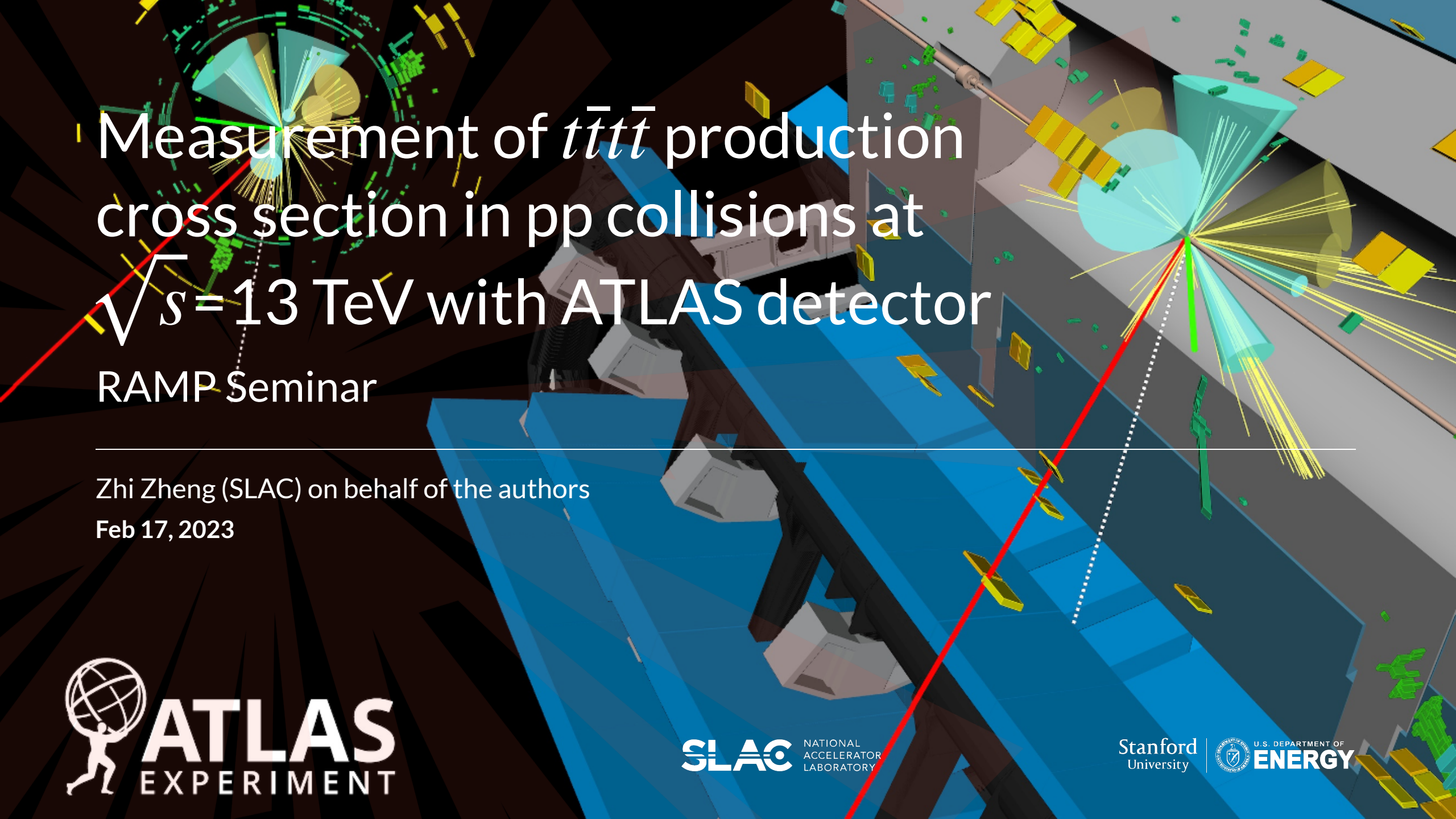


Measurement of $t\bar{t}t\bar{t}$ production cross section in pp collisions at $\sqrt{s}$ = 13 TeV with ATLAS detector

RAMP Seminar

Zhi Zheng (SLAC) on behalf of the authors

Feb 17, 2023

ATLAS EXPERIMENT

SLAC NATIONAL ACCELERATOR LABORATORY

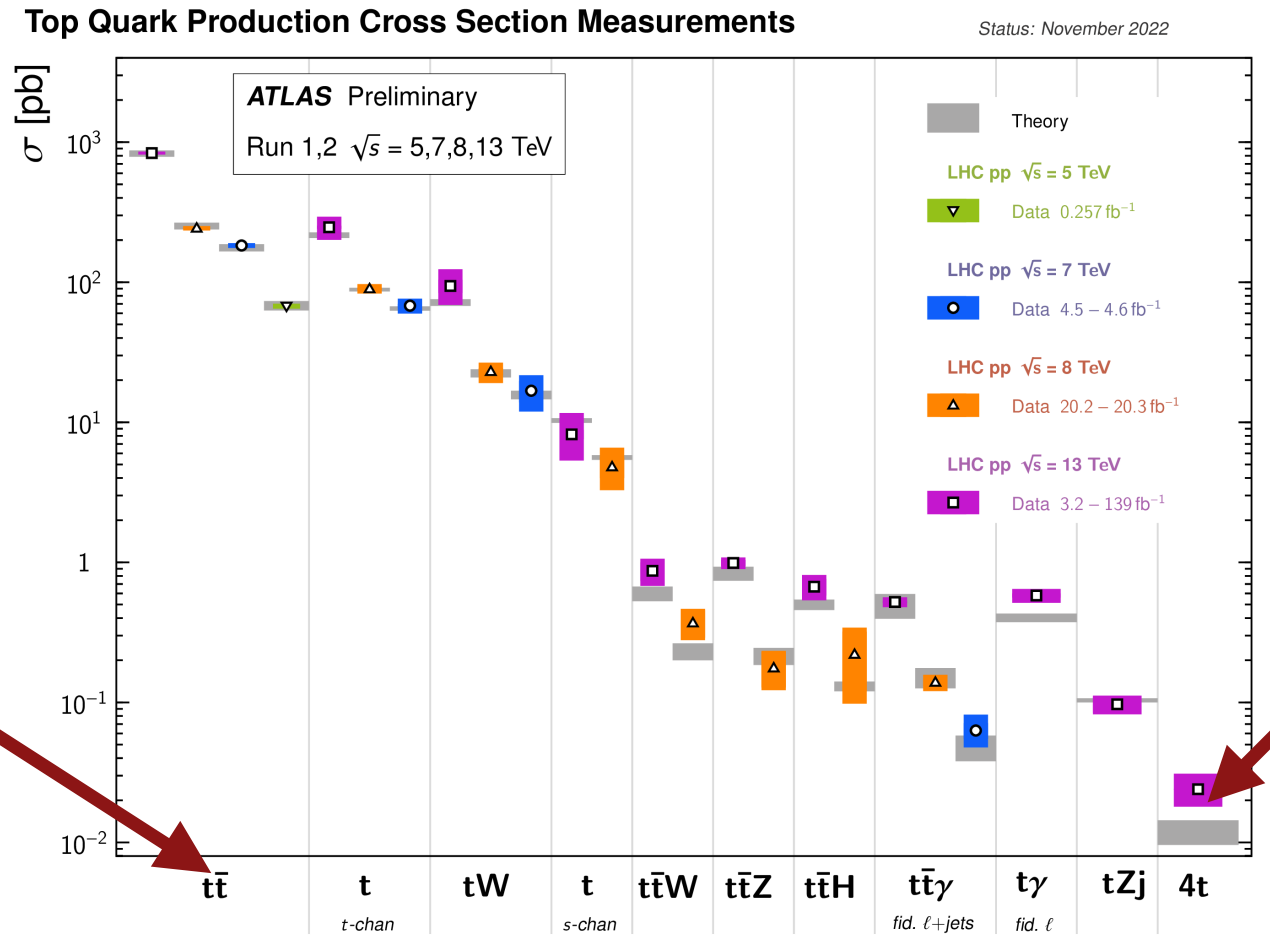
Stanford University

U.S. DEPARTMENT OF ENERGY

Why Four top is interesting ?

$t\bar{t}t\bar{t}$ is a very rare process in standard model (SM)

- $\sigma(t\bar{t}t\bar{t})_{NLO} \sim 12$ fb [JHEP 02 (2018) 031]



Around 25000 $t\bar{t}$ are produced every hour

Run 2 in total ~1800 $t\bar{t}t\bar{t}$ events produced

Why Four top is interesting ?

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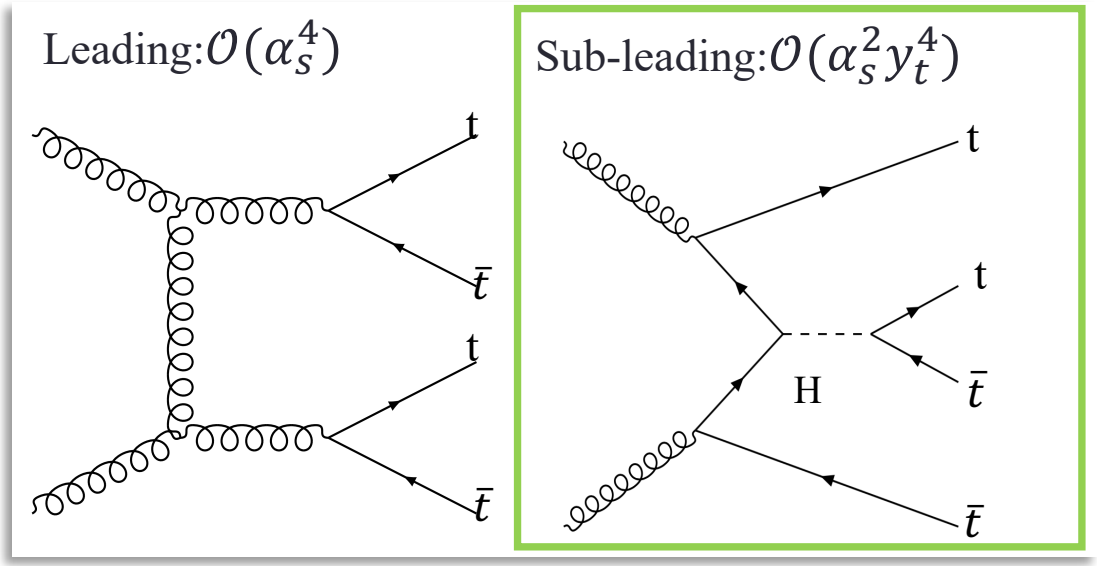
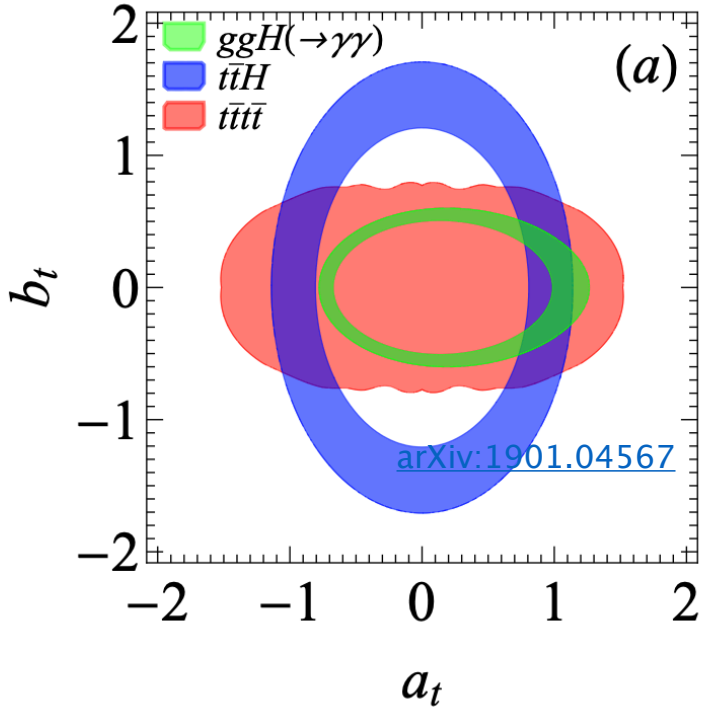
- $\sigma(t\bar{t}t\bar{t})_{NLO} \sim 12$ fb [JHEP 02 (2018) 031]

Sensitive to top Yukawa coupling and its CP properties

Very heavy final state with almost 700 GeV in total — naturally sensitive to many BSM models and EFT parameters

- Four-fermion couplings (e.g. $\mathcal{O}_{tt}^{1} = (\bar{t}\gamma_{\mu}t)(\bar{t}\gamma^{\mu}t)$) and tow-Higgs doublet model





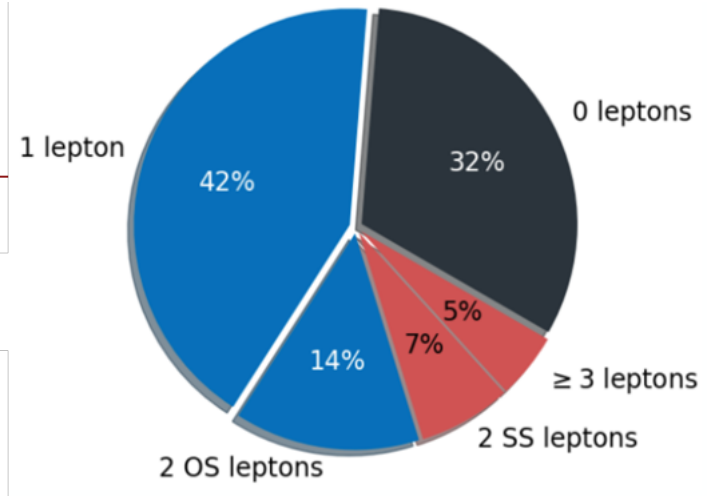
Probing Top Higgs interaction

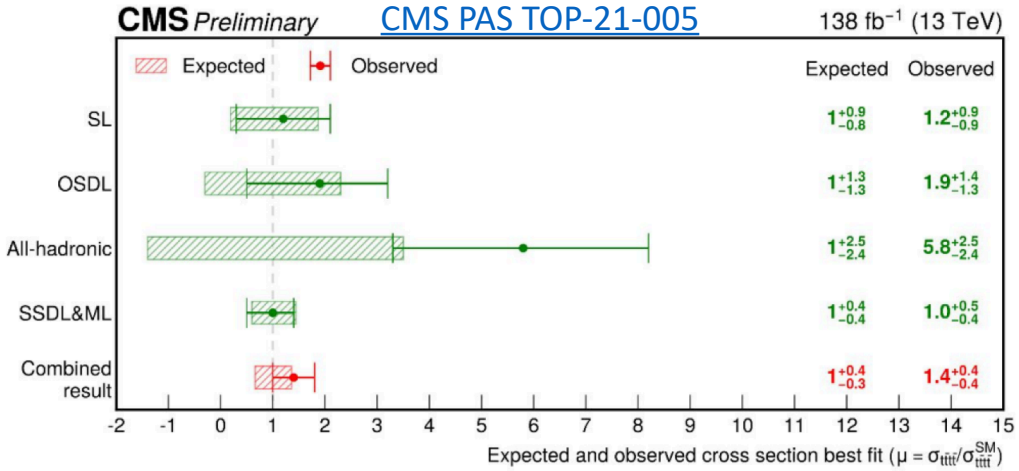
Four top: Signature

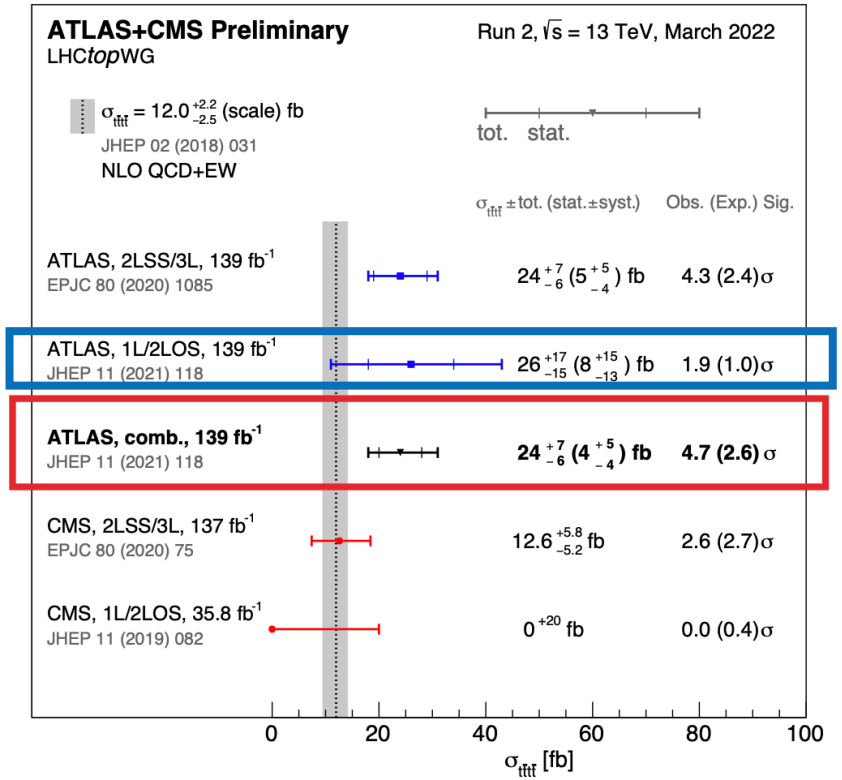
Four-top processes have high b-jets and jets multiplicity

3 channels are explored based on final states:

- All hadronic channel
- **Single lepton and two opposite sign lepton (1LOS)**
  - Larger branching fraction and Larger irreducible background
- **Same-sign di-lepton and multi-lepton (SSML)**
  - Smaller branching fraction and higher purity







Analysis strategy: 1LOS

Pre-selected events:

- 1L channel: one lepton and ≥ 7 jets and ≥ 2 b-tagged jets
- 2LOS channel: Two leptons with opposite-sign charge and ≥ 5 jets and ≥ 2 b-tagged jets

$t\bar{t}$+jets background is estimated using corrected MC simulation

- Correction factors are derived in data, improving the $t\bar{t}$+jets modeling at high Njets/Nbjets

A binned profile likelihood fit is performed in different event regions

- Split lepton channel, jets multiplicity and different b-tagging requirement
- Background model constrained by background-dominated regions

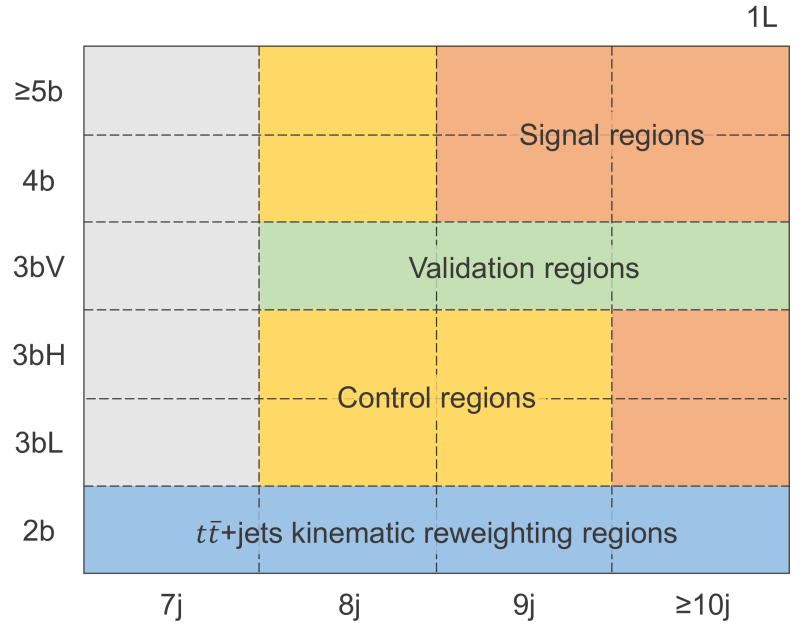
Event categorization

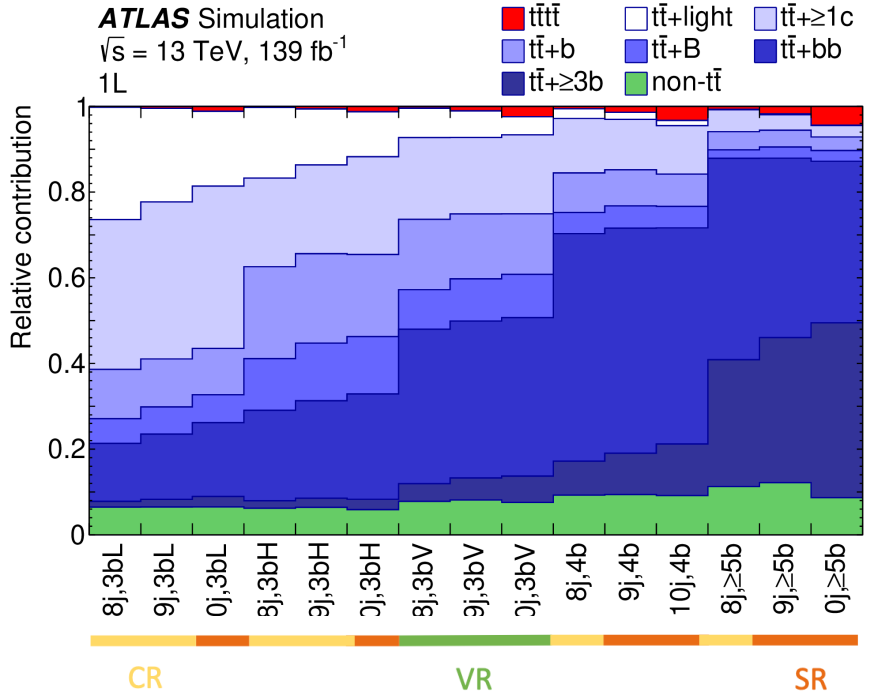
Events are categorized according to the number of jets and different b-tagging requirements

- Both number of b-tags and their quality

12 (9) **signal** and **control** regions for 1L (OS) used as input for the binned profile likelihood fit

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



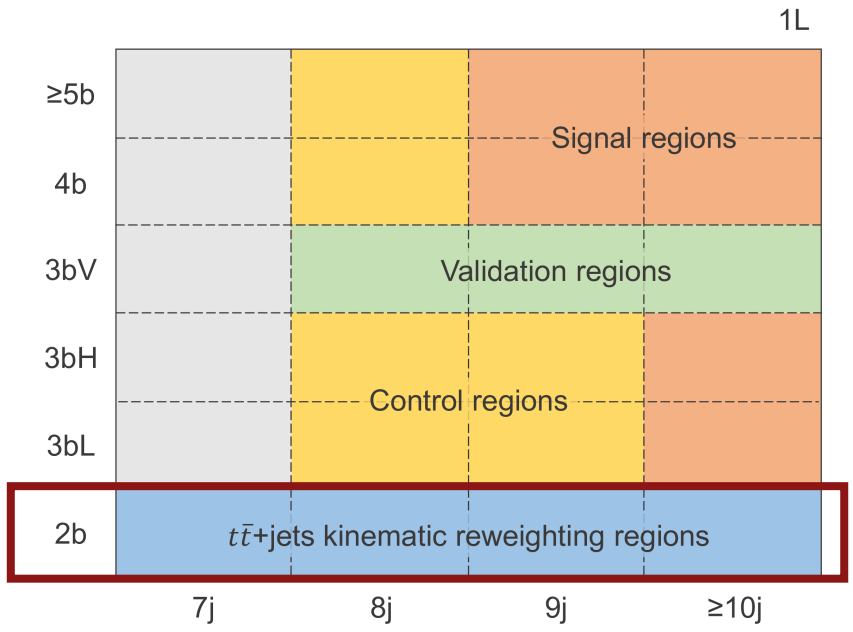


Background modeling: $t\bar{t}$+jets

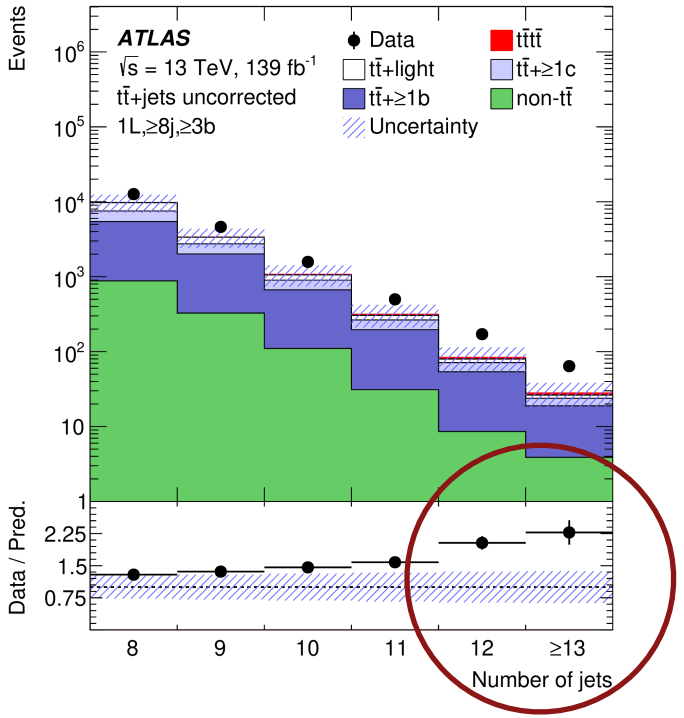
MC is known to mismodel the $t\bar{t}$+jets at H_T and high jet multiplicity

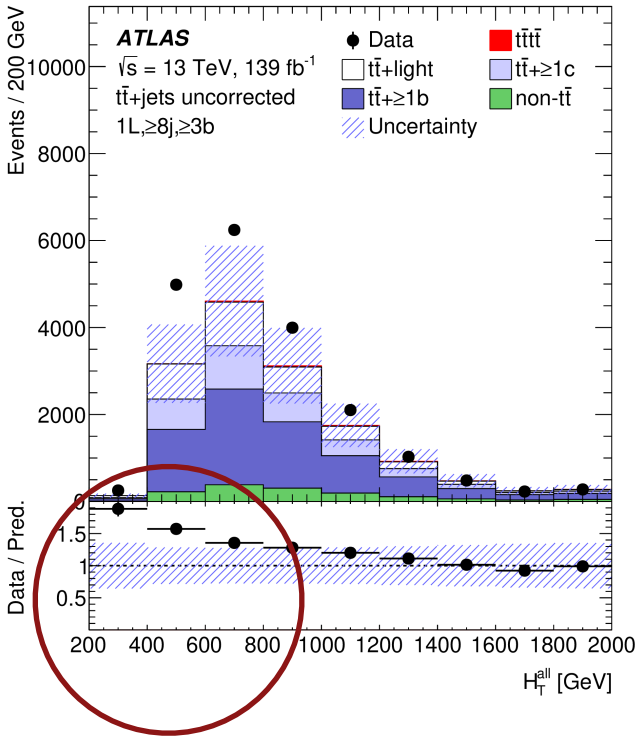
Developed techniques to tackle MC mismodelling in 2 b-tagged regions

- Derived rescaling factor at prefit level
- Designed a 3-step sequential re-weighting to target different type of mis-modeling
  - $N_{\text{jet}} \rightarrow H_T \rightarrow \Delta R_{\text{avg}}^{\text{jets}}$



Before correction





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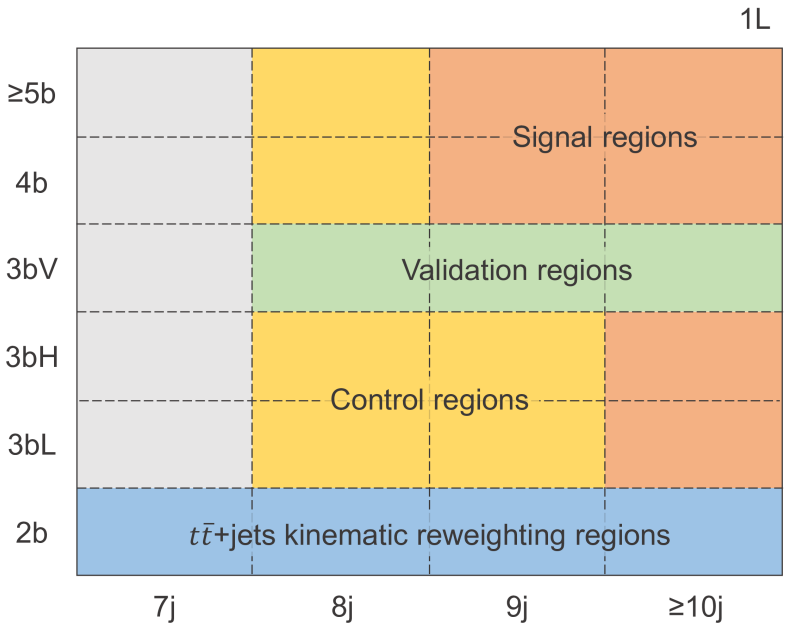
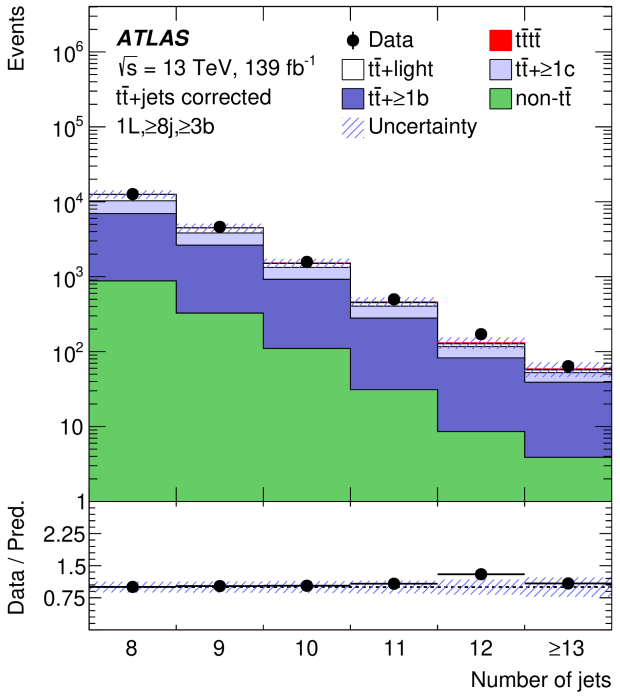
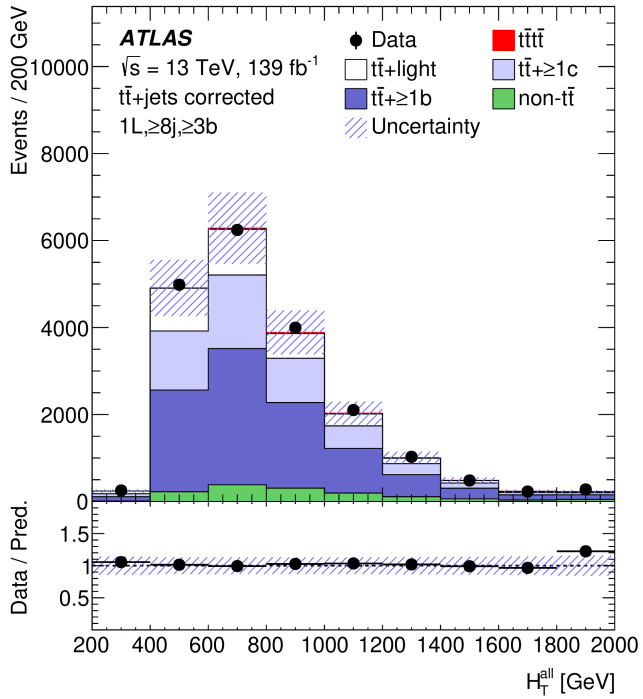


After correction





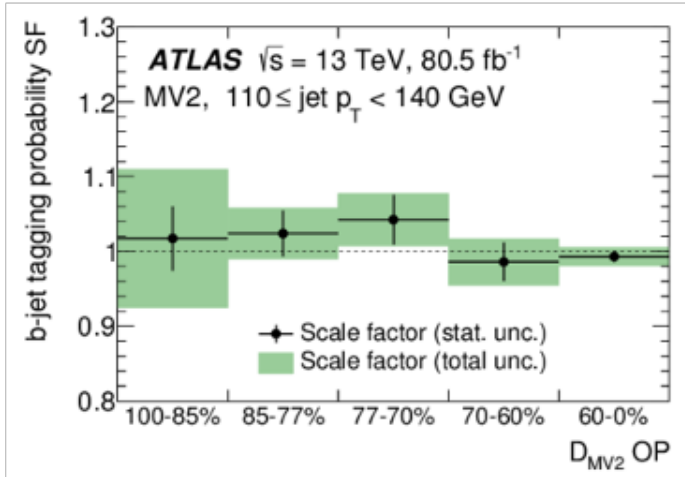
Use of BDT in the Signal Region

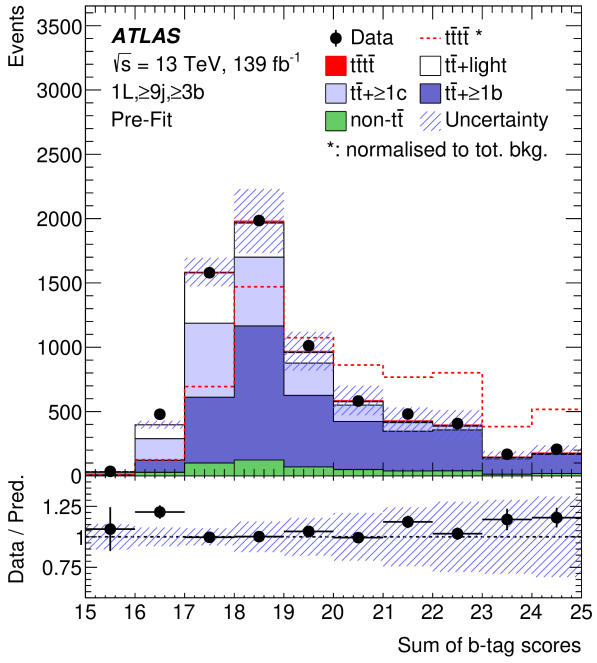
Signal is separated from background based on a multivariate discriminant build in the signal region by combining many input observables into a BDT

Observables are selected based on their discrimination power and the requirement of good modeling

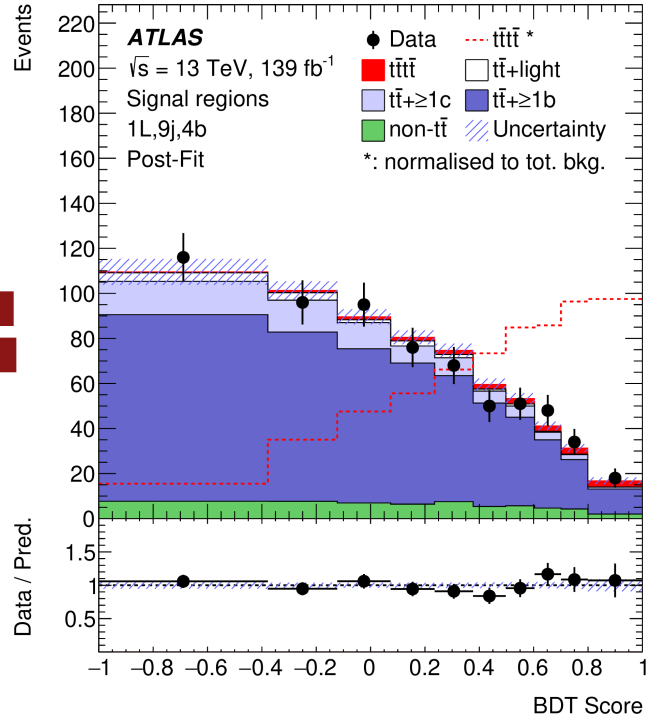
- B-tagging information: sum of the pseudo-continuous b-tagging discriminant score
- Lepton and jet kinematics

[Eur. Phys. J. C 79 (2019) 970]





+ Lepton, jet kinematics =



Fit result

Signal regions and control regions are used as input to a binned profiled likelihood fit

- HT used in CRs and BDT used in SRs

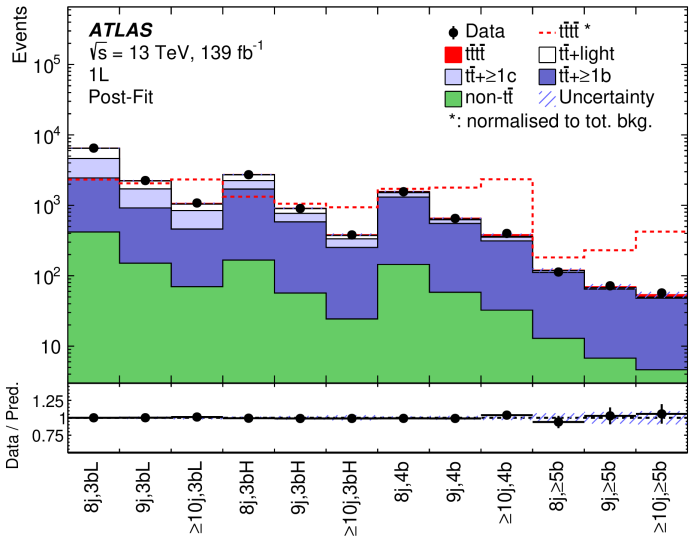
The measured μ found to be:

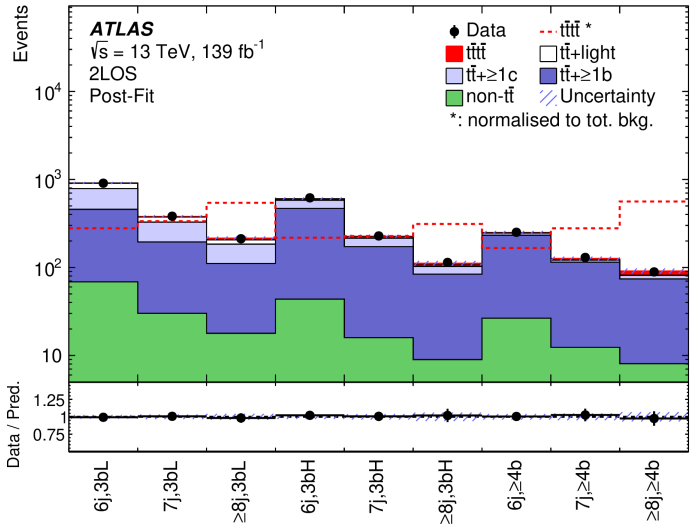
$$\mu = \sigma_{t\bar{t}t\bar{t}}/\sigma_{t\bar{t}t\bar{t}}^{SM} = 2.2^{+1.6}_{-1.2} = 2.2^{+0.7}_{-0.7}(stat.)^{+1.5}_{-1.0}(syst)$$

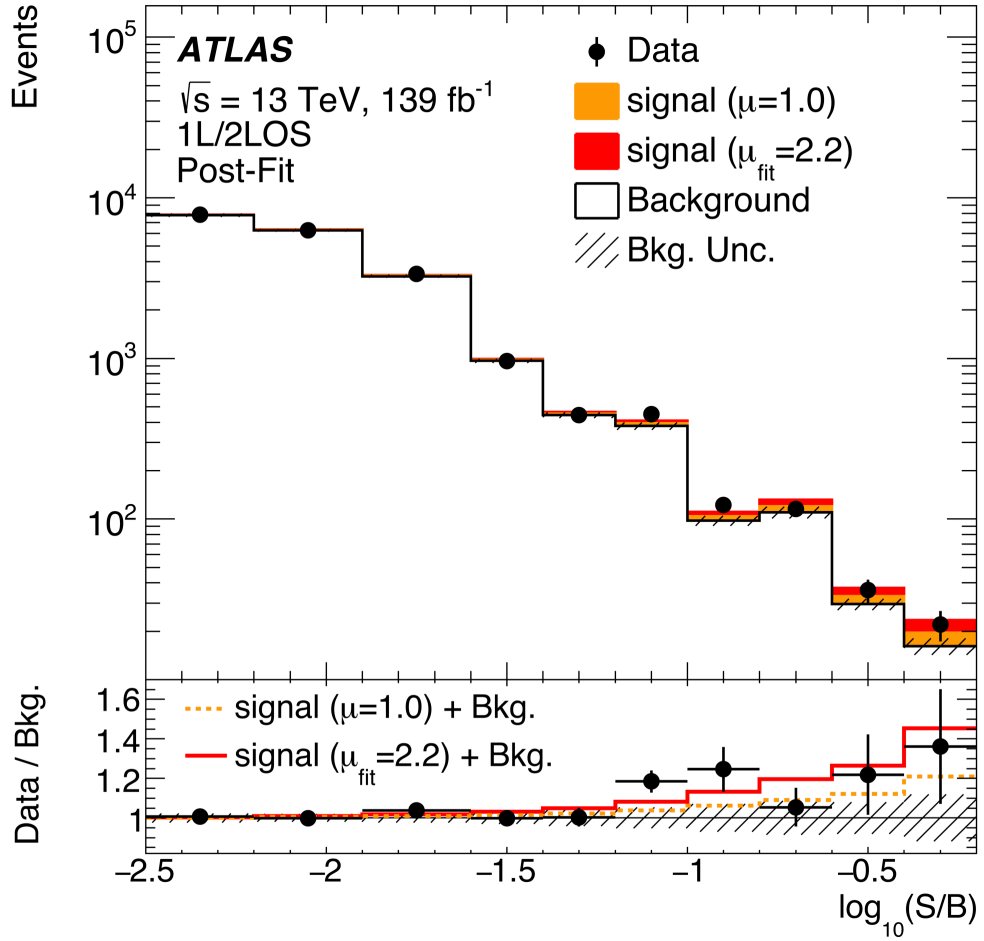
Measured cross section:

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

Observed (expected) significance: 1.9 (1.0) σ







Systematics

The dominant systematics uncertainties are coming from four-top signal and $t\bar{t}$+jets modeling uncertainties

Substantial impact from JES uncertainties and from b-tagging mis-tagging rates on light-jets

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

Combination with SSML

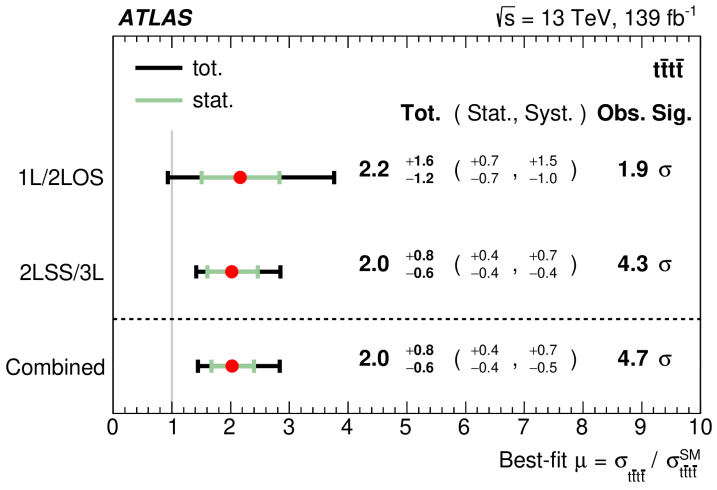
The combined four top cross section: $\sigma_{t\bar{t}t\bar{t}} = 25^{+7}_{-6}$ fb

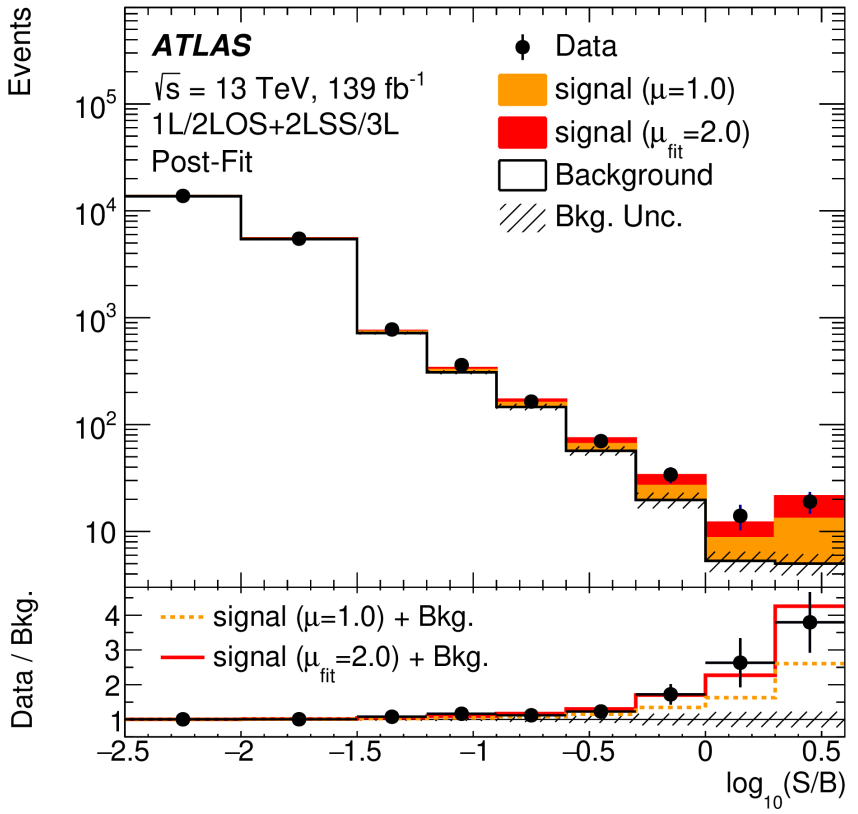
Compared with $\sigma^{SM}_{t\bar{t}t\bar{t}} = 12 \pm 2.4$ fb

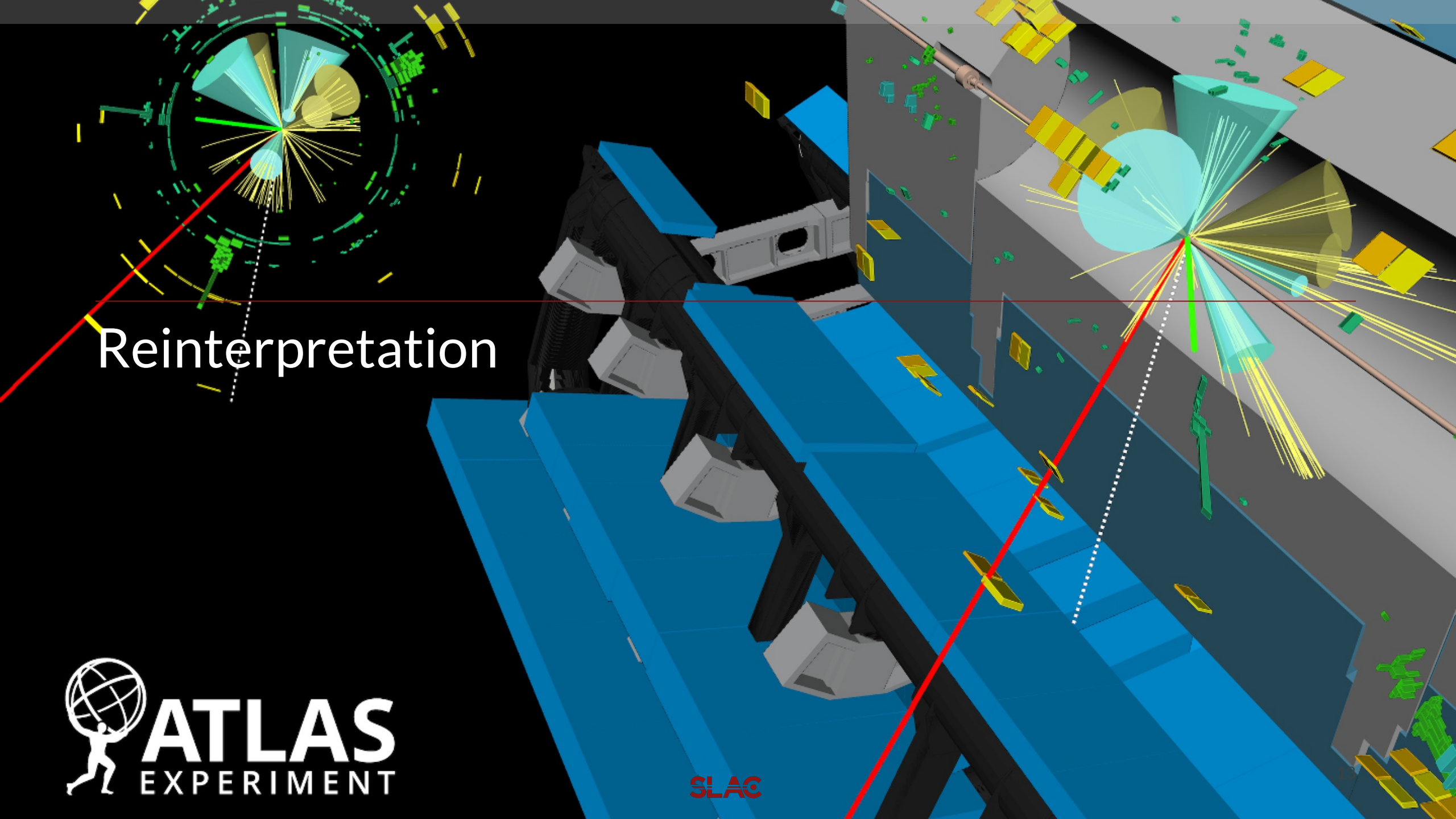
Compatible with the SM prediction with 2.0 σ

Observed (expected) significance: 4.7 (2.6) σ

Evidence for four top







Reinterpretation

ATLAS EXPERIMENT

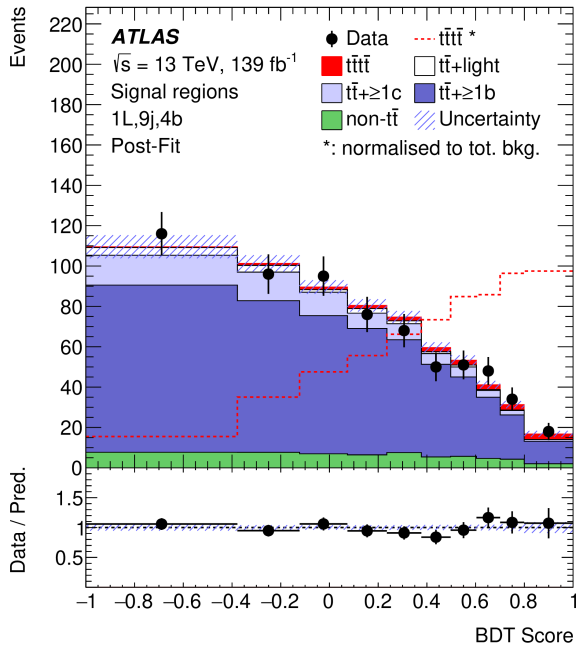
Reinterpretation: What is available on HEPData

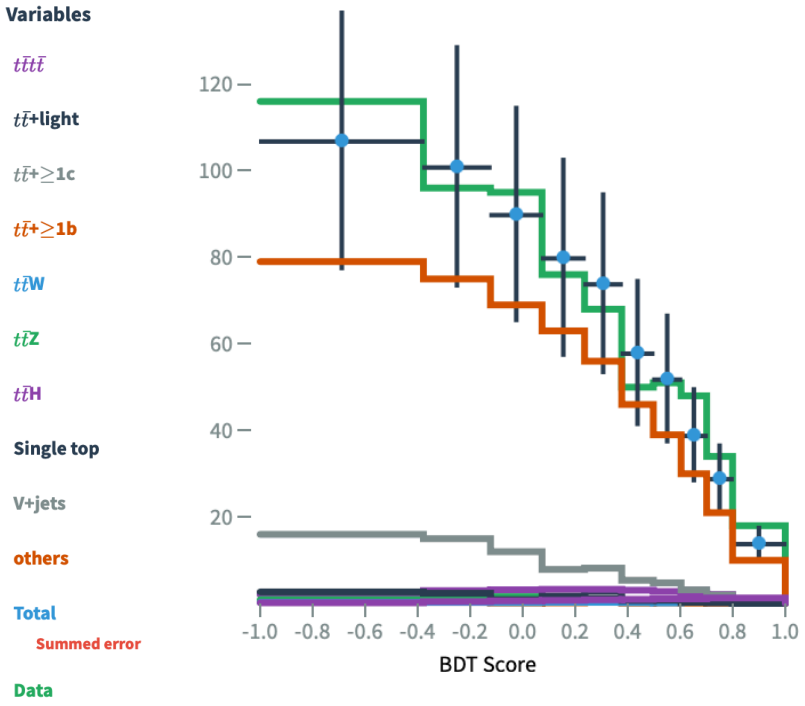
Reinterpretation material provided in [hepdata]

- Data and background (split by component) in SRs, CRs and VRs
- Data and background (split by component) for key distributions (sum of b-tag score, Njets, HT) in BDT training regions
- Ranking and group impact table
- Workspace

Reinterpretation material

Data and background in each bin used in the analysis





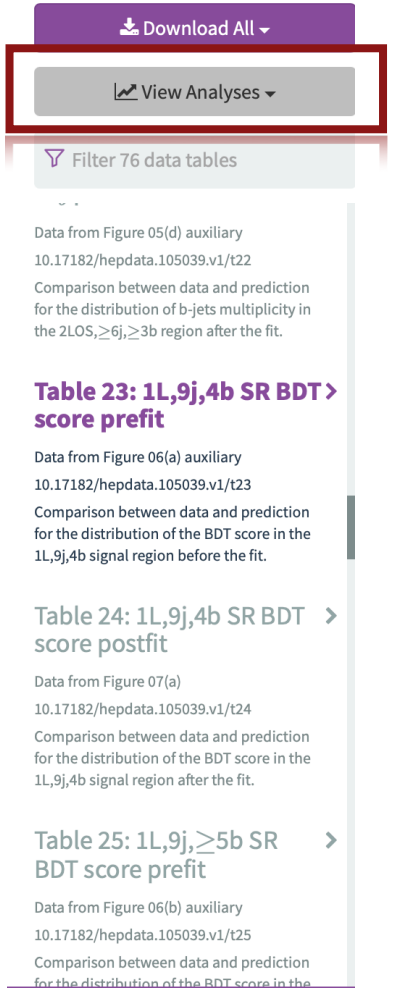
SQRT(s)	13000 GeV										
LUMINOSITY	139 fb^{-1}										
BDT Score	$t\bar{t}t\bar{t}$	$t\bar{t}$ +light	$t\bar{t}$+ ≥ 1c	$t\bar{t}$+ ≥ 1b	$t\bar{t}$W	$t\bar{t}$Z	$t\bar{t}$ H	Single top	V+jets	others	Total
-0.6891 (bin: -1 - -0.3782)	0.21	2.7	16	79	0.30	0.93	2.1	2.2	2.5	0.30	107 ±30
-0.2505 (bin: -0.3782 - -0.1228)	0.47	2.4	15	75	0.29	1.5	3.0	0.95	1.8	0.30	101 ±28
-0.0246 (bin: -0.1228 - 0.0736)	0.64	0.91	12	69	0.24	1.6	3.2	1.2	0.82	0.16	90 ±25
0.1546 (bin: 0.0736 - 0.2356)	0.75	1.7	7.9	63	0.32	0.96	3.3	1.1	0.72	0.19	80 ±23
0.3063 (bin: 0.2356 - 0.377)	0.89	1.1	8.2	56	0.31	1.1	3.3	2.8	0.56	0.31	74 ±21
0.4372 (bin: 0.377 - 0.4974)	0.99	0.70	5.4	46	0.24	0.65	3.1	0.70	0.54	0.14	58 ±17
0.5503 (bin: 0.4974 - 0.6032)	1.1	0.77	4.8	39	0.18	0.95	2.8	0.95	0.74	0.20	52 ±15
0.6519 (bin: 0.6032 - 0.7006)	1.1	0.32	3.2	30	0.31	0.96	2.5	0.46	0.28	0.12	39 ±11
0.7499 (bin: 0.7006 - 0.7992)	1.3	0.18	2.0	21	0.31	0.65	2.1	0.54	0.57	0.11	29 ±8
0.8996 (bin: 0.7992 - 1)	1.3	0.050	0.76	10	0.095	0.27	1.1	0.19	0.18	0.18	14 ±4

Reinterpretation material

Work space

Can access the workspace used in the analysis for both 1LOS analysis and combination

Can play the workspace with pyhf



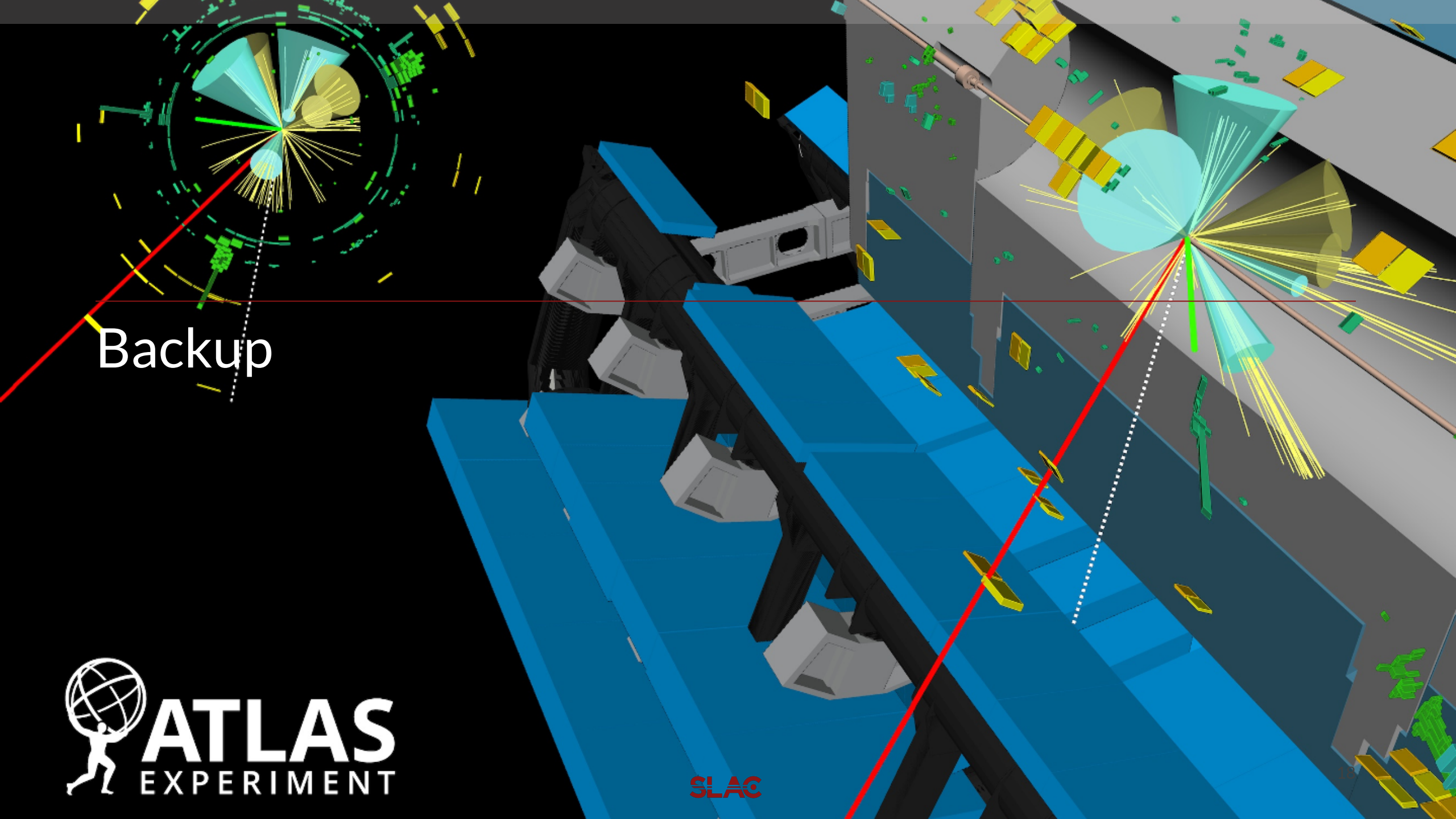
Conclusion

ATLAS finds further confirmation of evidence for four top process

A slight excess in the measured four-top cross section, but still compatible with SM prediction with 2σ in the combination

- Interesting to reinterpret

Understanding the $t\bar{t}$+jets background will help improve the analysis

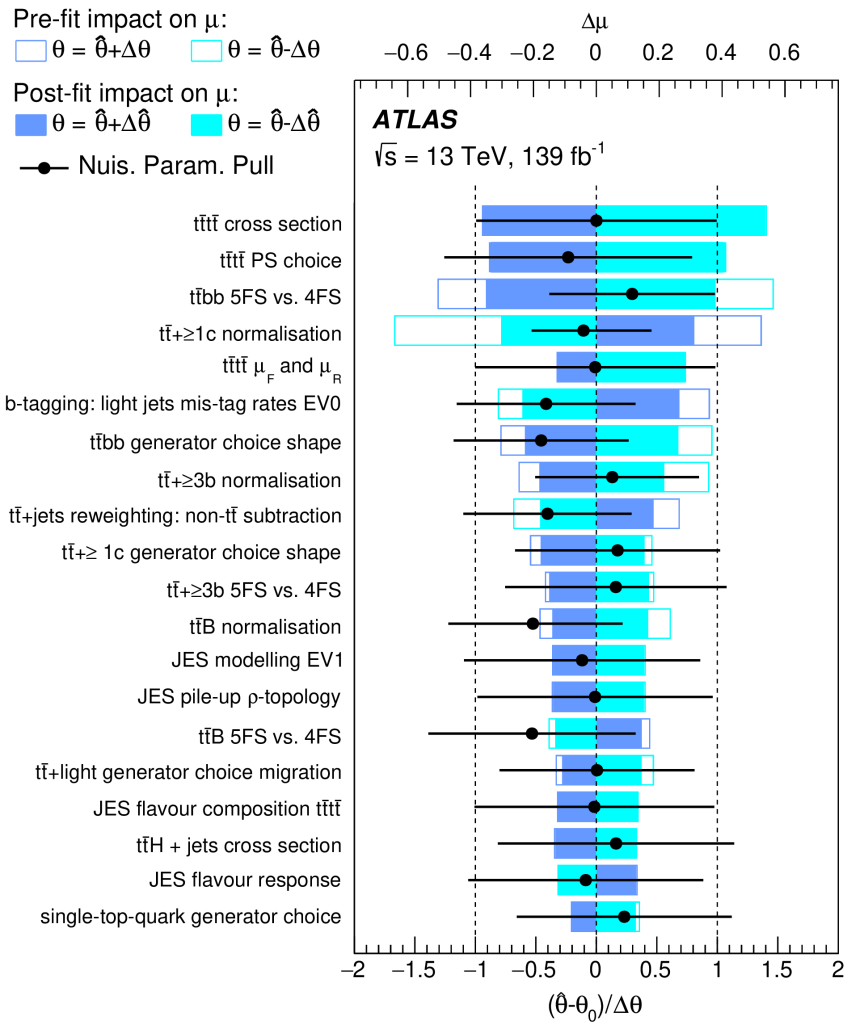


Backup

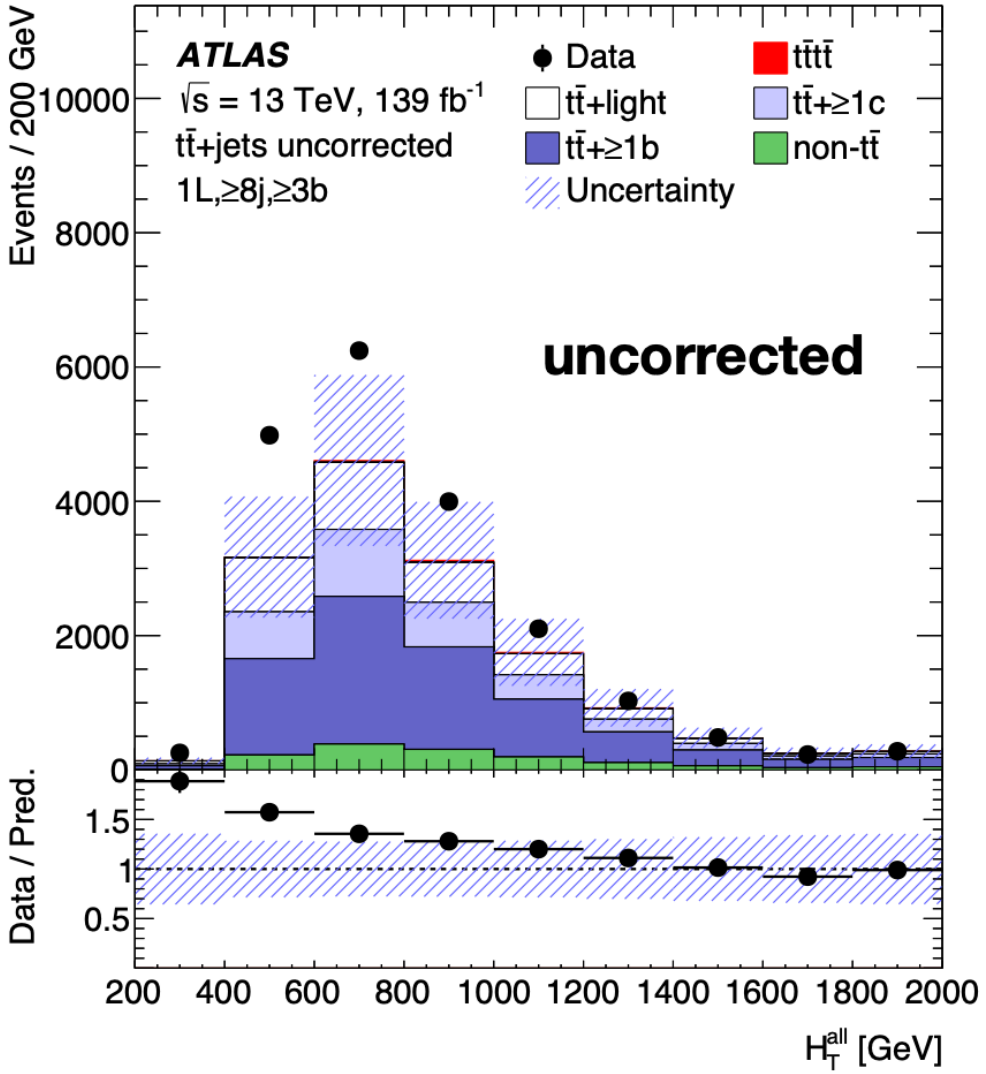
ATLAS EXPERIMENT

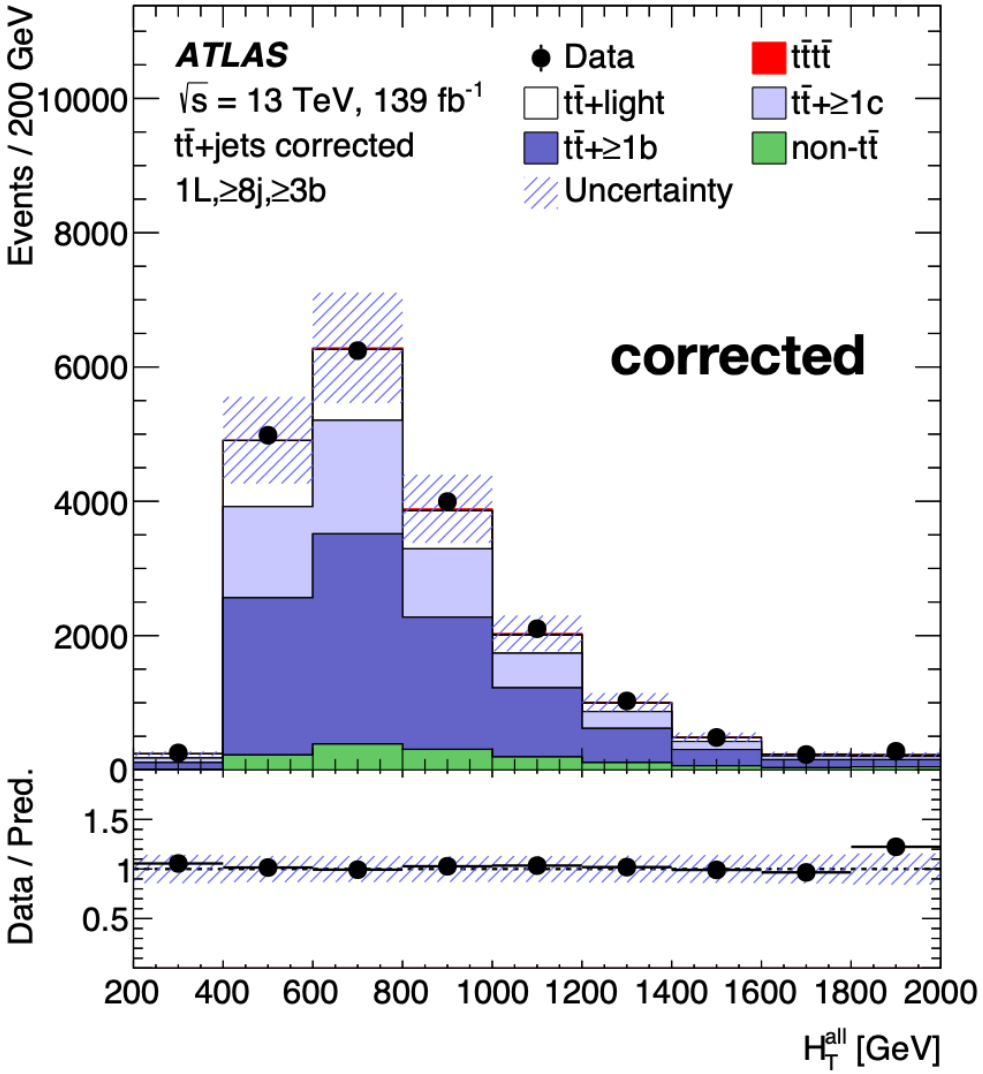
Systematics

Uncertainty source	Description	Components (number)
$t\bar{t}$+≥1b normalisation	±50%	$t\bar{t}$+b, $t\bar{t}$+$b\bar{b}$, $t\bar{t}$+B, $t\bar{t}$+≥3b (4)
$t\bar{t}$+≥1c normalisation	±50%	$t\bar{t}$+≥1c (1)
Generator choice	POWHEG vs MADGRAPH5_AMC@NLO	($t\bar{t}$+light, $t\bar{t}$+≥1c, $t\bar{t}$+b, $t\bar{t}$+$b\bar{b}$, $t\bar{t}$+B, $t\bar{t}$+≥3b) ⊗ (shape, migration) (12)
PS choice	PYTHIA 8 vs HERWIG 7	($t\bar{t}$+light, $t\bar{t}$+≥1c, $t\bar{t}$+b, $t\bar{t}$+$b\bar{b}$, $t\bar{t}$+B, $t\bar{t}$+≥3b) ⊗ (shape, migration) (12)
Renormalisation scale	Varying μ_r in POWHEG	$t\bar{t}$+light, $t\bar{t}$+≥1c, $t\bar{t}$+≥1b (3)
Factorisation scale	Varying μ_f in POWHEG	$t\bar{t}$+light, $t\bar{t}$+≥1c, $t\bar{t}$+≥1b (3)
ISR	Varying α_S^{ISR}(PS) in PYTHIA 8	$t\bar{t}$+light, $t\bar{t}$+≥1c, $t\bar{t}$+≥1b (3)
FSR	Varying μ_f (PS) in PYTHIA 8	$t\bar{t}$+light, $t\bar{t}$+≥1c, $t\bar{t}$+≥1b (3)
5FS vs 4FS	POWHEGBOXRES (4FS) vs POWHEGBOX (5FS)	$t\bar{t}$+b, $t\bar{t}$+$b\bar{b}$, $t\bar{t}$+B, $t\bar{t}$+≥3b (4)



$t\bar{t}$+jets modeling





BDT training

Name	Description
$\sum b$-tag	Sum of pseudo-continuous b-tagging score over the six jets with the highest score
N_{jets}	Number of jets
$\Delta R_{bb}^{\text{min}}$	Minimum ΔR between all pairs of b-tagged jets
$H_{\text{T}}^{\text{all}}$	Scalar sum of all jet and lepton transverse momenta
C^{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
$\Delta R_{b\ell}^{\text{min}}$	Minimum ΔR between all pairs of b-tagged jets and leptons
$\Delta R_{jj}^{\text{avg}}$	Average ΔR between all pairs of jets
m_{jjj}	Invariant mass of the closest triplet of jets
$E_{\text{T}}^{\text{miss}}$	Missing transverse momentum
m_{T}^{W}	W reconstructed transverse mass $m_T(\ell, E_{\text{T}}^{\text{miss}})$ (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