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ATLAS EXPERIMENT

Top quark (+X) cross-section measurements with the ATLAS detector

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on behalf of ATLAS collaboration

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Outline

The following top quark + X measurements from ATLAS experiment
with full Run 2 dataset, will be discussed today

- [NEW] WbWb differential cross-section measurement in eμ channel [arXiv:2506.14700]

- ttbar + b(b) differential cross-section measurement in eμ channel [JHEP 01 (2025) 068]

- ttbar + c(c) cross-section measurement in 1 and 2 lepton channels [Phys. Lett. B 860 (2025) 139177]

- [NEW] ttbar+2 photon: cross-section + σ(ttγγ)/σ(ttγ) measurement in 1lepton channel [arXiv:2506.05018]

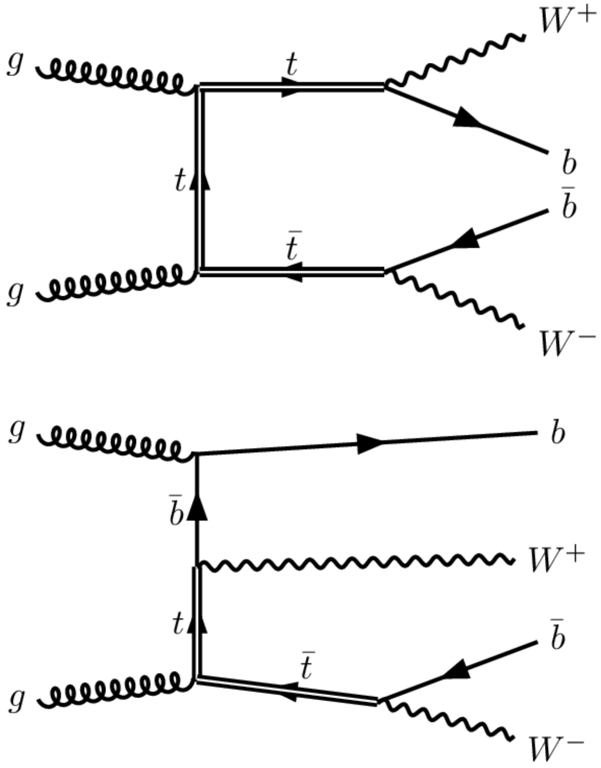
WbWb differential cross-section measurement: Introduction

The issue of interference between ttbar and tW (single-top) processes is well known

<u>Target of this **NEW** analysis:</u> measurements of

1. differential cross-section for interference sensitive observable

2. differential cross-section in several kinematic observables in inclusive regions to help WbWb modelling



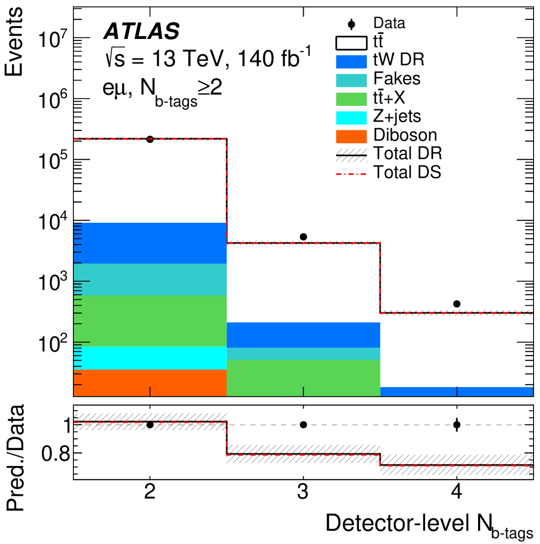
WbWb differential cross-section measurement: Analysis details

<u>Event selection</u> targeting WbWb final state with:
- 2 leptons with pT>28 GeV (eμ, opposite signs)
- >=2 b-tagged jets (pT>25 GeV) using 70% WP

N(b-jets) provide two interesting regions:
- **N(b-jets)=2**, additionally vetoing extra jets with 85% WP → sensitive to interference
- **N(b-jets)>=2**, inclusive region for all differential cross-section measurements

<u>Samples:</u>
Signal made from sum of ttbar and tW processes,
  - using Powheg+Pythia8,
  - tW with DR (diagram removal) scheme is used as nominal

Backgrounds include ttbar+W/Z/H, Z+jets, Diboson and also fake/non-prompt leptons (from ttbar,tW,Wjets)



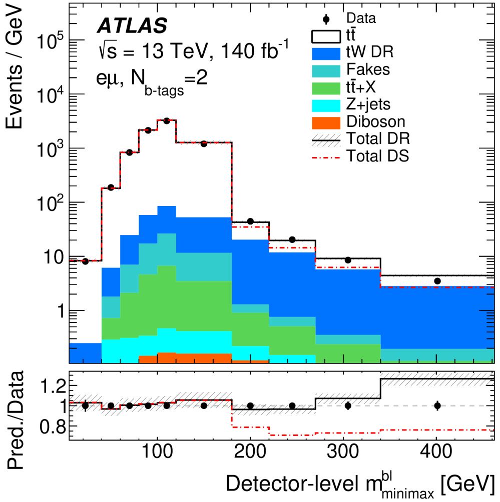
<u>Analysis steps:</u>
- Cut & count analysis
- Detector level distributions unfolded to particle level with similar phase spaces
(b-jets using b-hadron ghost association matching)
- using iterative Bayesian unfolding (IBU)

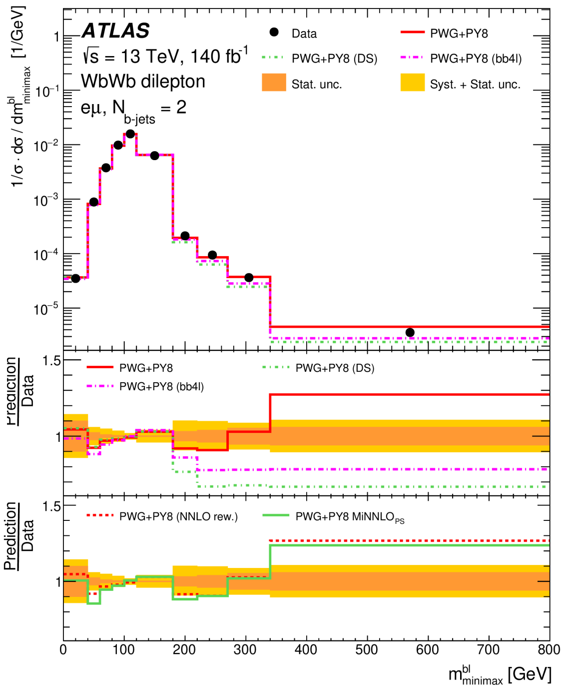
$$m^{bl}_{\mathrm{minimax}} \equiv \min\left\{\max\left(m^{b_1 l_1}, m^{b_2 l_2}\right), \max\left(m^{b_1 l_2}, m^{b_2 l_1}\right)\right\}$$

Magic of minimax:
- for ttbar this is bound to m(top) ~ 180 GeV
- sensitive to interference above 180 GeV
- N(b-jets)>2 would reduce sensitivity,
  → N(b-jets)=2 exclusive region used

DR vs DS (diagram subtraction) **sensitivity can be observed** in both detector level and unfolded results

Unfolded results also compared with other MC models:
- **bb4l sample: underestimates in the tail !**
- DS: least compatible
- NNLO vs nominal





WbWb differential cross-section measurement: 2b inclusive results

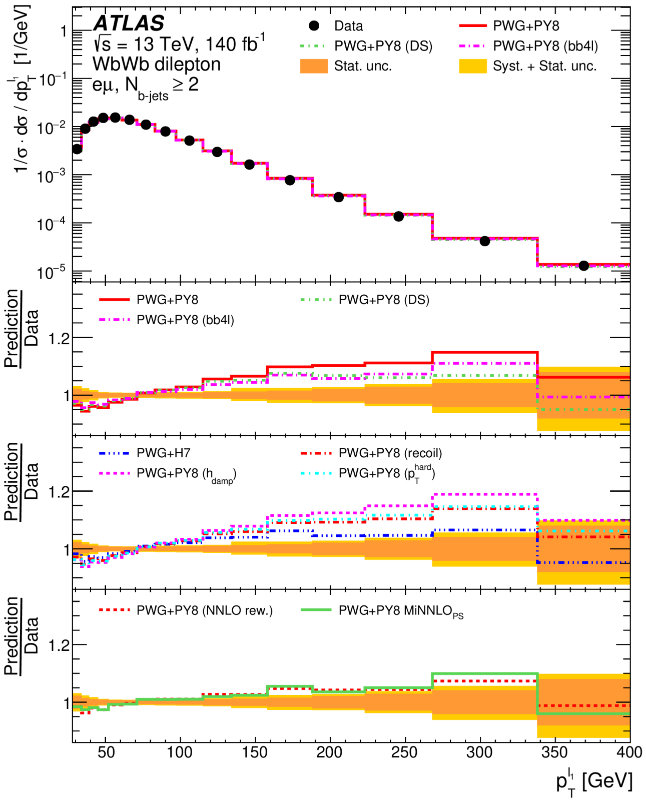
Differential cross-section for 11 observables are obtained in the 2b-inclusive region:
- pT of jets, leptons
- pT and mass of bb4l and bbll systems
- pT of bb system
- number of jets

Compatibility (via chi2, p-values):

- most of the predictions are not able to describe simultaneously all observables, trend found in previous measurements

- e.g. PWG+H7 compatible for leading lepton pT

- PWG+Py8 (NNLO reweighted) describes well all observables simultaneously



Integrated fiducial cross-section:

2b-exclusive region $\sigma_{\text{fid}} = 5.77 \pm 0.01\,(\text{stat.}) \pm 0.05\,(\text{lumi.})^{+0.27}_{-0.29}\,(\text{syst.})$ pb;

2b-inclusive region $\sigma_{\text{fid}} = 5.97 \pm 0.01\,(\text{stat.}) \pm 0.05\,(\text{lumi.})^{+0.27}_{-0.30}\,(\text{syst.})$ pb.

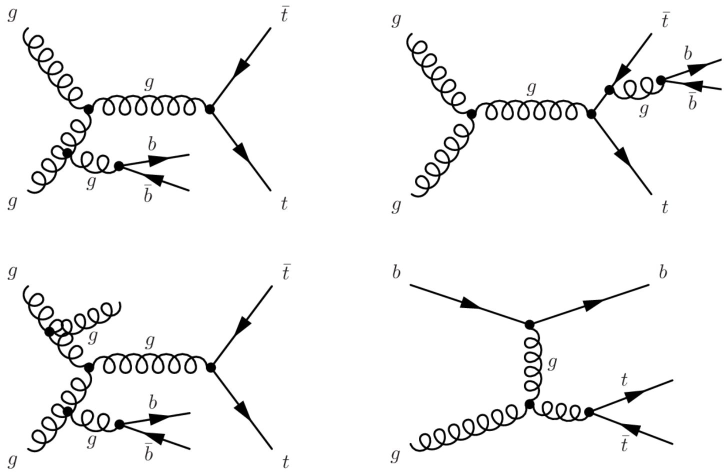
Phase space	$e\mu$, $N_{b\text{-jets}} = 2$	$e\mu$, $N_{b\text{-jets}} \geq 2$
Fiducial cross-section [pb]	5.77	5.97
Total Uncertainty [%]	$^{+4.6}_{-5.1}$	$^{+4.5}_{-5.0}$
Statistical [%]	±0.2	±0.2
Systematic [%]	$^{+4.5}_{-5.1}$	$^{+4.5}_{-5.0}$
Jets [%]	$^{+1.6}_{-1.8}$	$^{+1.8}_{-1.9}$
Pile-up [%]	±0.6	$^{+0.5}_{-0.6}$
Flavour tagging [%]	±2.9	±3.0
Background [%]	±0.3	±0.3
Leptons and $E_{\text{T}}^{\text{miss}}$ [%]	±1.8	±1.8
Luminosity [%]	±0.8	±0.8
tW modelling [%]	±0.1	±0.1
Generator parameters [%]	$^{+1.9}_{-2.9}$	$^{+1.7}_{-2.7}$
Parton shower [%]	±1.0	±0.8
Hard scattering [%]	±0.7	±0.7

ttbar+b(b): introduction

Motivation:
- ttbar in association with b-jets is challenging to model
- irreducible background of ttH(bb), 4tops, etc.

Analysis targets:
- measurement of cross-sections in eμ channel at particle-level fiducial regions:
  - eμ + >=3b, eμ + >=3b >=1light/c
  - eμ + >=4b, eμ + >=4b >=1light/c
- integrated fiducial cross-sections
- normalized differential cross-sections for many observables
  - differential cross-section measurement across large number of observables will benefit future MC modelling
  - some b-jet observables are assigned to top quark decay or additional jet using permutation based algorithm

Event selection:
- ttbar eμ channel selection with additional b-tagged jets using 77% WP



ttbar+b(b): integrated fiducial cross-section

Analysis strategy:

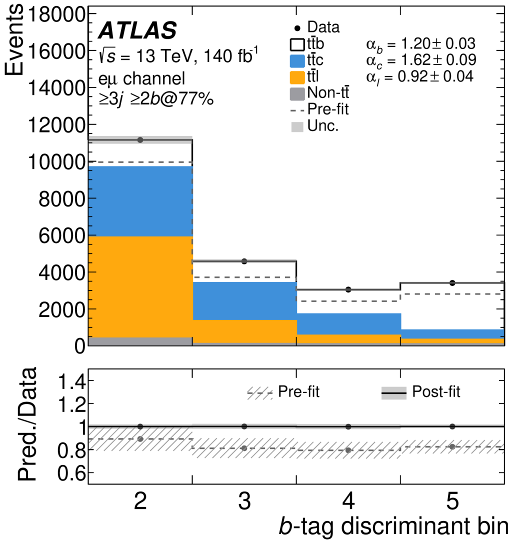
- Fits performed based on b-tagging discriminant bin

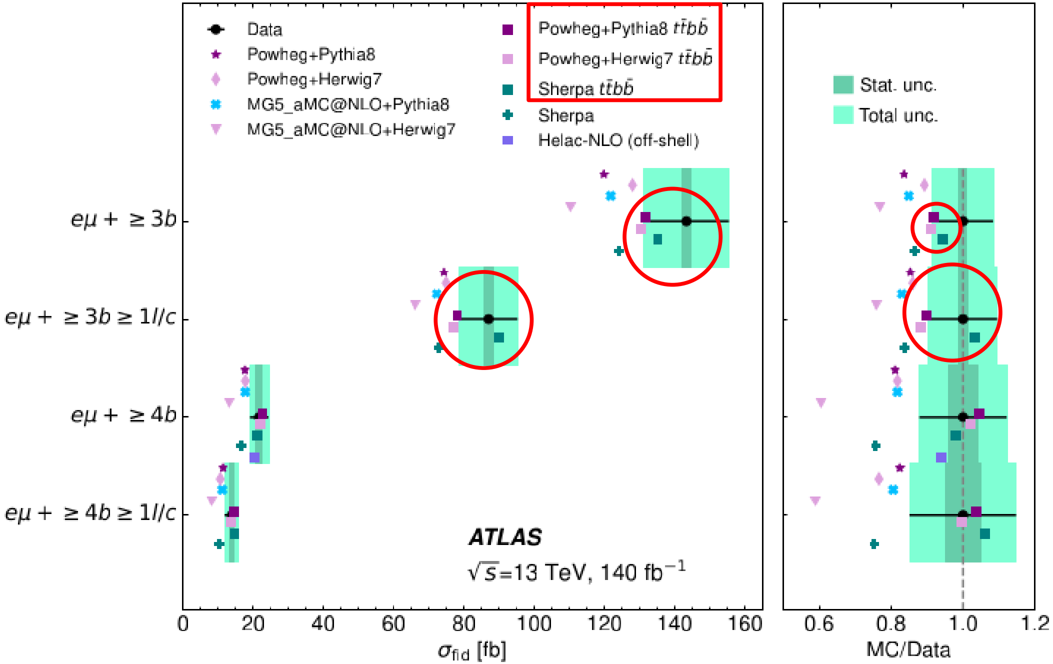
3rd highest b-tagging discriminant score among selected jets correspond to b-tagging efficiencies: 85%–77%, 77%–70%, 70%–60%, and < 60%, respectively

- Observable distributions unfolded using iterative bayesian unfolding

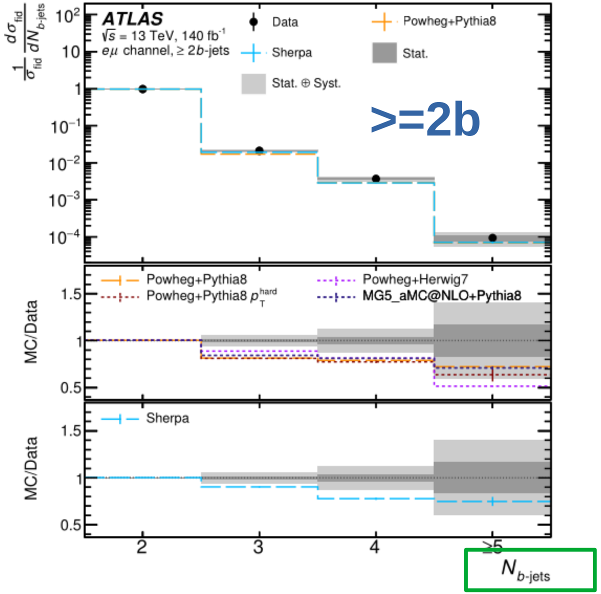
Integrated fiducial cross-sections:

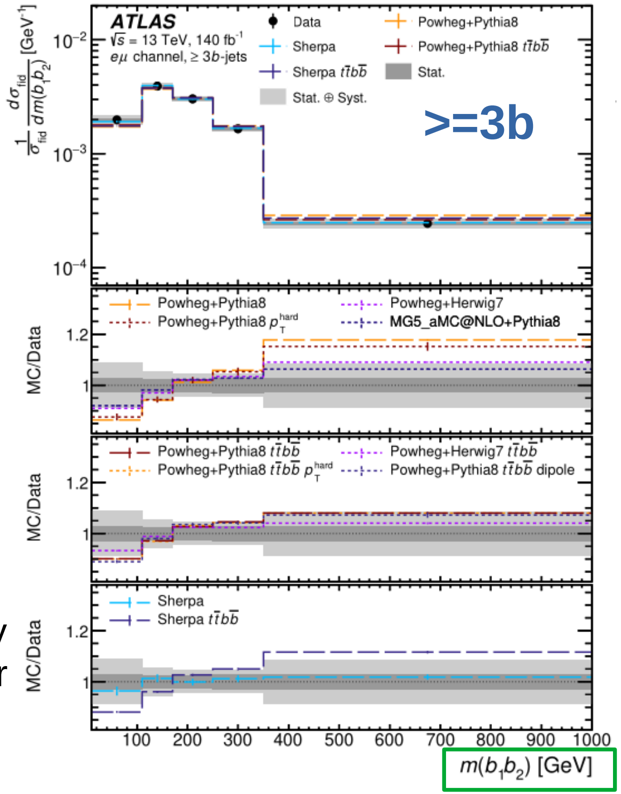
- dedicated ttbb samples have better agreement than ttbar samples
- disagreements present in >=3b regions
- less disagreements in >=4b regions

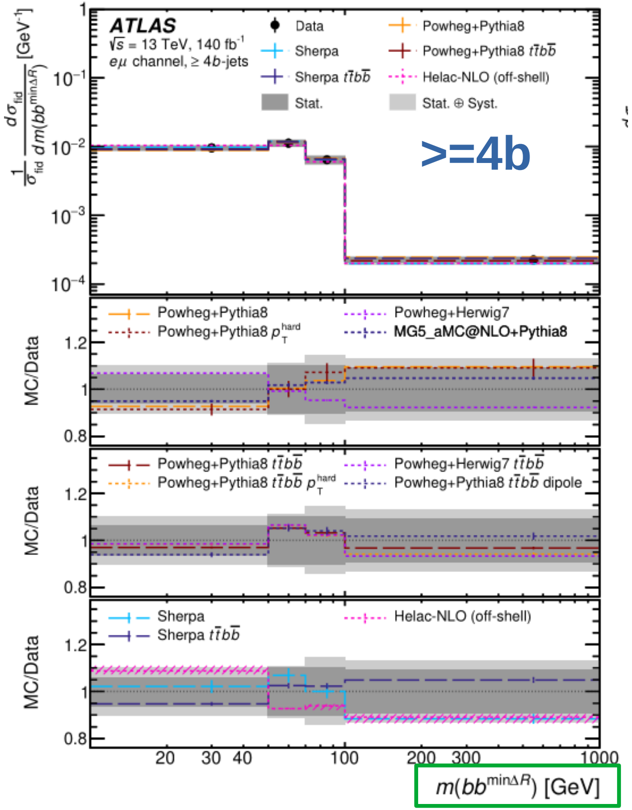




ttbar+b(b): normalized differential fiducial cross-sections





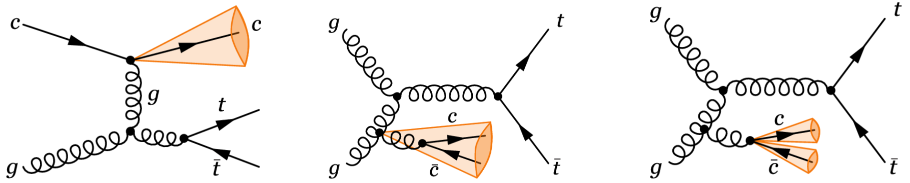


>2b jets have modelling discrepancy
- dedicated ttbb samples have better agreement than ttbar samples
- full list of observables is in backup

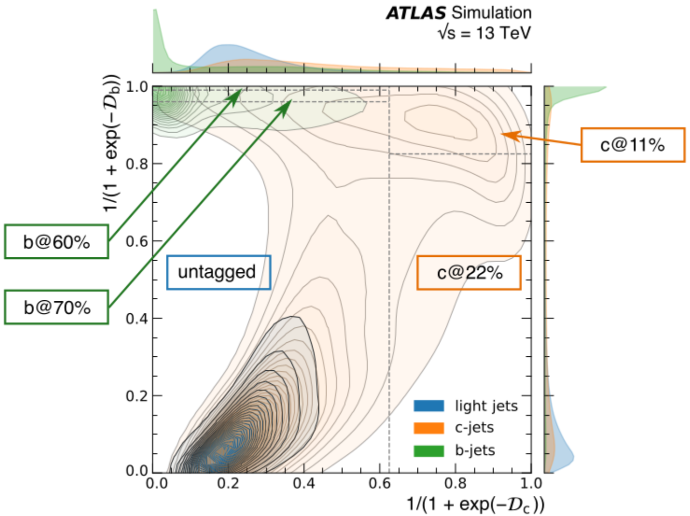
Phys. Lett. B 860 (2025) 139177

Motivation+Analysis goals:

- Similar to ttbar+b(b)
- 1st in ATLAS, inclusive cross-section measurements in **ttbar+1c and ttbar+>=2c separately**

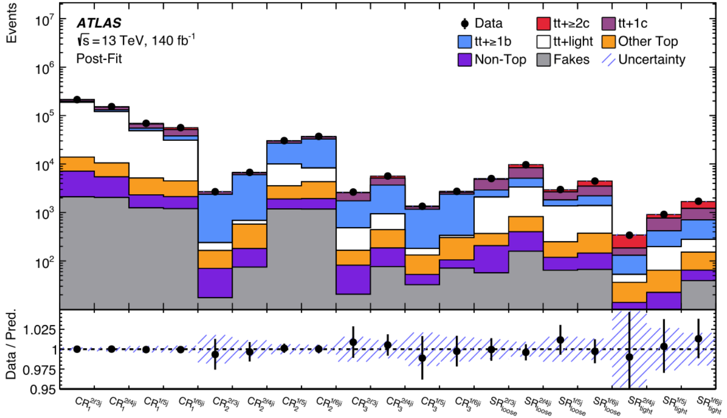


- in both 1 lepton and 2 lepton channels



Analysis strategy:

- using a custom flavour tagging algorithm to simultaneously tag b-jets and c-jets
- several control and signal regions defined for 1 lepton and 2 lepton channels
- a simultaneous combined fit is performed

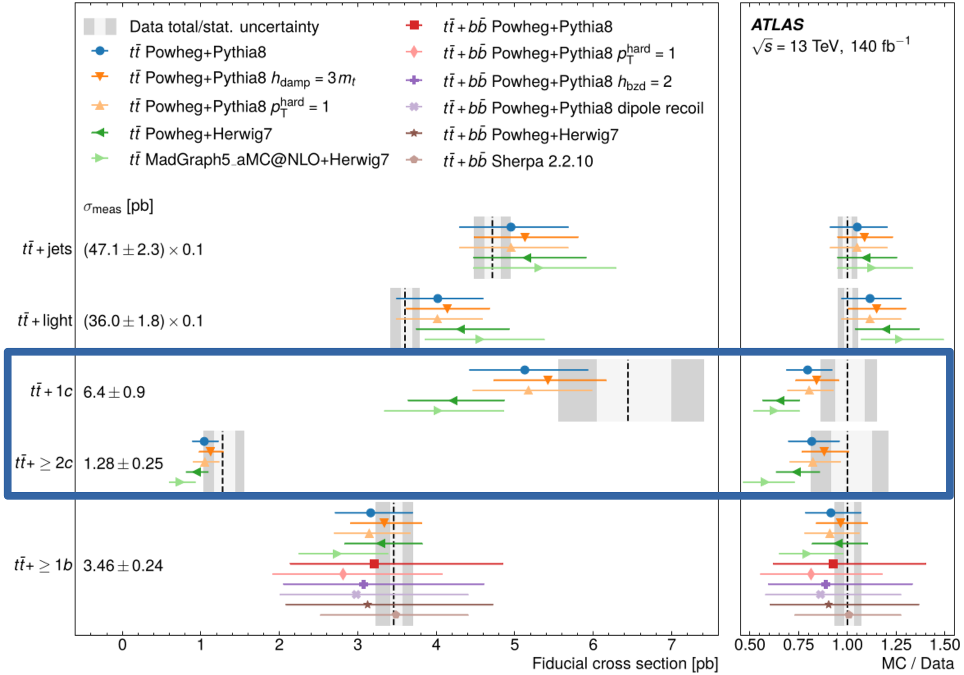


ttbar+c(c): results

The fitted cross-section for the two regions are:

$$\sigma^{\text{fid}}(t\bar{t} + \geq 2c) = 1.28\,^{+0.16}_{-0.10}\,(\text{stat})\,^{+0.21}_{-0.22}\,(\text{syst})\ \text{pb} = 1.28\,^{+0.27}_{-0.24}\ \text{pb},$$

$$\sigma^{\text{fid}}(t\bar{t} + 1c) = 6.4\,^{+0.5}_{-0.4}\,(\text{stat}) \pm 0.8\,(\text{syst})\ \text{pb} = 6.4\,^{+1.0}_{-0.9}\ \text{pb}.$$

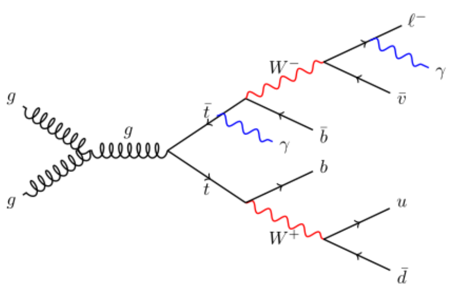


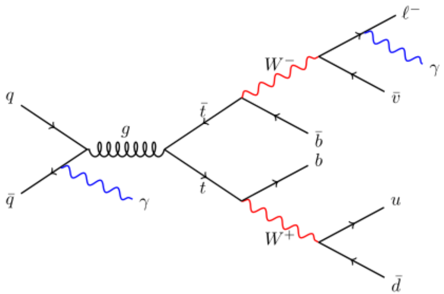
- The predictions of various MCs are consistent with the observed value but under-predict

- The measurements are limited by background modelling, b/c tagger calibration and statistics

ttbar+2 photon: Introduction

arXiv:2506.05018





ttyy: ttbar production in association with two photons coming from production or decay of top quarks

→ irreducible background to ttH(H→yy)

→ sensitive to the top-photon coupling

<u>Objectives:</u>

1. **(1st)** Measurement of ttyy process in 1 lepton channel
   → at particle level fiducial region

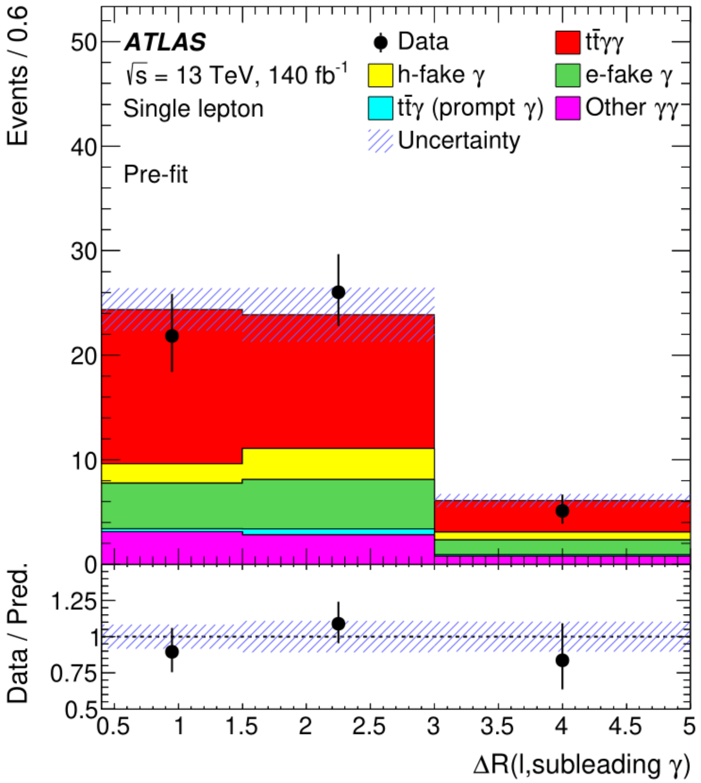
2. Measurement of R=σ(ttyy)/σ(tty)
   → possibility to constrain top-photon coupling
   → using the fit workspace of tty cross-section measurement (JHEP10(2024)191)

ttbar+2 photon: Event Selection and samples

Event selection of semileptonic decays using
1 e/mu, >=4 jets >=1 b-jet (with DL1r 70% WP)
&
2 tight+isolated photon with pT>20 GeV

Samples:
Signal: using ttyy 2→8 LO sample with MG5+Py8, with k-factor calculated from 2→4 NLO/LO samples

Backgrounds:
tty, single top+y(y), W/Z+y(y), VV+y(y), ttH(yy), ttW/Z(+yy) contributing as
- electron faked as photon
  → **e-fake y** (data-driven estimate)
- hadron faked as photon/photon from hadron decay
  → **h-fake y** (data-driven estimate)
- **Other yy** → background processes with 2 prompt photon
tty(prompt y) → tty events passing overlap removal

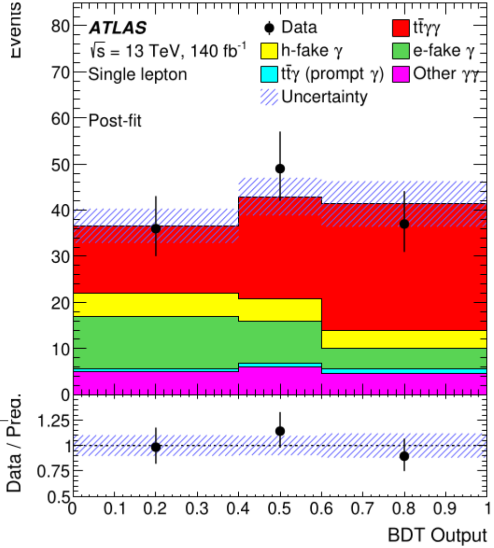


ttbar+2 photon: BDT output as fit variable

BDT with 19 input variables

Input variables
Photon conversion type (converted or unconverted) of the leading photon
ΔR between the leading and subleading photons
η of the subleading photon
Invariant mass of the subleading photon and lepton
Diphoton invariant mass
p_T of the leading jet
ΔR between the subleading photon and lepton
η of the leading photon
p_{T} of the subleading jet
ΔR between the leading photon and lepton
Pseudo-continuous b-tagging distribution of the jet with the highest score
Invariant mass of all jets, the lepton and the photons
$E_{\mathrm{T}}^{\mathrm{miss}}$
Invariant mass of the leading photon and closest b-jet
Invariant mass of the leading photon and lepton
p_{T} of the leading photon
Invariant mass of the subleading photon and closest b-jet
p_{T} of the subleading photon
Number of b-tagged jets (70% working point)

Binary classification with XGBoost
Using ttyy as signal and
tty+W/Z(+yy) as background



Profile likelihood fit on BDT output

- Fiducial phase-space defined as similar to the event selection and applying standard overlap removal procedure

Fiducial ttyy cross-section measured,

$$\sigma_{t\bar{t}\gamma\gamma} = 2.42^{+0.58}_{-0.53}\,\mathrm{fb} = 2.42^{+0.46}_{-0.38}\,(\mathrm{stat})\,^{+0.35}_{-0.38}(\mathrm{syst})\,\mathrm{fb}.$$

- total relative uncertainty of 23% (17% stat)

- **observed** with significance 5.2σ

ttbar+2 photon: ttyy/tty ratio measurement

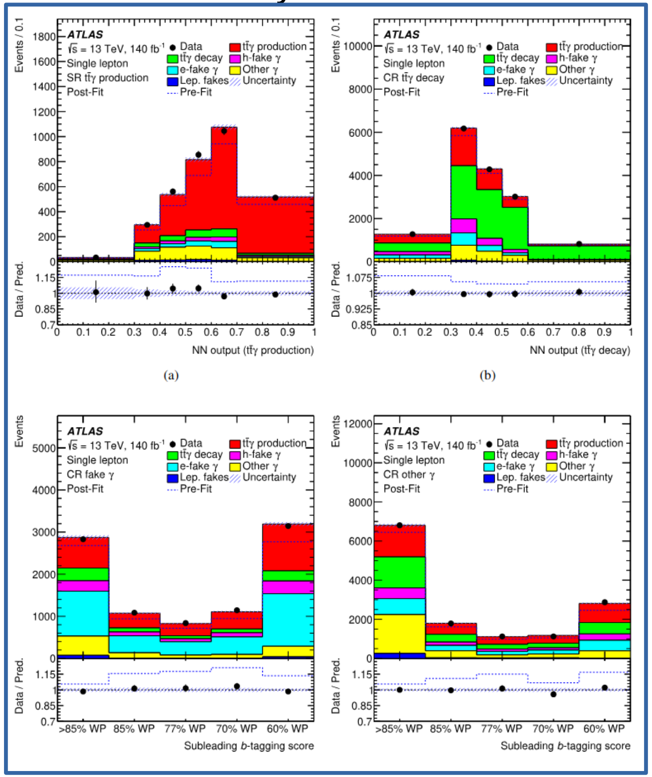
Reusing the fit workspace (4 regions) of tty (production+decay) cross-section measurement in 1 lepton [JHEP10(2024)191]
- along with ttyy BDT;
- tty normalization floated;
- simultaneous fit with all common uncertainties correlated

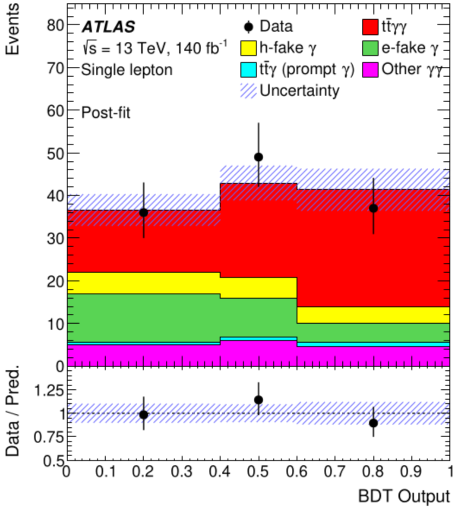
Measurement of ttyy/tty ratio,

$$R_{t\bar{t}\gamma\gamma/t\bar{t}\gamma} = (3.30^{+0.70}_{-0.65}) \times 10^{-3}$$
$$= (3.30^{+0.63}_{-0.55}\,(\text{stat})^{+0.32}_{-0.34}\,(\text{syst})) \times 10^{-3}.$$

With total uncertainty of 20% (stat 18%)

From tty cross-section





ttbar+2 photon: uncertainties

Source	$\Delta\sigma_{t\bar{t}\gamma\gamma}/\sigma_{t\bar{t}\gamma\gamma}$ [%]	$\Delta R_{t\bar{t}\gamma\gamma/t\bar{t}\gamma}/R_{t\bar{t}\gamma\gamma/t\bar{t}\gamma}$ [%]
$t\bar{t}\gamma\gamma$ modelling	1.4	1.3
Prompt-photon background norm. & modelling	4.4	5.8
Fake-photon background estimates	6.5	0.5
Fake-lepton background estimate	–	0.9
Jet	9.7	5.9
Photon	6.5	4.0
b-tagging	3.4	1.0
Leptons	1.5	0.3
Luminosity	1.4	0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.4	1.1
Pile-up	1.6	1.4
MC statistical uncertainties	2.5	2.8
Total systematic uncertainty	15.0	10.0

Effect of correlated systematic uncertainties in ratio measurement w.r.t. ttyy cross-section measurement:

- reduction in jet, photon, b-tagging, lepton, luminosity

- reduction in data-driven fake-photon background estimations

- larger effect of prompt-photon background modelling uncertainties

Summary and outlook

Four recent measurements of cross-sections of ttbar and ttbar associated production processes [WbWb, ttbar+b(b)/c(c), ttbar+2photon] are presented

These measurements are crucial for future improvements of the MC modelling

Improvement on some experimental uncertainties (e.g. flavour tagging) and higher data statistics would be useful for future iterations of some of these measurements

Extra materials

ttbar+2 photon: X, Xy, Xyy overlap removal

Overlap events (among prompt photon events only)
if photon @parton level have pT>15 GeV and dR(l,y)>0.2

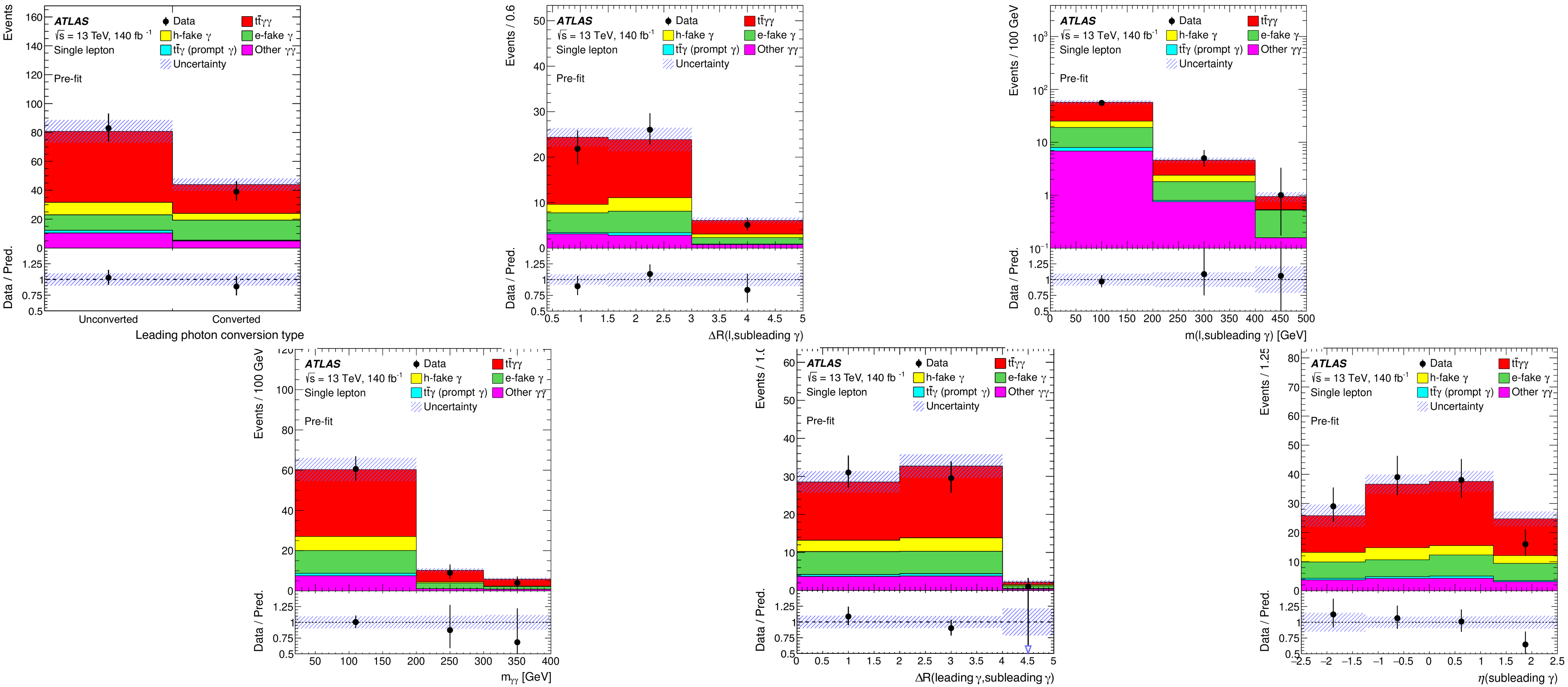
X: no ME photons, if any PS photon in overlap → remove event
Xy: 1 ME photon, 1 PS photon: if BOTH photons in overlap → remove event
Xyy: two photons from ME → event kept

ttbar+2 photon: significance

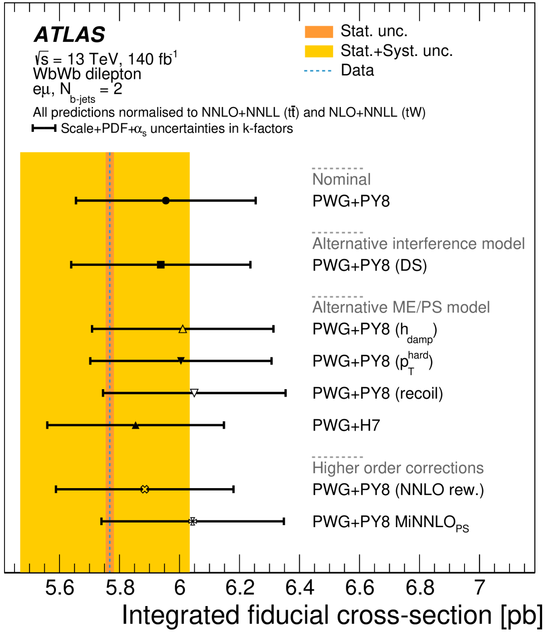
Observed significance w.r.t. background only hypothesis: 5.2σ

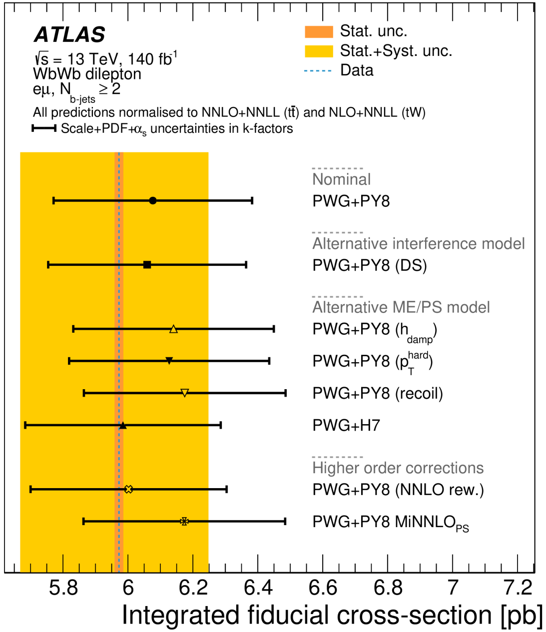
expected (assessed with toys):
5.7σ, with ttyy k-factor
3.8σ, without k-factor for ttyy, i.e. at LO

Ttyy: BDT input variables



WbWb: more results





WbWb: improvements

Improvements w.r.t. previous ATLAS analysis
(arXiv:1806.04667, 36 fb-1):

- differential cross-sections of several more observables
- improved modelling uncertainty prescriptions
- Full Run 2 dataset and updated object calibrations

ttbar+b(b): all measured observables

Observable	Description	Phase spaces $\geq 2b$	$\geq 3b$	$\geq 3b$ $\geq 1l/c$	$\geq 4b$	$\geq 4b$ $\geq 1l/c$
σ^{fid}	Fiducial total cross-section		✓	✓	✓	✓
$N_{b\text{-jets}}$	Number of b-jets	✓	✓			
$N_{l/c\text{-jets}}$	Number of light- or c-jets		✓		✓	
$H_{\text{T}}^{\text{had}}$	Scalar sum of p_{T} of all jets		✓		✓	
$H_{\text{T}}^{\text{all}}$	Scalar sum of p_{T} of charged leptons, jet and missing E_{T}		✓		✓	
$\Delta R^{bb}_{\text{avg}}$	Average angular distance in ΔR of b-jet pairs		✓		✓	
$\Delta\eta^{jj}_{\text{max}}$	Maximum absolute difference in η between any pair of jets		✓		✓	
$p_{\text{T}}(b_1)$	p_{T} of the hardest b-jet		✓		✓	
$p_{\text{T}}(b_2)$	p_{T} of second-hardest b-jet		✓		✓	
$p_{\text{T}}(b_3)$	p_{T} of third-hardest b-jet		✓		✓	
$p_{\text{T}}(b_4)$	p_{T} of fourth-hardest b-jet				✓	
$\eta(b_1)$	η of hardest b-jet		✓		✓	
$\eta(b_2)$	η of second-hardest b-jet		✓		✓	
$\eta(b_3)$	η of third-hardest b-jet		✓		✓	
$\eta(b_4)$	η of fourth-hardest b-jet				✓	
$p_{\text{T}}(l/c\text{-jet}_1)$	p_{T} of the hardest light- or c-jet			✓		✓
$\eta(l/c\text{-jet}_1)$	η of the hardest light- or c-jet			✓		✓
$m(b_1b_2)$	Invariant mass of two hardest b-jets in p_{T}		✓		✓	
$\Delta R(b_1, b_2)$	ΔR between two hardest b-jets		✓		✓	
$p_{\text{T}}(b_1b_2)$	p_{T} of two hardest b-jets		✓		✓	
$m(bb^{\min\Delta R})$	Invariant mass of two closest b-jets in ΔR				✓	
$p_{\text{T}}(bb^{\min\Delta R})$	p_{T} of the closest b-jets pair				✓	
$\min\Delta R(bb)$	Closest angular distance in ΔR among b-jets				✓	
$m(e\mu b_1b_2)$	Invariant mass of electron, muon and two hardest b-jets		✓		✓	
$p_{\text{T}}(b_1^{\text{top}})$	p_{T} of the hardest b-jet assigned to top quark		✓		✓	
$p_{\text{T}}(b_2^{\text{top}})$	p_{T} of the second-hardest b-jet assigned to top quark		✓		✓	
$p_{\text{T}}(b_1^{\text{add}})$	p_{T} of the hardest additional b-jet		✓		✓	
$p_{\text{T}}(b_2^{\text{add}})$	p_{T} of the second-hardest additional b-jet				✓	
$\eta(b_1^{\text{top}})$	η of the hardest b-jet assigned to top quark		✓		✓	
$\eta(b_2^{\text{top}})$	η of the second-hardest b-jet assigned to top quark		✓		✓	
$\eta(b_1^{\text{add}})$	η of the hardest additional b-jet		✓		✓	
$\eta(b_2^{\text{add}})$	η of the second-hardest additional b-jet				✓	
$m(bb^{\text{top}})$	Invariant mass of a pair of b-jets assigned to top quarks		✓		✓	
$p_{\text{T}}(bb^{\text{top}})$	p_{T} of a pair of b-jets assigned to top quarks		✓		✓	
$m(bb^{\text{add}})$	Invariant mass of a pair of additional b-jets				✓	
$p_{\text{T}}(bb^{\text{add}})$	p_{T} of a pair of additional b-jets				✓	
$m(e\mu bb^{\text{top}})$	Invariant mass of $e\mu$ and the b-jets pair assigned to top quarks		✓		✓	
$\Delta R(e\mu bb^{\text{top}}, b_1^{\text{add}})$	ΔR between the direction of the system of $e\mu$ and b-jet pair assigned to top and the direction of the hardest additional b-jet		✓		✓	
$\Delta R(e\mu bb^{\text{top}}, l/c\text{-jet}_1)$	ΔR between the direction of the system of $e\mu$ and b-jet pair assigned to top and the direction of the hardest light- or c-jet			✓		✓
$p_{\text{T}}(l/c\text{-jet}_1) - p_{\text{T}}(b_1^{\text{add}})$	Difference in p_{T} between the hardest l/c-jet and the additional b-jet			✓		✓

ttbar+c(c): regions

	$CR_1^{1\ell}$	$CR_2^{1\ell}$	$CR_3^{1\ell}$	$SR_{loose}^{1\ell}$	$SR_{tight}^{1\ell}$	$CR_1^{2\ell}$	$CR_2^{2\ell}$	$CR_3^{2\ell}$	$SR_{loose}^{2\ell}$	$SR_{tight}^{2\ell}$
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	–	–	–	–	–

ttbar+c(c): uncertainties

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