Measurements of $t\bar{t}$ in association with charm quarks at 13 TeV with the ATLAS experiment

arXiv:2409.11305 — ATLAS briefing

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on behalf of the ATLAS Collaboration

TOP 2024 Workshop

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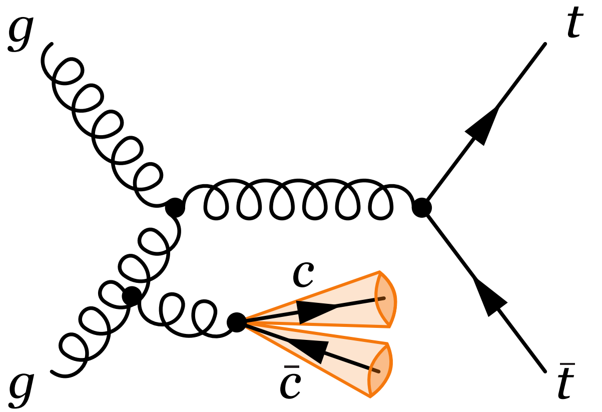
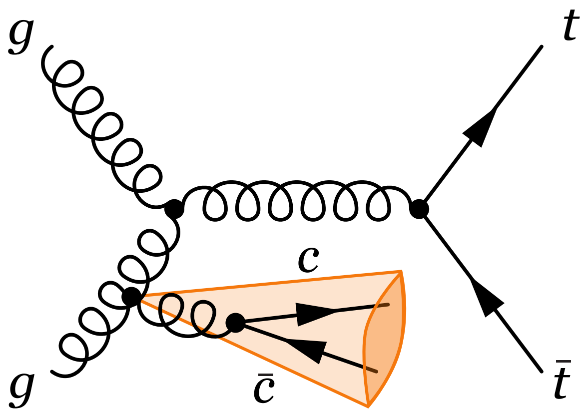
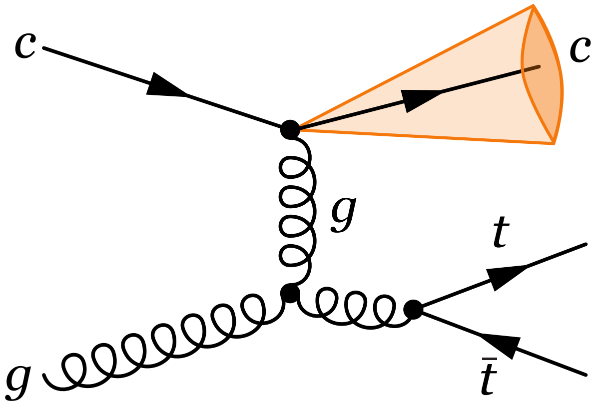
Introduction

- $\boldsymbol{t\bar{t}}$ **+ heavy-flavour jets process** = large irreducible background to many analyses
  - 4-top-quark production, 1L / 2LOS channel
  - $t\bar{t}H$ with $H \to b\bar{b}$ decays
- Heavy-flavour (HF) jets: jets originating from c-quarks and b-quarks (c-jets, b-jets)
- $t\bar{t} + HF$ is **challenging to model** – the $t\bar{t}$ and $b\bar{b}/c\bar{c}$ pair act on very different scales!
  - Several **computations for** $\boldsymbol{t\bar{t} + b\bar{b}}$ **available**, and MC generator implementations exist
  - No **dedicated simulation of** $\boldsymbol{t\bar{t} + c\bar{c}}$ available

see also E. Antipov's talk from Tuesday!



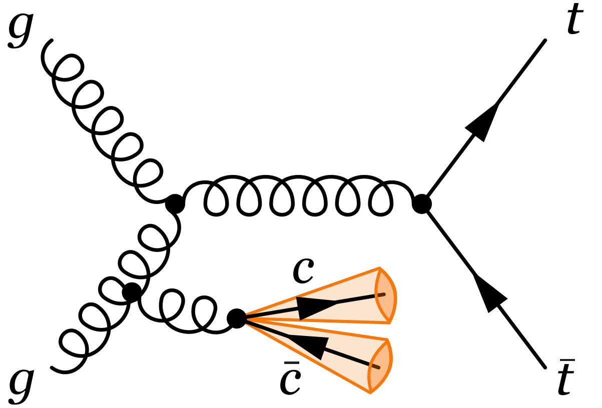


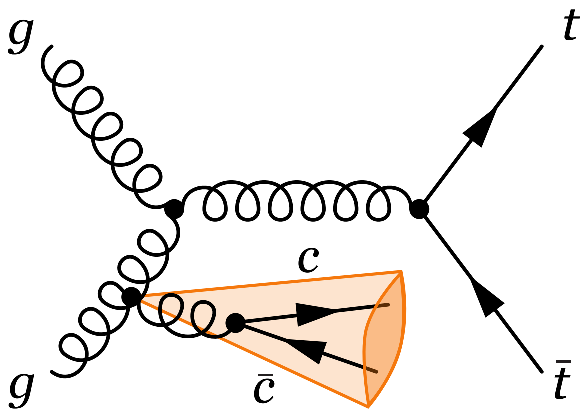


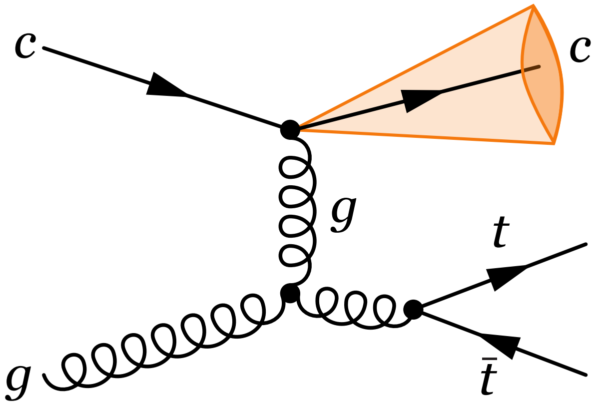
Introduction

Three $t\bar{t}$ + charm production scenarios:

1. Gluon splitting into $c\bar{c}$ pair, where both c-quarks form **independent** jets ($t\bar{t} + c\bar{c}$)
2. Gluon splitting into $c\bar{c}$ pair, but both c-quarks are **merged** into the same jet ($t\bar{t} + C$)
3. $t\bar{t}$ production initiated with a c-quark in the **initial state** ($t\bar{t} + c$)



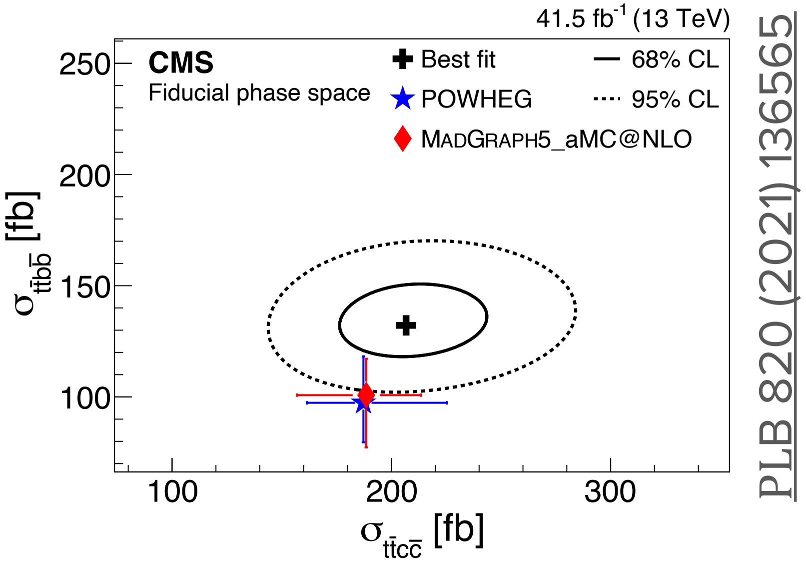




Experimentally, all of these are pivotal to understand, but the **modelling** of all is **equally challenging**!

Predictions and measurements

- **Best available predictions:** MC simulation of inclusive $t\bar{t}$ production at next-to-leading order (NLO) in QCD, interfaced to parton shower simulation (NLO+PS)
  - Caveat: none of the three $t\bar{t}$ + charm scenarios is simulated in the matrix element

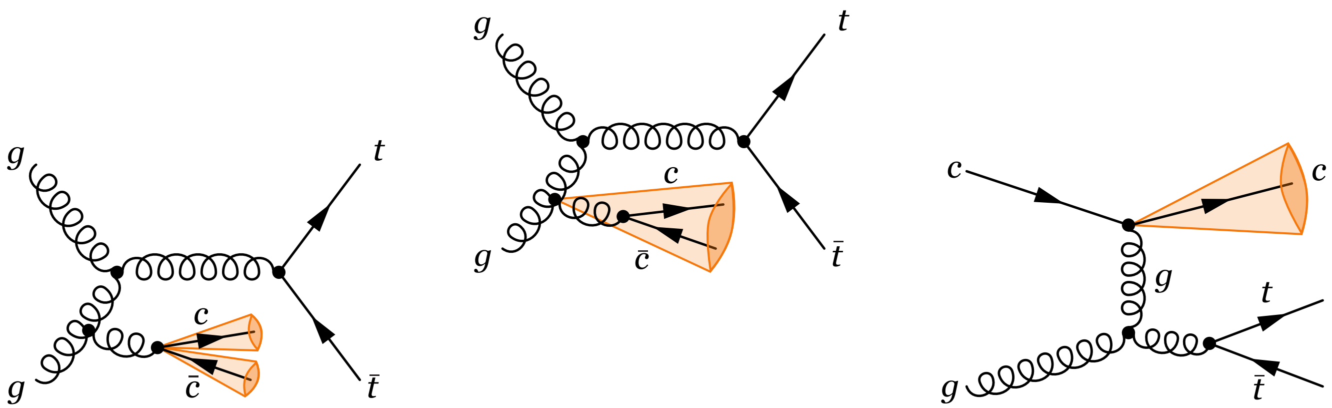


- **Dedicated $t\bar{t}$ + charm** [measurement by CMS](https://arxiv.org) in 2020:
  - Using 41.5 fb^{-1} of Run 2 data, only considering dilepton $t\bar{t}$ decays, focus on $t\bar{t} + c\bar{c}$, not on $t\bar{t} + 1c/C$
  - Comparison with NLO+PS simulations show agreement, but measured value slightly higher
- **ATLAS $t\bar{t}H(H \rightarrow b\bar{b})$ measurements** consistently find $t\bar{t}$ + charm rates higher than predicted by NLO+PS simulations, most recently this summer (arXiv:2407.10904)
- **No dedicated ATLAS measurement of $t\bar{t}$ + charm yet**

See C. Scheulen's YSF and L. Varriale's talks!

Analysis outline

New measurement:
arXiv:2409.11305



Inclusive $t\bar{t}$ + charm production of experimental interest, but the three production modes are of different origin and sensitive to different effects

→ **Separate measurement of $t\bar{t} + \geq 2c$ and $t\bar{t} + 1c$:**

- $t\bar{t} + \geq 2c$ = all final states with two or more c-jets, primarily driven by $t\bar{t} + c\bar{c}$
- $t\bar{t} + 1c$ = single c-quark production, merged $t\bar{t} + 1C$ scenario, $t\bar{t} + c\bar{c}$ with separate c-jets if one of them is outside the acceptance criteria

Measurement in **single-lepton** (1L) and **dilepton** (2L) final states:

- 1L: larger statistics, but additional contamination from c-quarks from W-boson decays
- 2L: rarer, but less background

Simulation setup

MC Samples

- Inclusive $t\bar{t}$, 5FS, PowhegBox + Pythia 8
- $t\bar{t} + b\bar{b}$, 4FS, PowhegBox-Res + Pythia 8

Categorised $t\bar{t}$ + jets events

- Reconstruct $R = 0.4$ jets at particle level, $p_{\mathrm{T}} > 15$ GeV, $|\eta| < 2.5$
- Exclude jets from $t\bar{t}$
- Classify events using ghost-association of extra jets with b/c-hadrons

Overlap-removed setup

- $t\bar{t} + b\bar{b}$ = subset of $t\bar{t}$
  → the samples overlap!
- Remove $t\bar{t} +\geq 1b$ from $t\bar{t}$
- Remove all but $t\bar{t} +\geq 1b$ from $t\bar{t} + b\bar{b}$

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Categories:

- $t\bar{t} + \geq 2c$
- $t\bar{t} + 1c$
- $t\bar{t} + \geq 1b$
- $t\bar{t} + \text{light}$

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Categories:

- $t\bar{t} + \geq 2c$
- $t\bar{t} + 1c$
- $t\bar{t} + \geq 1b$
- $t\bar{t}$ + light

Overlap-removed setup

- $t\bar{t} + b\bar{b}$ = subset of $t\bar{t}$ → the samples overlap!
- Remove $t\bar{t} + \geq 1b$ from $t\bar{t}$
- Remove all but $t\bar{t} + \geq 1b$ from $t\bar{t} + b\bar{b}$

Considered backgrounds:

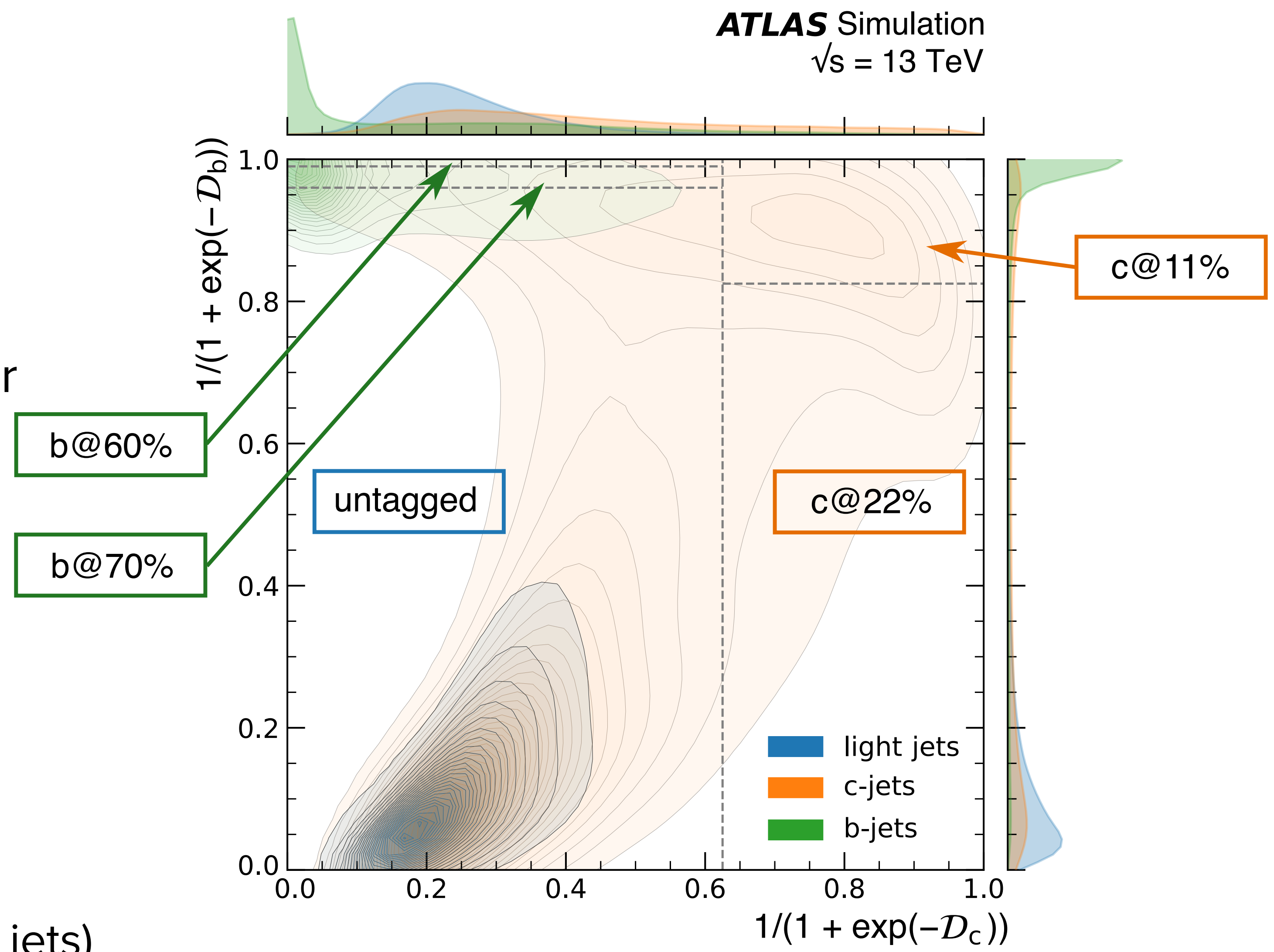
- "Other top" (single-top, associated production)
- "Non-top" (V+jets, diboson)
- Fake-lepton events (→ estimated from data)

The b/c-tagger

- Analysis relies on **simultaneous identification** of c-jets and b-jets
- Standard ATLAS DL1r flavour tagger provides probabilities $p_b, p_c, p_{\text{light}}$
- Reinterpreted on a **2D plane** with

$$\mathcal{D}_c = \log \frac{p_c}{f_b p_b + (1 - f_b) p_{\text{light}}}$$

- **5 working points defined in total:**
  - 2 optimised for b-jet identification
  - 2 optimised for c-jet identification
  - 1 untagged bin (dominated by light jets)



More details on DL1r: EPJC 83 (2023) 681

Event preselection

1L | 2L

- Full Run 2 ATLAS data sample, corresponding to 140 fb^{-1}
- Single-electron and single-muon triggers used in both channels

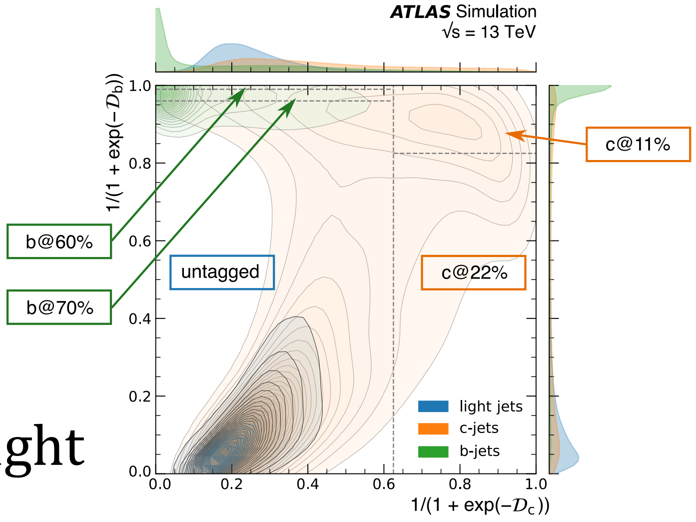
1L channel:

- =1 charged **lepton** (e, μ), trigger-matched
- ≥ 5 **jets**, ≥ 3 b/c-tagged (b@77% or c@22%)
- **Split** into regions with =5 and ≥6 jets

2L channel:

- =2 charged **leptons**, opposite electric charge, one trigger-matched
- ≥ 3 **jets**, with 2 ≥ b/c-tagged
- **Veto** lepton pairs with $m_{\ell\ell} < 15\ \mathrm{GeV}$ and close to *Z*-mass window
- **Split** into regions with =3 and ≥4 jets

Analysis regions



Use **the b/c-tagger working points** to define analysis regions:

- **12 control regions** (CRs) with different mix of $t\bar{t} + \geq 1b$ and $t\bar{t}$ + light
- **Four 1L signal regions** (SRs) and **three 2L signal regions**
  → 1L channel with additional c-quarks from W-boson decay

	$CR_1^{1\ell}$	$CR_2^{1\ell}$	$CR_3^{1\ell}$	$SR_{loose}^{1\ell}$	$SR_{tight}^{1\ell}$	$CR_1^{2\ell}$	$CR_2^{2\ell}$	$CR_3^{2\ell}$	$SR_{loose}^{2\ell}$	$SR_{tight}^{2\ell}$
N_{jets}	$= 5$ or ≥ 6					$= 3$ or ≥ 4				≥ 4
$b@70\%$	2	–	–	2	2	2	–	≥ 3	2	2
$b@60\%$	–	≥ 3	3	–	–	–	≥ 3	≤ 2	–	–
$c@22\%$	1	0	1	≥ 2	–	0	–	–	1	≥ 2
$c@11\%$	1	–	1	1	≥ 2	–	–	–	–	–

Cross-section extraction

Fit data in all 19 analysis regions with the profile likelihood fit approach:

- **Parameters of interest:** $t\bar{t} + \geq 2c$ and $t\bar{t} + 1c$ signal strengths
- **Systematic uncertainties** incorporated in the fit as **nuisance parameters** constrained by a Gaussian penalty term in the likelihood function
- Normalisation factors for $t\bar{t} + \geq 1\mathrm{b}$ and $t\bar{t} + \mathrm{light}$ are left **free-floating**

Measure cross-sections in a fiducial phase space at particle level

- Mimics the detector acceptance – similar requirements as in the event preselection
- ≥ 5 jets in 1L, ≥ 3 jets in 2L, but **no requirements** on the presence of b-jets or c-jets

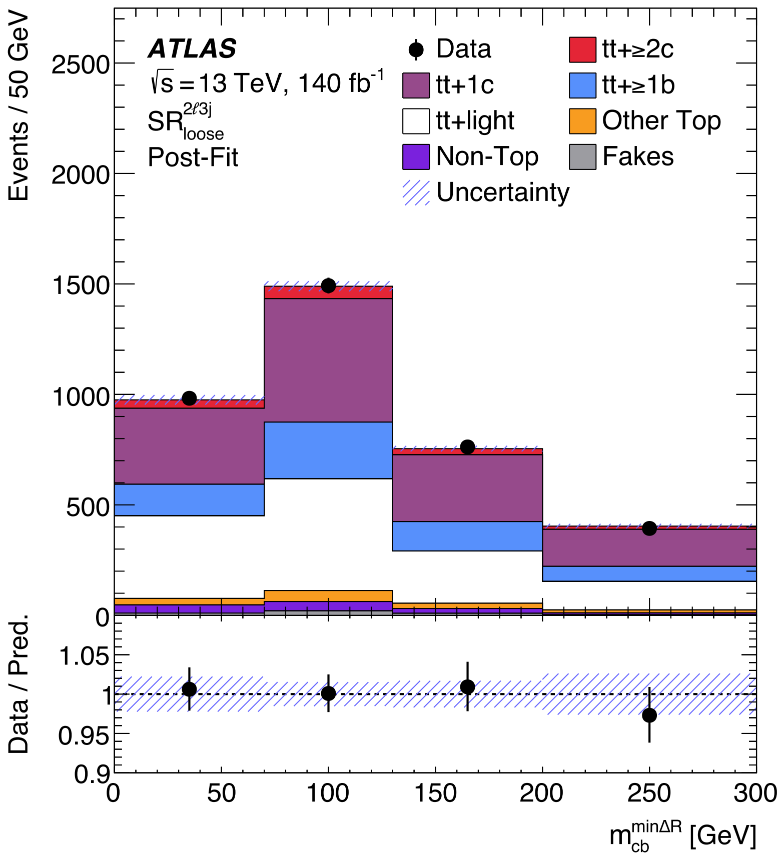
In addition, cross-sections measured in a more inclusive volume

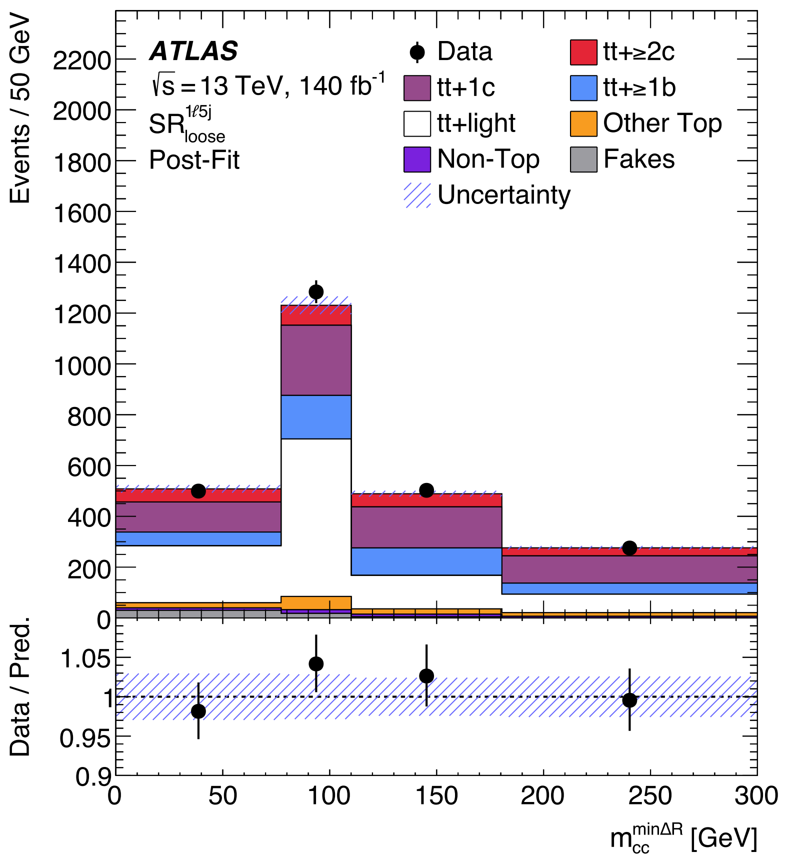
Region observables

All CRs are included as a **single bin** in the fit

SRs use observables with separation power between the $t\bar{t}$ + jets categories

- 3-jet-exclusive/5-jet-exclusive SRs: **invariant masses** between c-tagged/b-tagged jets
- 4-jet-inclusive and 6-jet-inclusive and regions: **jet multiplicity**





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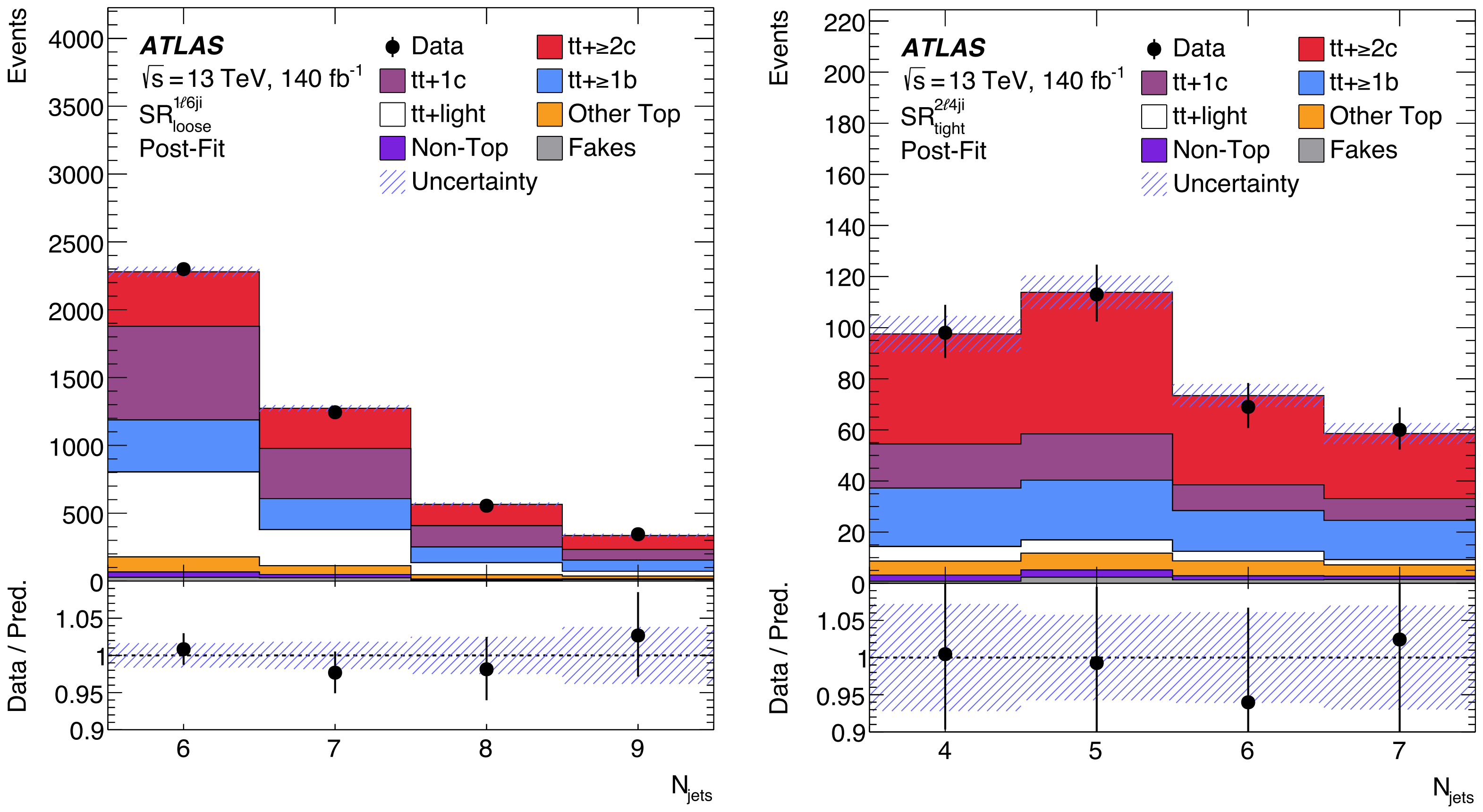

Systematic uncertainties

- Several **uncertainties in the modelling of $t\bar{t}$ and $t\bar{t} + b\bar{b}$** considered:
    - **NLO matching uncertainty**: $p_{\mathrm{T}}^{\mathrm{hard}}$ parameter setting
    - **Parton-shower (PS) variation**: Pythia 8 vs. Herwig 7
    - Others: scale uncertainties, ISR, FSR, PDF, h_{damp}, recoil scheme
    - All of them implemented **independently** for $t\bar{t} +\geq 1c$, $t\bar{t} +\geq 1b$ and $t\bar{t} + \mathrm{light}$
- Additional normalisation/modelling uncertainties on the other background processes
- Statistical uncertainties in the data-driven fake estimate
- **On all: instrumental uncertainties, including on the b/c-tagger calibration**

Cross-section results

Extracted fiducial cross-sections:

$$\sigma^{\text{fid}}(t\bar{t} + \geq 2c) = 1.28\,^{+0.16}_{-0.10}\,(\text{stat})\,^{+0.21}_{-0.22}\,(\text{syst})\text{ pb}$$
$$= 1.28\,^{+0.27}_{-0.24}\text{ pb}$$
$$\sigma^{\text{fid}}(t\bar{t} + 1c) = 6.4\,^{+0.5}_{-0.4}\,(\text{stat}) \pm 0.8\,(\text{syst})\text{ pb}$$
$$= 6.4\,^{+1.0}_{-0.9}\text{ pb}$$

Uncertainty group	Fractional uncertainty [%] on $\sigma^{\text{fid}}(t\bar{t} + \geq 2c)$	Fractional uncertainty [%] on $\sigma^{\text{fid}}(t\bar{t} + 1c)$
$t\bar{t} + \geq 1c$ modeling	9	8
Background modeling:		
$t\bar{t} + \geq 1b$	4	4
$t\bar{t}$ + light	6	4
Others	2.5	1.7
Instrumental:		
b-tagging	2.2	1.8
c-tagging	9	4
light mis-tagging	2.2	3.4
JES/JER	6	3.5
Others	1.3	0.9
MC statistics	3.1	2.5
Total systematic uncertainty	17	12
Data statistical uncertainty	11	7
Total	20	14

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$$\sigma^{\text{fid}}(t\bar{t} + 1c) = 6.4\,^{+0.5}_{-0.4}\,(\text{stat}) \pm 0.8\,(\text{syst})\text{ pb}$$
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Measurements limited by:

- Data statistics
- Modelling of the $t\bar{t} + \geq 1c$ signal
- Calibration of the b/c-tagger

Uncertainty group	Fractional uncertainty [%] on $\sigma^{\text{fid}}(t\bar{t} + \geq 2c)$	Fractional uncertainty [%] on $\sigma^{\text{fid}}(t\bar{t} + 1c)$
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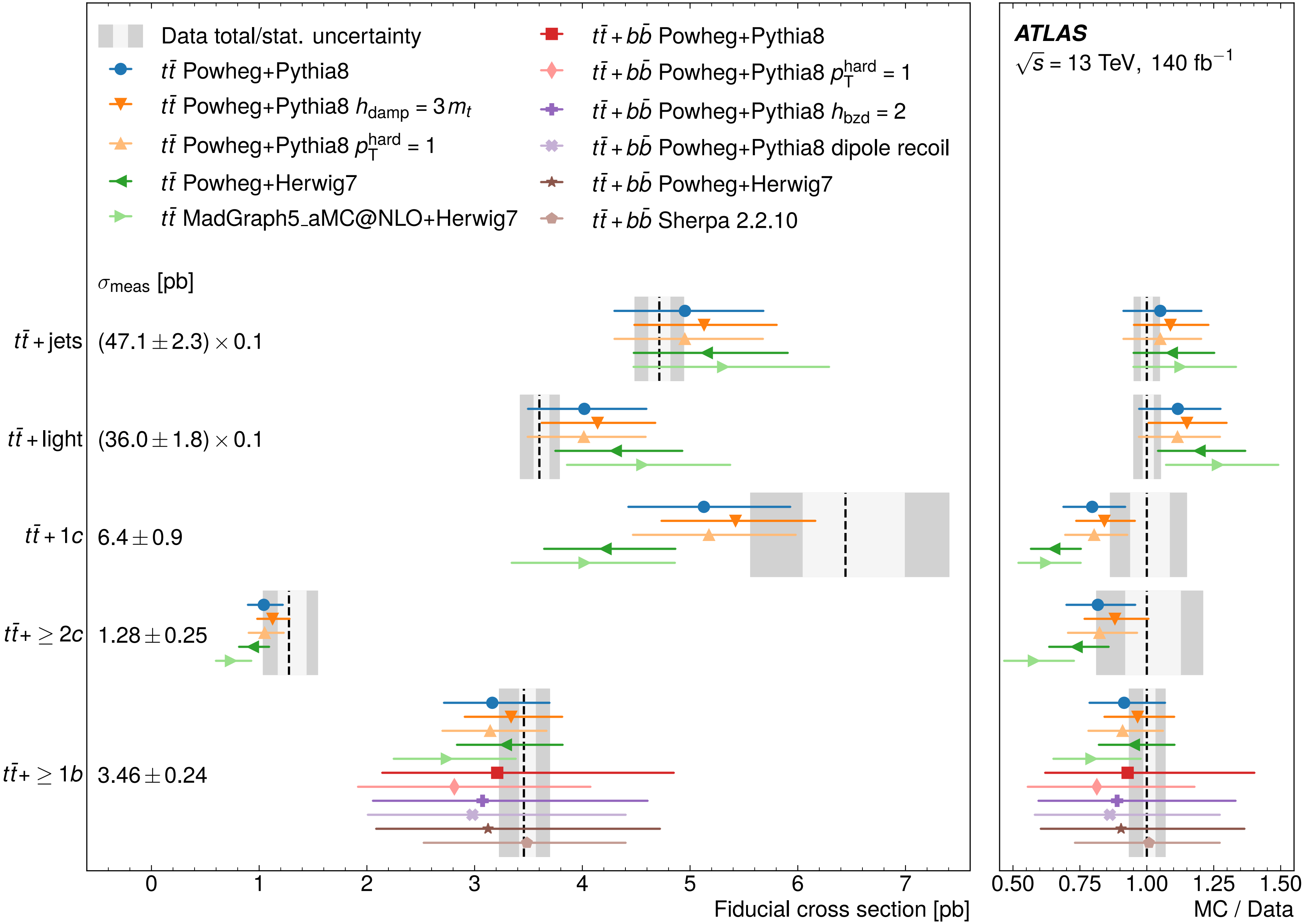
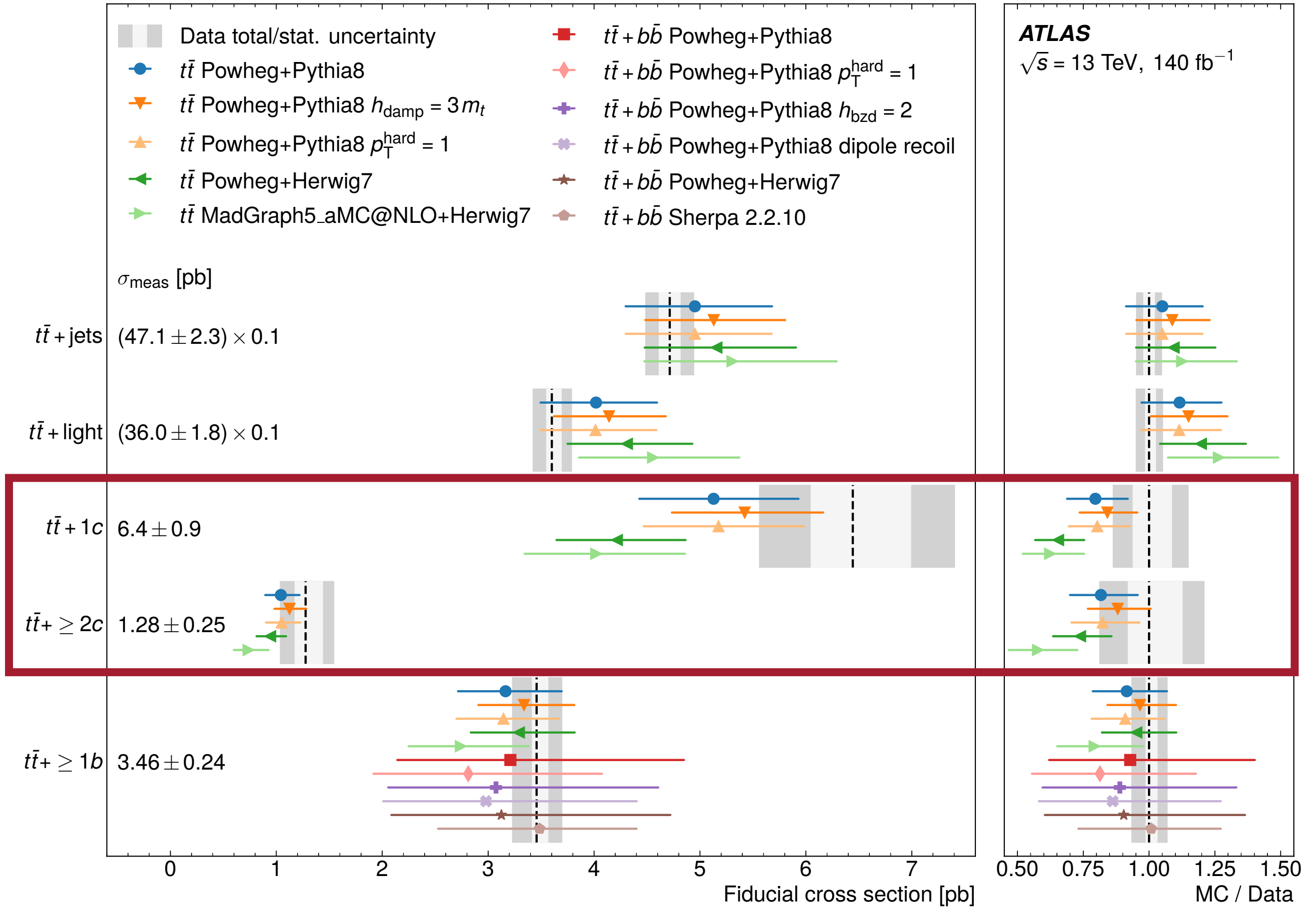


N.B. All $t\bar{t}$ predictions are inclusively reweighted to the NNLO cross-section from Top++2.0.
All $t\bar{t} + b\bar{b}$ predictions are reweighted to the NLO cross-section calculated by Powheg.

Results compared

Predictions for $t\bar{t} + \geq 2c$ and $t\bar{t} + 1c$ cross-sections from **NLO+PS simulation**:

- **Largely consistent** with measurements, but **underprediction** of observed cross-sections by 0.5 to 2.0 standard deviations
- **Powheg+Pythia8** setups agree within measurement and pred. uncertainties
- Worse agreement for Powheg+Herwig7 and aMC@NLO+Herwig7
- $t\bar{t} + \geq 1b$ normalisation factor **consistent** with recent ATLAS $t\bar{t} + b\bar{b}$ measurement (arXiv:2407.13473)



Cross-section ratios

- Determined cross-section ratios of $t\bar{t} + \geq 2c$ and $t\bar{t} + 1c$ to total $t\bar{t}$ + jets production
- Benefits from the **cancellation of several systematic uncertainties** (detector instrumentation and calibration), potentially reducing the overall uncertainties

$$R^{\text{inc}}_{t\bar{t}+\geq 2c} = (1.23 \pm 0.25)\% \qquad R^{\text{fid}}_{t\bar{t}+\geq 2c} = (2.7 \pm 0.5)\%$$

$$R^{\text{inc}}_{t\bar{t}+1c} = (8.8 \pm 1.3)\% \qquad R^{\text{fid}}_{t\bar{t}+1c} = (13.7 \pm 1.8)\%$$

- Fiducial: **relative uncertainties of 18% and 13%** (cross-sections: 20% and 14%)
- **Agreement** with combined Powheg+Pythia $t\bar{t}$ and $t\bar{t} + b\bar{b}$ prediction at the level of 1.0 to 1.4 (0.9 to 1.1) standard deviations in the fiducial (inclusive) measurement

Conclusions

- **ATLAS measurement** of $t\bar{t} + \geq 2c$ and $t\bar{t} + 1c$ (fiducial and inclusive) cross-sections
  - $t\bar{t}$ + charm = important process to understand for many rare final states
  - Dedicated computations and/or 3FS simulation setups would aid our understanding
- **b/c-tagger**: custom flavour-tagging algorithm to simultaneously b-tag and c-tag jets
- Measured fiducial cross-sections and ratios to total $t\bar{t}$ + jets production
- NLO+PS predictions **largely consistent** with results, but all underpredict measured values

	Measured	$t\bar{t}$ or $t\bar{t}+b\bar{b}$ POWHEG+PYTHIA8
$\sigma^{\text{fid}}(t\bar{t}+\geq 1b)$ [pb]	3.46 ± 0.24	3.2 ± 1.6
$\sigma^{\text{fid}}(t\bar{t}+\geq 2c)$ [pb]	1.28 ± 0.25	1.04 ± 0.18
$\sigma^{\text{fid}}(t\bar{t}+1c)$ [pb]	6.4 ± 0.9	5.1 ± 0.8
$\sigma^{\text{inc}}(t\bar{t}+\geq 1b)$ [pb]	13.0 ± 0.9	12 ± 4
$\sigma^{\text{inc}}(t\bar{t}+\geq 2c)$ [pb]	5.4 ± 1.1	4.4 ± 0.7
$\sigma^{\text{inc}}(t\bar{t}+1c)$ [pb]	38 ± 6	31 ± 4
$R^{\text{fid}}_{t\bar{t}+\geq 1b}$ [%]	7.2 ± 0.4	6.5 ± 3.3
$R^{\text{fid}}_{t\bar{t}+\geq 2c}$ [%]	2.7 ± 0.5	2.1 ± 0.4
$R^{\text{fid}}_{t\bar{t}+1c}$ [%]	13.7 ± 1.8	10.3 ± 1.6
$R^{\text{inc}}_{t\bar{t}+\geq 1b}$ [%]	3.14 ± 0.23	2.6 ± 0.8
$R^{\text{inc}}_{t\bar{t}+\geq 2c}$ [%]	1.23 ± 0.25	0.97 ± 0.16
$R^{\text{inc}}_{t\bar{t}+1c}$ [%]	8.8 ± 1.3	6.9 ± 1.0

Thank you!

arXiv:2409.11305

ATLAS briefing

MC Simulation (1)

- **MC samples** used to estimate rates of most contributing processes
- **Inclusive $t\bar{t}$ events** simulated with Powheg Box + Pythia 8
  - Modelling variations with different parameter settings: h_{damp}, $p_{\mathrm{T}}^{\mathrm{hard}}$, …
  - Alternative simulation setups: Powheg+Herwig 7 and aMC@NLO+Herwig 7
  - All use the five-flavour scheme, assuming massless b-quarks in the matrix element
- **Dedicated $t\bar{t} + b\bar{b}$ simulation** in PowhegBox-Res + Pythia 8
  - Uses the four-flavour scheme with massive b-quarks ($b\bar{b}$ pair generated in the ME)
  - Similar suite of modelling variations and alternative setups

MC simulation (2)

$t\bar{t}$ + jets classification scheme applied to events from $t\bar{t}$ and $t\bar{t} + b\bar{b}$ simulation:

1. **Reconstruct anti-k_t jets** at particle level with $R = 0.4, p_{\mathrm{T}} > 15\ \mathrm{GeV}, |\eta| < 2.5$
2. Check **ghost association** of the jets to b-hadrons and c-hadrons with $p_{\mathrm{T}} > 5\ \mathrm{GeV}$
   1. Those associated with ≥1 b-hadron → particle-level b-jet
   2. Those associated with ≥1 c-hadron and no b-hadron → particle-level c-jet
3. **Exclude** all jets that originate from the decays of the top quarks and W bosons
4. **Based on the remaining jets, classify the event into:**
   1. $t\bar{t} + \geq 1b$ if the event has one or more b-jets
   2. $t\bar{t} + \geq 2c$ if the event has two or more c-jets, and no b-jets
   3. $t\bar{t} + 1\mathrm{c}$ if the event has exactly on c-jet and no b-jets
   4. $t\bar{t} + \mathrm{light}$ for all others

MC Simulation (3)

Other processes considered:

- **"Other Top":** single-top-quark production (t-channel, s-channel, tW), $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$, tZq, tWZ. Some of these have alternative setups
- **"Non-Top":** W+jets, Z+jets, diboson
- **"Fakes":** fake-lepton contributions, estimated from data using the matrix method
  - Prompt-lepton efficiencies via tag-and-probe method in Z-boson decays
  - Fake-lepton efficiencies from events with ≥3 jets, ≥2 b-tagged jets (70% DL1r), one lepton fulfilling looser ID and quality criteria than in the standard analysis (and no isolation req.). Enriched fake region by requiring MET + leptonic W mass ≤ 60 GeV

b/c-tagger calibration

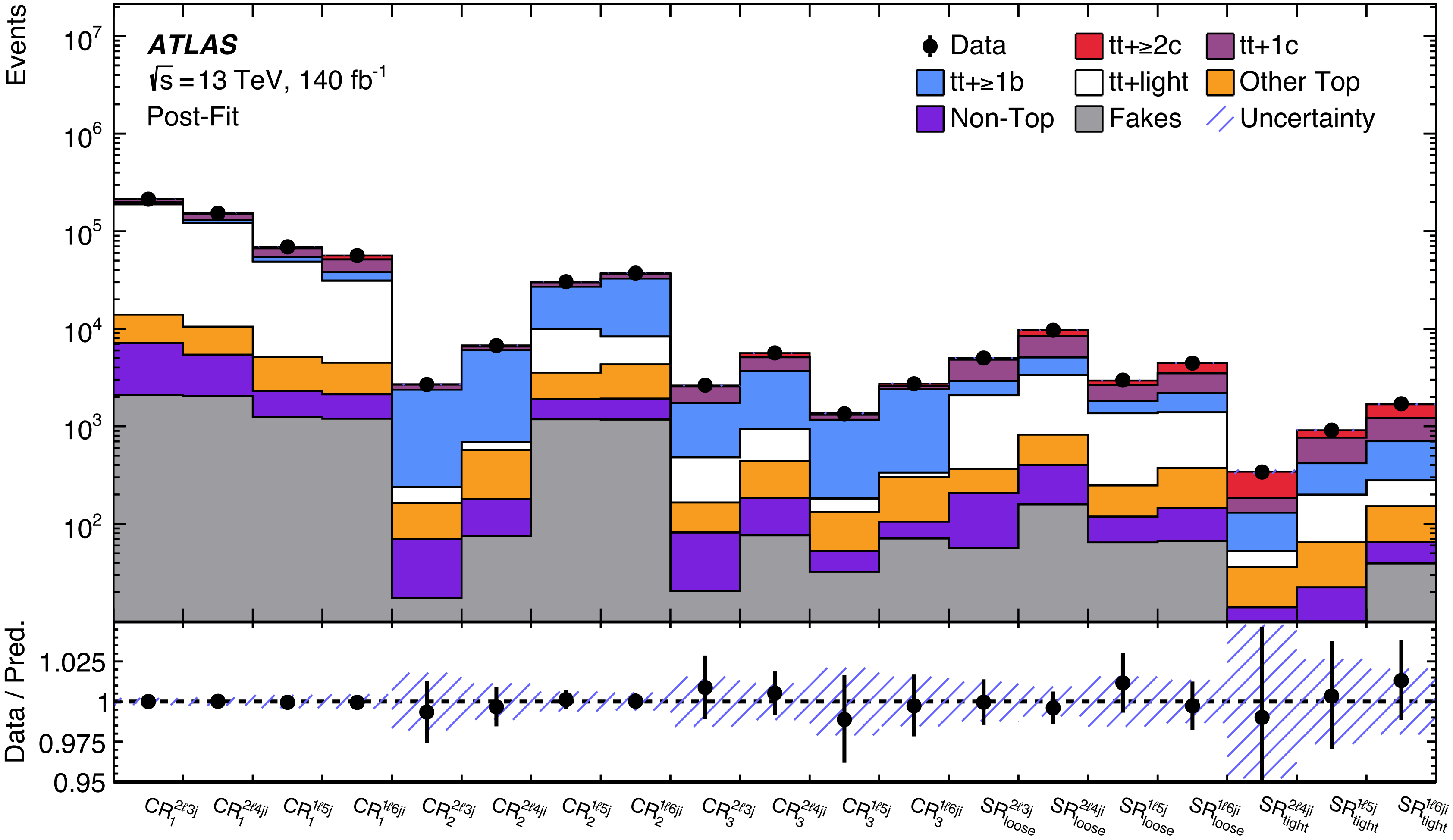
- Following standard procedures to extract simulation-to-data scale factors (SFs): EPJC 79 (2019) 970, EPJC 82 (2022) 95, EPJC 83 (2023) 728
- **b-jet and c-jet calibration** in $t\bar{t}$ events, orthogonal to the analysis regions: ≤4(2) jets
  - All b-tagging SFs close to unity
  - More variation in the c-tagging SFs: b@70% with average SF values around 0.9, some bins incompatible with unity
- **Light-flavour calibration** via the negative-tag method, all compatible with unity
  - b@60% does not enable calibration due to extensive b-jet contamination. SFs are set to unity following the standard DL1r procedure
- Additional simulation-to-simulation SFs to account for differences in tagging efficiencies

b/c-tagger working points

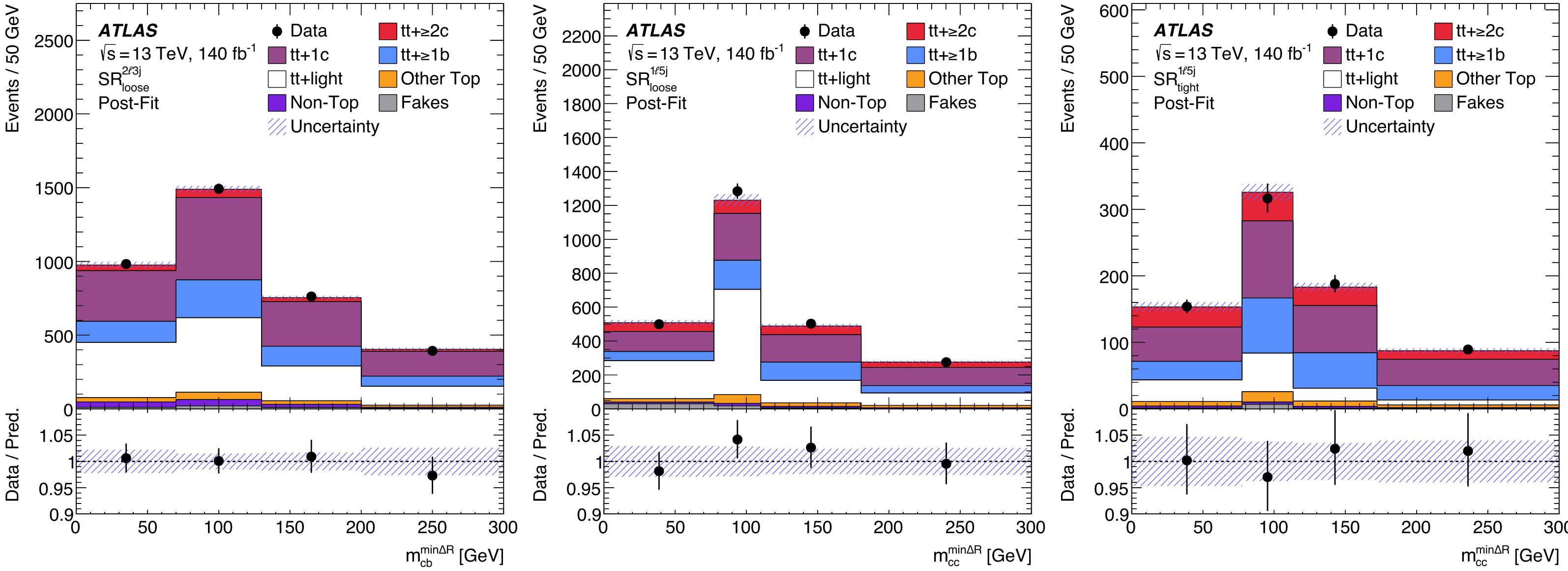
	Efficiency	c-jet rejection	light-jet rejection	$\mathcal{D}'_b$	$\mathcal{D}'_c$
b@60%	60.3%	37.1	2320	≥0.990	<0.625
b@70%	70.0%	12.2	573	≥0.963	<0.625

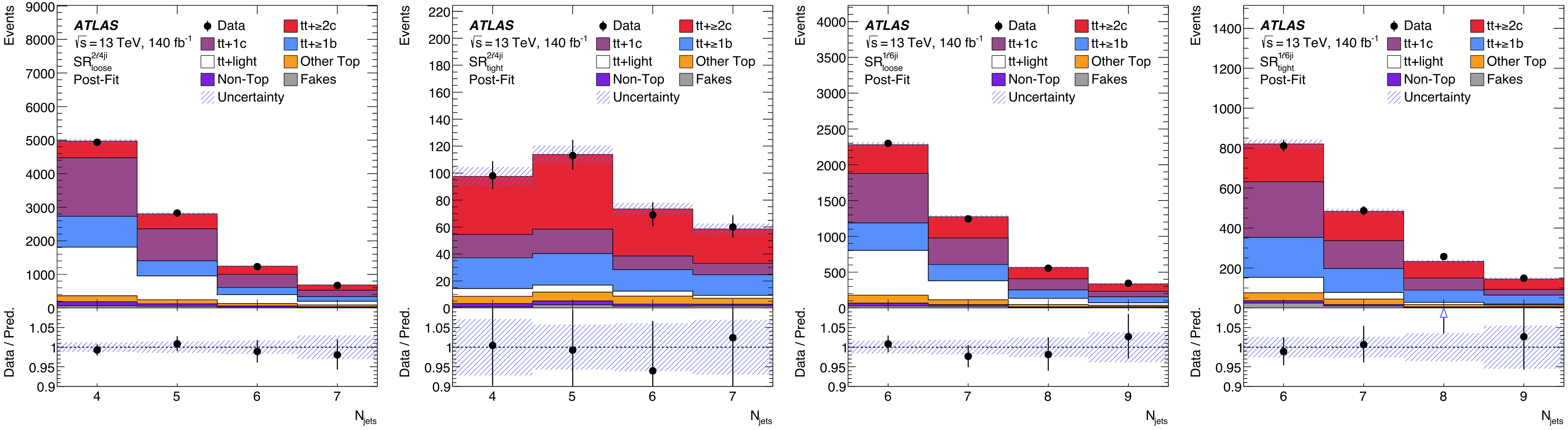
	Efficiency	b-jet rejection	light-jet rejection	$\mathcal{D}'_b$	$\mathcal{D}'_c$
c@11%	11.3%	28.7	1051	≥0.825	≥0.625
c@22%	22.4%	18.9	104	—	≥0.625

Analysis regions post-fit



Signal regions post-fit





Measured and predicted cross-sections

	$t\bar{t} + \geq 2c$ [pb]	$t\bar{t} + 1c$ [pb]	$t\bar{t} + \geq 1b$ [pb]	$t\bar{t}$ + light [pb]	$t\bar{t}$ + jets [pb]
$t\bar{t}$ Powheg+Pythia 8	1.04 ± 0.18	5.1 ± 0.8	3.2 ± 0.5	40 ± 6	50 ± 7
$t\bar{t}$ Powheg+Pythia 8, $h_{\text{damp}} = 3\,m_t$	1.12 ± 0.16	5.4 ± 0.7	3.3 ± 0.5	41 ± 5	51 ± 7
$t\bar{t}$ Powheg+Pythia 8, $p_{\text{T}}^{\text{hard}} = 1$	1.05 ± 0.18	5.2 ± 0.8	3.1 ± 0.5	40 ± 6	50 ± 7
$t\bar{t}$ Powheg+Herwig 7	0.94 ± 0.16	4.2 ± 0.7	3.3 ± 0.5	43 ± 6	52 ± 8
$t\bar{t}$ MadGraph5_aMC@NLO+Herwig 7	0.74 ± 0.19	4.0 ± 0.8	2.7 ± 0.6	46 ± 8	53 ± 10
$t\bar{t} + b\bar{b}$ Powheg+Pythia 8	—	—	3.2 ± 1.6	—	—
$t\bar{t} + b\bar{b}$ Powheg+Pythia 8, $p_{\text{T}}^{\text{hard}} = 1$	—	—	2.8 ± 1.3	—	—
$t\bar{t} + b\bar{b}$ Powheg+Pythia 8, $h_{\text{bzd}} = 2$	—	—	3.1 ± 1.5	—	—
$t\bar{t} + b\bar{b}$ Powheg+Pythia 8, dipole recoil	—	—	3.0 ± 1.4	—	—
$t\bar{t} + b\bar{b}$ Powheg+Herwig 7	—	—	3.1 ± 1.6	—	—
$t\bar{t} + b\bar{b}$ Sherpa 2.2.10	—	—	3.5 ± 1.0	—	—
Data	1.28 ± 0.25	6.4 ± 0.9	3.46 ± 0.24	36.0 ± 1.8	47.1 ± 2.3

Pre-fit yields

	$CR_1^{1\ell 5j}$	$CR_1^{1\ell 6ji}$	$CR_2^{1\ell 5j}$	$CR_2^{1\ell 6ji}$	$CR_3^{1\ell 5j}$	$CR_3^{1\ell 6ji}$
$t\bar{t} + \geq 2c$	1920 ± 180	4100 ± 400	370 ± 40	780 ± 100	40 ± 8	120 ± 19
$t\bar{t} + 1c$	10 200 ± 1100	10 200 ± 1300	2380 ± 210	2500 ± 400	115 ± 21	150 ± 33
$t\bar{t} + \geq 1b$	4800 ± 1300	6800 ± 1000	14 000 ± 4000	23 200 ± 2300	1000 ± 400	1950 ± 210
$t\bar{t}$ + light	50 000 ± 6000	32 000 ± 4000	7100 ± 900	4700 ± 800	45 ± 16	51 ± 26
Other Top	2700 ± 600	2300 ± 500	1600 ± 400	2300 ± 600	80 ± 22	190 ± 50
Non-Top	1000 ± 400	840 ± 330	670 ± 250	680 ± 260	18 ± 7	32 ± 13
Fakes	1500 ± 800	1500 ± 700	1500 ± 700	1500 ± 700	42 ± 26	90 ± 50
Total	72 000 ± 7000	57 000 ± 6000	27 000 ± 4000	35 700 ± 3300	1170 ± 280	2590 ± 270
Data	69 136	56 277	30 388	37 209	1345	2728

	$CR_1^{2\ell 3j}$	$CR_1^{2\ell 4ji}$	$CR_2^{2\ell 3j}$	$CR_2^{2\ell 4ji}$	$CR_3^{2\ell 3j}$	$CR_3^{2\ell 4ji}$
$t\bar{t} + \geq 2c$	950 ± 140	2860 ± 240	17 ± 4	139 ± 21	54 ± 13	410 ± 40
$t\bar{t} + 1c$	10 600 ± 1100	13 400 ± 1700	226 ± 29	390 ± 70	570 ± 100	970 ± 200
$t\bar{t} + \geq 1b$	6200 ± 2500	8700 ± 900	1800 ± 700	4900 ± 500	2450 ± 190	830 ± 270
$t\bar{t}$ + light	192 000 ± 24 000	125 000 ± 10 000	72 ± 14	121 ± 33	300 ± 70	500 ± 110
Other Top	6700 ± 1200	5000 ± 1100	98 ± 30	400 ± 110	83 ± 20	250 ± 60
Non-top	4800 ± 1600	3200 ± 1100	50 ± 18	99 ± 34	57 ± 21	102 ± 35
Fakes	2100 ± 500	2000 ± 500	17 ± 4	74 ± 19	20 ± 5	75 ± 19
Total	223 000 ± 24 000	160 000 ± 12 000	2200 ± 700	6100 ± 500	2100 ± 400	4800 ± 400
Data	213 185	152 931	2682	6725	2640	5655

Pre-fit yields

	$SR^{2\ell 3j}_{loose}$	$SR^{2\ell 4ji}_{loose}$	$SR^{1\ell 5j}_{loose}$	$SR^{1\ell 6ji}_{loose}$	$SR^{2\ell 4ji}_{tight}$	$SR^{1\ell 5j}_{tight}$	$SR^{1\ell 6ji}_{tight}$
$t\bar{t} + \geq 2c$	180 ± 50	1130 ± 80	250 ± 50	830 ± 150	139 ± 23	124 ± 27	410 ± 70
$t\bar{t} + 1c$	1380 ± 300	2200 ± 600	640 ± 120	920 ± 230	36 ± 13	260 ± 50	350 ± 100
$t\bar{t} + \geq 1b$	670 ± 270	1590 ± 110	350 ± 130	790 ± 140	78 ± 12	180 ± 60	420 ± 60
$t\bar{t}$ + light	1780 ± 320	2900 ± 500	1110 ± 210	1170 ± 290	24 ± 12	120 ± 40	130 ± 50
Other Top	150 ± 40	410 ± 80	119 ± 35	210 ± 50	21 ± 5	40 ± 9	85 ± 24
Non-top	140 ± 50	220 ± 80	47 ± 19	66 ± 27	8 ± 3	12 ± 5	23 ± 9
Fakes	53 ± 14	150 ± 40	80 ± 50	80 ± 50	6 ± 2	11 ± 8	49 ± 29
Total	4300 ± 500	8700 ± 900	2600 ± 400	4100 ± 600	310 ± 40	740 ± 110	1460 ± 220
Data	5015	9668	2976	4443	340	913	1705

Post-fit yields

	$CR_1^{1\ell 5j}$	$CR_1^{1\ell 6ji}$	$CR_2^{1\ell 5j}$	$CR_2^{1\ell 6ji}$	$CR_3^{1\ell 5j}$	$CR_3^{1\ell 6ji}$
$t\bar{t} + \geq 2c$	2300 ± 500	5000 ± 800	470 ± 110	1000 ± 190	47 ± 10	140 ± 21
$t\bar{t} + 1c$	12 100 ± 1900	13 400 ± 1600	2900 ± 400	3500 ± 400	149 ± 16	209 ± 23
$t\bar{t} + \geq 1b$	6000 ± 330	6800 ± 330	16 900 ± 700	24 400 ± 900	980 ± 40	2050 ± 80
$t\bar{t}$ + light	43 600 ± 1900	26 700 ± 1600	6460 ± 320	4020 ± 330	50 ± 11	34 ± 15
Other Top	2800 ± 600	2400 ± 500	1700 ± 400	2400 ± 600	80 ± 22	200 ± 60
Non-Top	1100 ± 400	930 ± 350	720 ± 260	750 ± 280	20 ± 8	34 ± 13
Fakes	1200 ± 600	1200 ± 500	1200 ± 500	1200 ± 500	32 ± 18	71 ± 35
Total	69 170 ± 280	56 310 ± 260	30 350 ± 190	37 200 ± 210	1360 ± 29	2740 ± 40
Data	69 136	56 277	30 388	37 209	1345	2728

	$CR_1^{2\ell 3j}$	$CR_1^{2\ell 4ji}$	$CR_2^{2\ell 3j}$	$CR_2^{2\ell 4ji}$	$CR_3^{2\ell 3j}$	$CR_3^{2\ell 4ji}$
$t\bar{t} + \geq 2c$	1130 ± 270	3600 ± 800	21 ± 5	168 ± 34	62 ± 14	520 ± 90
$t\bar{t} + 1c$	14 500 ± 1800	18 900 ± 2300	307 ± 33	560 ± 50	810 ± 80	1420 ± 140
$t\bar{t} + \geq 1b$	8500 ± 800	8900 ± 600	2130 ± 70	5330 ± 160	1260 ± 60	2740 ± 120
$t\bar{t}$ + light	175 100 ± 2700	111 000 ± 2700	75 ± 10	117 ± 20	320 ± 40	500 ± 70
Other Top	6800 ± 1200	5100 ± 1100	94 ± 29	390 ± 110	84 ± 20	260 ± 60
Non-Top	5000 ± 1700	3400 ± 1100	53 ± 18	105 ± 35	61 ± 22	110 ± 40
Fakes	2100 ± 500	2000 ± 500	17 ± 4	75 ± 19	20 ± 5	76 ± 19
Total	213 200 ± 500	152 900 ± 400	2700 ± 50	6750 ± 80	2620 ± 40	5630 ± 70
Data	213 185	152 931	2682	6725	2640	5655

Post-fit yields

	$SR^{2\ell 3j}_{loose}$	$SR^{2\ell 4ji}_{loose}$	$SR^{1\ell 5j}_{loose}$	$SR^{1\ell 6ji}_{loose}$	$SR^{2\ell 4ji}_{tight}$	$SR^{1\ell 5j}_{tight}$	$SR^{1\ell 6ji}_{tight}$
$t\bar{t} + \geq 2c$	190 ± 40	1350 ± 220	280 ± 50	960 ± 140	159 ± 22	144 ± 26	470 ± 70
$t\bar{t} + 1c$	1910 ± 180	3270 ± 330	850 ± 90	1300 ± 150	54 ± 8	347 ± 32	510 ± 60
$t\bar{t} + \geq 1b$	830 ± 40	1710 ± 70	450 ± 26	810 ± 50	77 ± 5	220 ± 13	425 ± 22
$t\bar{t}$ + light	1720 ± 160	2540 ± 250	1120 ± 90	1020 ± 140	17 ± 5	134 ± 28	127 ± 34
Other Top	160 ± 40	420 ± 80	130 ± 40	230 ± 50	22 ± 6	42 ± 9	87 ± 24
Non-Top	150 ± 50	240 ± 80	54 ± 20	78 ± 30	8 ± 3	14 ± 5	25 ± 9
Fakes	57 ± 14	160 ± 40	64 ± 32	70 ± 40	6 ± 2	8 ± 6	39 ± 20
Total	5020 ± 60	9710 ± 90	2940 ± 50	4460 ± 60	343 ± 16	910 ± 24	1683 ± 35
Data	5015	9668	2976	4443	340	913	1705

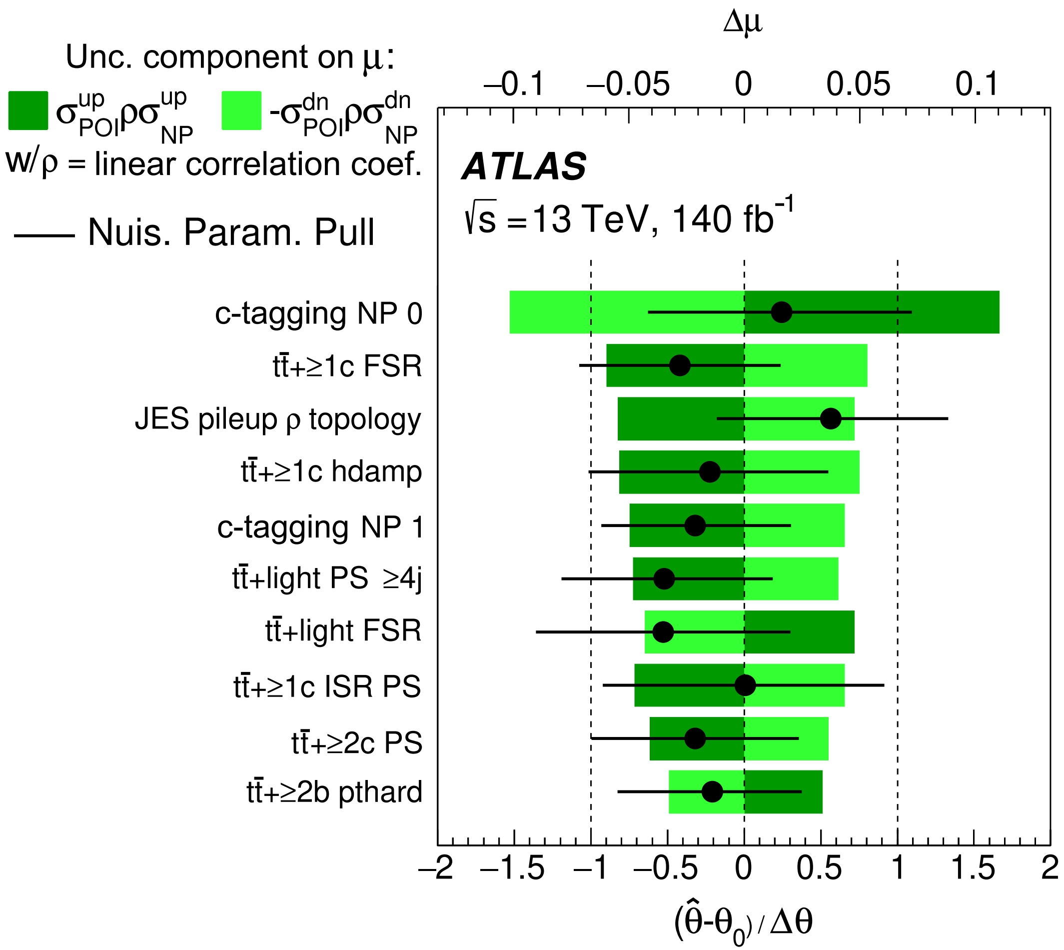
Compatibility tests

- **Independent** $t\bar{t} + \geq 2c$ and $t\bar{t} + 1c$ normalisation factors in **both channels**
  - Results are consistent within uncertainties, 1L channel prefers slightly larger $t\bar{t} + \geq 2c$ value
  - High compatibility with nominal result (57.7% in a χ^2)

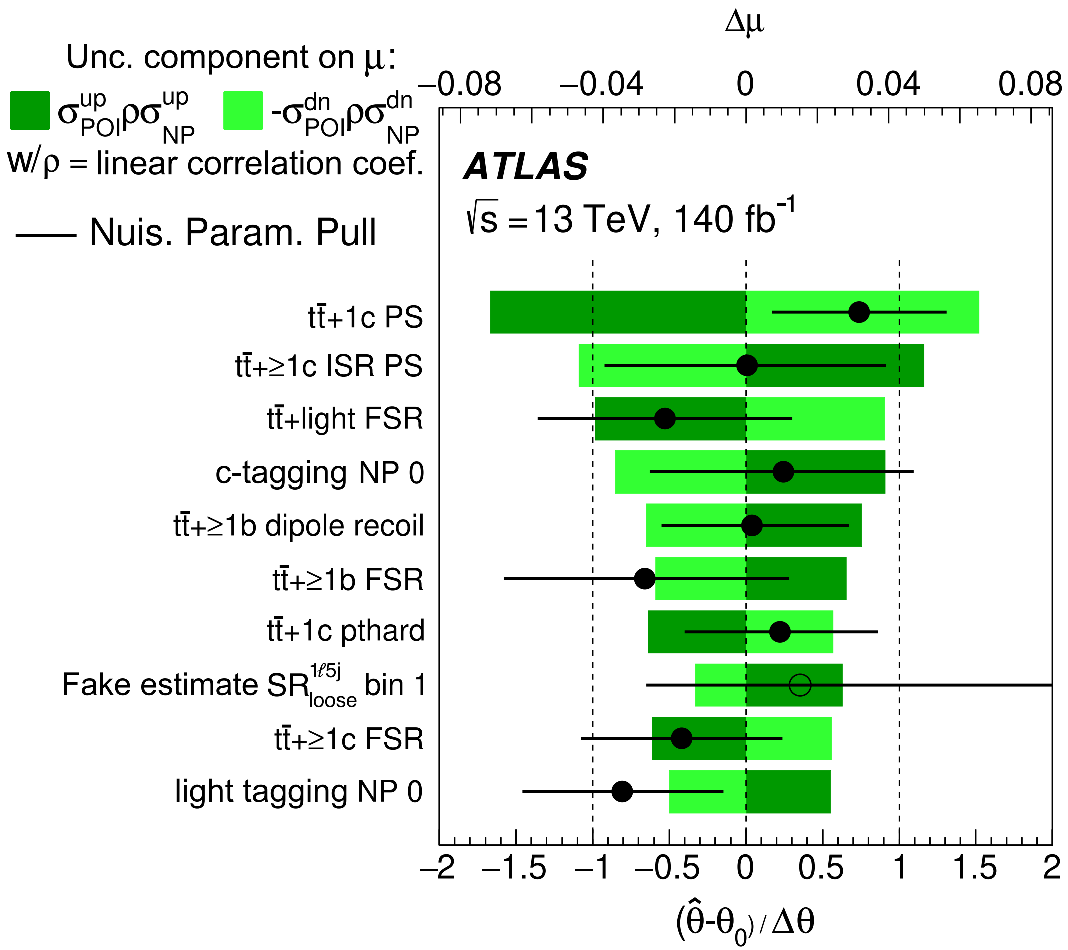
- **Joint parameter of interest** for $t\bar{t} + \geq 2c$ and $t\bar{t} + 1c$ normalisation
  - Re-correlate all corresponding modelling uncertainties
  - Resulting cross-section: $\sigma^{\text{fid}}(t\bar{t} + \geq 1c) = (8.2 \pm 0.9)$ pb
  - Consistent with the nominal result, increased relative precision (11% vs. 20% and 14%)

Nuisance parameter ranking

$\sigma^{\text{fid}}(t\bar{t} + \geq 2c)$

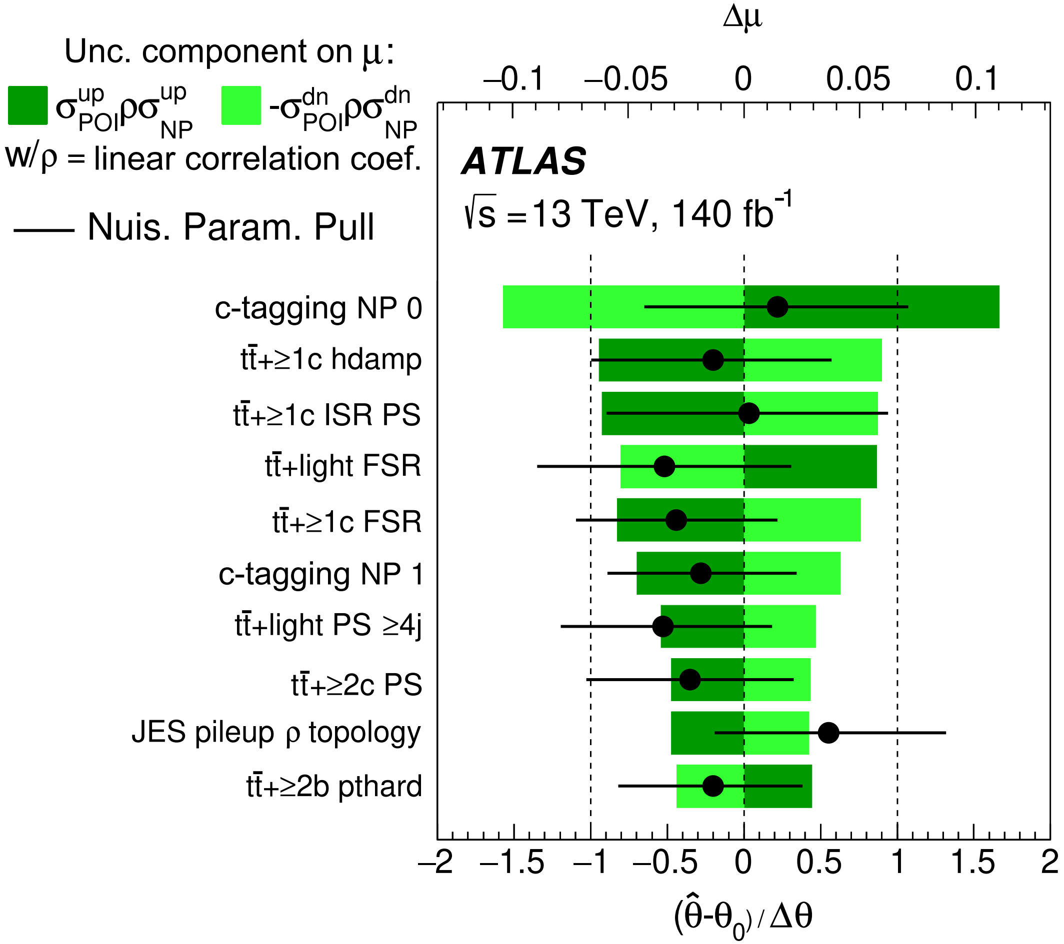


$\sigma^{\text{fid}}(t\bar{t} + 1c)$



Nuisance parameter ranking

$R^{\mathrm{fid}}_{t\bar{t}+\geq 2c}$



$R^{\mathrm{fid}}_{t\bar{t}+1c}$