



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



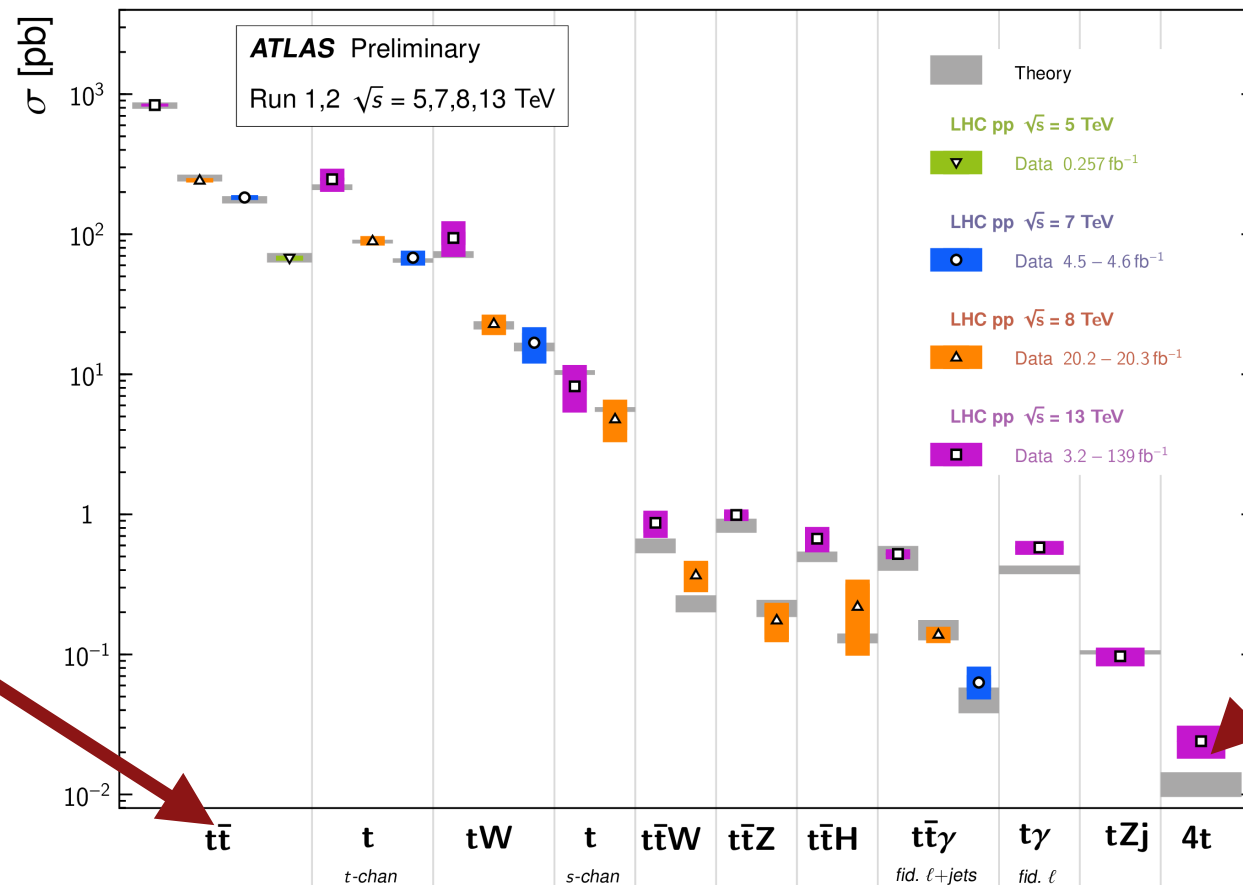
Why Four top is interesting ?

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

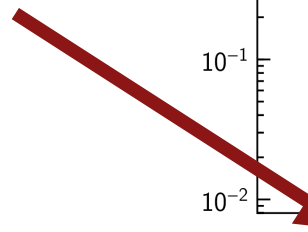
- $\sigma(t\bar{t}\bar{t}\bar{t})_{NLO} \sim 12 \text{ fb}$ [JHEP 02 (2018) 031]

Top Quark Production Cross Section Measurements

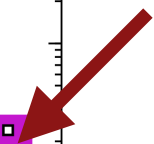
Status: November 2022



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



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



Why Four top is interesting ?

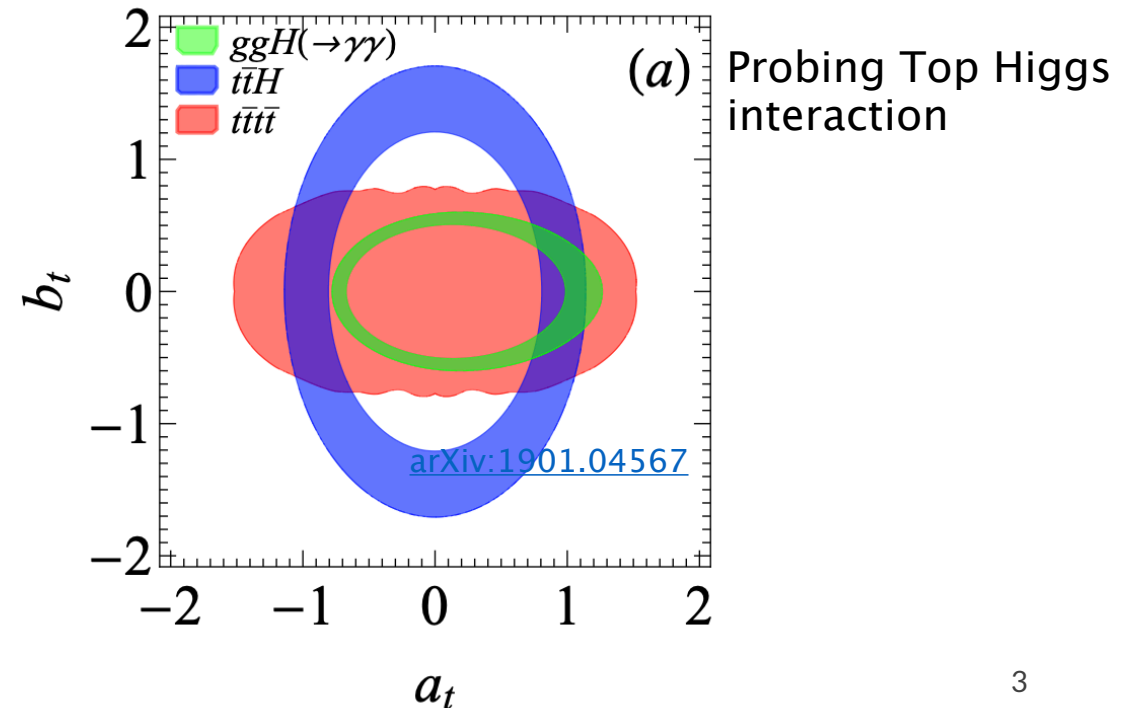
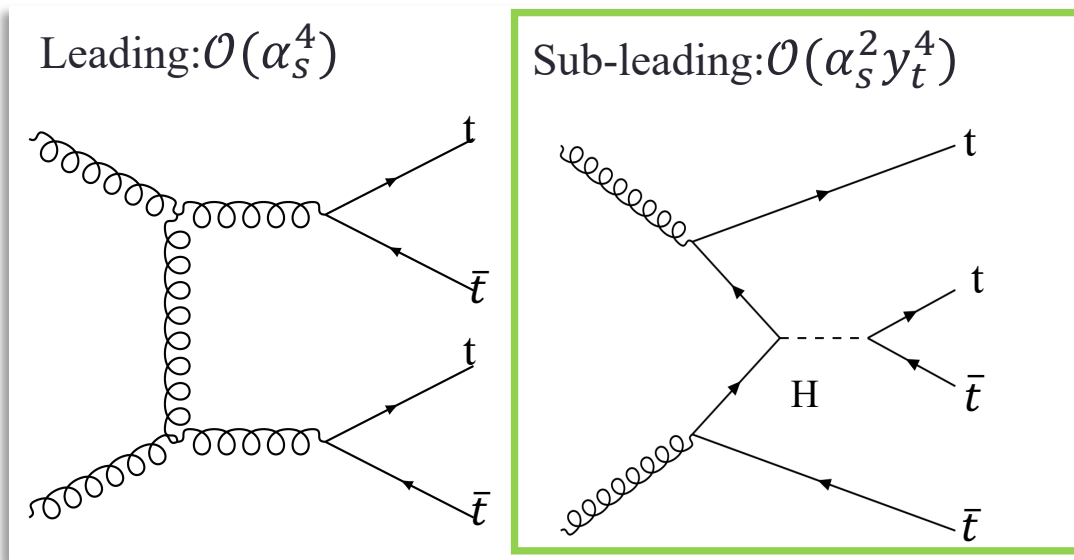
$t\bar{t}t\bar{t}$ is a very rare process in standard model (SM)

- $\sigma(t\bar{t}t\bar{t})_{NLO} \sim 12 \text{ fb}$ [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

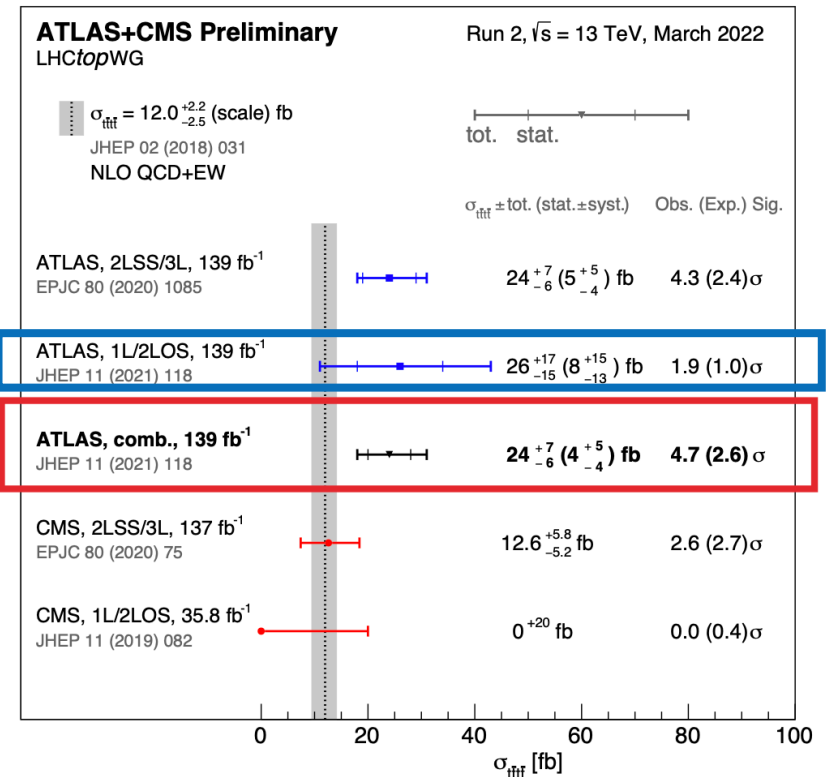
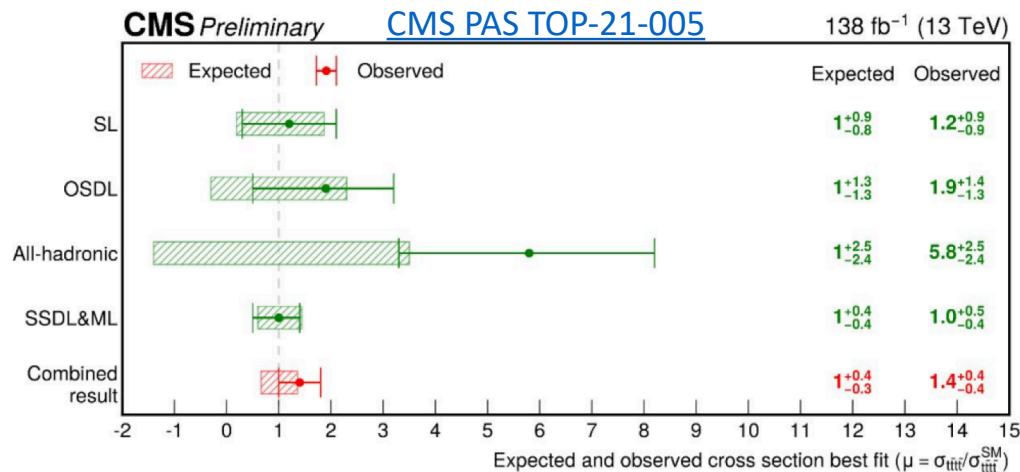
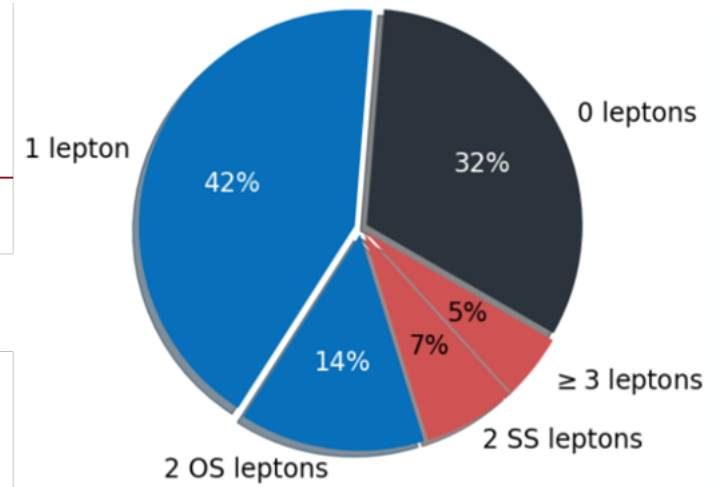
- Four-fermion couplings (e.g. $\mathcal{O}_{tt}^1 = (\bar{t}\gamma_\mu t)(\bar{t}\gamma^\mu t)$) and tow-Higgs doublet model



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 $N_{\text{jets}}/N_{\text{bjets}}$

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

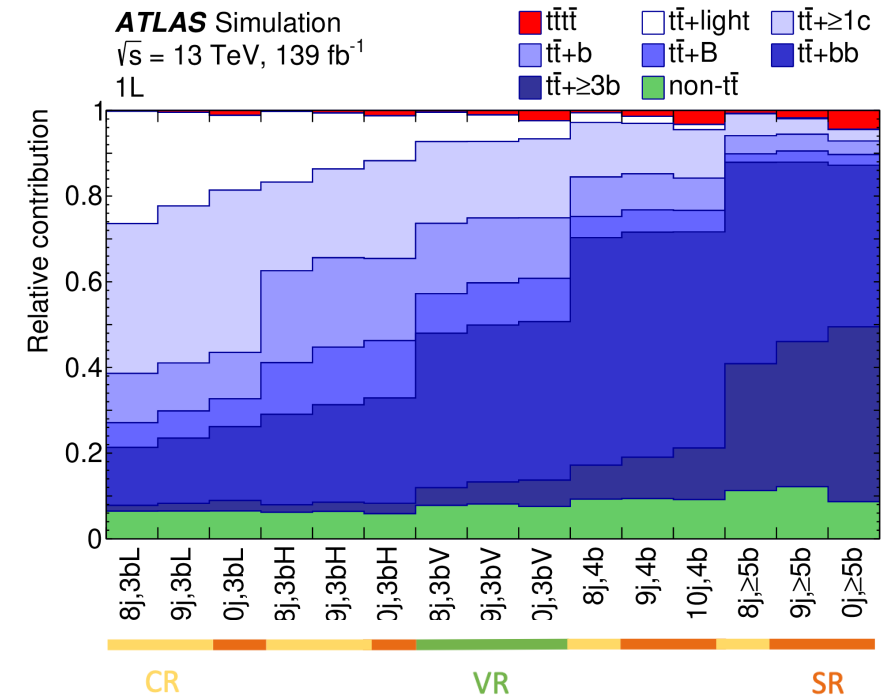
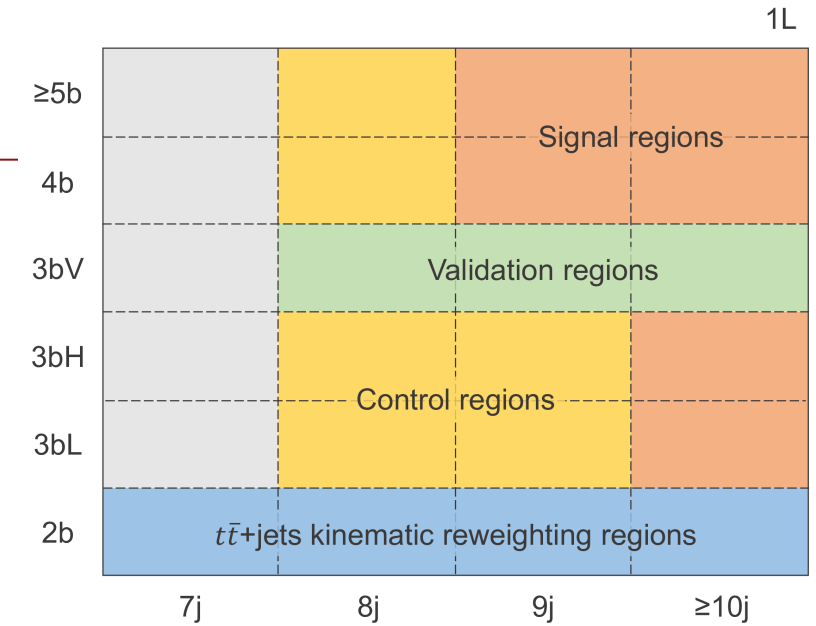
Event categorization

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
$\geq 4b$ (2LOS)	-	≥ 4	-
4b (1L)	-	= 4	-
$\geq 5b$ (1L)	-	≥ 5	-



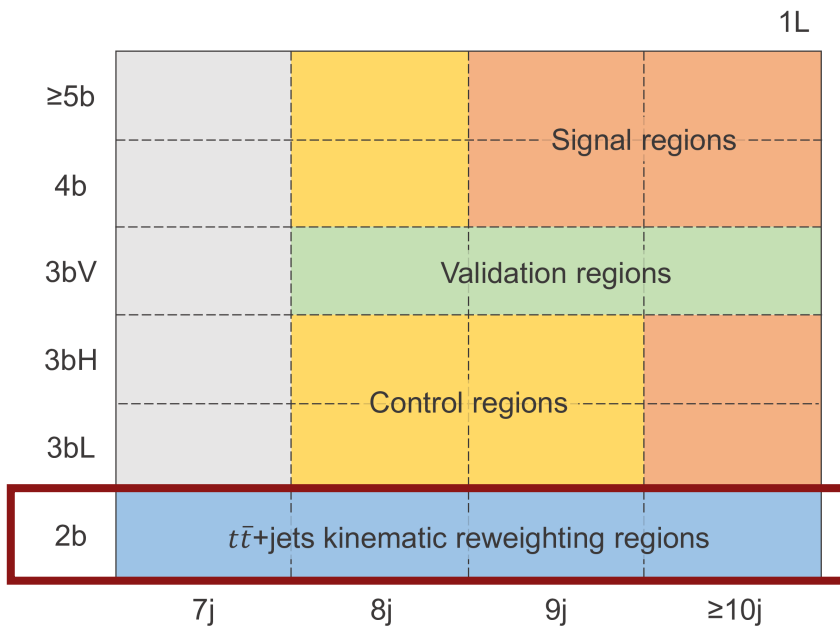
Background modeling: $t\bar{t}$ +jets

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

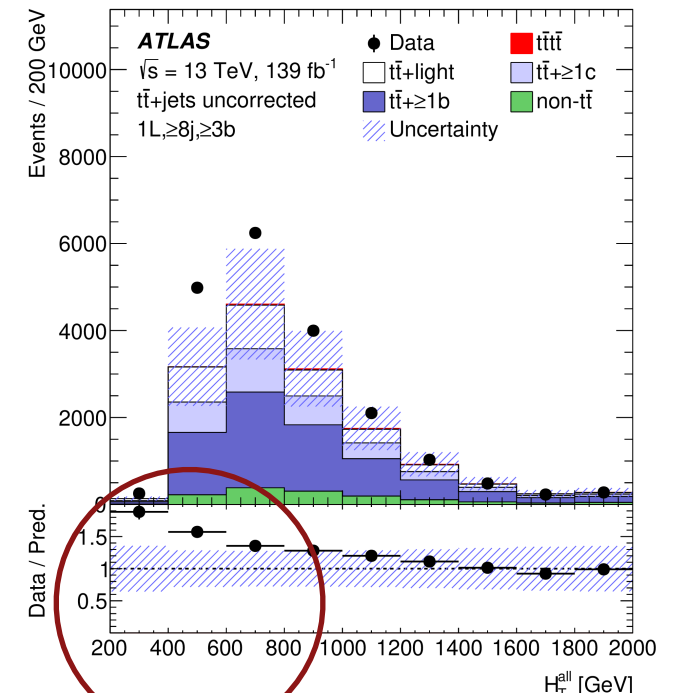
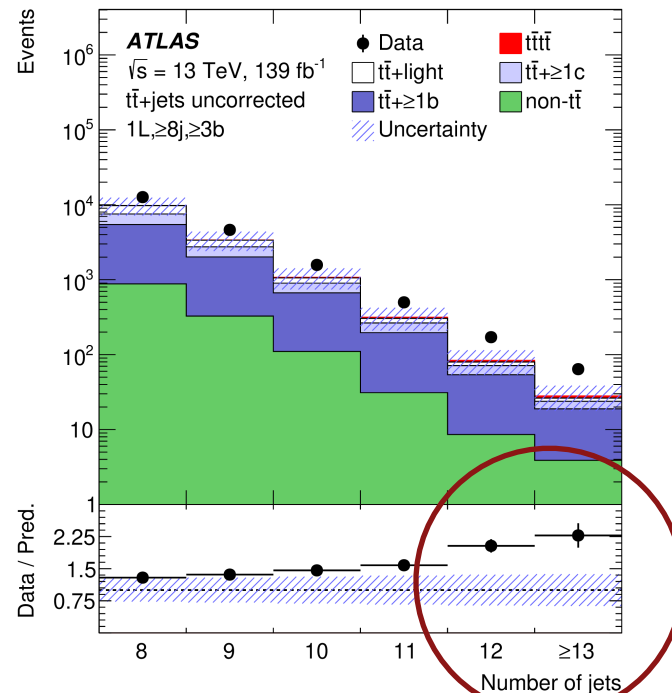
Developed techniques to tackle MC mismodelling in 2 b-tagged regions

- 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



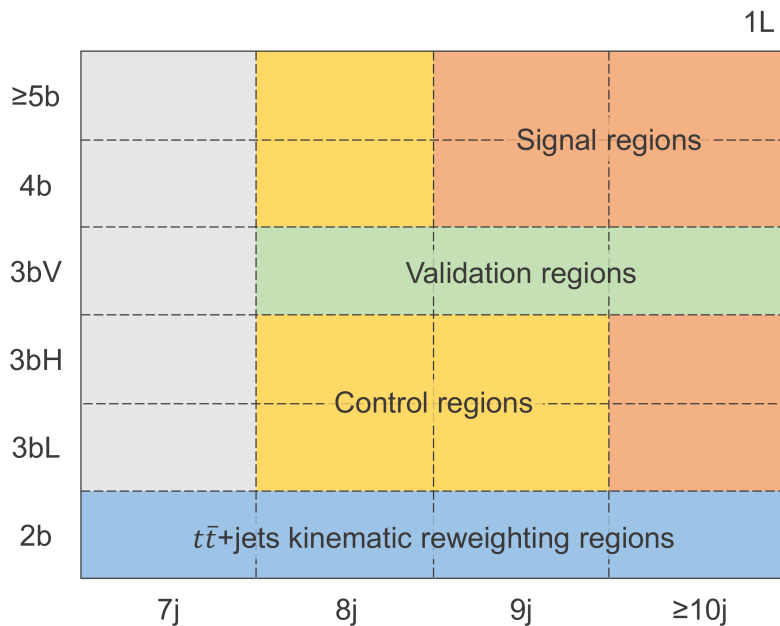
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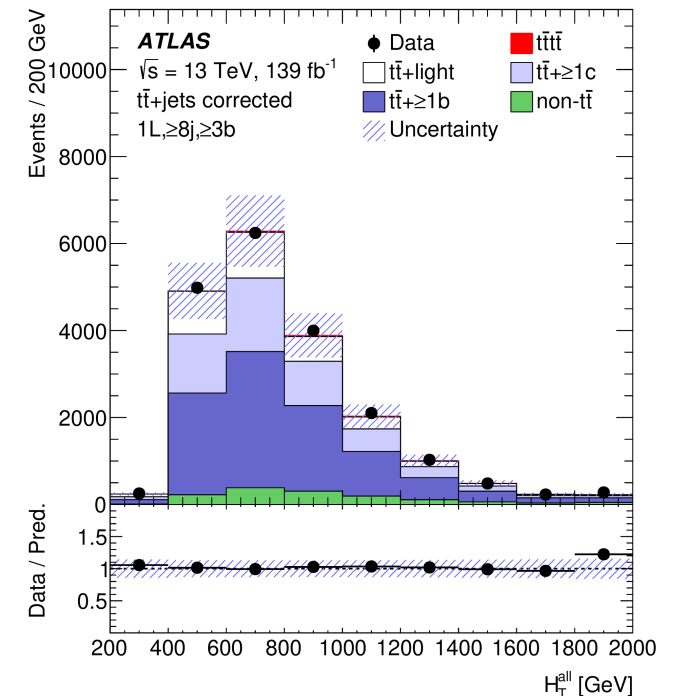
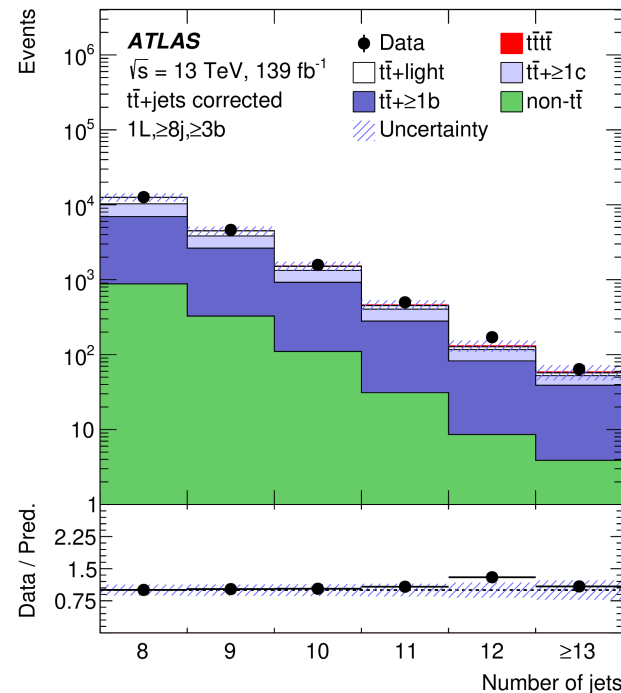
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After correction



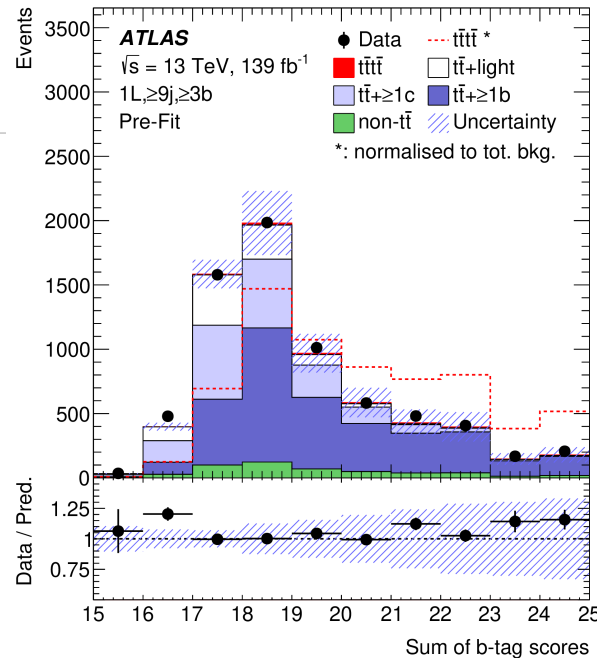
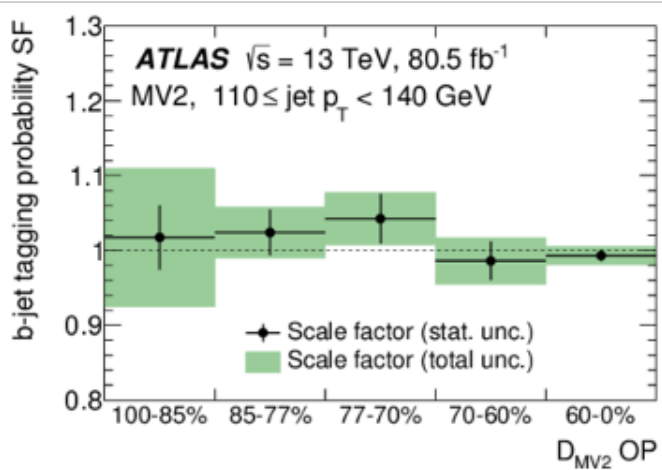
Use of BDT in the Signal Region

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

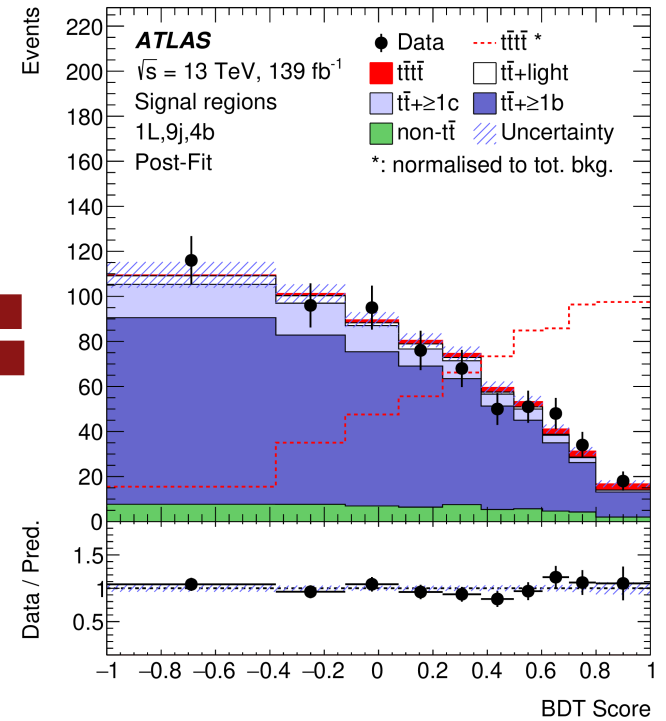
Observables are selected based on their discrimination power and the requirement of good modeling

- 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

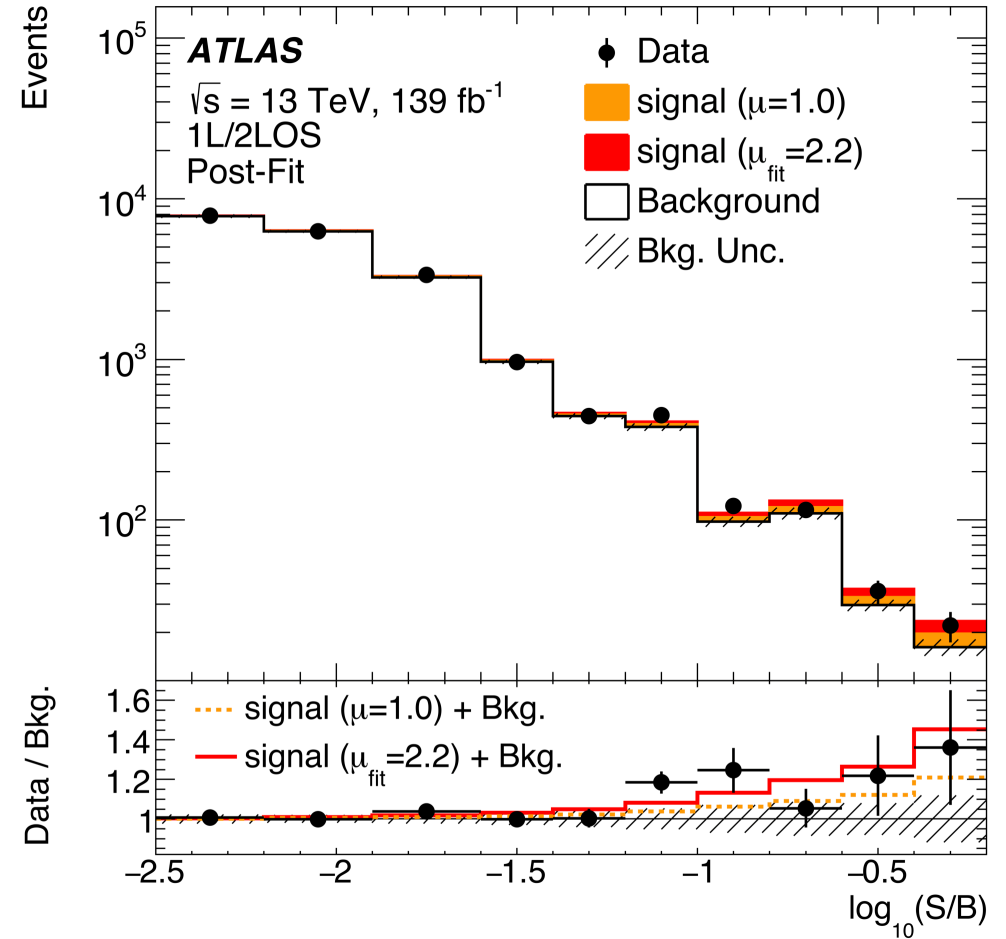
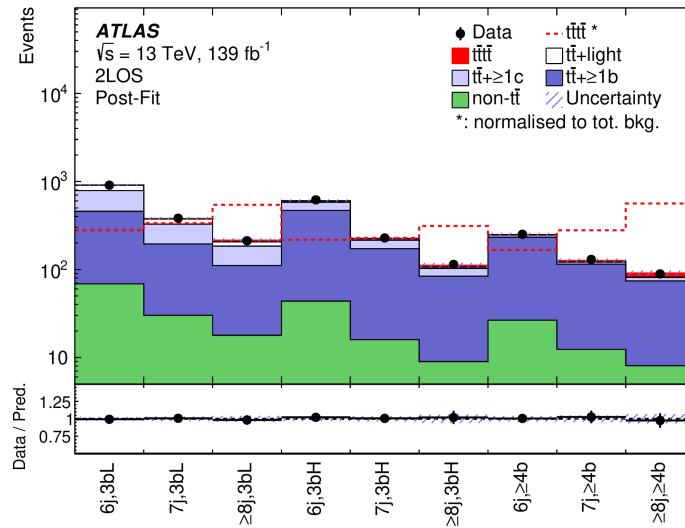
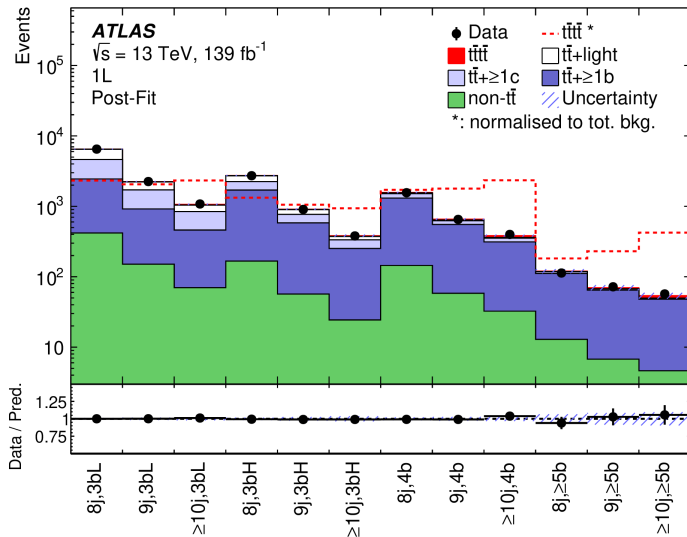
The measured μ found to be:

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

Measured cross section:

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

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	$\Delta\sigma_{t\bar{t}\bar{t}}$ [fb]	
Signal Modelling		
→ $t\bar{t}\bar{t}$ 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

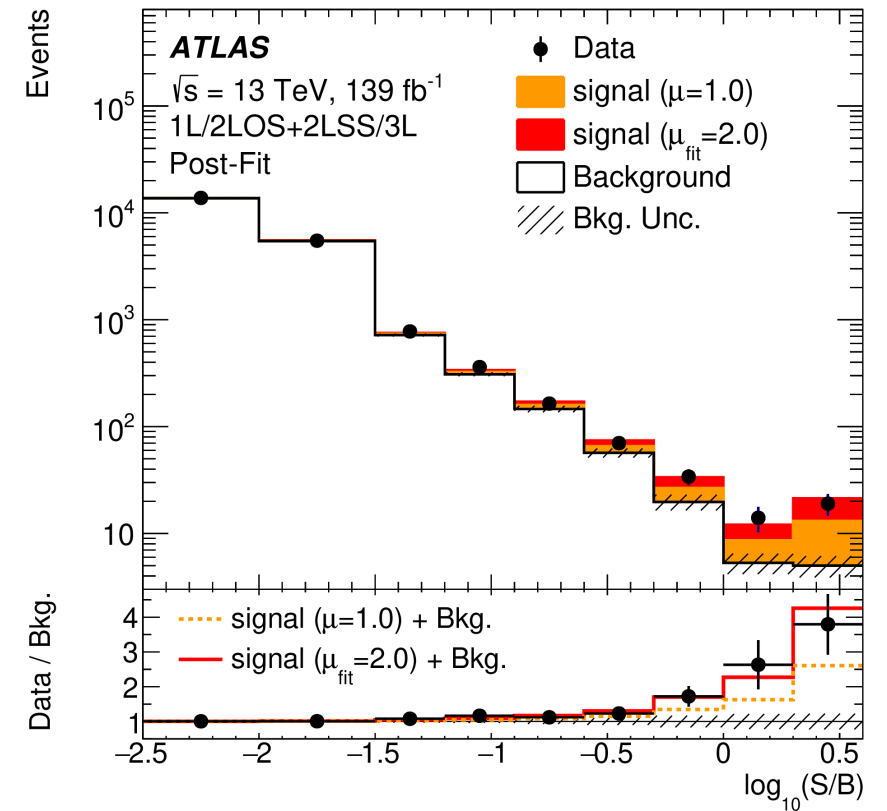
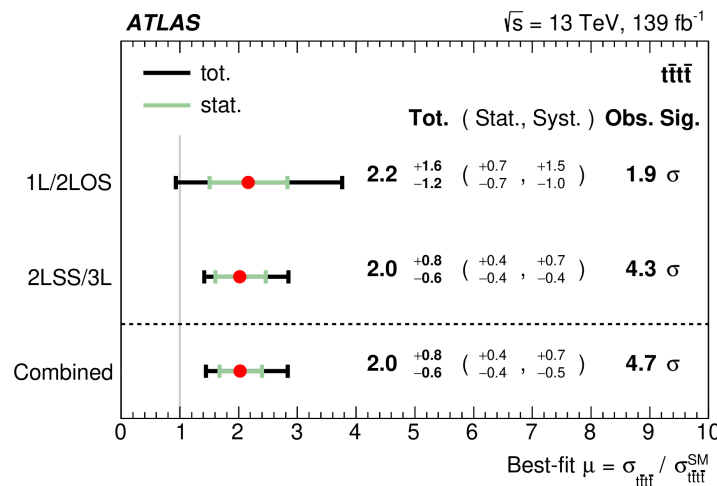
The combined four top cross section: $\sigma_{t\bar{t}t\bar{t}} = 25_{-6}^{+7} \text{ fb}$

Compared with $\sigma_{t\bar{t}t\bar{t}}^{SM} = 12 \pm 2.4 \text{ fb}$

Compatible with the SM prediction with 2.0σ

Observed (expected) significance: $4.7 (2.6) \sigma$

Evidence for four top



A 3D visualization of the ATLAS detector. The detector is shown in blue and grey, with various components like calorimeters and tracking chambers. A red line represents the path of an incoming particle, which interacts at a point (indicated by a white dotted line). From this interaction point, several tracks emerge, some in yellow and some in cyan, representing different types of particles. The tracks are shown as lines originating from the interaction point and extending through the detector. The background is dark, highlighting the detector and the particle tracks.

Reinterpretation

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

◀ Hide Publication Information

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

The ATLAS collaboration

Aad, Georges , Abbott, Braden Keim , Abbott, Dale , Abed Abud, Adam , Abeling, Kira , Abhayasinghe, Deshan Kavishka , Abidi, Haider , Abramowicz, Halina , Abreu, Henso , Abulaiti, Yiming

JHEP 11 (2021) 118, 2021.

<https://doi.org/10.17182/hepdata.105039>

Journal

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Abstract (data abstract)

CERN-LHC, ATLAS. Measurements of the of four-top-quark production cross section using events with single lepton (electron or muon) or an opposite-sign lepton pair, in association with multiple jets in proton-proton collisions at a centre-of-mass energy of 13 TeV with 139 fb^{-1} of data. The result is combined with the previous measurement performed by the ATLAS Collaboration in the multilepton final state.

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Data from Figure 05(d) auxiliary
10.17182/hepdata.105039.v1/t22
Comparison between data and prediction for the distribution of b-jets multiplicity in the $2LOS_{\geq 6j, \geq 3b}$ region after the fit.

Table 23: 1L,9j,4b SR BDT score prefit

Data from Figure 06(a) auxiliary
10.17182/hepdata.105039.v1/t23
Comparison between data and prediction for the distribution of the BDT score in the 1L,9j,4b signal region before the fit.

Table 24: 1L,9j,4b SR BDT score postfit

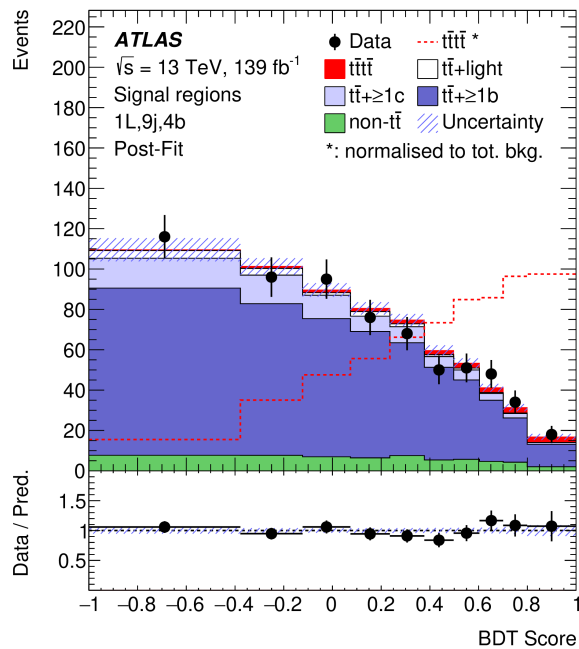
Data from Figure 07(a)
10.17182/hepdata.105039.v1/t24
Comparison between data and prediction for the distribution of the BDT score in the 1L,9j,4b signal region after the fit.

Table 25: 1L,9j, $\geq 5b$ SR BDT score prefit

Data from Figure 06(b) auxiliary
10.17182/hepdata.105039.v1/t25
Comparison between data and prediction for the distribution of the BDT score in the

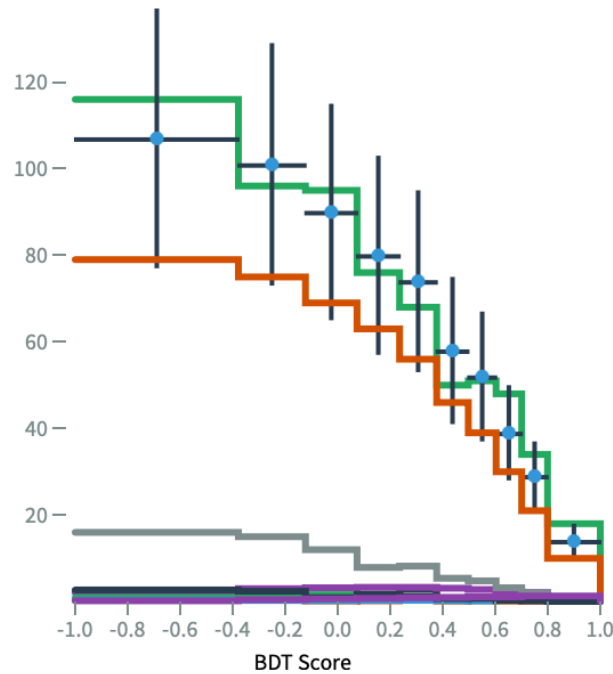
Reinterpretation material

Data and background in each bin used in the analysis



Variables

- $t\bar{t}\bar{t}$
- $t\bar{t}$ +light
- $t\bar{t}+\geq 1c$
- $t\bar{t}+\geq 1b$
- $t\bar{t}W$
- $t\bar{t}Z$
- $t\bar{t}H$
- Single top
- V+jets
- others
- Total
- Summed error
- Data



SQRT(s)	13000 GeV										
LUMINOSITY	139 fb ⁻¹										
BDT Score	$t\bar{t}\bar{t}$	$t\bar{t}$ +light	$t\bar{t}+\geq 1c$	$t\bar{t}+\geq 1b$	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	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

```
workspace_1LOS.json 10.17182/hepdata.105039.v1/r1
Archive of full likelihood from the 1L/2LOS channel in the

{
  "channels": [
    {
      "name": "ljets_8j3bL_CR_HT_all",
      "samples": [
        {
          "data": [
            0.2619302106314403,
            3.551365528672369,
            3.618559846462551,
            1.9899839472282626,
            0.9043540460099155,
            0.7127012527272792
          ],
          "modifiers": [
            {
              "data": null,
              "name": "lumi",
              "type": "lumi"
            },
            {
              "data": {
                "hi": 1.2,
                "lo": 0.8
              },
              "name": "tttt_Xsec",
              "type": "normsys"
            },
            {

```

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Data from Figure 05(d) auxiliary
10.17182/hepdata.105039.v1/t22
Comparison between data and prediction for the distribution of b-jets multiplicity in the 2LOS, $\geq 6j, \geq 3b$ region after the fit.

Table 23: 1L,9j,4b SR BDT score prefit

Data from Figure 06(a) auxiliary
10.17182/hepdata.105039.v1/t23
Comparison between data and prediction for the distribution of the BDT score in the 1L,9j,4b signal region before the fit.

Table 24: 1L,9j,4b SR BDT score postfit

Data from Figure 07(a)
10.17182/hepdata.105039.v1/t24
Comparison between data and prediction for the distribution of the BDT score in the 1L,9j,4b signal region after the fit.

Table 25: 1L,9j, $\geq 5b$ SR BDT score prefit

Data from Figure 06(b) auxiliary
10.17182/hepdata.105039.v1/t25
Comparison between data and prediction for the distribution of the BDT score in the

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

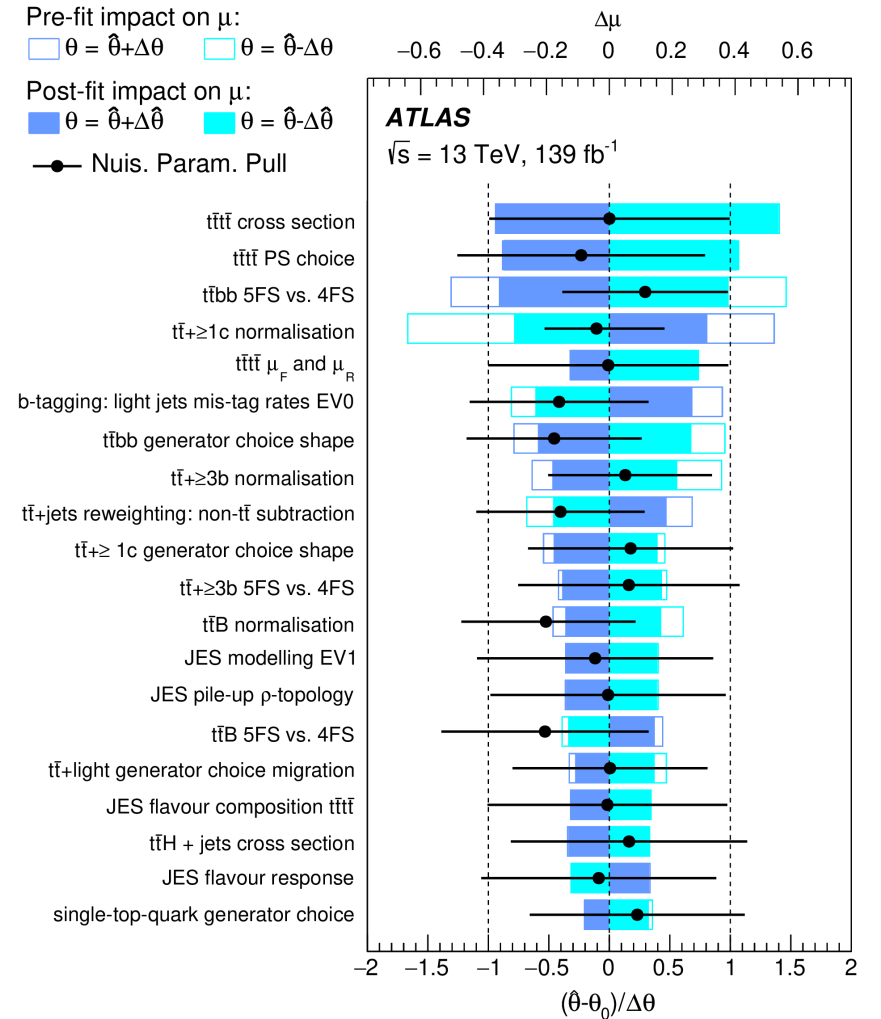


Backup

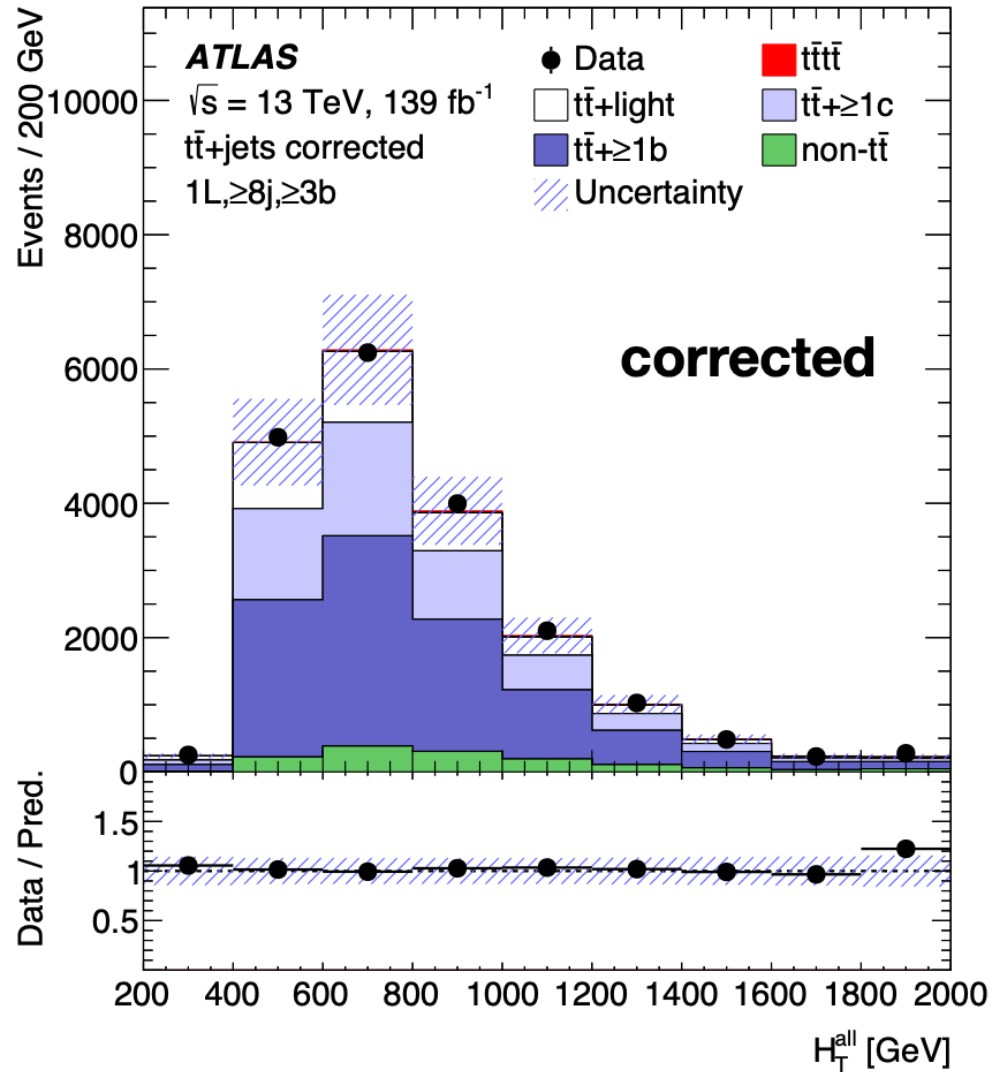
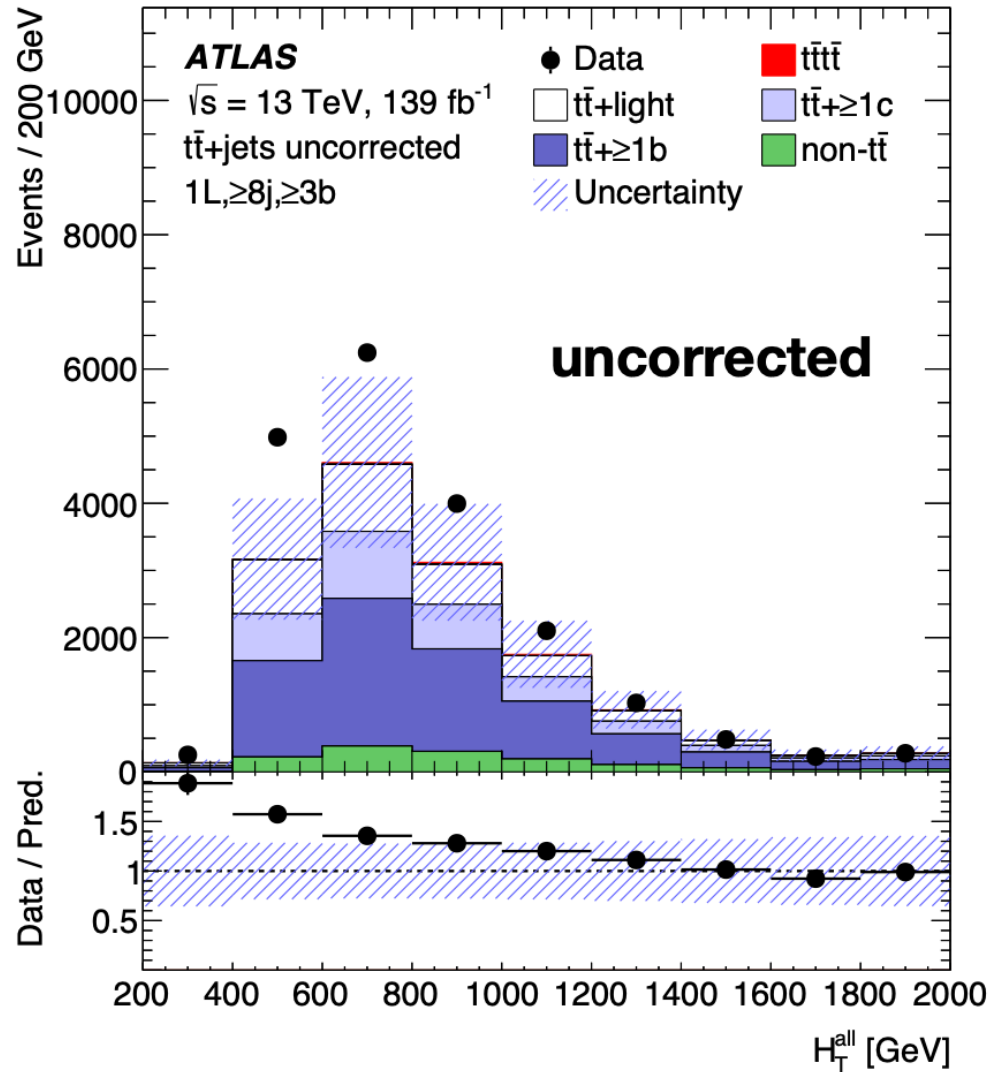
The image is a 3D visualization of the ATLAS experiment detector. It shows a complex arrangement of blue, grey, and yellow components. A red line, representing a particle track, enters from the left and passes through the detector. A dotted white line follows a similar path. On the right, a large cyan sphere is surrounded by a fan of yellow lines, representing particle production or decay. The background is black with various colored lines and shapes, suggesting a particle physics simulation or data visualization.

Systematics

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



$t\bar{t}$ +jets modeling



BDT training

Name	Description
$\sum b\text{-tag}$	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 $m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}})$ (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