Inclusive and Differential $t\bar{t}b\bar{b}$ Measurements with ATLAS and CMS Detectors

Javier Brochero on behalf of
the ATLAS and CMS Collaborations

CIEMAT

CMS

ATLAS EXPERIMENT

cfp CIEMAT física de partículas

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

EXCELENCIA MARÍA DE MAEZTU

12TH INTERNATIONAL WORKSHOP ON TOP QUARK PHYSICS

22 - 27 September 2019 Beijing

Outline and motivation

TOP 2019

Outline

1. Introduction
2. Experimental approach
3. Inclusive $\mathrm{t\bar{t}b\bar{b}}$ cross section
   - All jets
   - Lepton+jets
   - Dilepton
4. Differential $\mathrm{t\bar{t}b\bar{b}}$ cross section
5. Summary

Motivation

- Large uncertainties in the $\mathrm{t\bar{t}b\bar{b}}$ NLO calculations due to the μ_R/μ_F scale variations
- $\mathrm{t\bar{t}}$ and $\mathrm{b\bar{b}}$ processes have very different scales
- Precise measurements (inc./diff.) will improve the $\mathrm{t\bar{t}}$+jets MC simulation
- Important background for $\mathrm{t\bar{t}H}$ and for many searches of NP

2016 datasets:

- Measurement of the $\mathrm{t\bar{t}b\bar{b}}$ production cross section in the all-jet final state in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ [arXiv:1909.05306]
- Measurement of the cross section for $\mathrm{t\bar{t}}$ production with additional jets and b jets in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ [CMS PAS-TOP-18-002]

2015 and 2016 datasets:

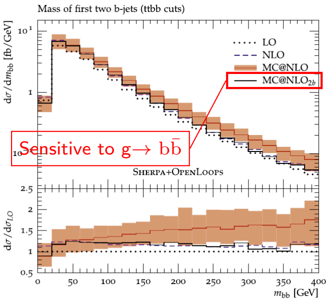
- Measurements of inclusive and differential fiducial cross-sections of $\mathrm{t\bar{t}}$ production with additional heavy-flavour jets in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ with the ATLAS detector [JHEP 1904 (2019) 046]

$t\bar{t}b\bar{b}$ prediction

TOP 2019

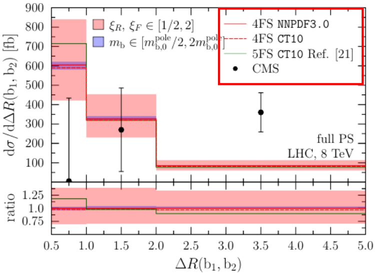
Sherpa+OpenLoops PLB 734 (2014) 210

- NLO $t\bar{t}b\bar{b}$ (scale uncer. $\approx$ 25%)
- 4-flavour scheme (4FS), massive b quarks



PowHel + Pythia arXiv: 1709.06915

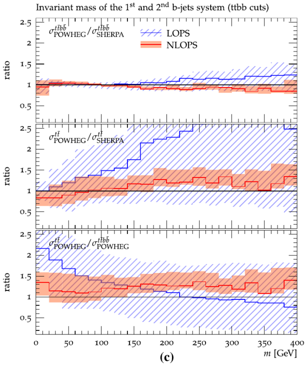
- NLO+PS, massive b quark, 4FS
- Good level of agreement but some differences where 4FS shows harder shape



$t\bar{t}b\bar{b}$ prediction

NLOPS predictions based on the Powheg-Box Eur. Phys. J. C (2018) 78:502

- NLO+PS precision for $t\bar{t}b\bar{b}$ observables
- Pretty good agreement with Sherpa
- Scale uncertainties at fixed-order NLO amount to 25-30% and are dominated by renormalisation-scale variations.



	LO	NLO	$\frac{\text{NLO}}{\text{LO}}$	LOPS	$\frac{\text{LOPS}}{\text{LO}}$	NLOPS	$\frac{\text{NLOPS}}{\text{NLO}}$	LHE	$\frac{\text{LHE}}{\text{NLO}}$
σ_{ttb} (fb)	$6545^{+74\%}_{-39\%}$	$12813^{+34\%}_{-27\%}$	1.96	$7006^{+75\%}_{-39\%}$	1.07	$13090^{+39\%}_{-29\%}$	1.02	$13029^{+36\%}_{-28\%}$	1.02
σ_{ttbb} (fb)	$1209^{+70\%}_{-38\%}$	$2261^{+30\%}_{-26\%}$	1.87	$1562^{+73\%}_{-39\%}$	1.29	$2537^{+40\%}_{-29\%}$	1.12	$2392^{+34\%}_{-27\%}$	1.06
$\sigma_{\text{ttbb}_{100}}$ (fb)	$358^{+70\%}_{-38\%}$	$640^{+26\%}_{-25\%}$	1.79	$584^{+73\%}_{-39\%}$	1.63	$810^{+41\%}_{-29\%}$	1.27	$678^{+31\%}_{-26\%}$	1.06
$\frac{\sigma_{\text{ttb}}}{\sigma_{\text{ttbb}}}$	5.41	5.67	1.05	4.48	0.83	5.16	0.91	5.45	0.96
$\frac{\sigma_{\text{ttbb}}}{\sigma_{\text{ttbb}_{100}}}$	3.38	3.53	1.05	2.67	0.79	3.13	0.88	3.53	1.00

$\sigma_{t\bar{t}b\bar{b}}$: Experimental Approach

What we have

Three different final states:

- all-jets: Higher Br. $\geq$ 8 jets. Low purity
- lepton+jets: Medium Br. $\geq$ 6 jets. Good purity
- dilepton: Lower Br. $\geq$ 4 jets. High purity

What we do

- Medium/tight event selection to keep a high statistics. Purity will depend of the decay mode.
- Discriminant variables are the ones associated to the additional jets.
  - Use all b jets in the event (ATLAS)
  - Identify additional jets (CMS)
- Extract $\sigma_{t\bar{t}b\bar{b}}$:
  - Inclusive: template fit
  - Differential: Unfolding

What we need

- Select a subsample of data events with a high purity of $t\bar{t}b\bar{b}$ ($t\bar{t}jj$)
- Find a strong discriminant between $t\bar{t}b\bar{b}$ category Vs other $t\bar{t}jj$ and SM bkg processes.

What we show

- Inclusive $t\bar{t}b\bar{b}$ cross sections in different phase space regions
- Differential $t\bar{t}b\bar{b}$ cross sections
- Inclusive $t\bar{t}jj$ cross sections in different visible and full phase space
- Cross section ratios ($t\bar{t}b\bar{b}/t\bar{t}jj$) in different visible and full phase space

Inclusive $\sigma_{t\bar{t}b\bar{b}}$ in the all jets channel

Event selection

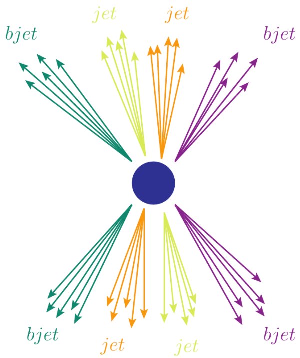
1. At least 8 jets
2. ≥ 2 b jets
   CSVv2 with a b jet ID $\mathcal{E} \approx 65\%$ misID $\approx 1\%$ for light jets
3. $H_T > 500\,\mathrm{GeV}$

QCD background I

- Light jets from $t\bar{t}$ Vs QCD: Quark jets Vs Gluon jets
- Quark-gluon likelihood ratio (QGLR)
  For each event, Compare two hypothesis:
  4 jets from quarks Vs 4 jets from gluons

QCD background II

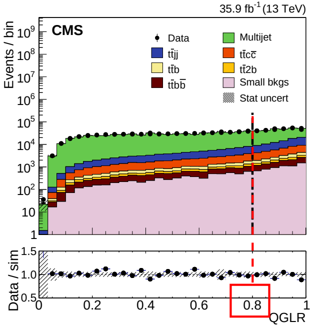
- Further QCD rejection
- Classification Without Labels (CWOLa)

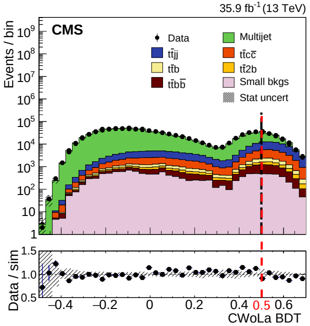


- QCD multijet background rejection
- identification of the additional jets

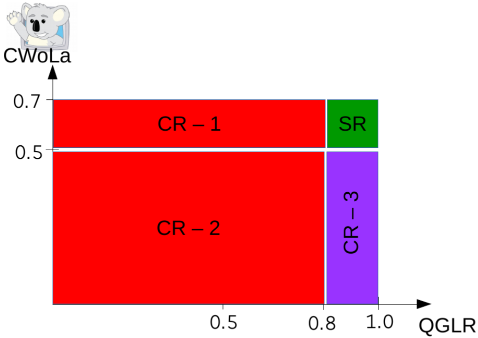
Multivariate analysis

QCD multijet background





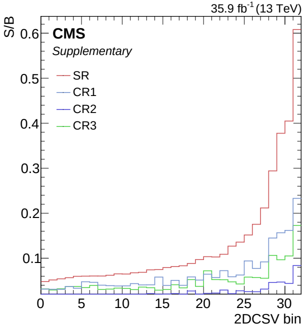
ABCD Method

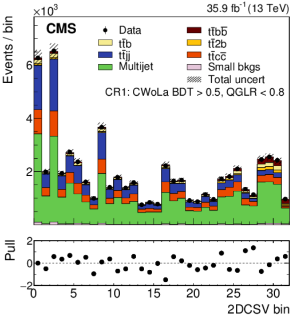


- Signal region definition: QGLR$\geq$ 0.8 and CWoLa$\geq$ 0.5
- ABCD method to estimate the QCD multijet background

BDT for jet identification

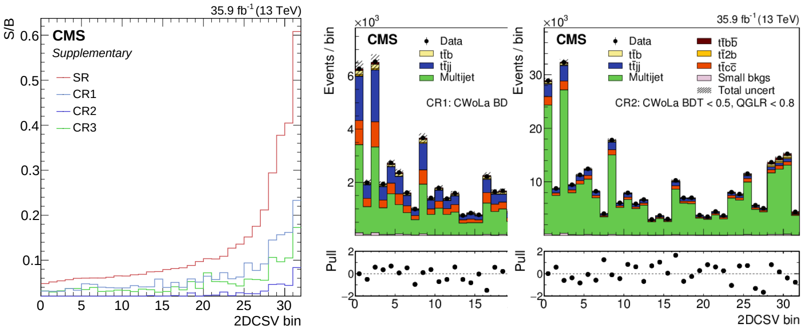
- Correct jet combination ID: Boosted decision tree (BDT)
  1. Jets from $t\bar{t}$ and additional jets
  2. With 8 jets $\rightarrow$ 28 ways to assign them to the $t\bar{t}$ process
  3. Avoid indistinguishable combinations
  4. Further reduction with a $\chi^2(m_{12}, m_{123}, m'_{45}, m'_{456})$
- Training: Correct permutation Vs Wrong distinguishable combinations
  - Efficiency $\approx$ 60%
- Select the 2 additional jets with the highest b jet discriminant





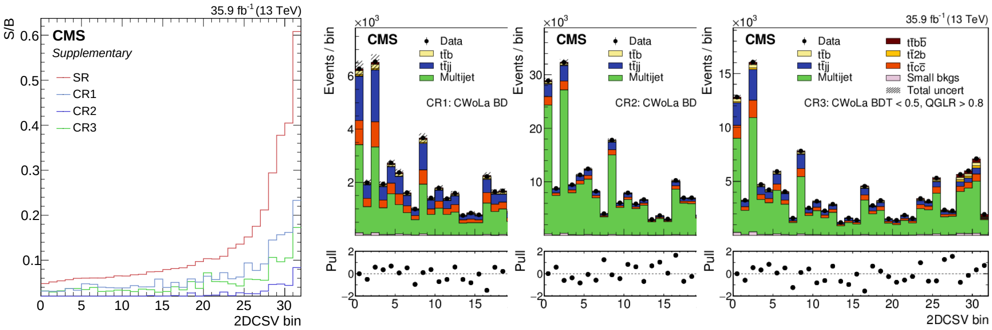
BDT for jet identification

- Correct jet combination ID: Boosted decision tree (BDT)
  1. Jets from $t\bar{t}$ and additional jets
  2. With 8 jets $\rightarrow$ 28 ways to assign them to the $t\bar{t}$ process
  3. Avoid indistinguishable combinations
  4. Further reduction with a $\chi^2(m_{12}, m_{123}, m'_{45}, m'_{456})$
- Training: Correct permutation Vs Wrong distinguishable combinations
  - Efficiency $\approx$ 60%
- Select the 2 additional jets with the highest b jet discriminant



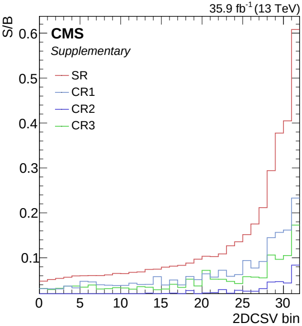
BDT for jet identification

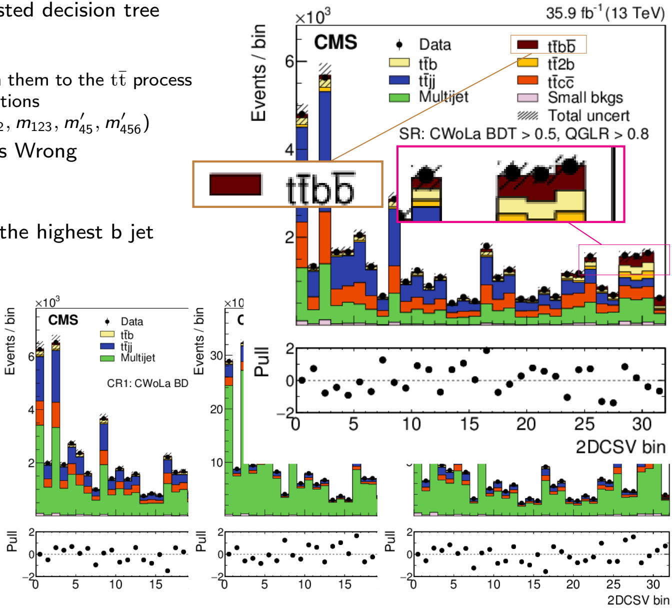
- Correct jet combination ID: Boosted decision tree (BDT)
  1. Jets from $t\bar{t}$ and additional jets
  2. With 8 jets $\rightarrow$ 28 ways to assign them to the $t\bar{t}$ process
  3. Avoid indistinguishable combinations
  4. Further reduction with a $\chi^2(m_{12}, m_{123}, m'_{45}, m'_{456})$
- Training: Correct permutation Vs Wrong distinguishable combinations
  - Efficiency $\approx$ 60%
- Select the 2 additional jets with the highest b jet discriminant



BDT for jet identification

- Correct jet combination ID: Boosted decision tree (BDT)
  1. Jets from $t\bar{t}$ and additional jets
  2. With 8 jets → 28 ways to assign them to the $t\bar{t}$ process
  3. Avoid indistinguishable combinations
  4. Further reduction with a $\chi^2(m_{12}, m_{123}, m'_{45}, m'_{456})$
- Training: Correct permutation Vs Wrong distinguishable combinations
  - Efficiency ≈ 60%
- Select the 2 additional jets with the highest b jet discriminant





Systematic Uncertainties and Results

Source	FPS PI (%)	FPS PB (%)
Simulated sample size	$^{+15}_{-11}$	$^{+15}_{-11}$
Quark-gluon likelihood	$^{+13}_{-8}$	$^{+13}_{-8}$
b tagging of b quark	± 10	± 10
JES and JER	$^{+5.1}_{-5.2}$	$^{+5.0}_{-5.4}$
Trigger efficiency	$^{+2.6}_{-2.1}$	$^{+2.5}_{-2.2}$
...		
μ_R and μ_F scales	$^{+13}_{-9}$	$^{+13}_{-9}$
Parton shower scale	$^{+11}_{-8}$	$^{+11}_{-8}$
UE tune	$^{+9.0}_{-5.3}$	$^{+9.0}_{-5.2}$
Colour reconnection	± 7.2	± 7.1
$t\bar{t}c\bar{c}$ normalization	$^{+3.2}_{-4.4}$	$^{+2.9}_{-4.5}$
...		
Total	$^{+28}_{-23}$	$^{+28}_{-23}$

- Systematic uncertainties included into the fit as nuisance parameters
- Measurement dominated by systematic uncertainties

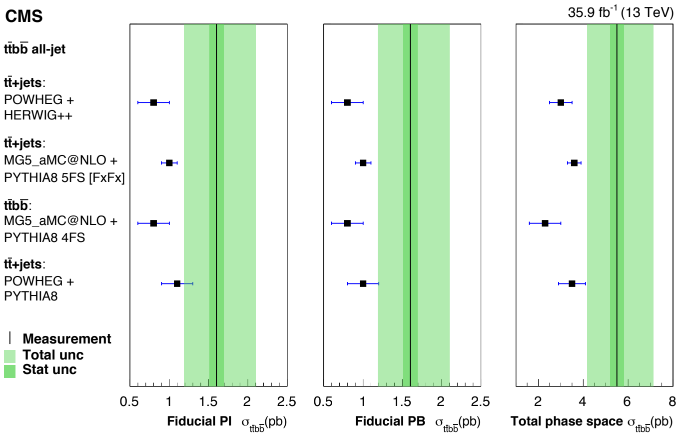
Fiducial phase space regions (FPS) at particle level:

- **PB**: ≥ 4 b jets (2 add b jets) and ≥ 8 jets
- **PI**: ≥ 4 b jets and ≥ 8 jets

Total phase space: 2 additional particle level b jets

	FPS PI (pb)	FPS PB (pb)	TPS (pb)
Measurement	$1.6 \pm 0.1^{+0.5}_{-0.4}$	$1.6 \pm 0.1^{+0.5}_{-0.4}$	$5.5 \pm 0.3^{+1.6}_{-1.3}$
POWHEG ($t\bar{t}$)	1.1 ± 0.2	1.0 ± 0.2	3.5 ± 0.6
POWHEG ($t\bar{t}$) + HERWIG ++	0.8 ± 0.2	0.8 ± 0.2	3.0 ± 0.5
MG5_aMC@NLO (4FS $t\bar{t}b\bar{b}$)	0.8 ± 0.2	0.8 ± 0.2	2.3 ± 0.7
MG5_aMC@NLO (5FS $t\bar{t}$+jets FxFx)	1.0 ± 0.1	1.0 ± 0.1	3.6 ± 0.3

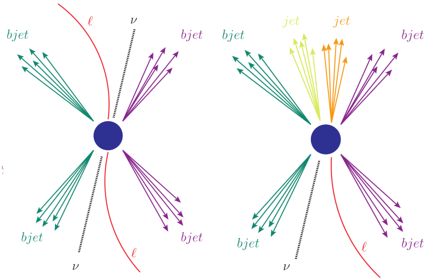
Systematic Uncertainties and Results



	FPS PI (pb)	FPS PB (pb)	TPS (pb)
Measurement	$1.6 \pm 0.1^{+0.5}_{-0.4}$	$1.6 \pm 0.1^{+0.5}_{-0.4}$	$5.5 \pm 0.3^{+1.6}_{-1.3}$
POWHEG ($t\bar{t}$)	1.1 ± 0.2	1.0 ± 0.2	3.5 ± 0.6
POWHEG ($t\bar{t}$) + HERWIG ++	0.8 ± 0.2	0.8 ± 0.2	3.0 ± 0.5
MG5_aMC@NLO (4FS $t\bar{t}b\bar{b}$)	0.8 ± 0.2	0.8 ± 0.2	2.3 ± 0.7
MG5_aMC@NLO (5FS $t\bar{t}$+jets FxFx)	1.0 ± 0.1	1.0 ± 0.1	3.6 ± 0.3

$\sigma_{t\bar{t}b\bar{b}}$ in multileptons final state

- Final state with 1 or 2 leptons
- Tight event selection to remove non $t\bar{t}$ SM processes.
- With a pure $t\bar{t}jj$ sample → identify additional jets from the $t\bar{t}$
  - Approach depends of the number of jets in the event!
- Find discriminant variable(s) to distinguish $t\bar{t}b\bar{b}$ from other $t\bar{t}$ events



Dilepton selection

Final state: $2\ell + 2$ b jets $+ \geq 2$ add. (b) jets

1. $\mu\mu$, ee and μe
2. $m_{\ell\ell} > 20\,\mathrm{GeV}$
3. Additional veto in the Z boson mass window for SF
4. At least 4 jets
5. At least 2 b jets
   CSV2 ID $\mathcal{E} \approx 70\%$ misID $\approx 1\%$

Lepton+jets selection

Final state: $\ell + 2$ b jets $+ 2$ jets $+ \geq 2$ add. (b) jets

1. muon or electron
2. At least 6 jets
3. At least 2 b jets
   CSV2 ID $\mathcal{E} \approx 50\%$ misID $\approx 0.1\%$

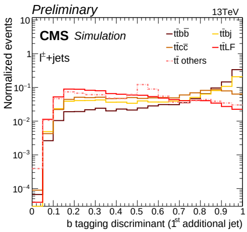
Additional jets identification

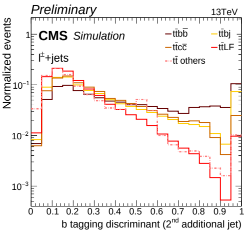
Lepton+jets channel

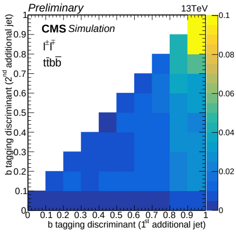
- Selection → 84% $t\bar{t}jj$ events in the SR
- 6 jets → 15 pair combinations!
- $t\bar{t}$ reconstruction
  1. Kinematic fit reconstruction for all the jet combinations
  2. Select the combination with the highest probability (2 jets from top, 2 jets from W)
  3. jets not included in the solution (≥ 2) → additional jets
  4. Arrange add. jets by b jet discriminant

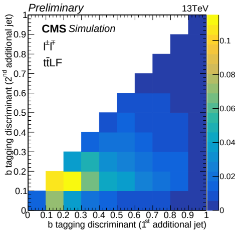
Dilepton channel

- Selection → 75% $t\bar{t}jj$ events in the SR
- 6 pair combinations!
- Arrange jets by b jet discriminant value
  1. First and second jet → from top ≈ 85%
  2. Third and fourth jets → additional ones









$\sigma_{t\bar{t}b\bar{b}}$ extraction

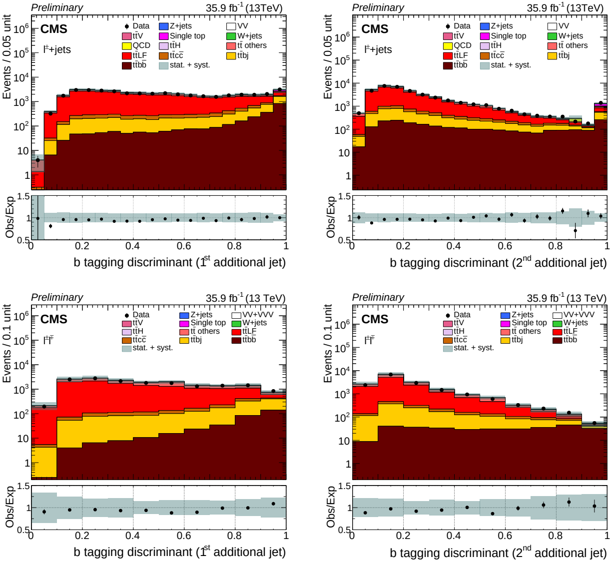
- 2 dim. template fit
- POI: $\sigma_{t\bar{t}jj}$ and $R_{t\bar{t}b\bar{b}/t\bar{t}jj}$ ratio in TWO different VPS
- $\sigma_{t\bar{t}b\bar{b}} = \sigma_{t\bar{t}jj} \times R_{t\bar{t}b\bar{b}/t\bar{t}jj}$

Visible phase space regions (VPS) at particle level:

- **Dilepton**: $\ell\ell + \geq 4$ jets (4 b jets) with $p_T^{jet} > 30$ GeV
- **Lepton+jets**: $\ell + \geq 6$ jets (4 b jets) with $p_T^{jet} > 20$ GeV

Full phase space: 2 additional particle level b jets + $t\bar{t}$

First additional jet   Second additional jet



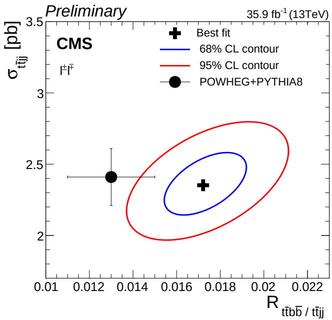
Systematic Uncertainties

Source	$R_{t\bar{t}b\bar{b}/t\bar{t}jj}$ [%]		$\sigma_{t\bar{t}jj}$ [%]	
	Dilepton	Lepton+jets	Dilepton	Lepton+jets
Lepton uncertainties				
Trigger	< 0.1	0.2	1.0	0.5
Lepton identification	0.6	0.2	1.1	1.3
Lepton energy scale	–	< 0.1	–	0.1
Jet uncertainties				
Jet energy resolution (JER)	0.4	0.3	0.3	0.7
Jet energy scale (JES)	1.5	1.2	2.9	3.6
b tagging uncertainties				
c flavor b tag lin.	2.2	2.0	1.0	0.3
c flavor b tag quad.	0.7	1.2	0.3	0.2
heavy flavor b tag	4.0	0.1	0.5	0.9
heavy flavor b tag lin.	0.9	0.4	1.5	0.5
heavy flavor b tag quad.	2.0	0.3	1.5	0.8
light flavor b tag	4.9	0.9	5.5	4.9
light flavor b tag lin.	0.1	0.2	0.3	1.1
light flavor b tag quad.	0.7	0.7	0.1	1.4
Theory uncertainties				
Initial state radiation (ISR)	1.0	2.2	2.5	1.2
Final state radiation (FSR)	0.8	0.7	2.5	5.9
ME-PS matching	0.5	< 0.1	1.8	1.9
Underlying events (UE)	1.5	1.5	0.4	1.4
Q^2 scale (ME)	0.1	0.4	0.1	1.4
top-p_T	0.2	0.4	1.6	0.3
Ratio $R^{MC}_{t\bar{t}bj/t\bar{t}b\bar{b}}$	1.4	0.2	1.3	0.7
Other uncertainties				
Pileup	0.7	0.2	1.3	0.1
Backgrounds	0.3	2.0	0.7	1.2
Simulated sample size	1.5	2.8	0.1	2.2
Luminosity	0.2	0.5	2.6	3.1
Total	8.0	5.5	8.8	10.0

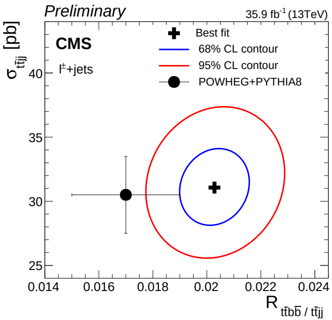
- Systematic uncertainties included into the fit as nuisance parameters
- In the cross section ratio some systematic uncertainties are cancelled:
  1. Lepton/trigger scale factors
  2. Luminosity
- Additional modelling uncertainties affecting the full phase space results
  1. PDF
  2. Color reconnection

Results: Visible phase space

Dilepton Channel

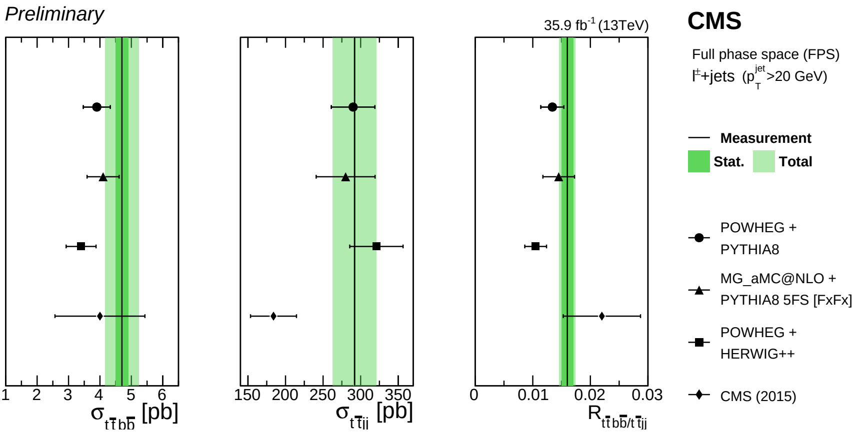


Lepton+jets Channel



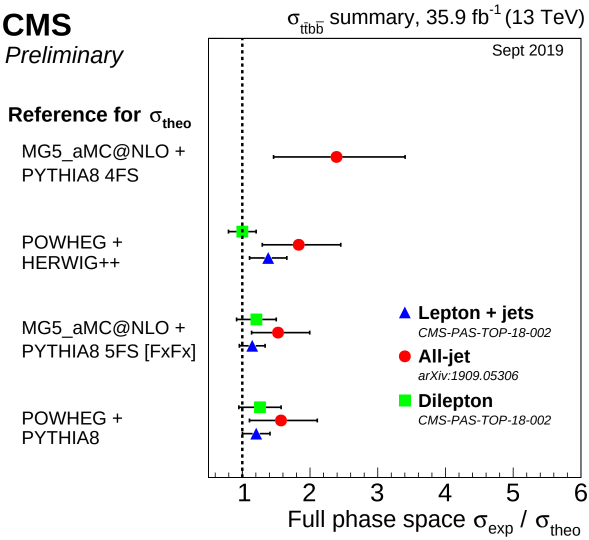
	$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}jj}$ [pb]	$\frac{\sigma_{t\bar{t}b\bar{b}}}{\sigma_{t\bar{t}jj}}$
Dilepton channel (visible phase space $p_T^{jet} > 30\,\text{GeV}$)			
POWHEG + PYTHIA 8	0.032 ± 0.004	2.41 ± 0.21	0.013 ± 0.002
Measurement	$0.040 \pm 0.002 \pm 0.005$	$2.36 \pm 0.02 \pm 0.20$	$0.017 \pm 0.001 \pm 0.001$
Lepton+jets channel (visible phase space $p_T^{jet} > 20\,\text{GeV}$)			
POWHEG + PYTHIA 8	0.52 ± 0.06	30.5 ± 3	0.017 ± 0.002
Measurement	$0.62 \pm 0.03 \pm 0.07$	$31.0 \pm 0.2 \pm 2.9$	$0.020 \pm 0.001 \pm 0.001$

Results: Full phase space



$\sigma_{t\bar{t}b\bar{b}}$ and $R_{t\bar{t}b\bar{b}/t\bar{t}jj}$ slightly higher in data

CMS Summary Plot



$\sigma_{t\bar{t}b\bar{b}}$(exp) slightly higher than $\sigma_{t\bar{t}b\bar{b}}$(theo)

Event selection

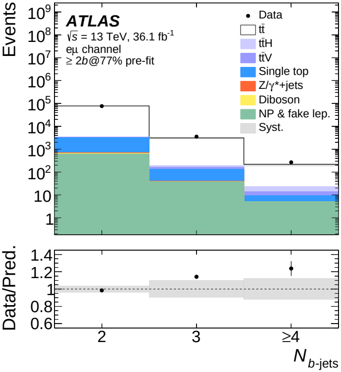
Selection dilepton

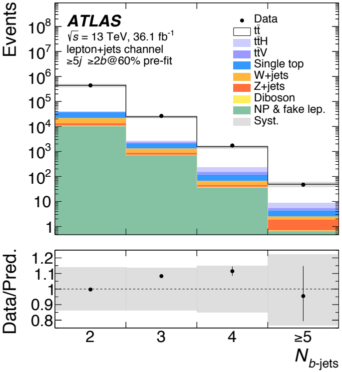
1. Well identified μe couple (OS)
2. at least 2 jets
3. $\geq 2/3/4$ b jet
   MV2c10 algorithm $\rightarrow$ b jet efficiency = 77%

Selection lepton+jets

1. Muon or electron
2. At least 5 jets
3. $\geq 2/3/4$ b-tagged
   MV2c10 algorithm $\rightarrow$ b jet efficiency = 60%

- Background estimated from data:
  1. Z/γ^*+jets: Z mass peak from SF
  2. Non-prompt and fake leptons: Matrix method





$\sigma_{t\bar{t}b\bar{b}}$ extraction

Dilepton channel

μe: Fit over the 3rd b jet discriminant

- Two POI: $\alpha_{t\bar{t}b}$ and $\alpha_{t\bar{t}cl}$
- Where:
  1. $t\bar{t}b$: $\geq$3 b jets
  2. $t\bar{t}cl$: Events don't meet the $t\bar{t}b$ criteria

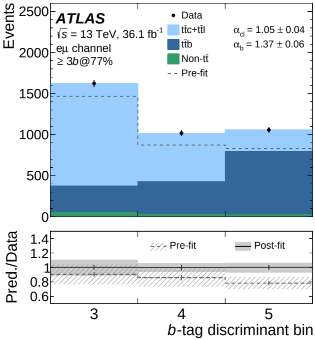
Lepton+jets channel

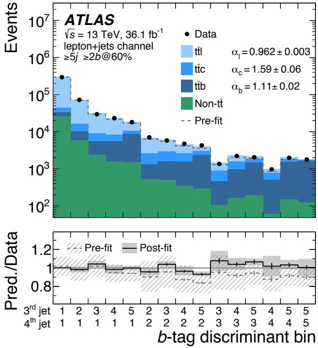
ℓ**+jets**: 2D fit over the 3rd & 4th b jet discriminant

- Three POI: $\alpha_{t\bar{t}b}$, $\alpha_{t\bar{t}c}$ and $\alpha_{t\bar{t}l}$
- Where:
  1. $t\bar{t}b$: $\geq$3 b jets
  2. $t\bar{t}c$: $<$3 b jets and $\geq$ 2 c jets
  3. $t\bar{t}l$ Events don't meet the previous criteria

- $t\bar{t}$+b: $t\bar{t}jj$ + $t\bar{t}H$ + $t\bar{t}Z$
- No jet origin identification:
  - reduce dependency in MC simulation
- differential distributions for b jets are provided

Bin	$\mathcal{E}_{b\ tagging}$[%]
1	100-85
2	85-77
3	77-70
4	70-60
5	$<$60



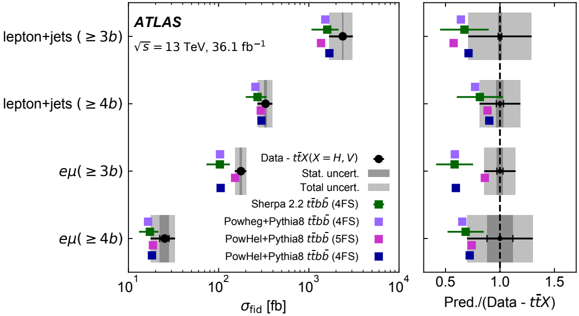


Systematic Uncertainties

Source	Fiducial cross-section phase space			
	$e\mu$		lepton + jets	
	$\geq 3b$ unc. [%]	$\geq 4b$ unc. [%]	$\geq 5j, \geq 3b$ unc. [%]	$\geq 6j, \geq 4b$ unc. [%]
Data statistics	2.7	9.0	1.7	3.0
Luminosity	2.1	2.1	2.3	2.3
Jet	2.6	4.3	3.6	7.2
b-tagging	4.5	5.2	17	8.6
Lepton	0.9	0.8	0.8	0.9
Pile-up	2.1	3.5	1.6	1.3
$t\bar{t}c$ fit variation	5.9	11	-	-
Non-$t\bar{t}$ bkg	0.8	2.0	1.7	1.8
Detector+background total syst.	8.5	14	18	12
Parton shower	9.0	6.5	12	6.3
Generator	0.2	18	16	8.7
ISR/FSR	4.0	3.9	6.2	2.9
PDF	0.6	0.4	0.3	0.1
$t\bar{t}V/t\bar{t}H$	0.7	1.4	2.2	0.3
MC sample statistics	1.8	5.3	1.2	4.3
$t\bar{t}$ modelling total syst.	10	20	21	12
Total syst.	13	24	28	17
Total	13	26	28	17

Total uncertainty dominated by other $t\bar{t}$ processes, top modelling and b tagging uncertainties

Inclusive Results



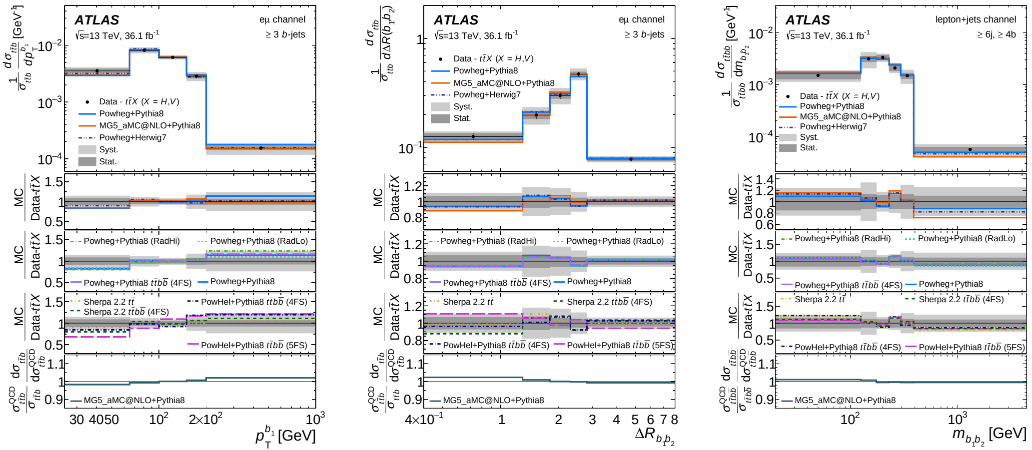
Fiducial phase-space

- Use particle level objects
- Similar definition to the RECO requirements
  1. one μe pair + $\geq 3/4$ b jets
  2. one e or μ + $\geq 5/6$ jets + $\geq 3/4$ b jets

	$e\mu$ [fb]		lepton + jets [fb]	
	$\geq 3b$	$\geq 4b$	$\geq 5j, \geq 3b$	$\geq 6j, \geq 4b$
Measured	181 $\pm$ 5 (stat) $\pm$ 24 (syst)	27 $\pm$ 3 (stat) $\pm$ 7 (syst)	2450 $\pm$ 40 (stat) $\pm$ 690 (syst)	359 $\pm$ 11 (stat) $\pm$ 61 (syst)
$t\bar{t}X(X = H, V)$ MC	4	2	80	28
Measured $- t\bar{t}X$	177	25	2370	331
Sherpa 2.2 $t\bar{t}b\bar{b}$ (4FS)	103 ± 30	17.3 ± 4.2	1600 ± 530	270 ± 70
Powheg+Pythia 8 $t\bar{t}b\bar{b}$ (4FS)	104	16.5	1520	260
PowHel+Pythia 8 $t\bar{t}b\bar{b}$ (5FS)	152	18.7	1360	290
PowHel+Pythia 8 $t\bar{t}b\bar{b}$ (4FS)	105	18.2	1690	300

Differential $\sigma_{t\bar{t}b\bar{b}}$

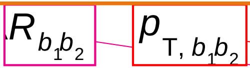
- μe: At least 3 b jets. Lepton+jets: At least 4 b jets.
- Differential cross section provided as a function of:
  - b jet multiplicity
  - H_T
  - H_T^{had}
  - Jet p_T
  - b jet p_T
  - m_{bb}
  - $p_T{}^{bb}$
  - ΔR_{bb}

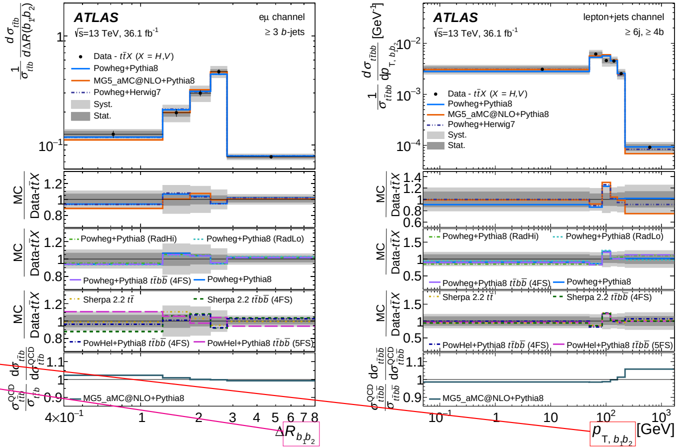


Differential $\sigma_{t\bar{t}b\bar{b}}$

- μe: At least 3 b jets. Lepton+jets: At least 4 b jets.
- Differential cross section provided as a function of:
  - b jet multiplicity
  - H_T
  - H_T^{had}
  - Jet p_T
  - b jet p_T
  - m_{bb}
  - $p_T{}^{bb}$
  - ΔR_{bb}

- The pair made from the two b-jets closest in angular distance is expected to be formed by b-jets from gluon splitting
- The pair made from the two highest-p_T b-jets is expected to be dominated by top-pair production.





Summary

- The ATLAS and CMS Collaborations have a strong program in the measurement of the $\mathrm{t\bar{t}}$ production plus additional heavy flavour jets.
- The uncertainties in the $\mathrm{t\bar{t}b\bar{b}}$ cross section measurements are mainly dominated by the top modelling and jets uncertainties, especially, b tagging uncertainties.
- All the current analysis show a slightly higher $\sigma_{\mathrm{t\bar{t}b\bar{b}}}$ measurement with respect to the predictions.
- Differential cross section measurements will benefit of the full Run2 dataset.
- For the incoming analysis, a discussion about the definition of the phase space regions will be crucial in order to simplify comparisons.

BACKUP

All-jets systematic uncertainties

Source	FPS PI (%)	FPS PB (%)
Simulated sample size	$^{+15}_{-11}$	$^{+15}_{-11}$
Quark-gluon likelihood	$^{+13}_{-8}$	$^{+13}_{-8}$
b tagging of b quark	± 10	± 10
JES and JER	$^{+5.1}_{-5.2}$	$^{+5.0}_{-5.4}$
Integrated luminosity	$^{+2.8}_{-2.2}$	$^{+2.4}_{-2.2}$
Trigger efficiency	$^{+2.6}_{-2.1}$	$^{+2.5}_{-2.2}$
Pileup	$^{+2.3}_{-2.0}$	$^{+2.2}_{-1.9}$
μ_{R} and μ_{F} scales	$^{+13}_{-9}$	$^{+13}_{-9}$
Parton shower scale	$^{+11}_{-8}$	$^{+11}_{-8}$
UE tune	$^{+9.0}_{-5.3}$	$^{+9.0}_{-5.2}$
Colour reconnection	± 7.2	± 7.1
Shower matching (h_{damp})	$^{+4.3}_{-2.8}$	$^{+3.8}_{-2.7}$
$\mathrm{t\bar{t}c\bar{c}}$ normalization	$^{+3.2}_{-4.4}$	$^{+2.9}_{-4.5}$
Modelling of $\mathrm{p_T}$ of top quark	± 2.5	± 2.4
PDFs	$^{+2.2}_{-2.0}$	$^{+2.2}_{-2.0}$
Total	$^{+28}_{-23}$	$^{+28}_{-23}$

b tagging

CMS

- Discriminant shape correction
- Contamination from:
  1. HF (varying 20% the LF contamination)
  2. LF (varying 20% the HF contamination)
  3. cF: SF $= 1.$ (Conservative uncertainty)
  4. Statistical uncertainty

ATLAS

- Discriminant WP corrections
- SF extracted from $\ell\ell$ (b-tag) and ℓ+jets (c-jet mistag)
- c-jet mis-tag SF $\approx$ 6-22%
- Light-jet mis-tag SF $\approx$ 15-75%

Dilepton Yields

Process	$2b$	$\geq 3b$	$\geq 4b$
Signal ($t\bar{t} + t\bar{t}H + t\bar{t}V$)	74 400 ± 2 900	3 200 ± 310	210 ± 29
$t\bar{t}$	74 200 ± 2 900	3 100 ± 310	190 ± 29
$t\bar{t}H$	45.3 ± 6.6	36.5 ± 7.0	9.4 ± 3.3
$t\bar{t}V$	190 ± 16	33.5 ± 6.7	4.4 ± 2.2
Background	3 150 ± 810	140 ± 53	9.2 ± 5.6
Single top	2 460 ± 540	96 ± 32	4.1 ± 2.5
NP and fake lep.	600 ± 600	43 ± 43	5.1 ± 5.1
Z/γ^*+jets	53 ± 13	1.3 ± 0.3	0.07 ± 0.02
Diboson	38 ± 20	1.0 ± 1.1	< 0.01
Expected	77 600 ± 3 000	3 320 ± 320	216 ± 30
Observed	76 425	3 809	267

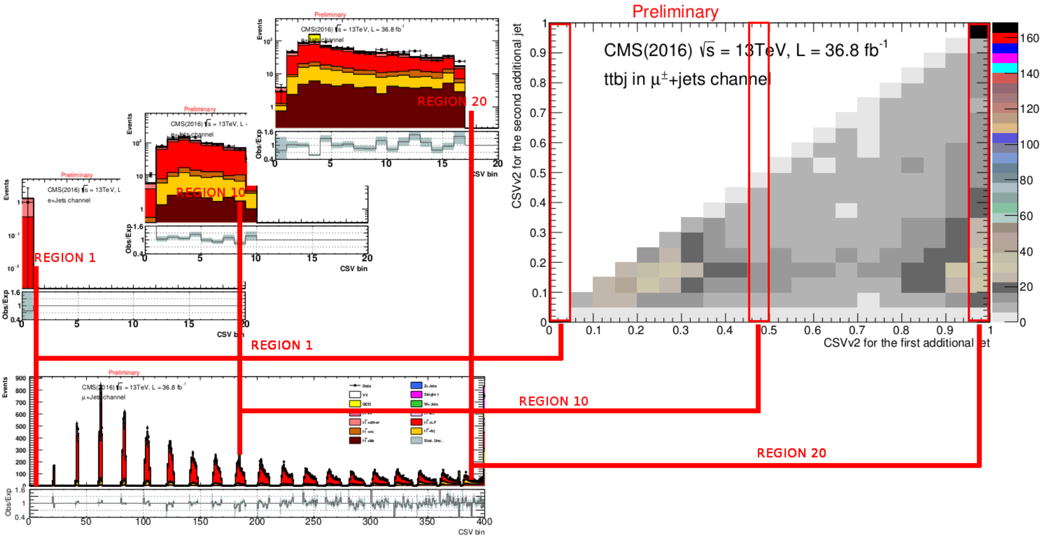
Table 2. Predicted and observed $e\mu$ channel event yields in $2b$, $\geq 3b$ and $\geq 4b$ selections. The quoted errors are symmetrised and indicate total statistical and systematic uncertainties in predictions due to experimental sources.

Dilepton Yields

Process	$\geq 5j, \geq 2b$	$\geq 5j, \geq 3b$	$\geq 5j, = 3b$	$\geq 6j, \geq 4b$
Signal				
$(t\bar{t} + t\bar{t}H + t\bar{t}V)$	429 000 ± 42 000	23 700 ± 2 200	22 300 ± 2 100	1 130 ± 110
$t\bar{t}$	426 000 ± 42 000	23 000 ± 2 200	21 700 ± 2 100	1 030 ± 110
$t\bar{t}H$	1 250 ± 58	437 ± 23	351 ± 18	68.3 ± 5.8
$t\bar{t}V$	2 020 ± 110	250 ± 16	215 ± 14	28.3 ± 2.8
Background	39 500 ± 7 900	2 230 ± 470	2 110 ± 450	87 ± 23
Single top	16 400 ± 2 000	856 ± 99	803 ± 94	35.7 ± 6.5
NP and fake lep.	11 000 ± 5 500	740 ± 380	710 ± 360	32 ± 21
W+jets	8 600 ± 5 300	440 ± 270	410 ± 260	11.0 ± 6.9
Z/γ^*+jets	2 960 ± 480	164 ± 26	155 ± 26	5.9 ± 1.5
Diboson	529 ± 80	34.0 ± 5.6	32.0 ± 5.5	1.79 ± 0.58
Expected	469 000 ± 42 000	26 000 ± 2 300	24 400 ± 2 200	1 220 ± 110
Observed	469 793	28 167	26 389	1 316

Table 3. Predicted and observed lepton+jets event yields in the $\geq 5j \geq 2b$, $\geq 5j \geq 3b$, $\geq 5j = 3b$, and $\geq 6j \geq 4b$ selections. The quoted uncertainties are symmetrised and indicate total statistical and systematic uncertainties in predictions due to experimental sources.

Histogram construction



Histogram construction

Table 1: The definition of objects in the visible and full phase space are listed. Details of the particle-level definitions are described in the text. The symbol ℓ denotes a lepton (e or μ).

Channel	Jet p_{T}	Phase space	$\mathrm{t\bar{t}b\bar{b}}$	$\mathrm{t\bar{t}jj}$
Dilepton	$p_{\mathrm{T}} > 30\,\mathrm{GeV}$	VPS	$\ell\ell$ + 4 jets (4 b jets)	$\ell\ell$ + 4 jets (2 b jets)
		FPS	$\mathrm{t\bar{t}}$ and 2 b jets (not from $\mathrm{t\bar{t}}$)	$\mathrm{t\bar{t}}$ and 2 jets (not from $\mathrm{t\bar{t}}$)
Lepton+jets	$p_{\mathrm{T}} > 20\,\mathrm{GeV}$	VPS	ℓ + 6 jets (4 b jets)	ℓ + 6 jets (2 b jets)
		FPS	$\mathrm{t\bar{t}}$ and 2 b jets (not from $\mathrm{t\bar{t}}$)	$\mathrm{t\bar{t}}$ and 2 jets (not from $\mathrm{t\bar{t}}$)