



European Research Council



$t\bar{t}t\bar{t}$  production at ATLAS

[ATLAS-CONF-2021-013](#)

- with one or two opposite-sign leptons
  - combination with same-sign dilepton and multilepton
- 

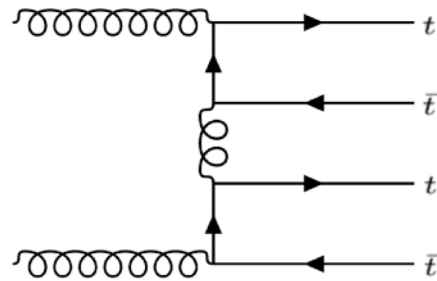
Quake Y. Qin

on behalf of the ATLAS Collaboration

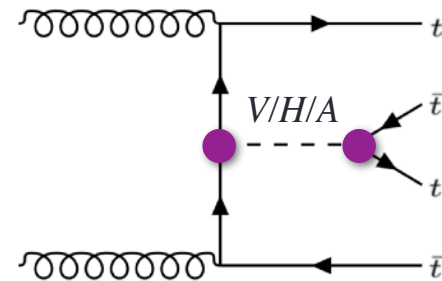
[LHC Top WG meeting](#)



# Introduction

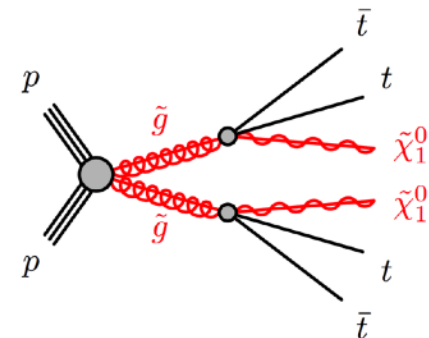


Leading:  $\mathcal{O}(\alpha_S^4)$



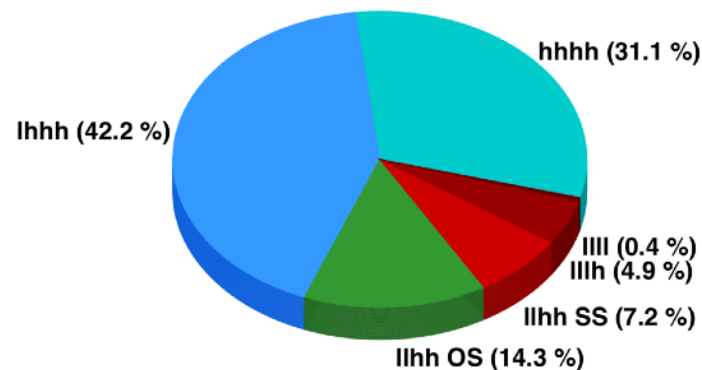
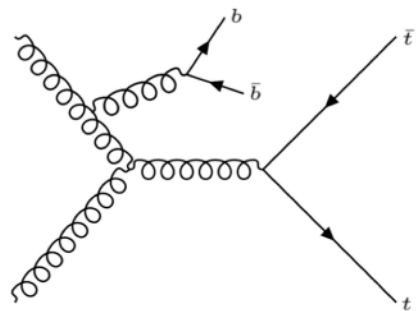
Sub-leading:  
 $\mathcal{O}(\alpha_S^2 y_t^4)$ ,  $\mathcal{O}(\alpha_S^2 \alpha^2)$

- $t\bar{t}t\bar{t}$  production at the LHC has very small cross-section in SM
  - $12.0_{-2.5}^{+2.2}$  fb from the latest NLO calculation with EW corrections at 13 TeV  
[R. Frederix, D. Pagani and M. Zaro, JHEP 02 \(2018\) 031](#)
- Sensitive to top-Yukawa coupling ( $\sigma_{t\bar{t}H(t\bar{t})} \propto y_t^4$ ), both the magnitude and CP
- Extremely high energy scale production makes it naturally sensitive to many BSM models
  - 2HDM, SUSY
  - various four-fermion coupling EFT operators

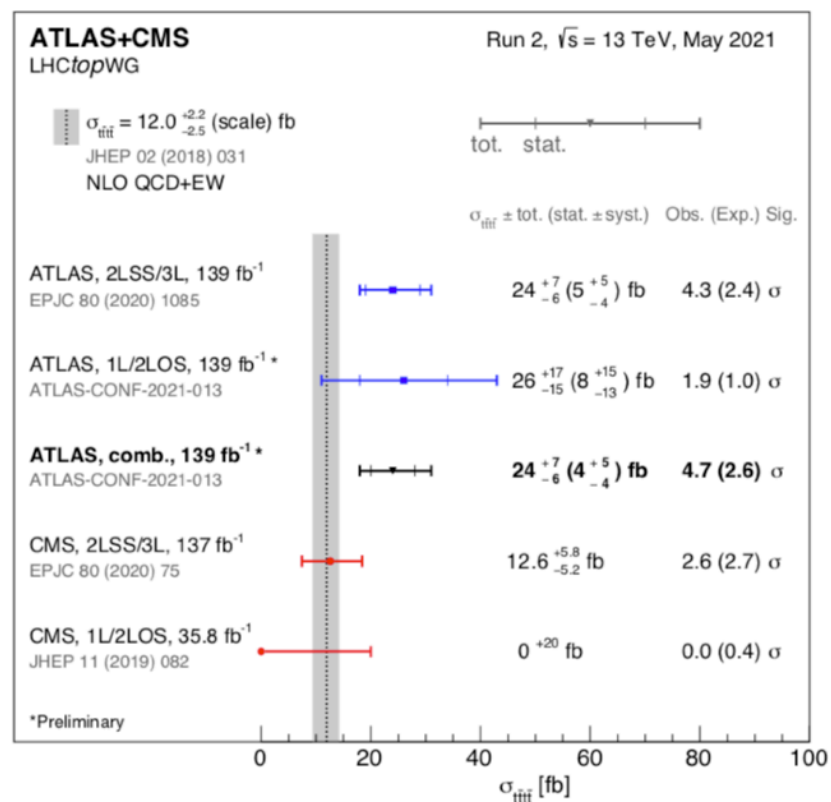


# Introduction

- Final states characterised by the number of leptons, with a large number of jets and  $b$ -jets
- Analyses performed using different leptonic final states, motivated by background sources
  - same-sign dilepton and multilepton channel (2LSS/3L)
    - main background from  $t\bar{t}X$  and events with non-prompt leptons
    - the cleanest and most sensitive channel
  - single lepton and opposite-sign dilepton channel (1L/2LOS)
    - large branching ratio (57%)
    - large irreducible  $t\bar{t}$ +jets background, mainly  $t\bar{t}b\bar{b}$
    - overall lower sensitivity, but complementary to 2LSS/3L

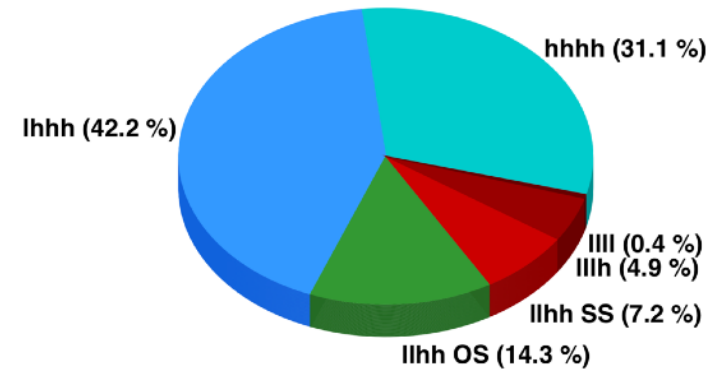
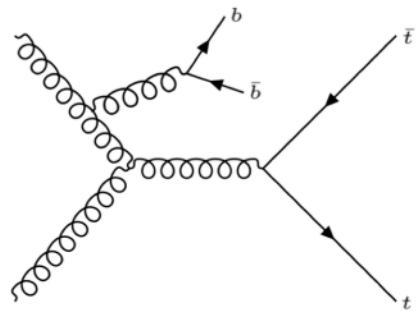


[ATL-PHYS-PUB-2021-013](https://arxiv.org/abs/2103.01133)

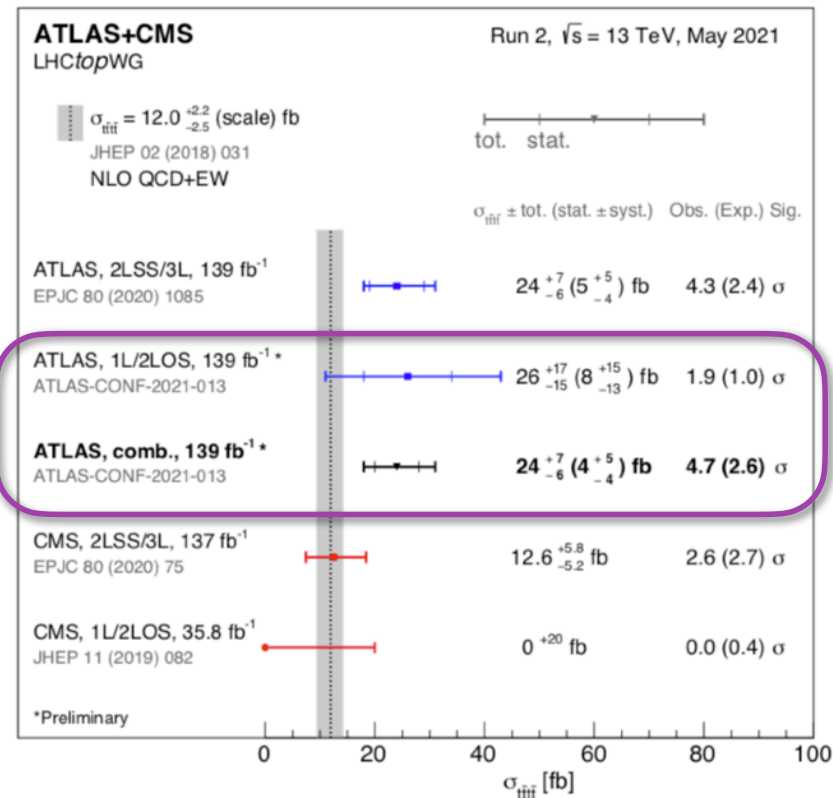


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[ATL-PHYS-PUB-2021-013](https://arxiv.org/abs/2103.01181)



# Analysis strategy

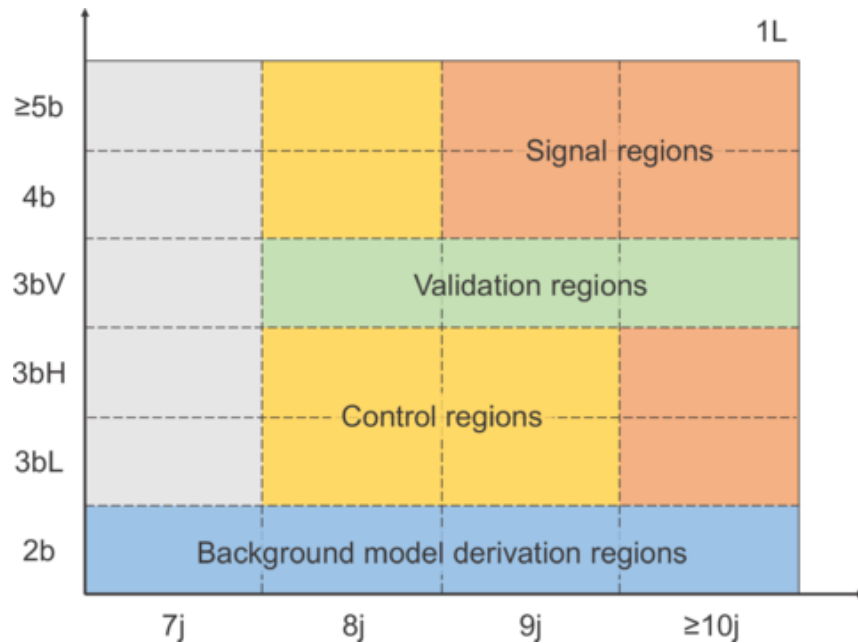
- Targeting very high  $N_{\text{jets}}$  and  $N_{\text{b-tag}}$  regions
  - 1L signal: expect 4 b-jets and another 6 jets from the 3 hadronic W decays
  - 2LOS signal: expect 4 b-jets and another 4 jets from 2 hadronic W decays
- Challenging modelling of the  $t\bar{t}$ +jets background
  - under-estimated  $t\bar{t}$ +HF components in MC predictions
  - badly modelled kinematics: 6 additional jets beyond the tree level  $t\bar{t}$  diagram
- Adopted a series of **pre-fit level treatment on the  $t\bar{t}$ +jets background** to mitigate the mismodelling
- Profile likelihood fit to extract the signal
  - **sophisticated scheme of systematic uncertainties** to absorb the residual mismodelling
  - use MVA to separate signal from the background

# $t\bar{t}$ +jets events classification

- The major background  $t\bar{t}$ +jets is broken down into different components according to the flavour of the additional jets not from top decay
- the classification is based on a dR-matching between particle level jets and b/c-hadrons
  - $t\bar{t}+\geq 1b$ : at least 1 particle level jet matched a b-hadron not from top decay
  - $t\bar{t}+\geq 1c$ : at least 1 particle level jet matched a c-hadron not from top decay and not  $t\bar{t}+\geq 1b$
  - $t\bar{t}+\text{light}$ : all other events
- **Further breakdown of the major component  $t\bar{t}+\geq 1b$  for the relevant systematics**
  - $t\bar{t}+b$ : a single particle level jet matched to a b-hadron
  - $t\bar{t}+B$ : a particle level jet matched to 2 b-hadrons
  - $t\bar{t}+bb$ : 2 particle level jets, each matched to a b-hadron
  - $t\bar{t}+\geq 3b$ : all other events, including  $t\bar{t}bbbb$ ,  $t\bar{t}bB$ ,  $t\bar{t}BB$  etc

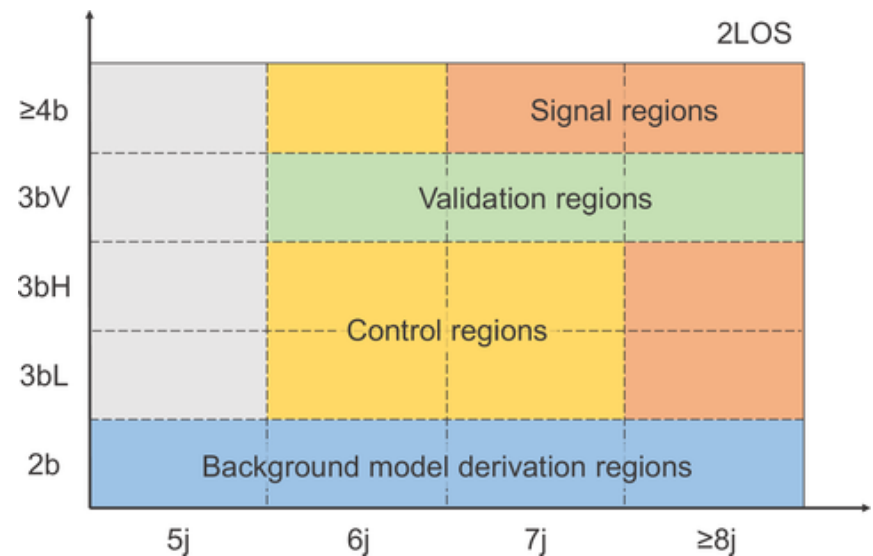
# Event categorisation

- Use b-tagging as the handle of the different  $t\bar{t}$  flavour components
  - define regions with loose to tight b-tagging requirements on the additional jets
- combined with  $N_{\text{jets}}$  requirement to define control/signal/validation regions



Name	$N_b^{60\%}$	$N_b^{70\%}$	$N_b^{85\%}$
2b	-	= 2	-
3bL	$\leq 2$	= 3	-
3bH	= 3	= 3	= 3
3bV	= 3	= 3	$\geq 4$
$\geq 4b$ (2LOS)	-	$\geq 4$	-
4b (1L)	-	= 4	-
$\geq 5b$ (1L)	-	$\geq 5$	-

- \*  $N_b^{X\%}$ : number of b-tag at X% working point
- \* 3bL/H: low or high in truth b-jet purity
- \* 3bV: validation



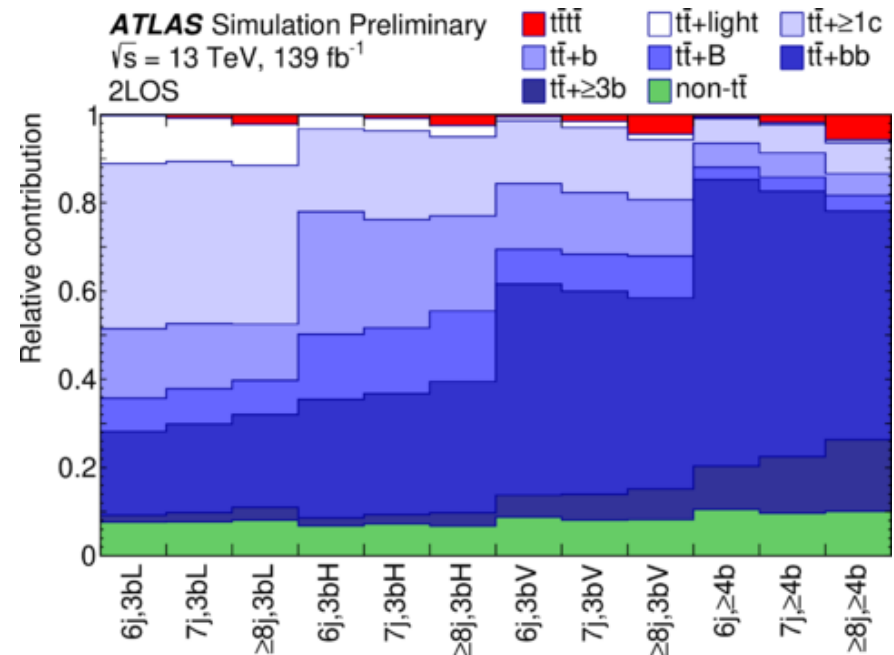
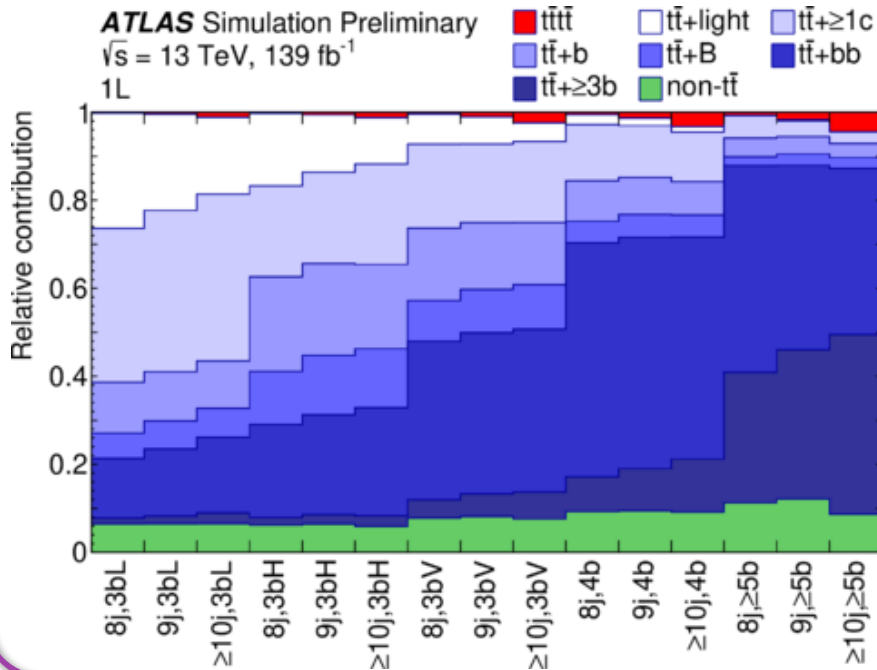
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## background composition in all regions



# Corrections to $t\bar{t}$ +jets

- **Mitigate the  $t\bar{t}$ +jets mismodelling prior to the profile likelihood fit**
  - Derive rescaling factors for  $t\bar{t}+\geq 1b$ ,  $t\bar{t}+\geq 1c$  and  $t\bar{t}$ +light to improve the under-estimated  $t\bar{t}$ +HF components in MC predictions
    - using a fit to data in the different b-tag regions 2b, 3bL, 3bH and  $\geq 4b$  (inclusive in  $N_{\text{jets}}$ )

$t\bar{t}+\geq 1b$	$t\bar{t}+\geq 1c$	$t\bar{t}$ +light
<b>1.33 <math>\pm</math> 0.06</b>	<b>1.58 <math>\pm</math> 0.18</b>	<b>0.99 <math>\pm</math> 0.05</b>

*Fitted regions*

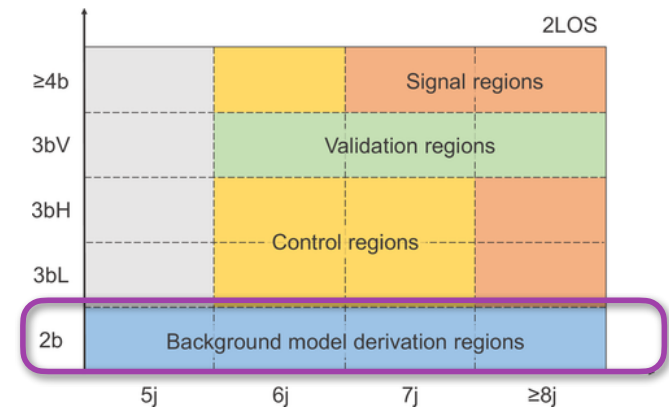
$\geq 4b$		
3bH		
3bL		
2b		
	1L $\geq 8j$	2LOS $\geq 6j$

# Corrections to $t\bar{t}$ +jets

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  - Derive a sequential kinematic reweighting to improve the badly modelled kinematics
    - derived in the 2b regions, so that overall MC matched data in the 2b regions, and applied to  $\geq 3b$  regions

$$R = \frac{\text{data} - \text{MC}_{\text{non } t\bar{t}}}{\text{MC}_{t\bar{t}}} \Bigg|_{2b}$$

- correct for  $N_{\text{jets}}$ ,  $N_{\text{large-R jets}}$ ,  $H_T^{\text{all}}$ , and angular distribution  $dR_{\text{avg}}(j,j)$
- all  $t\bar{t}$  systematic uncertainties are reweighted in the same way, serving as constraints using 2b data

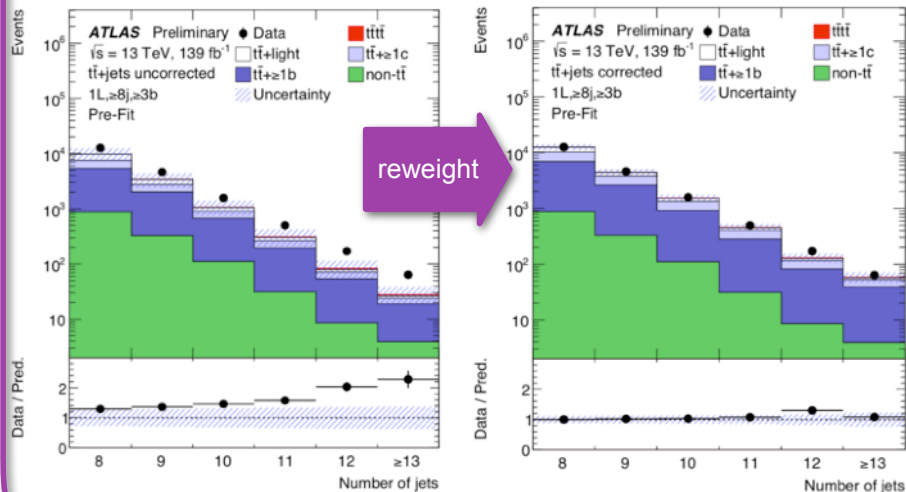


\*  $H_T^{\text{all}}$ : scalar sum of all objects'  $p_T$

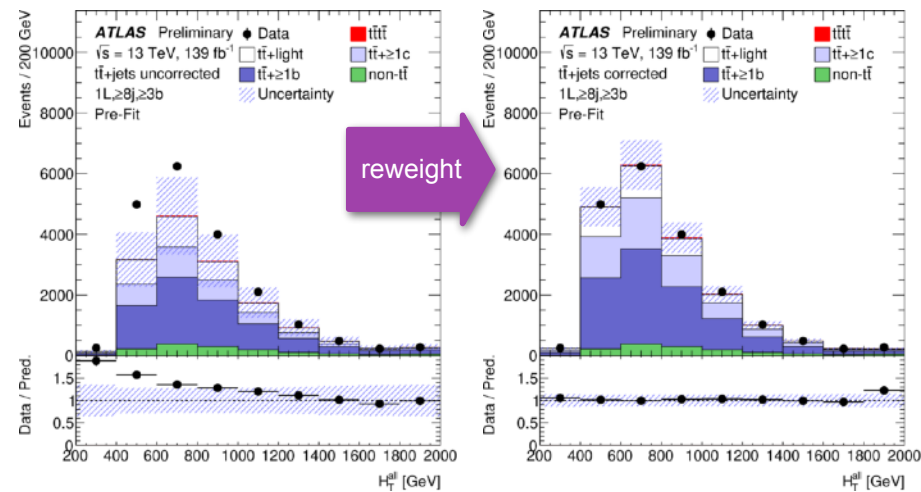
# Corrections to $t\bar{t}$ +jets

- Mitigate the  $t\bar{t}$ +jets mismodelling prior to the profile likelihood fit
  - Derive rescaling factors for  $t\bar{t}+\geq 1b$ ,  $t\bar{t}+\geq 1c$  and  $t\bar{t}$ +light to improve the under-estimated  $t\bar{t}$ +HF components in MC predictions
  - Derive a sequential kinematic reweighting to improve the badly modelled kinematics
- Significantly reduce the pre-fit level mismodelling and the pulls in the fit to data

$N_{\text{jets}}$

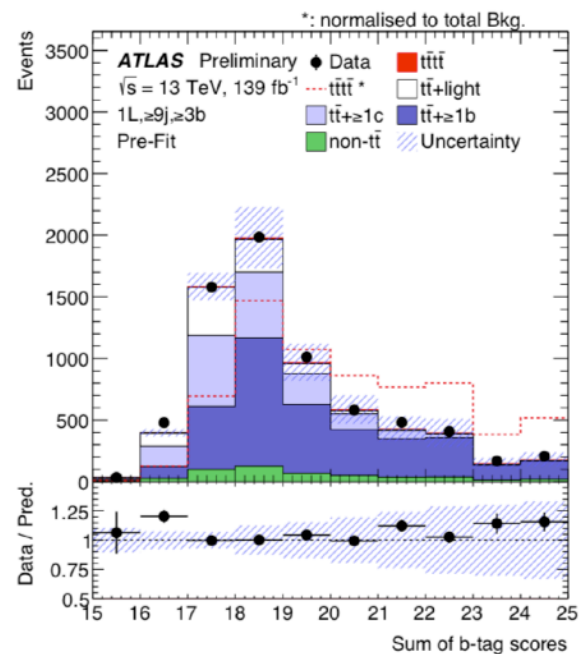
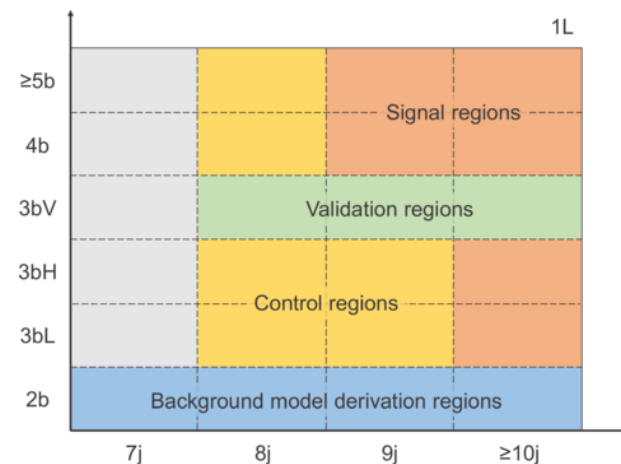


$H_T^{\text{all}}$



# Signal extraction

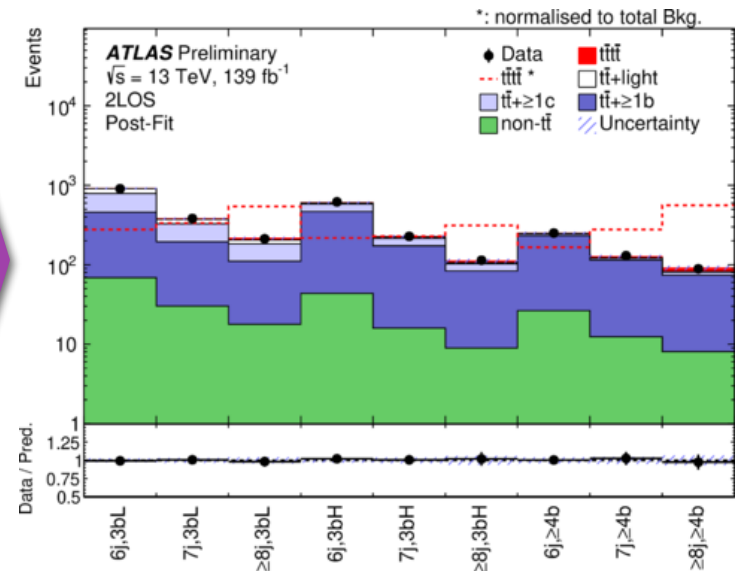
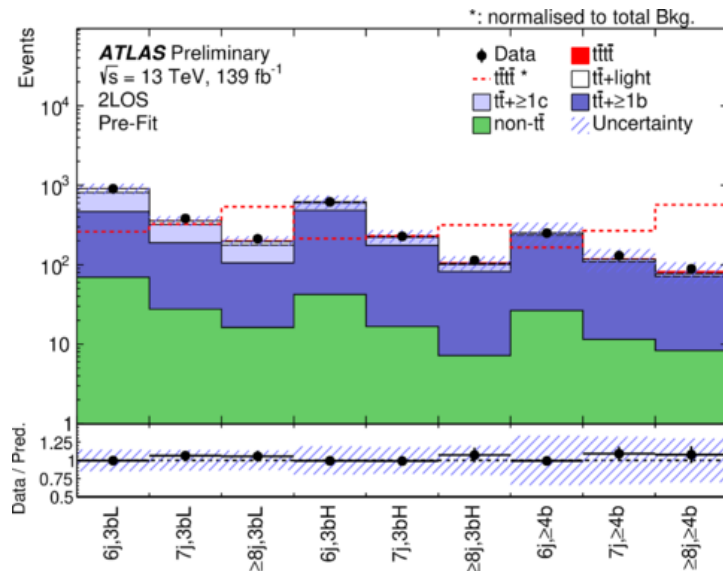
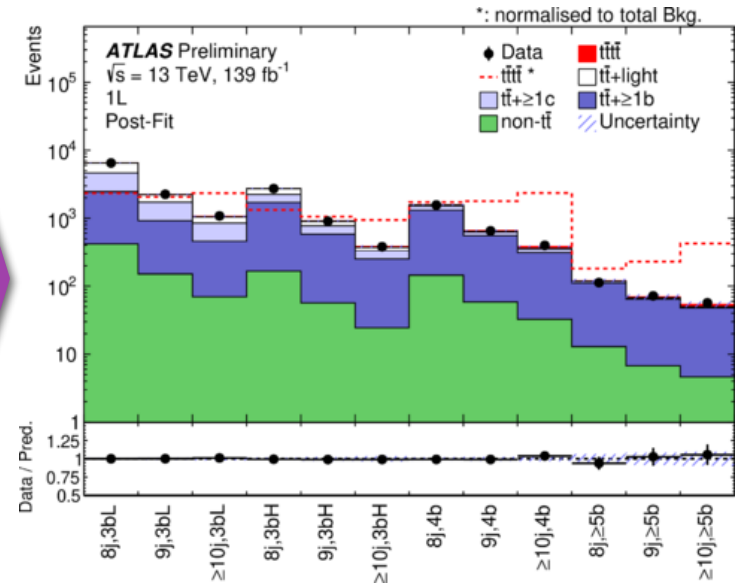
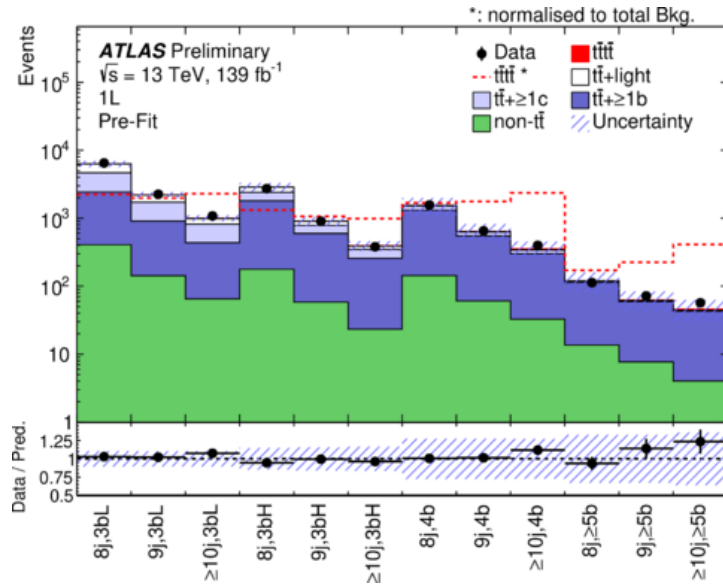
- Profile likelihood fit to all control and signal regions to extract the signal
  - $t\bar{t}$  modelling is further adjusted in the profiling according to systematics
  - $H_T^{\text{all}}$  is fitted in the control regions
    - use the better understood shape to control the systematics
- BDT in signal regions to provide discrimination against all background
  - using 14 variables: global event variables, kinematics of reconstructed objects and pairs of objects, jet b-tagging information, large- $R$  jets,  $E_T^{\text{miss}}$
  - trained in separate  $N_{\text{jets}}$  regions: 1L ( $9j, \geq 10j$ ); 2L ( $7j, \geq 8j$ )
  - most discriminating variables: sum of b-tag scores of the first 6 jets and  $N_{\text{jets}}$  in  $1L \geq 10j$  and  $2L \geq 8j$



# Systematic uncertainties on $t\bar{t}$ +jets modelling

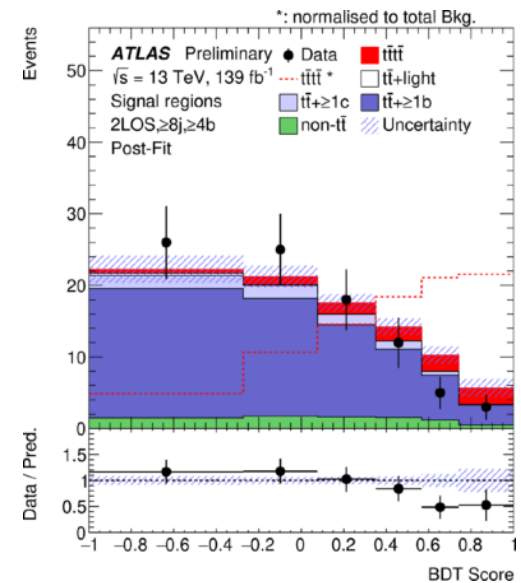
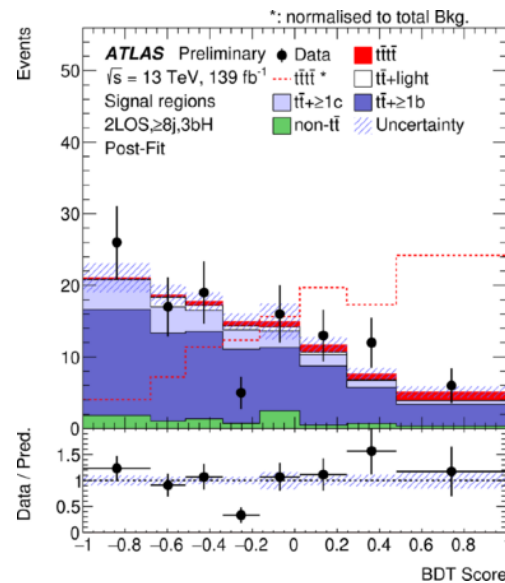
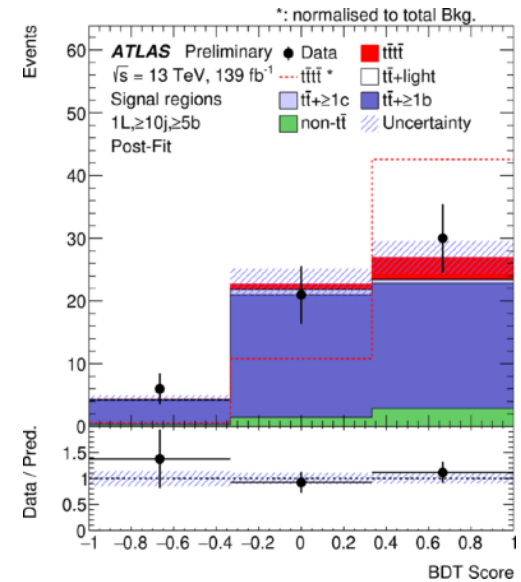
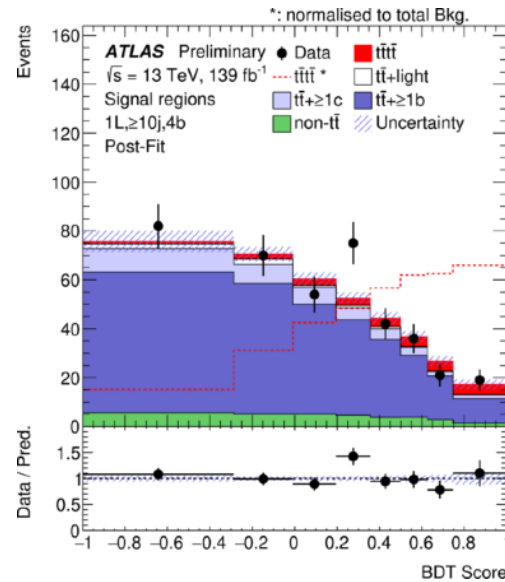
ttbar modelling systematic	Components		
<b>tt+HF normalisation:</b> - 50% prior	tt+b		
	tt+B		
	tt+bb		
	tt+≥3b		
	tt+≥1c		
<b>generator choice:</b> - Powheg+Pythia8 vs. aMC@NLO+Pythia8 - conservative in exploring unknown phase space	tt+b	⊗	shape
	tt+B		
	tt+bb		
	tt+≥3b	⊗	migration
	tt+≥1c		
	tt+light		
<b>parton shower choice:</b> - Powheg+Pythia8 vs. Powheg+Herwig7	tt+b	⊗	shape
	tt+B		
	tt+bb		
	tt+≥3b	⊗	migration
	tt+≥1c		
	tt+light		
<b>tt+≥1b 5- vs. 4-flavour scheme (FS):</b> - 5FS Powheg+Pythia8 vs. 4FS Powheg+Pythia8	tt+b		
	tt+B		
	tt+bb		
	tt+≥3b		
<b>all other scale uncertainties</b>	tt+≥1b		
	tt+≥1c		
	tt+light		

# Pre- and post-fit



# Post-fit distributions in the signal regions

- The most signal-enriched regions in 1L and 2LOS channels



# Results

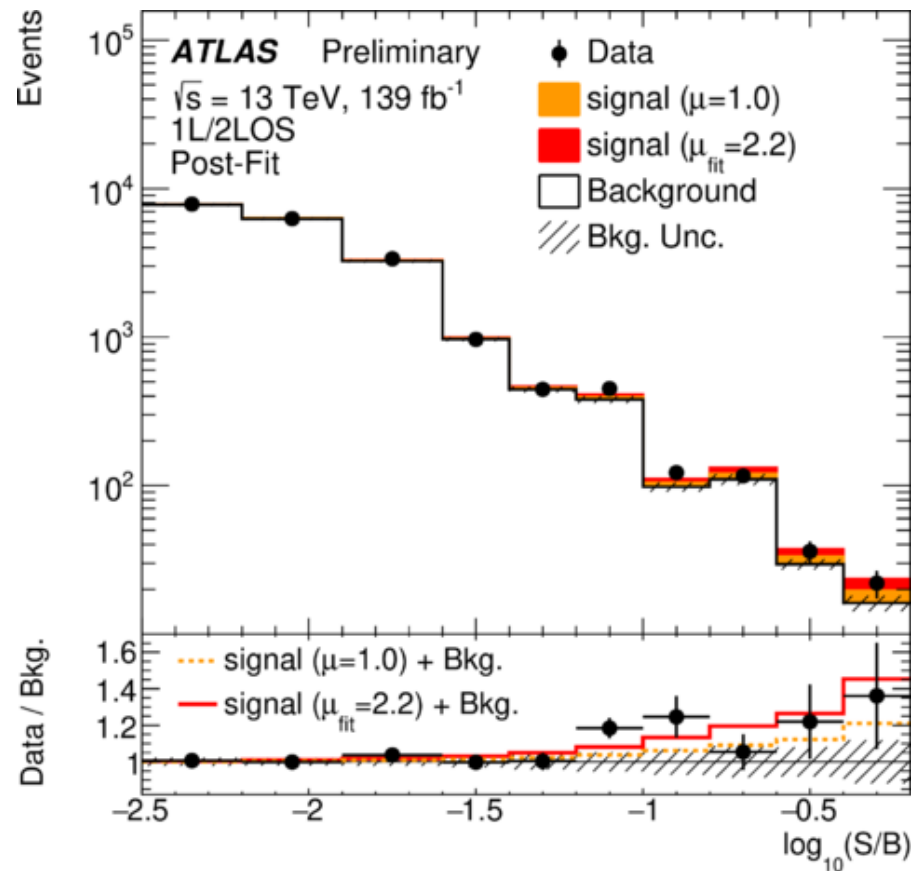
- Fitted signal strength

$$\mu = 2.2 \pm 0.7 \text{ (stat.) } {}^{+1.5}_{-1.0} \text{ (syst.)} = 2.2^{+1.6}_{-1.2}$$

- Cross section

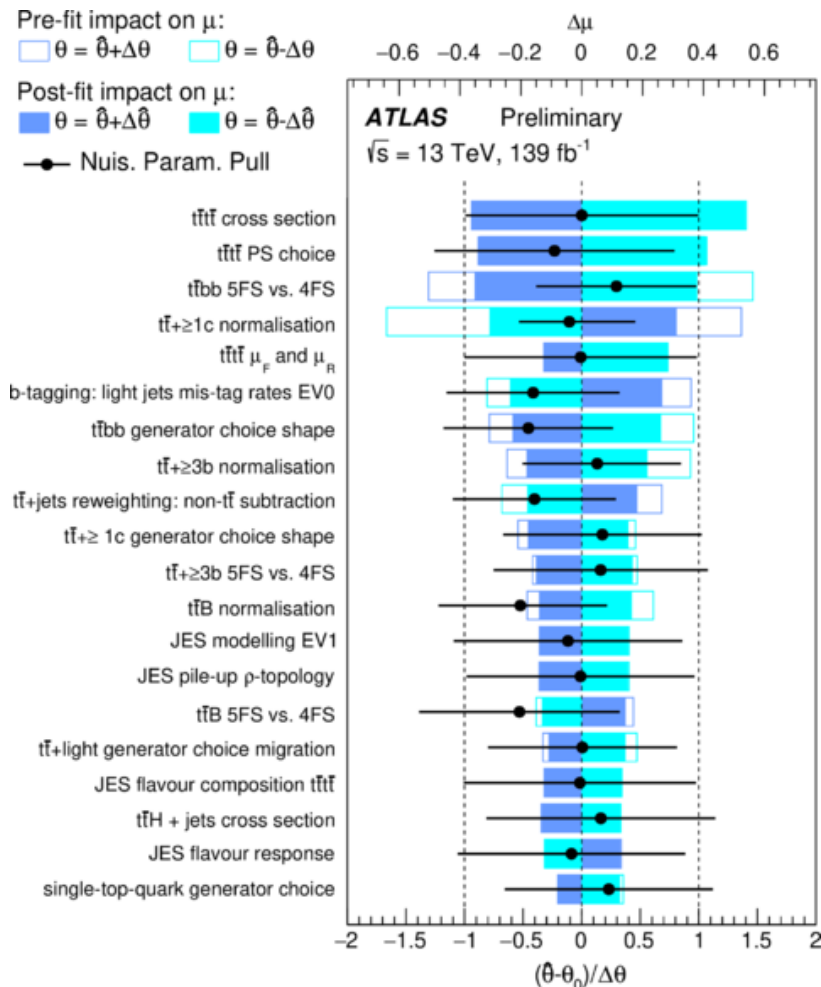
$$\sigma_{t\bar{t}\bar{t}} = 26 \pm 8 \text{ (stat.) } {}^{+15}_{-13} \text{ (syst.)} = 26^{+17}_{-15} \text{ fb}$$

- observed (expected) significance 1.9 (1.0)  $\sigma$



# Impact from systematic uncertainties

- Dominant uncertainties are from  $t\bar{t}t\bar{t}$  modelling and  $t\bar{t}$ +HF modelling
- Jet and b-tagging related systematics are also important source of uncertainties



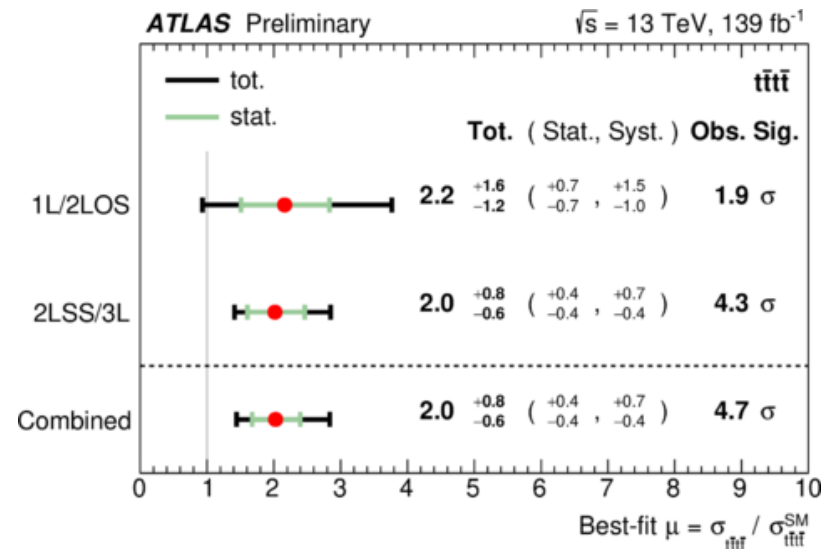
Uncertainty source	$\Delta\sigma_{t\bar{t}t\bar{t}}$ [fb]	
<b>Signal Modelling</b>		
$t\bar{t}t\bar{t}$ modelling	+8	-3
<b>Background Modelling</b>		
$t\bar{t}+\geq 1b$ modelling	+8	-7
$t\bar{t}+\geq 1c$ modelling	+5	-4
$t\bar{t}$ +jets reweighting	+4	-3
Other background modelling	+4	-3
$t\bar{t}$ +light modelling	+2	-2
<b>Experimental</b>		
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	
<b>Total systematic uncertainty</b>		
<b>Statistical uncertainty</b>		
<b>Total uncertainty</b>		

# Combination with 2LSS/3L channel

- 2LSS/3L results: [Eur. Phys. J. C 80 \(2020\) 1085](#)
- Combined profile likelihood fit
  - Detector systematics are mostly correlated between the two channels
  - The most important systematics (mostly modelling related ones) are treated as uncorrelated
    - $t\bar{t}W$  for 2LSS/3L
    - $t\bar{t}+\text{jets}$  for 1L/2LOS
- best-fit  $\mu = 2.0^{+0.8}_{-0.6}$ , compatible with the SM prediction within  $2\sigma$ 
  - consistent results between the two channels and the combination
- measured cross section

$$\sigma_{t\bar{t}t\bar{t}} = 24 \pm 4 \text{ (stat.) }^{+5}_{-4} \text{ (syst.)} = 24^{+7}_{-6} \text{ fb}$$

- observed (expected) significance **4.7 (2.6)  $\sigma$** 
  - sizeable improvement w.r.t. 2LSS/3L result



# Summary and outlook

- $t\bar{t}t\bar{t}$  production is a rare but interesting process
- Searches have been conducted in different leptonic final states
  - ATLAS reported evidence of the production in the 2LSS/3L channel with a significance of  $4.3\sigma$
- This talk presents the analysis in the 1L/2LOS channel

- challenging final state and modelling of  $t\bar{t}$ +jets background

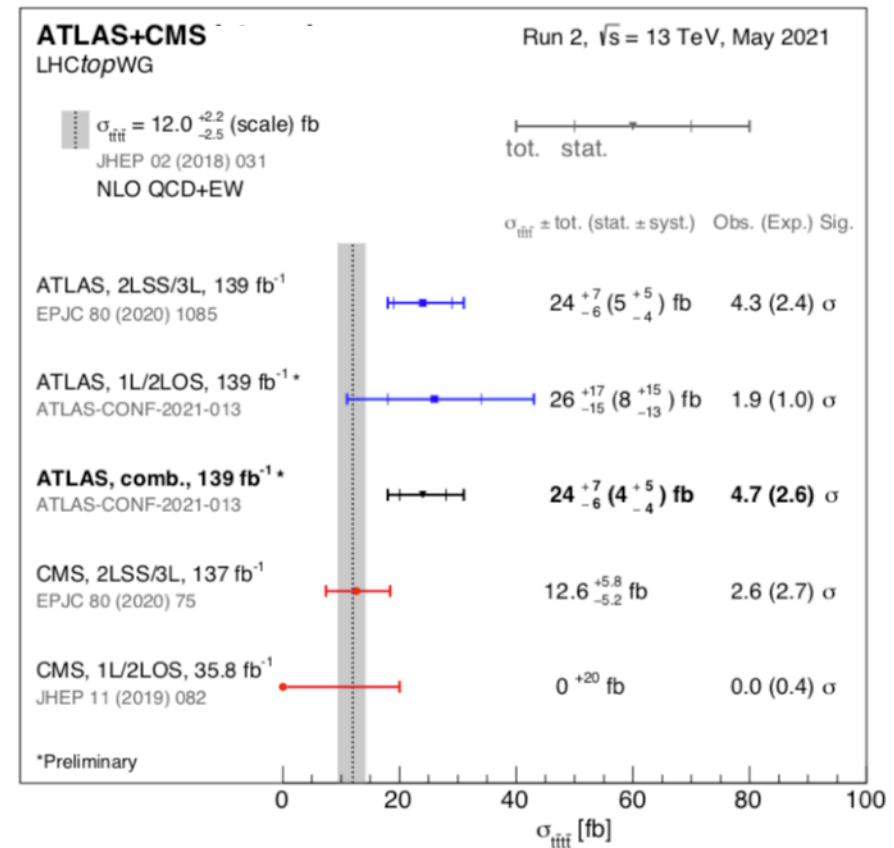
- consistent result with 2LSS/3L

- Combining 1L/2LOS and 2LSS/3L channels yields a significance of  $4.7\sigma$
- Measured cross section is compatible with the SM prediction within  $2\sigma$

- There's space for improvement

- explore event reconstruction
- refinement on the dominant systematic uncertainties

[ATL-PHYS-PUB-2021-013](#)



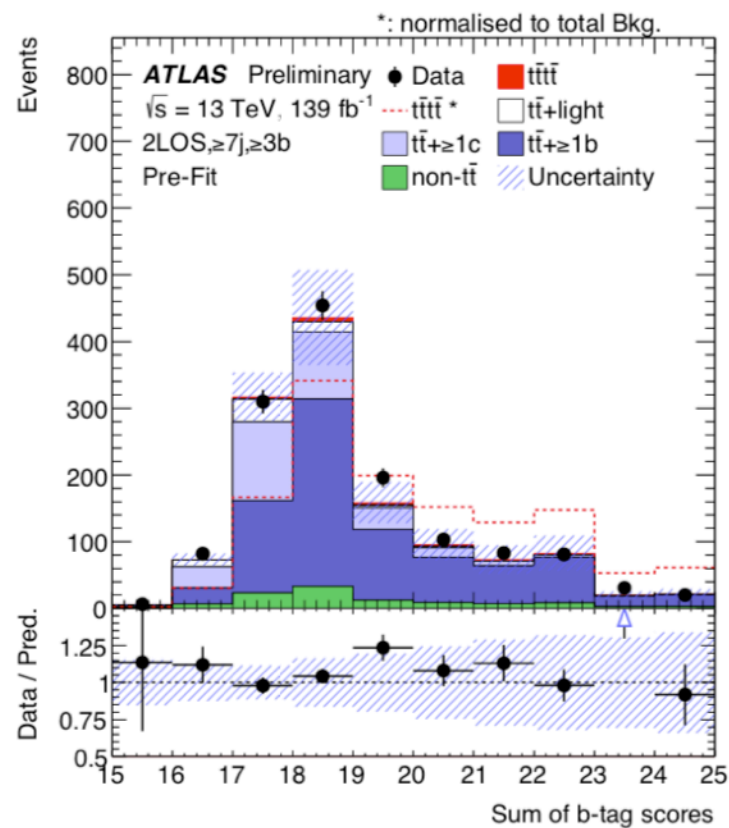
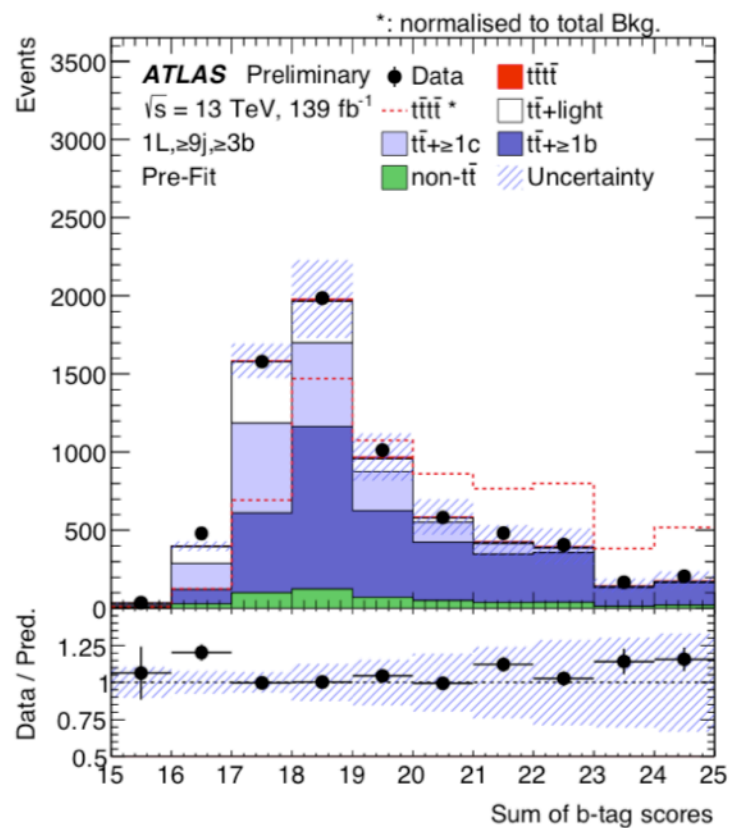
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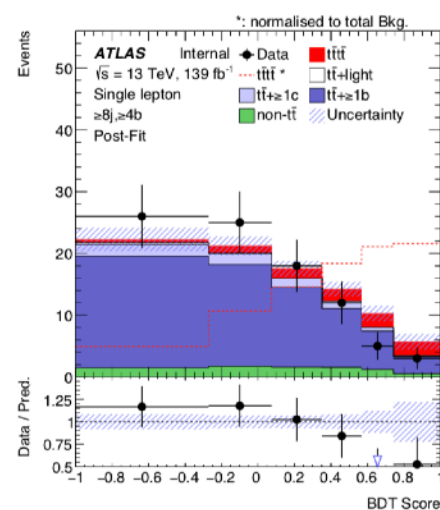
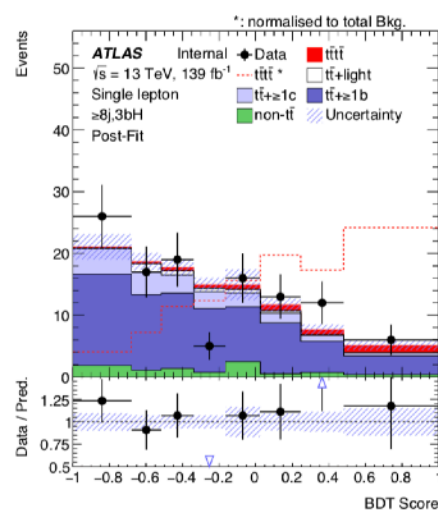
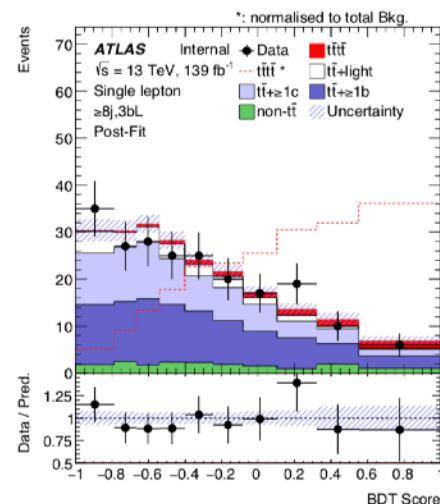
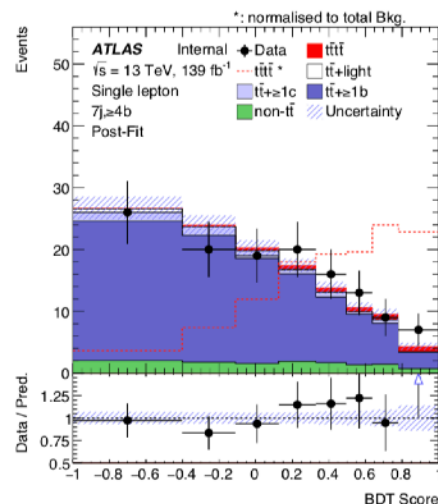
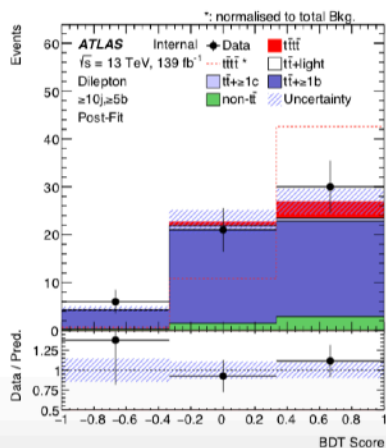
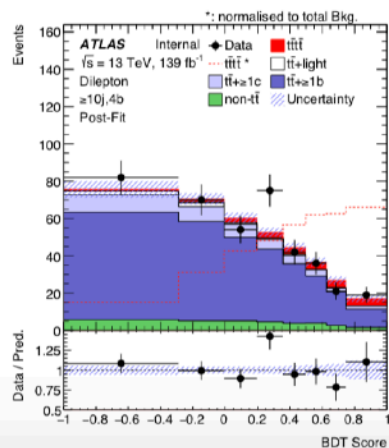
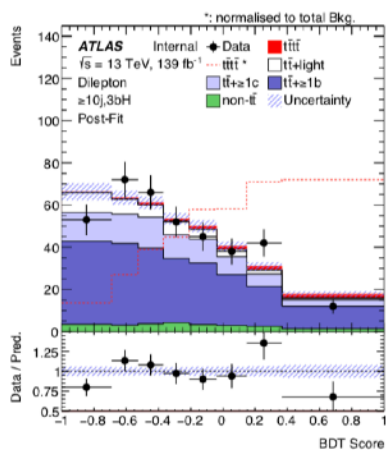
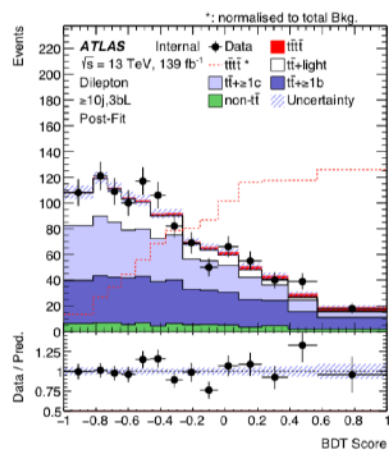
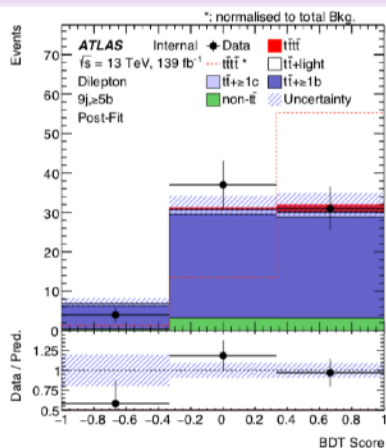
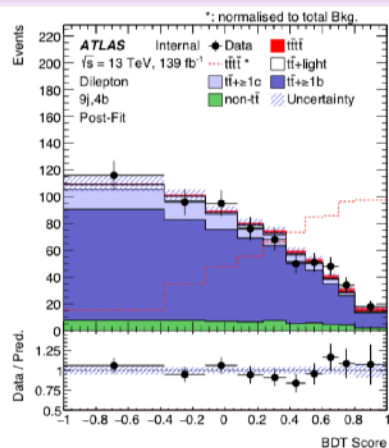
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# BDT input variables

Name	Description
$\sum b\text{-tag}$	Sum of pseudo-continuous $b$ -tagging score over the six jets with the highest score
$N_{\text{jets}}$	Jets multiplicity
$\Delta R_{bb}^{\min}$	Minimum $\Delta R$ among all pair of $b$ -tagged jets
$H_{\text{T}}^{\text{all}}$	Jet and lepton activity
$C^{\text{all}}$	Centrality ( $\sum_i p_{\text{T}i} / \sum_i E_i$ ) of the leptons and jets
$p_{\text{T}}^{\text{lead}}$	Transverse momentum of the leading jet
$\Delta R_{b\ell}^{\min}$	Minimum $\Delta R$ among all pairs of $b$ -tagged jets and leptons
$\Delta R_{jj}^{\text{avg}}$	Average $\Delta R$ among all pairs of jets
$m_{\text{jjj}}$	Invariant mass of the closest triplet of jets
$E_{\text{T}}^{\text{miss}}$	Missing transverse momentum
$m_{\text{T}}^{\text{W}}$	$W$ reconstructed transverse mass $m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}})$ (1L)
$N_{\text{LR-jets}}$	Number of large- $R$ jets with a mass above 100 GeV
$\sum d_{12}$	Sum of the first $k_t$ splitting scale $d_{12}$ of all large- $R$ jets
$\sum d_{23}$	Sum of the second $k_t$ splitting scale $d_{23}$ of all large- $R$ jets

# Sum of b-tag scores





# 2LSS/3L systematics

Uncertainty source	$\Delta\mu$	
<b>Signal modelling</b>		
$t\bar{t}t\bar{t}$ cross section	+0.56	-0.31
$t\bar{t}t\bar{t}$ modelling	+0.15	-0.09
<b>Background modelling</b>		
$t\bar{t}W$ +jets modelling	+0.26	-0.27
$t\bar{t}t$ modelling	+0.10	-0.07
Non-prompt leptons modelling	+0.05	-0.04
$t\bar{t}H$ +jets modelling	+0.04	-0.01
$t\bar{t}Z$ +jets modelling	+0.02	-0.04
Other background modelling	+0.03	-0.02
Charge misassignment	+0.01	-0.02
<b>Instrumental</b>		
Jet uncertainties	+0.12	-0.08
Jet flavour tagging (light-flavour 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
Jet flavour tagging ( $c$ -jets)	+0.03	-0.01
Other experimental uncertainties	+0.03	-0.01
Total systematic uncertainty	+0.70	-0.44
<b>Statistical</b>		
Non-prompt leptons normalisation (HF, Mat. Conv., Low $m_{\gamma^*}$ )	+0.05	-0.04
$t\bar{t}W$ normalisation	+0.04	-0.04
Total uncertainty	+0.83	-0.60

