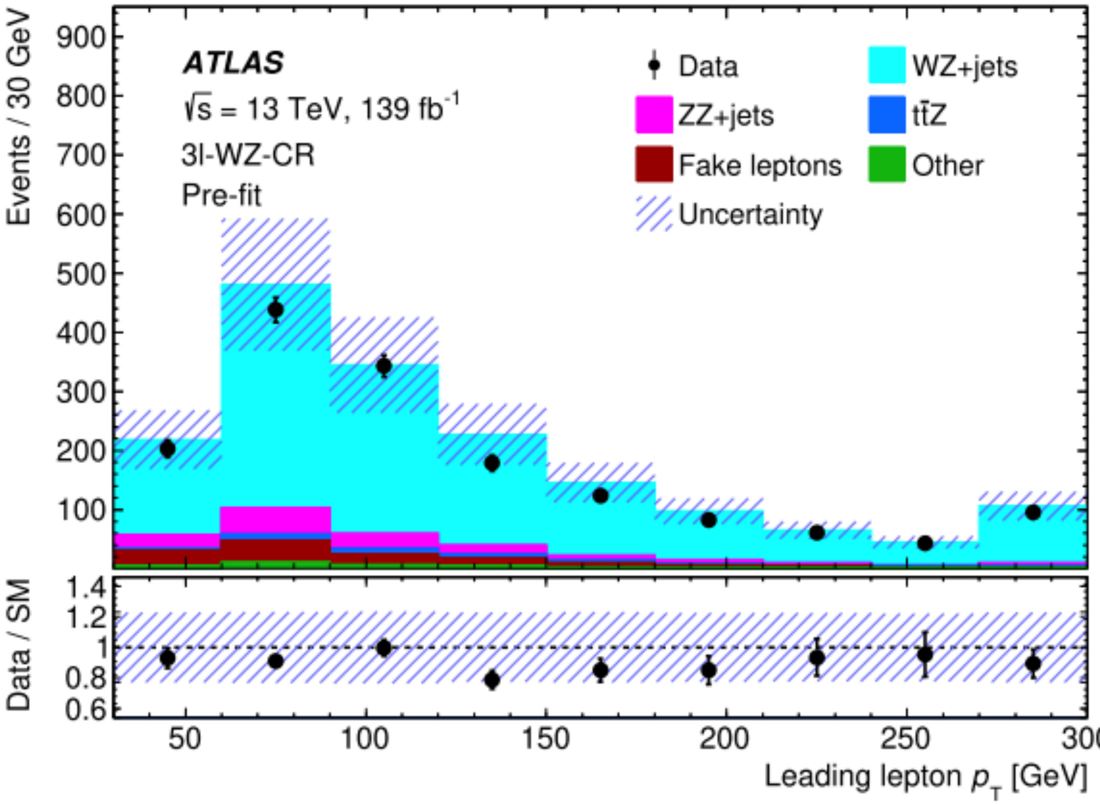
Variable	4ℓ-SF-$1b$	4ℓ-SF-$2b$	4ℓ-DF-$1b$	4ℓ-DF-$2b$
$N_\ell (\ell = e, \mu)$	$= 4$			
	$\geq$1 OSSF lepton pair with $\lvert m_{\ell\ell}^{Z} - m_Z \rvert < 10$ GeV			
	for all OSSF combinations: $m_{\text{OSSF}} > 10$ GeV			
p_{T} (ℓ_1, ℓ_2, ℓ_3, ℓ_4)	> 27, 20, 10, 7 GeV			
$\ell\ell^{\text{non-}Z}$	e^+e^- or $\mu^+\mu^-$	e^+e^- or $\mu^+\mu^-$	$e^\pm\mu^\mp$	$e^\pm\mu^\mp$
$E_{\text{T}}^{\text{miss}}$	> 100 GeV, if $\lvert m_{\ell\ell}^{\text{non-}Z} - m_Z \rvert \leq 10$ GeV	> 50 GeV, if $\lvert m_{\ell\ell}^{\text{non-}Z} - m_Z \rvert \leq 10$ GeV	–	–
	> 50 GeV, if $\lvert m_{\ell\ell}^{\text{non-}Z} - m_Z \rvert > 10$ GeV	–		
N_{jets}	≥ 2	≥ 2	≥ 2	≥ 2
$N_{b\text{-jets}}$@85%	$= 1$	≥ 2	$= 1$	≥ 2

back-up (ttZ)

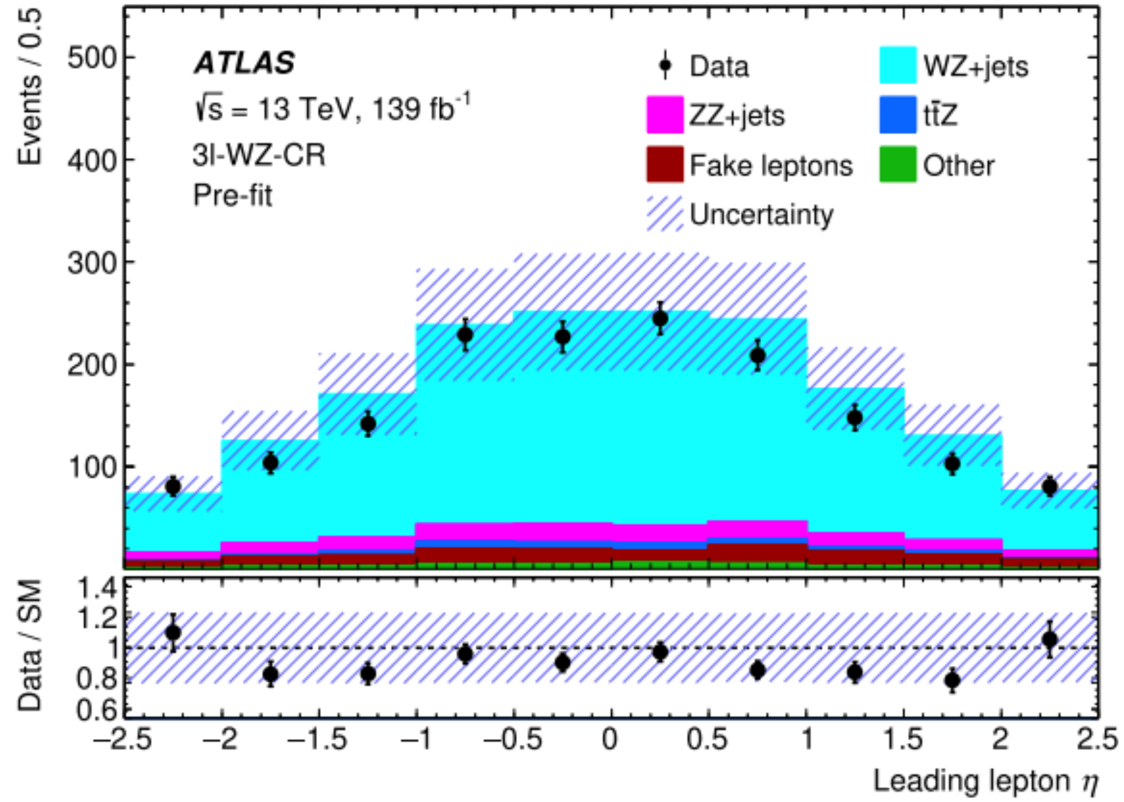
Table 3 Definitions of the control regions targeting the WZ + jets, $WZ \rightarrow \ell\ell\ell\nu$ (left) and ZZ + jets, $ZZ \rightarrow \ell\ell\ell\ell$ processes (right): the control regions are used to obtain normalisations of the light-flavour components of the WZ/ZZ + jets backgrounds from data

Variable	3ℓ-WZ-CR	4ℓ-ZZ-CR
N_ℓ ($\ell = e, \mu$)	$= 3$	$= 4$
	1 OSSF lepton pair with	2 OSSF lepton pairs with
	$\|m_{\ell\ell} - m_Z\| < 10$ GeV	$\|m_{\ell\ell} - m_Z\| < 10$ GeV
p_T (ℓ_1, ℓ_2, ℓ_3, ℓ_4)	$> 27, 20, 20$ GeV	$> 27, 20, 10, 7$ GeV
N_jets	≥ 3	–
$N_{b\text{-jets}}$@85%	$= 0$	–
$E_\mathrm{T}^\mathrm{miss}$	–	20 GeV $< E_\mathrm{T}^\mathrm{miss} <$ 40 GeV

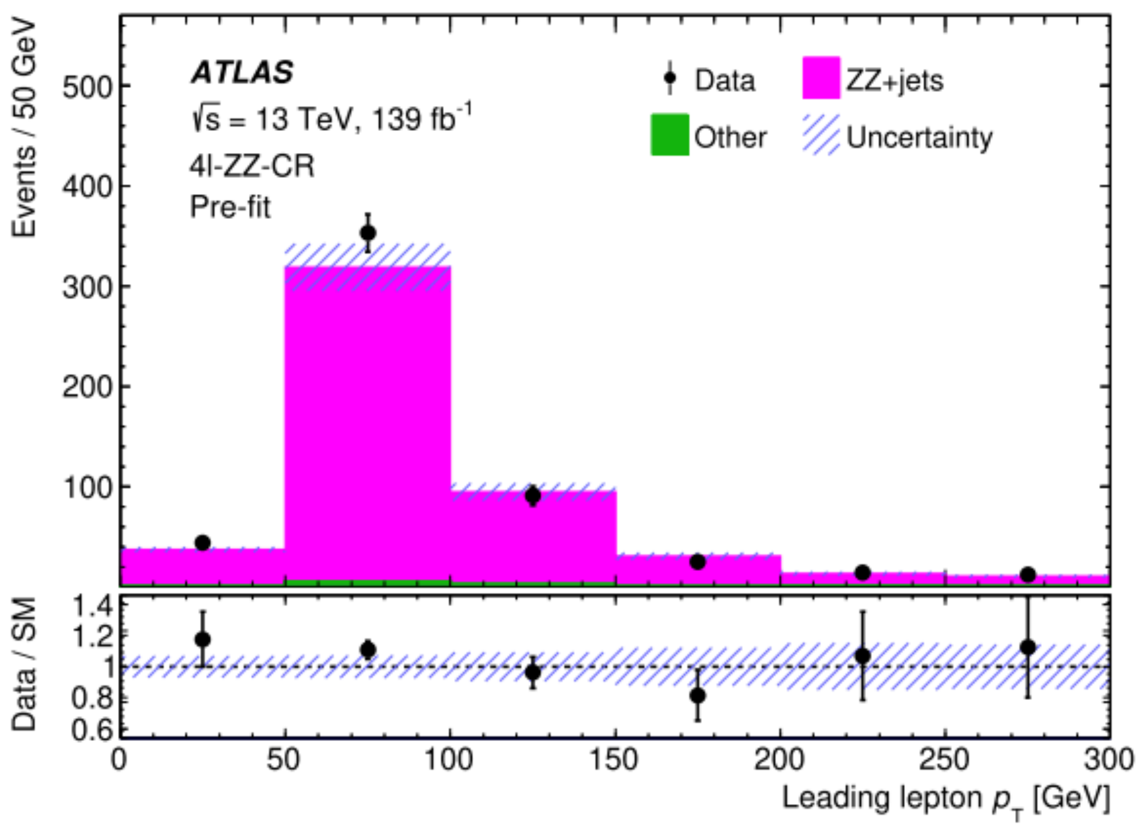
back-up (ttZ)



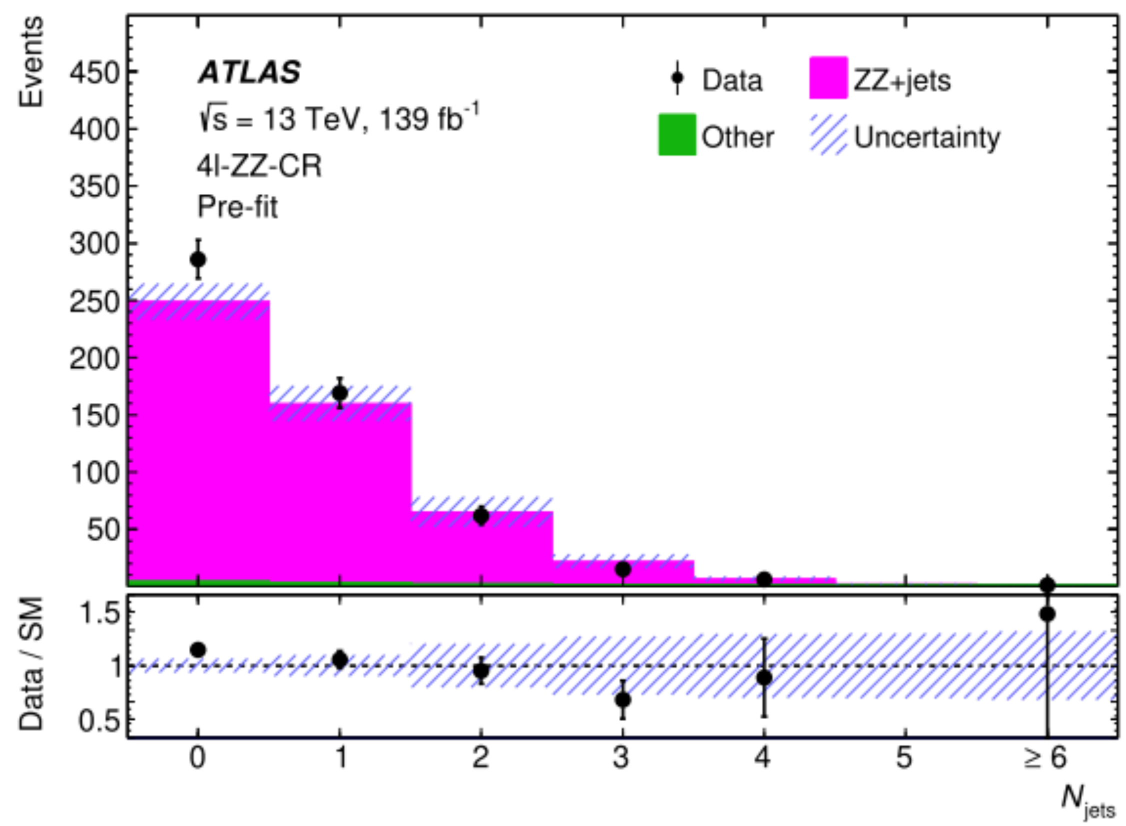
(a)



(b)



(a)



(b)

back-up (ttZ)

Table 7 List of relative uncertainties of the measured inclusive $t\bar{t}Z$ cross section from the combined fit. The uncertainties are symmetrised for presentation and grouped into the categories described in the text. The quadrature sum of the individual uncertainties is not equal to the total uncertainty due to correlations introduced by the fit

Uncertainty	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]
$t\bar{t}Z$ parton shower	3.1
tWZ modelling	2.9
b-tagging	2.9
WZ/ZZ + jets modelling	2.8
tZq modelling	2.6
Lepton	2.3
Luminosity	2.2
Jets + $E_{\mathrm{T}}^{\mathrm{miss}}$	2.1
Fake leptons	2.1
$t\bar{t}Z$ ISR	1.6
$t\bar{t}Z$ μ_{f} and μ_{r} scales	0.9
Other backgrounds	0.7
Pile-up	0.7
$t\bar{t}Z$ PDF	0.2
Total systematic	8.4
Data statistics	5.2
Total	10

back-up (ttZ)

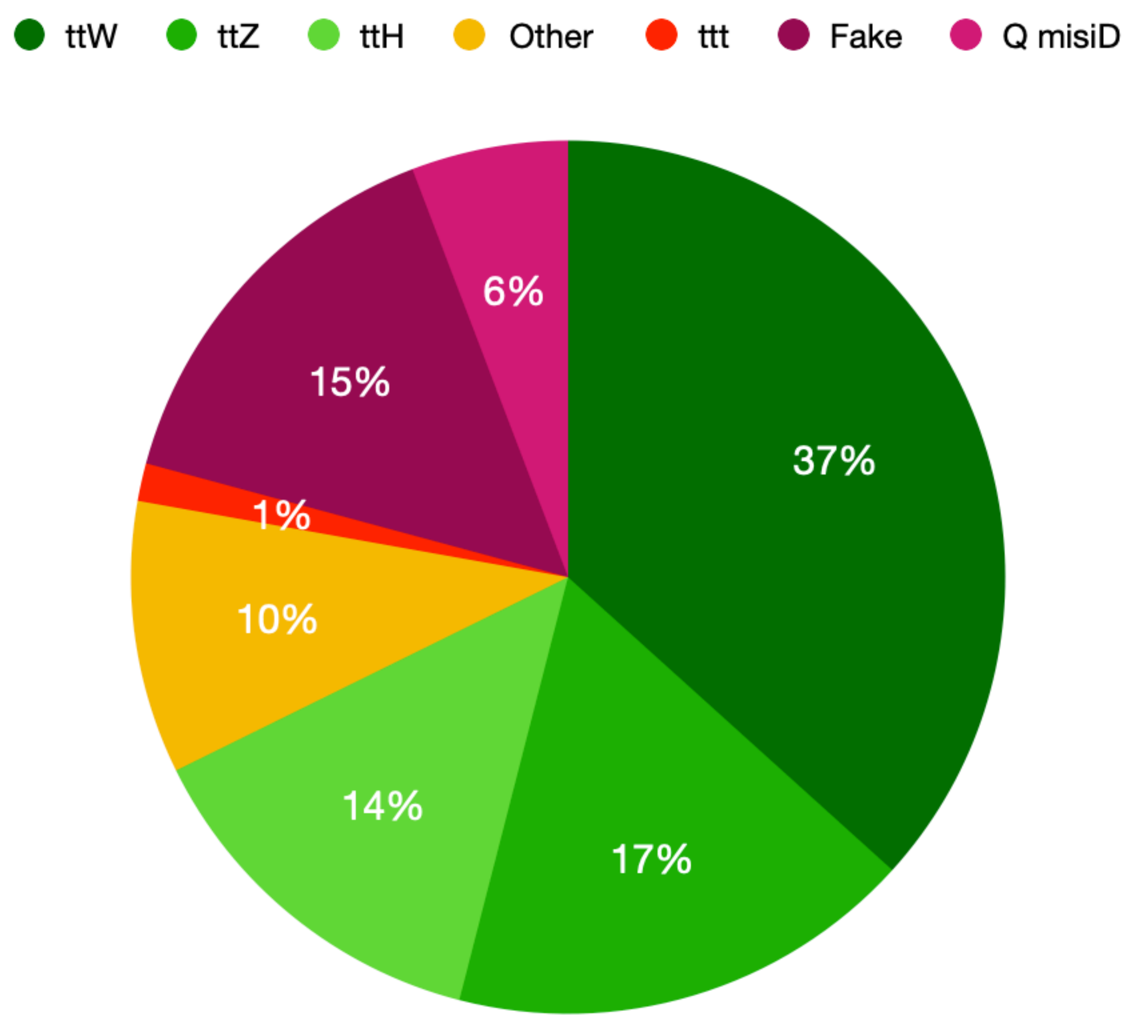
Table 8 Summary of the variables used for the differential measurements. Some variables are considered for the trilepton or tetralepton signal regions only, as indicated. The jet multiplicity is measured for the two topologies separately, whereas for the variables related only to the kinematics of the Z boson (p_{T}^{Z} and $|y^{Z}|$), the trilepton and tetralepton regions are combined

Variable	Definition
$3\ell + 4\ell$	
p_{T}^{Z}	Transverse momentum of the Z boson
$\|y^{Z}\|$	Absolute value of the rapidity of the Z boson
3ℓ	
N_{jets}	Number of selected jets with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $\|\eta\| < 2.5$
$p_{\mathrm{T}}^{\ell,\text{non-}Z}$	Transverse momentum of the lepton which is not associated with the Z boson
$\|\Delta\phi(Z, t_{\mathrm{lep}})\|$	Azimuthal separation between the Z boson and the top quark (antiquark) featuring the $W \to \ell\nu$ decay
$\|\Delta y(Z, t_{\mathrm{lep}})\|$	Absolute rapidity difference between the Z boson and the top quark (antiquark) featuring the $W \to \ell\nu$ decay
4ℓ	
N_{jets}	Number of selected jets with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $\|\eta\| < 2.5$
$\|\Delta\phi(\ell_t^+, \ell_{\bar{t}}^-)\|$	Azimuthal separation between the two leptons from the $t\bar{t}$ system
$\|\Delta\phi(t\bar{t}, Z)\|$	Azimuthal separation between the Z boson and the $t\bar{t}$ system
$p_{\mathrm{T}}^{t\bar{t}}$	Transverse momentum of the $t\bar{t}$ system

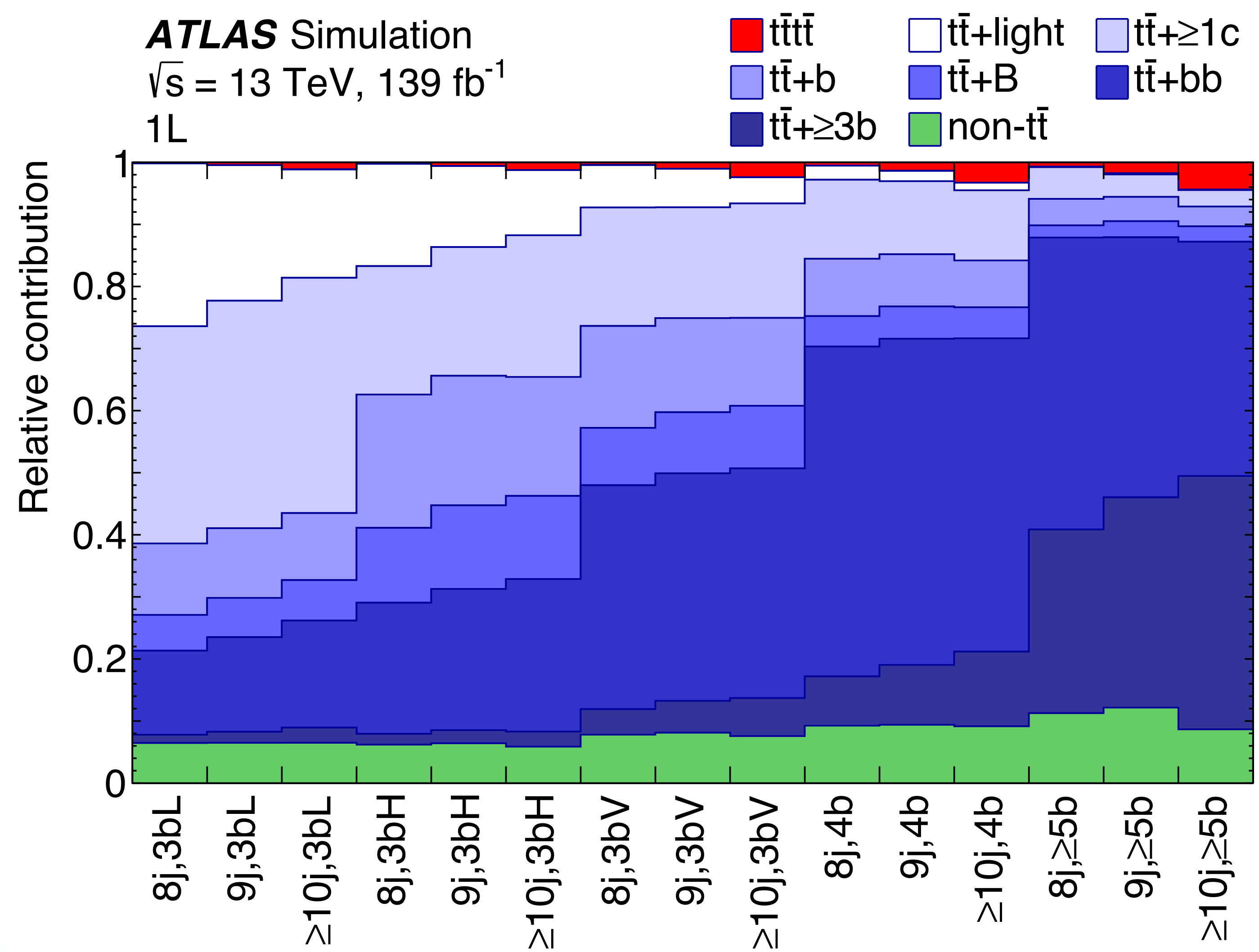
back-up ($t\bar{t}t\bar{t}$)

backgrounds

in 2ℓSS/3ℓ



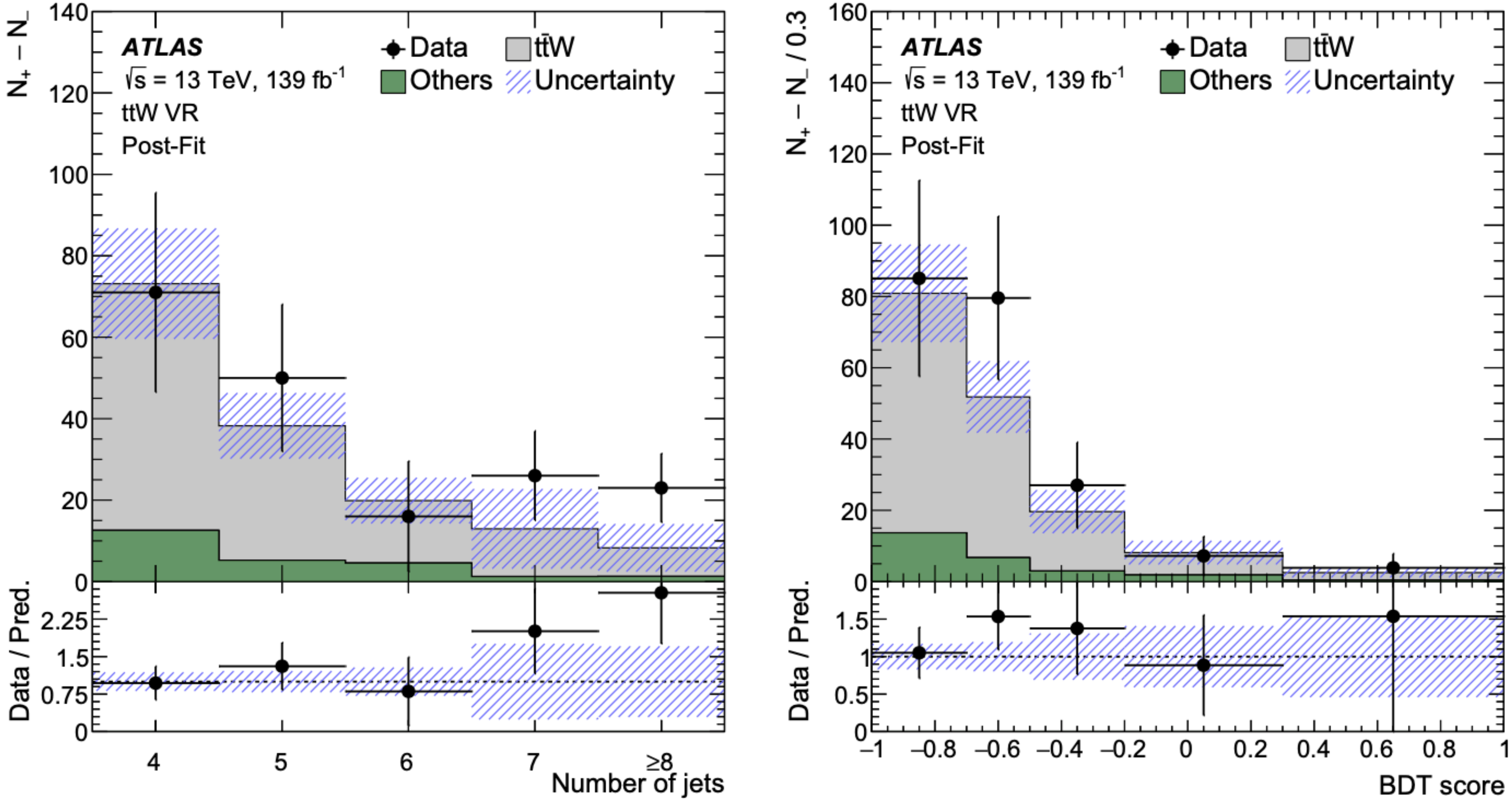
in 1ℓ/2ℓOS



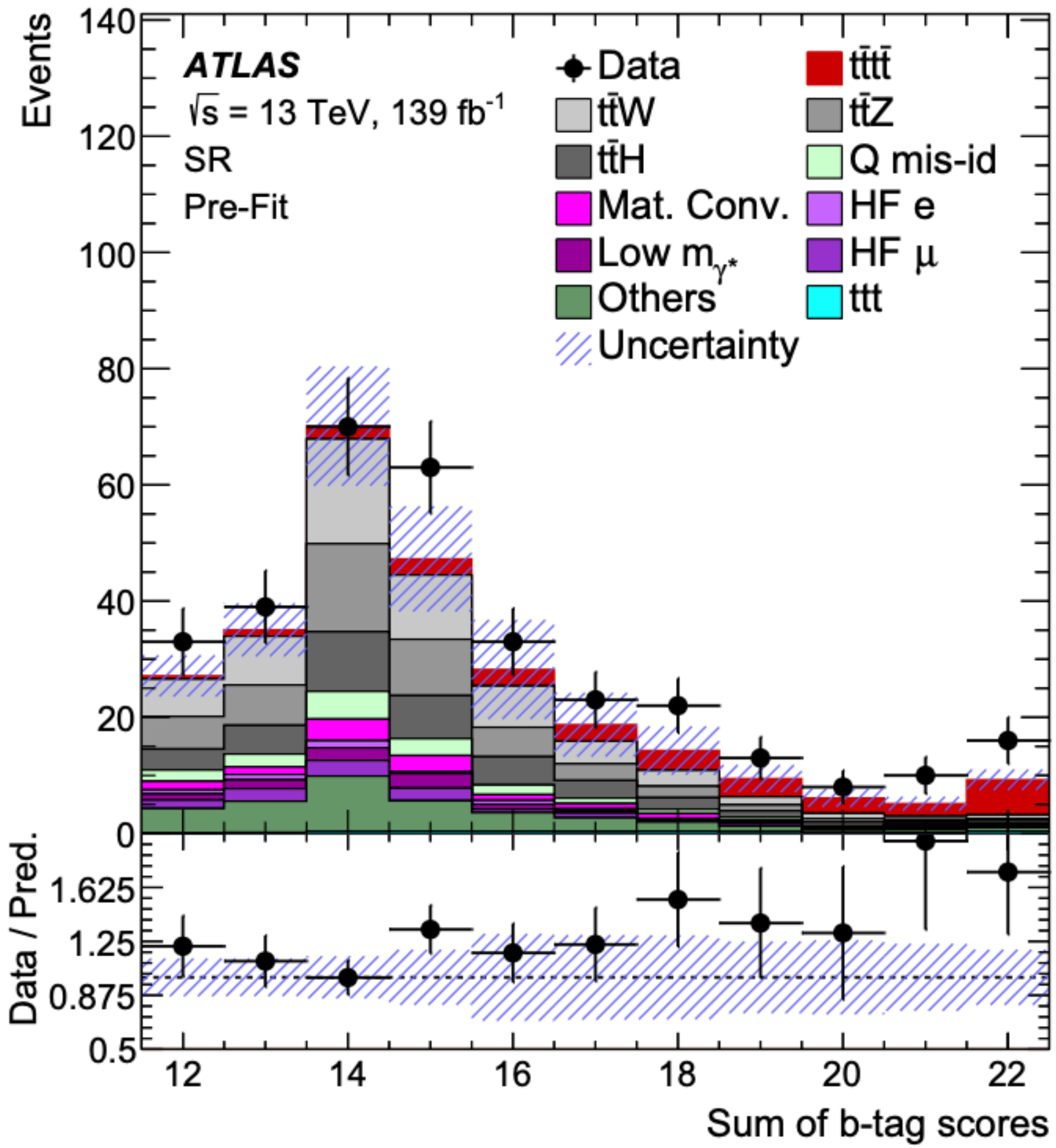
Parameter	$NF_{t\bar{t}W}$	$NF_{\text{Mat. Conv.}}$	$NF_{\text{Low } M_{ee}}$	$NF_{\text{HF } e}$	$NF_{\text{HF } \mu}$
Value	1.6 ± 0.3	1.6 ± 0.5	0.9 ± 0.4	0.8 ± 0.4	1.0 ± 0.4

back-up ($t\bar{t}t\bar{t}$)

ttW validation region in 2ℓSS/3ℓ



Sum of b-tag scores as input to the BDT



back-up ($t\bar{t}t\bar{t}$)

Uncertainties

in 2ℓSS/3ℓ

Uncertainty source	$\Delta\mu$	
Signal modelling		
$t\bar{t}t\bar{t}$ cross section	+0.56	−0.31
$t\bar{t}t\bar{t}$ modelling	+0.15	−0.09
Background modelling		
$t\bar{t}W$ modelling	+0.26	−0.27
$t\bar{t}t$ modeling	+0.10	−0.07
Non-prompt leptons modeling	+0.05	−0.04
$t\bar{t}H$ modelling	+0.04	−0.01
$t\bar{t}Z$ modelling	+0.02	−0.04
Charge misassignment	+0.01	−0.02
Instrumental		
Jet uncertainties	+0.12	−0.08
Jet flavour tagging (light-jets)	+0.11	−0.06
Simulation sample size	+0.06	−0.06
Luminosity	+0.05	−0.03
Jet flavour tagging (b-jets)	+0.04	−0.02
Other experimental uncertainties	+0.03	−0.01
Jet flavour tagging (c-jets)	+0.03	−0.01
Total systematic uncertainty	+0.69	−0.46
Statistical	+0.42	−0.39
Non-prompt leptons normalisation(HF, material conversions)	+0.05	−0.04
$t\bar{t}W$ normalisation	+0.04	−0.04
Total uncertainty	+0.82	−0.62

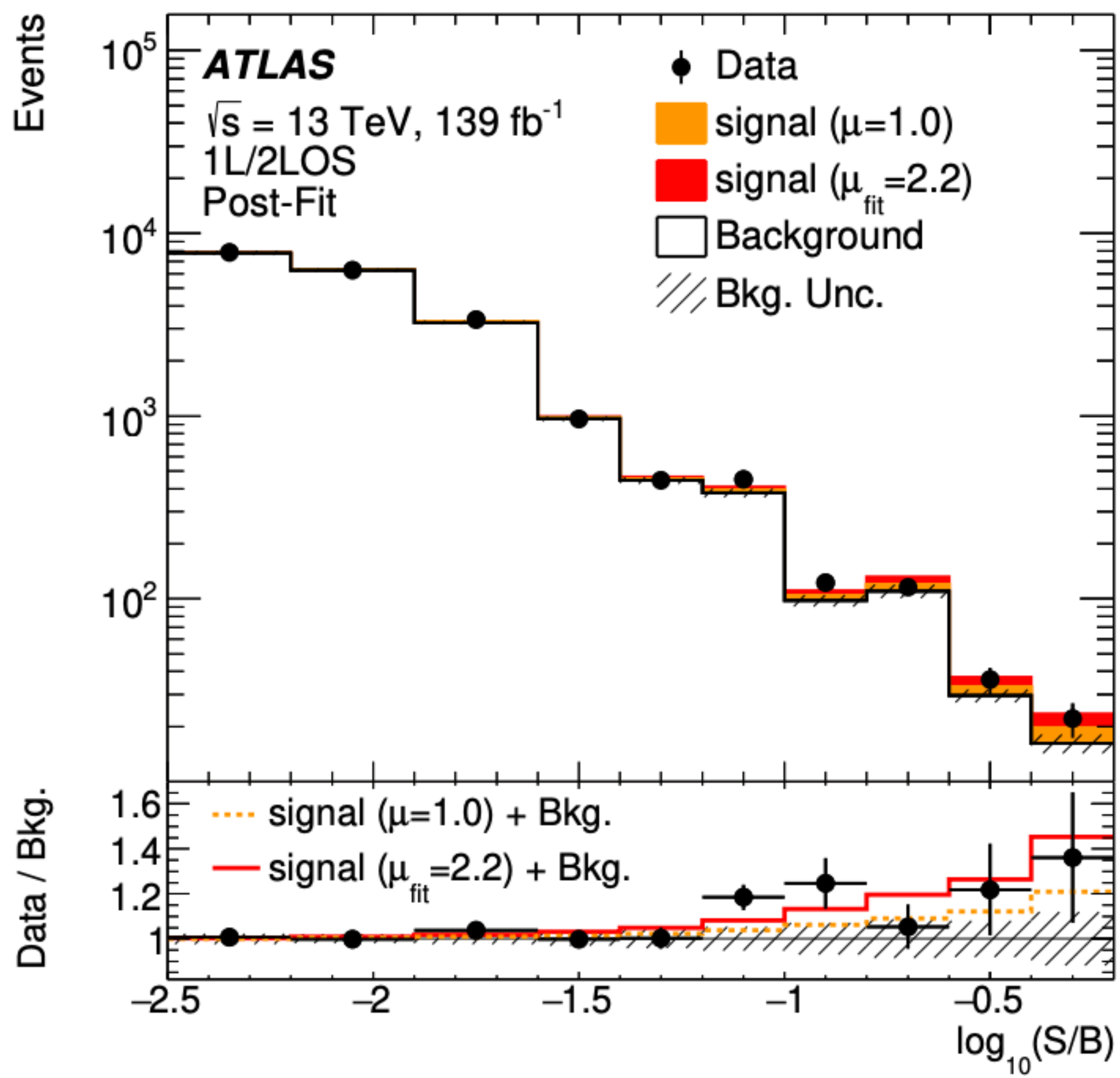
in 1ℓ/2ℓOS

Uncertainty source	$\Delta\sigma_{t\bar{t}t\bar{t}}$ [fb]	
Signal Modelling		
$t\bar{t}t\bar{t}$ modelling	+8	-3
Background Modelling		
$t\bar{t}+\geq 1b$ modelling	+8	-7
$t\bar{t}+\geq 1c$ modelling	+5	-4
$t\bar{t}$+jets reweighting	+4	-3
Other background modelling	+4	-3
$t\bar{t}$+light modelling	+2	-2
Experimental		
Jet energy scale and resolution	+6	-4
b-tagging efficiency and mis-tag rates	+4	-3
MC statistical uncertainties	+2	-2
Luminosity	< 1	
Other uncertainties	< 1	
Total systematic uncertainty	+15	-12
Statistical uncertainty	+8	-8
Total uncertainty	+17	-15

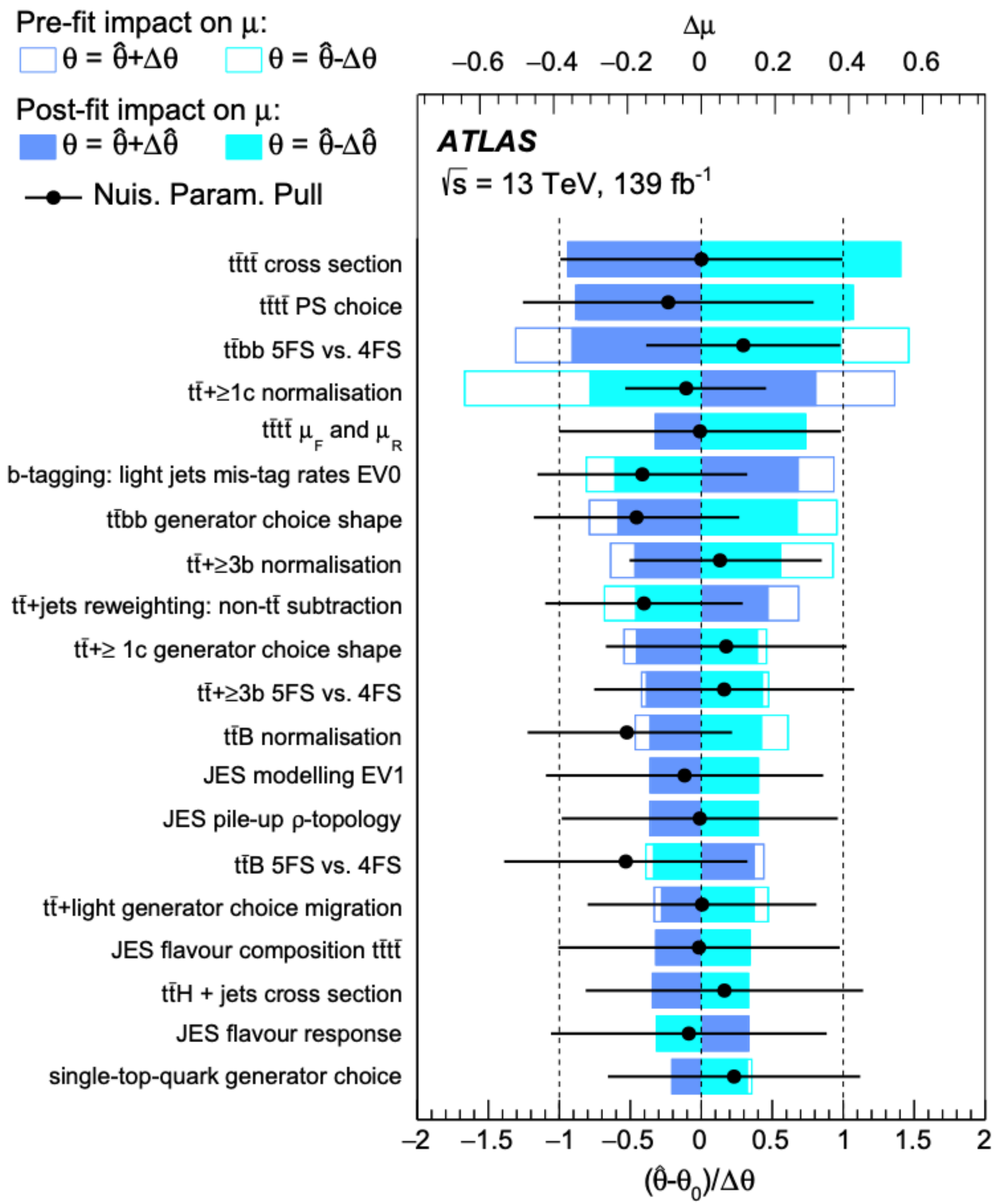
back-up ($t\bar{t}t\bar{t}$)

Observed and expected event yields as function of $\log_{10}(S/B)$ - post-fit

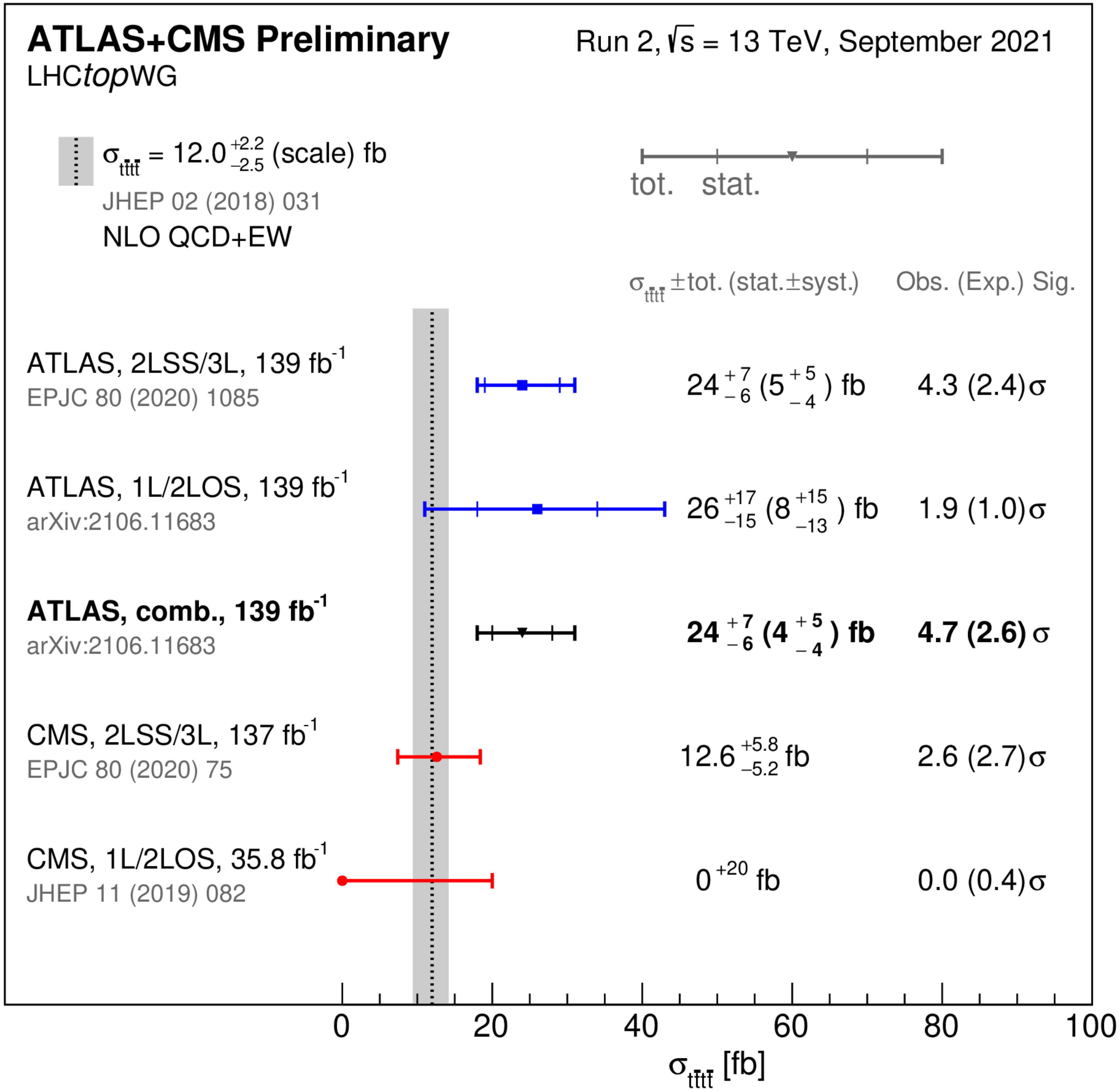
best fit $\mu = 2.2$ and $\mu = 1.0$ are shown



back-up ($t\bar{t}t\bar{t}$)



back-up ($t\bar{t}t\bar{t}$)



back-up (FCNC, top-gluon with $t \to l\nu b$)

Table 4: Impact of systematic uncertainties on the expected upper limits on the branching ratios of the FCNC decay modes $\mathcal{B}(t \to u+g)$ and $\mathcal{B}(t \to c+g)$. Four scenarios are considered: (1) include only data statistical uncertainties, (2) include the experimental systematic uncertainties in addition, (3) include all systematic uncertainties except for the MC statistical uncertainties and (4) include all uncertainties.

Scenario	Description	$\mathcal{B}_{95}^{\mathrm{exp}}(t \to u+g)$	$\mathcal{B}_{95}^{\mathrm{exp}}(t \to c+g)$
(1)	Data statistical only	1.1×10^{-5}	2.4×10^{-5}
(2)	Experimental uncertainties also	3.1×10^{-5}	12×10^{-5}
(3)	All uncertainties except MC statistical	3.9×10^{-5}	18×10^{-5}
(4)	All uncertainties	4.9×10^{-5}	20×10^{-5}