$t\bar{t}$ + X at ATLAS

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On behalf of the ATLAS Collaboration

TOP2018

Bad Neuenahr, Germany

18th September 2018

Introduction

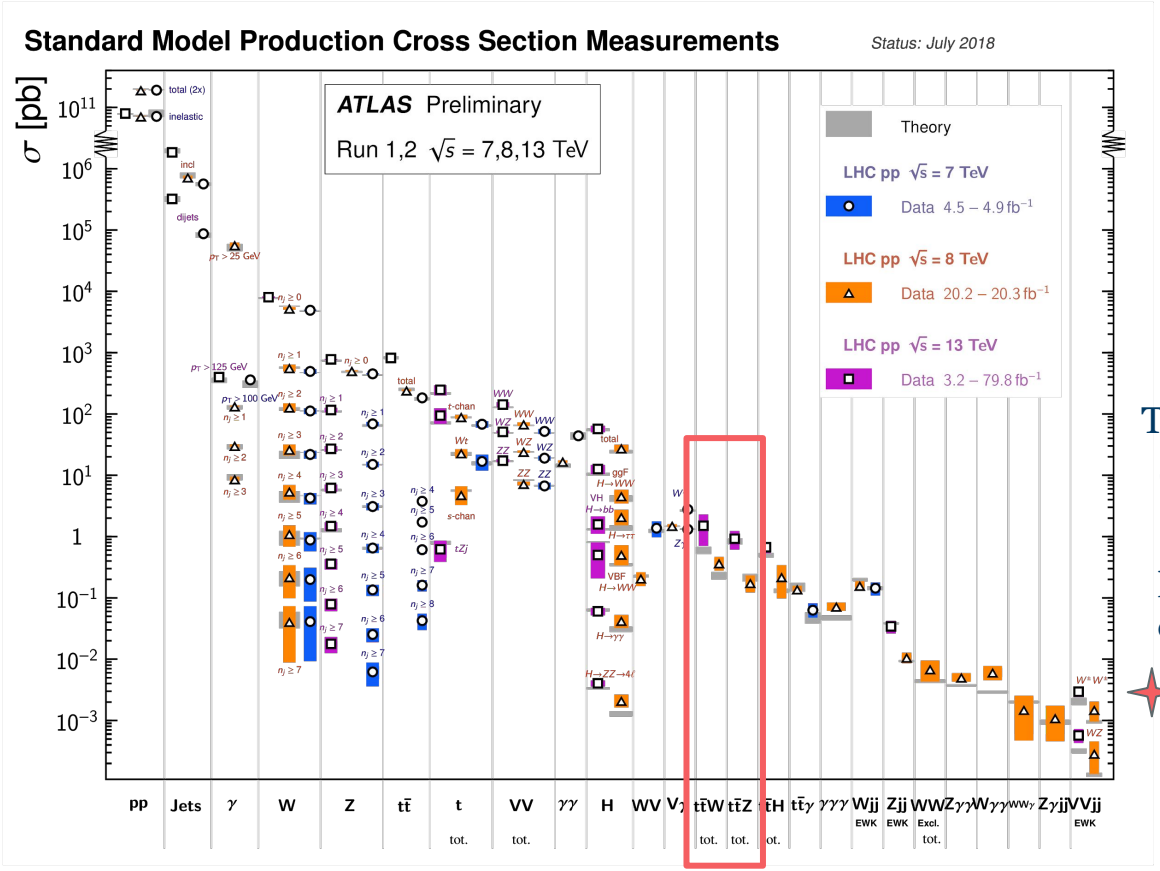
- $t\bar{t}V$ (via $t\bar{t}Z$) provides a direct probe of the weak couplings of the top quark
- An important background for Beyond the Standard Model physics searches with various final states.
  - Stop searches and electroweak SUSY productions.
  - Deviations from SM can be probed with EFT.
- Also an important background for $t\bar{t}H$ multilepton searches and four-top production.

This talk is on $t\bar{t}$ + X,
where X refers to Z, W or $t\bar{t}$.

Will refer to $t\bar{t}V$,
where V means Z or W.

- Measurement of SM four-top cross-section becoming possible with current LHC statistics.
- Possible enhancement of SM cross-sections from new physics through the production of heavy objects in association with a top-quark pair.

Introduction

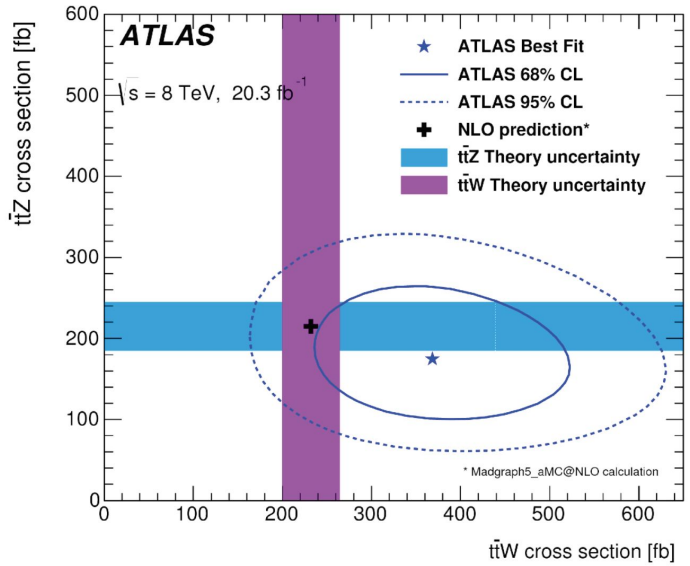


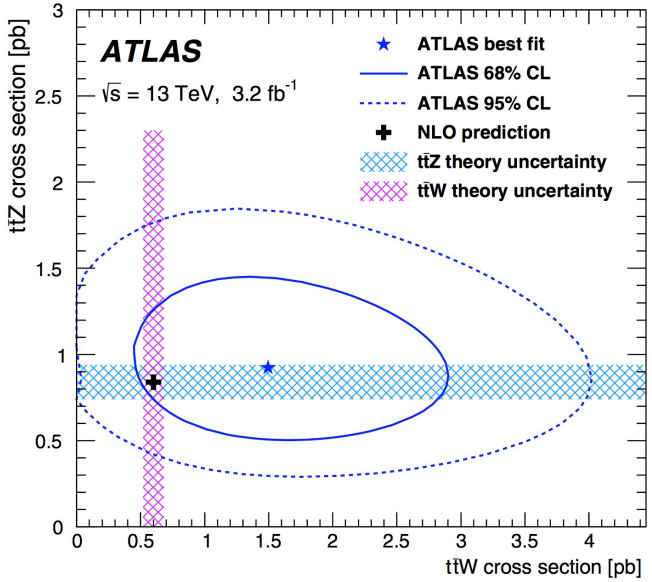
Standard Model total and fiducial production cross section measurements.

Theoretical SM cross-section for four-top production is 9.2 fb (NLO).

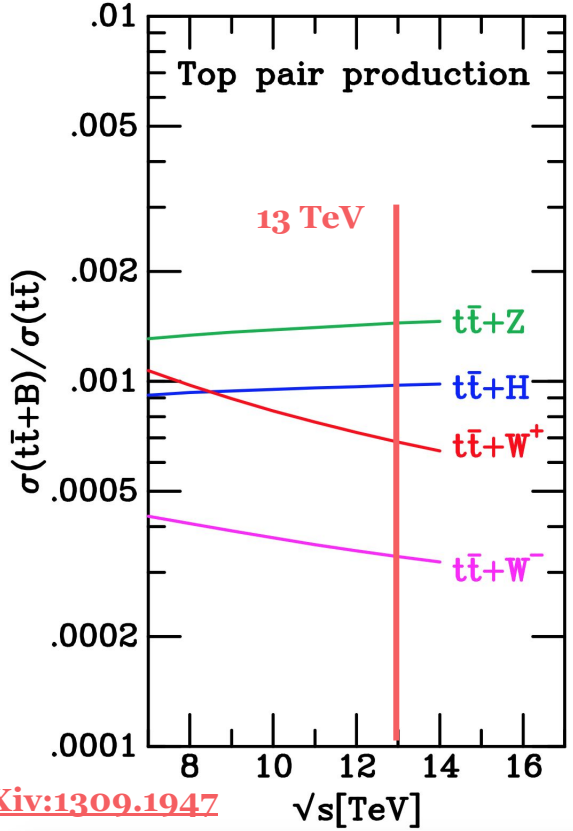
$t\bar{t}V$

- Previous measurements:
  - with the full 8 TeV dataset JHEP 11 (2015) 172
    - significance of 5.0σ (4.2σ) over the background-only hypothesis for $t\bar{t}W$ ($t\bar{t}Z$) production
  - with the 3.2 fb^{-1} 2015 13 TeV dataset Eur. Phys. J. C77 (2017) 40





$t\bar{t}V$



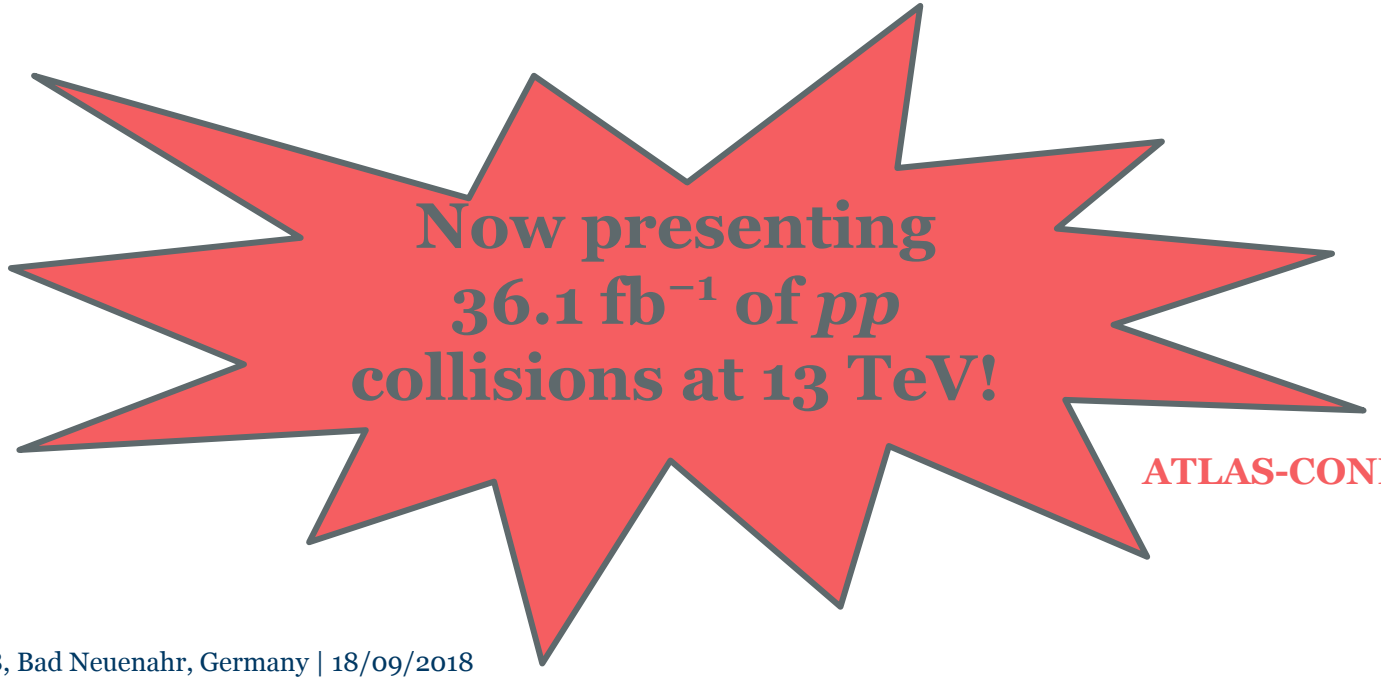
arXiv:1309.1947

- Limiting factors for 8 TeV measurement:
  - Statistically limited analysis.
  - For $t\bar{t}W$ fit, dominant syst. uncert. was modelling of fake leptons and background processes with misidentified charge.
  - For $t\bar{t}Z$ fit, dominant syst. uncert. source was the modelling of backgrounds from simulation.

- Going from 8 TeV to 13 TeV was more advantageous for $t\bar{t}Z$ than for $t\bar{t}W$, due to rapidly increasing backgrounds for $t\bar{t}W$.

$t\bar{t}V$

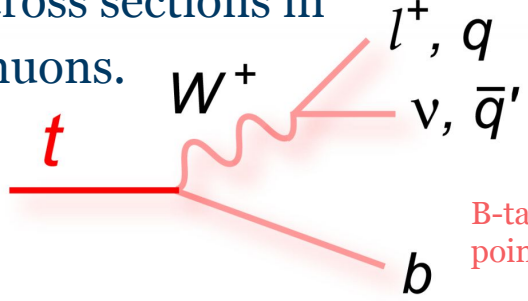
- Previous measurements:
  - with the full 8 TeV dataset JHEP 11 (2015) 172
  - with the 3.2 fb^{-1} 2015 13 TeV dataset Eur. Phys. J. C77 (2017) 40



ATLAS-CONF-2018-047

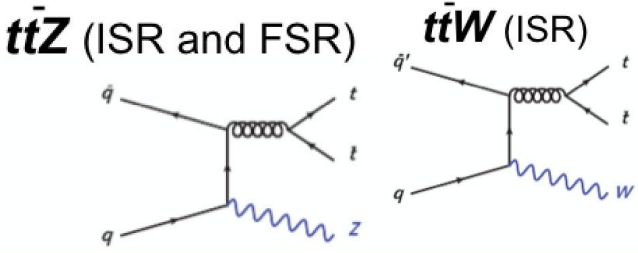
$t\bar{t}V$ Signal

- A measurement of the $t\bar{t}Z$ and $t\bar{t}W$ production cross sections in final states with 2, 3 or 4 isolated electrons or muons.
- Using 36.1 fb^{-1} from 2015+16 (13 TeV).

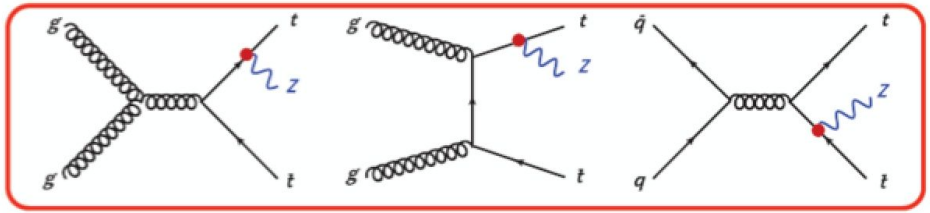


B-tagging working point is 77%

Process	$t\bar{t}$ decay	Boson decay	Channel
$t\bar{t}W$	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{\pm}\nu$	2ℓSS
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{\pm}\nu$	$t\bar{t}W$-trilepton
$t\bar{t}Z$	$(q\bar{q}b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	2ℓOSSF
	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	$t\bar{t}Z$-trilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{+}\ell^{-}$	Tetralepton



- Each channel is further divided into multiple regions to maximize the sensitivity of the measurement.



$t\bar{t}V$ Backgrounds

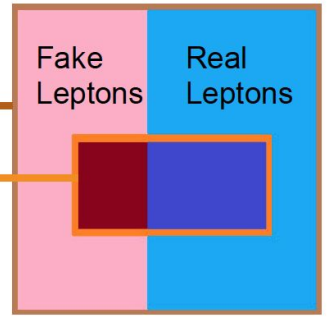
- Background events containing prompt leptons from MC.
- Normalisation corrections obtained from the control regions included in the fit
  - WZ in 3L channel,
  - ZZ in 4L channel,
  - Z+1HF, Z+2HF in 2LOS channel
- Data-driven approach for $t\bar{t}$ background in 2LOS.
  - VRs: 2l-**SF**-OS → 2L-**DF**-OS
- Contributions from charge-flip events (significant for 2Lee and 2Leμ) estimated from data.
  - 2Lμμ is negligible - probability of misidentifying the charge of a muon in p_T range is v. small.
- Backgrounds with ≥ 1 fake leptons modelled using data in dedicated CRs.

Fake lepton background

- In the ttW analysis and the 3L ttZ channel, the fake lepton background is estimated by using the matrix method.

- For the 4L region, the semi data-driven fake factor method is used:
  - Correction factors describing the potential data/MC discrepancy are extracted in a dedicated CR
    - enriched with processes that contain >1 fake electron or muon.

loose lepton selection alongside the **tight**



Define **fake** and **real** efficiency as

$f = \frac{\text{fake}}{\text{fake}}$ $r = \frac{\text{real}}{\text{real}}$

$$N^{\text{loose}} = N^{\text{loose}}_{\text{real}} + N^{\text{loose}}_{\text{fake}}$$
$$N^{\text{tight}} = r \cdot N^{\text{loose}}_{\text{real}} + f \cdot N^{\text{loose}}_{\text{fake}}$$

$t\bar{t}V$ - $t\bar{t}Z$ 2L: OSSF

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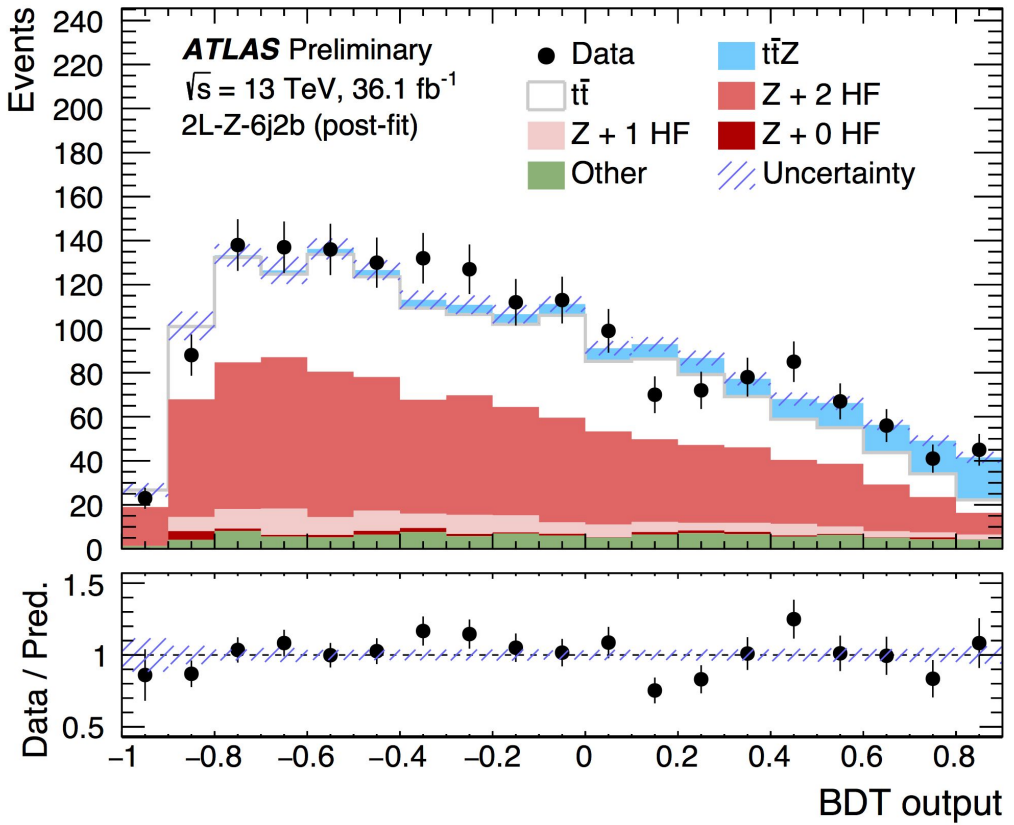
Selection:

- Exactly two leptons with opposite sign and same flavour.
- $|M_{ll} - M_Z| < 10$ GeV
- N_j: ≥6, =5, ≥6
- N_b: =1, ≥2, ≥2 (respectively)

Backgrounds:

- Characterised by large backgrounds from Z+jets and $t\bar{t}$.
- Z+jets is constrained using low BDT score events.
  - Normalisation factors of Z+1HF and Z+2HF are determined in the fit to data.
- Data driven method used for tt background.

Boosted Decision Trees (BDTs) are used to separate signal from background in each region separately.



$t\bar{t}V$ - $t\bar{t}Z$ 3L

Four signal regions, with N_j and N_b depending on signal region.

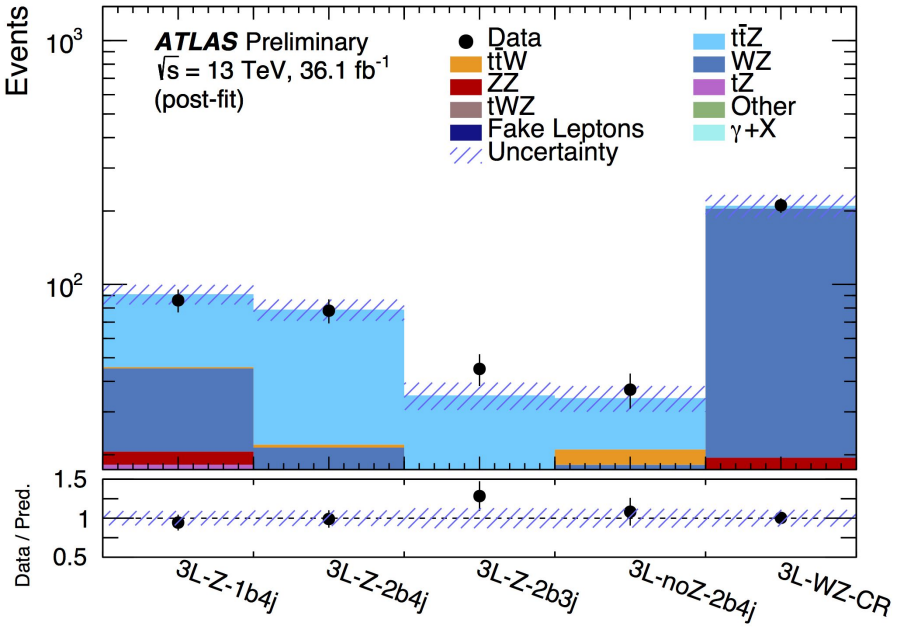
- 3L-noZ-2b4j: targets $t\bar{t}Z$ with an offshell Z* or γ* and is orthogonal to the three leptons regions used for the $t\bar{t}W$ analysis.

Selection: 3 leptons with sum of charges ± 1

- N_j: ≥4, 3, ≥4, ≥4
  N_b: 1, ≥2, ≥2, ≥2 (respectively)
- $|M_{ll} - M_Z| < 10$ GeV, except noZ

Dominant backgrounds:

- diboson production, tZ and tWZ, and Z+jets production with fake lepton.



Good pre-fit agreement between observed values and expected

CR used for WZ background, free parameter in the fit.

$t\bar{t}V$ - $t\bar{t}Z$ 4L

More from Sebastian in the YSF!

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Signature:

- Defined according to the relative flavour of the two leptons of *Z*2:
  - different (DF) or same flavour (SF)
  - # of *b*-tagged jets: one or, at least two (1*b*, 2*b*).
- Four signal regions: 4l-DF-1b, 4l-DF-2b, 4l-SF-1b & 4l-SF-2b.

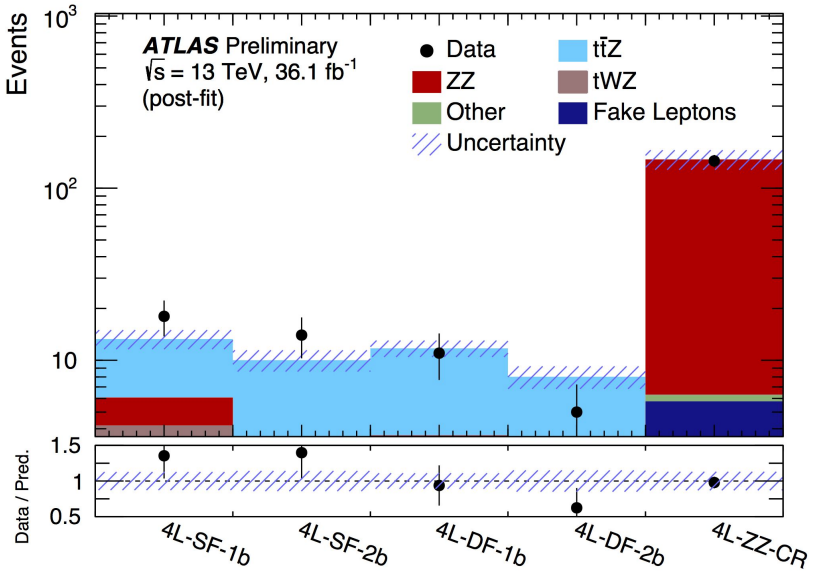
In SF regions:

E_T^{miss} requirements suppress ZZ background.

In 1-b-tag regions:

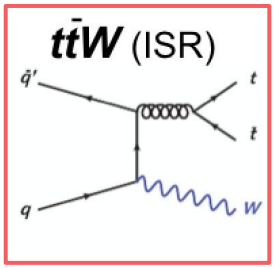
Requirements on p_{T34}, suppress fake leptons.

CR used to determine ZZ normalisation, free parameter in the fit.



Good pre-fit agreement between observed values and expected

tt̄V - tt̄W



Initial state is qq only.

A rare source of SS leptons

2LSS selection:

- 12 dilepton same sign regions depending on #b-jets, lepton flavour and charge.
- $|M_{ll} - M_Z| > 10$ GeV for 2e and 2μ.

Major backgrounds:

- Fake leptons and charge flips.

Non-negligible signal contamination in CRs

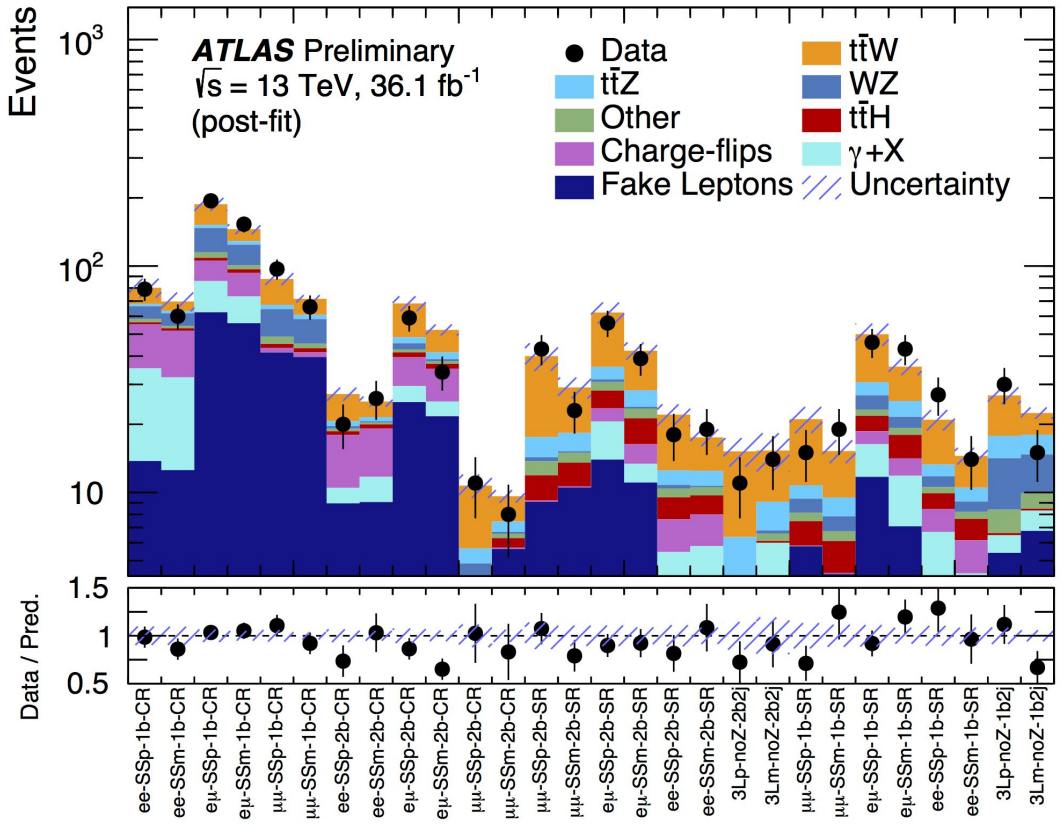
- Used in the fit
- Signal strength, μ(tt̄W), and fake lepton background are anticorrelated.

3L selection:

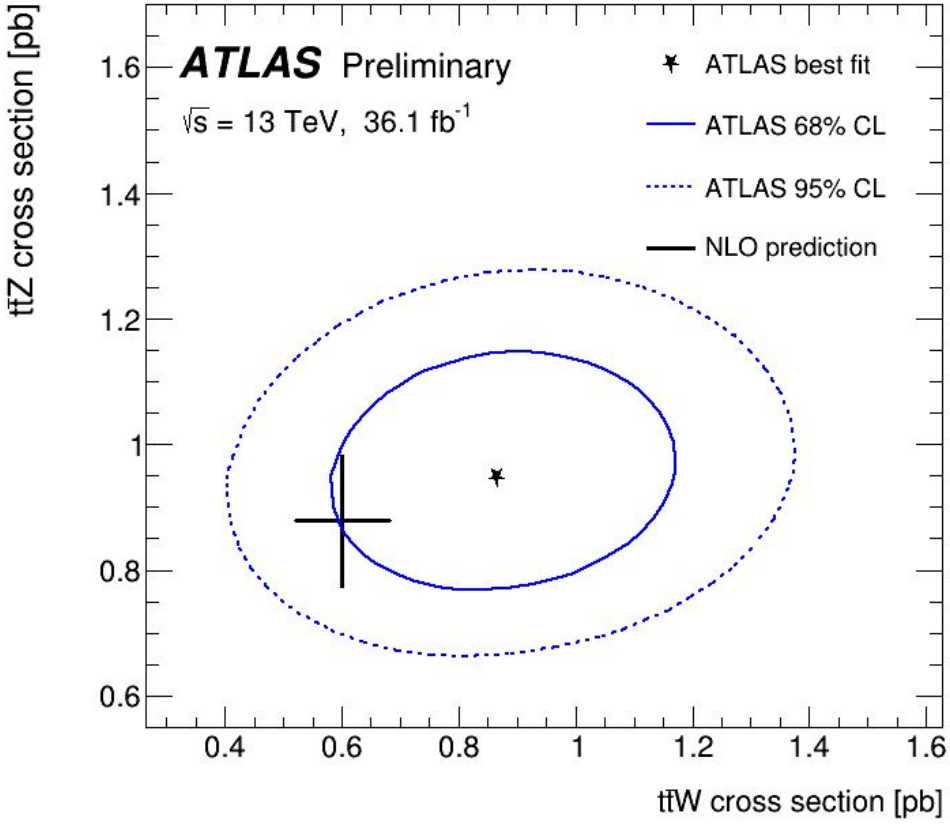
- Four trilepton regions sensitive to ttW depending on #b-jets and lepton charge

Major backgrounds:

- Fake leptons and diboson.



$t\bar{t}V$ Simultaneous fit



Fit configuration	$\mu_{t\bar{t}Z}$	$\mu_{t\bar{t}W}$
Combined	1.08 ± 0.14	1.44 ± 0.32
2ℓ-OS	0.73 ± 0.28	-
3ℓ $t\bar{t}Z$	1.08 ± 0.18	-
2ℓ-SS and 3ℓ $t\bar{t}W$	-	1.41 ± 0.33
4ℓ	1.21 ± 0.29	-

Combined fit measured:

$\sigma(t\bar{t}Z)$ = 0.95 ± 0.13 pb

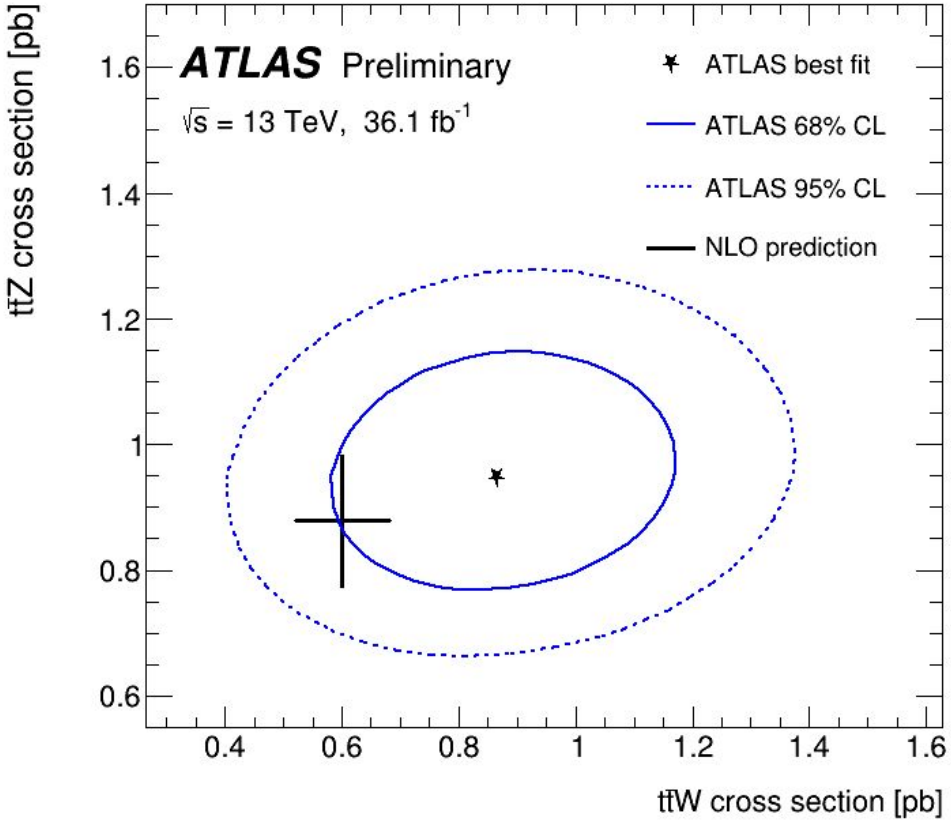
$\sigma(t\bar{t}W)$ = 0.87 ± 0.19 pb

and yields significance of:

$t\bar{t}W$: 4.3σ (3.4σ) observed (expected)

$t\bar{t}Z$ has a significance > 5σ.

$t\bar{t}V$ Simultaneous fit



Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	2.9%	4.5%
CR and simulated sample statistics	1.8%	7.6%
JES/JER	1.9%	4.1%
Flavor tagging	4.2%	3.7%
Other object-related	3.7%	2.5%
Data-driven background normalization	2.4%	3.9%
Modeling of backgrounds from simulation	5.3%	2.6%
Background cross sections	2.3%	4.9%
Fake leptons and charge misID	1.8%	5.7%
$t\bar{t}Z$ modeling	4.9%	0.7%
$t\bar{t}W$ modeling	0.3%	8.5%
Total systematic	10.2%	16.0%
Statistical	8.4%	15.2%
Total	13.0%	22.2%

Constraints on BSM

- Interpretations of the inclusive cross-section measurement in terms of Effective Field Theory (EFT).
  - Set constraints on the five operators which modify the ttZ̄ vertex: $O_{\phi Q}^{(3)}, O_{\phi Q}^{(1)}, O_{\phi t}, O_{tW}, O_{tB}$
  - First two enter the ttZ̄ vertex as a linear combination
    - measurement is sensitive to the difference: $C_{\phi Q}^{(3)} - C_{\phi Q}^{(1)}$
  - Only one operator is considered at a time.

Coefficient	Expected limits at 68% and 95 % CL	Observed limits at 68% and 95 % CL	Previous constraints at 95 % CL JHEP **05** (2016) 052
$(C_{\phi Q}^{(3)} - C_{\phi Q}^{(1)})/\Lambda^2$	[-2.1, 1.9], [-4.6, 3.7]	[-1.0, 2.7], [-3.4, 4.3]	[-3.4, 7.5]
$C_{\phi t}/\Lambda^2$	[-3.8, 2.8], [-23, 5.0]	[-2.0, 3.6], [-27, 5.7]	[-2.0, 5.7]
C_{tB}/Λ^2	[-8.3, 8.6], [-12, 13]	[-11, 10], [-15, 15]	[-16, 43]
C_{tW}/Λ^2	[-2.8, 2.8], [-4.0, 4.1]	[-2.2, 2.5], [-3.6, 3.8]	[-0.15, 1.9]

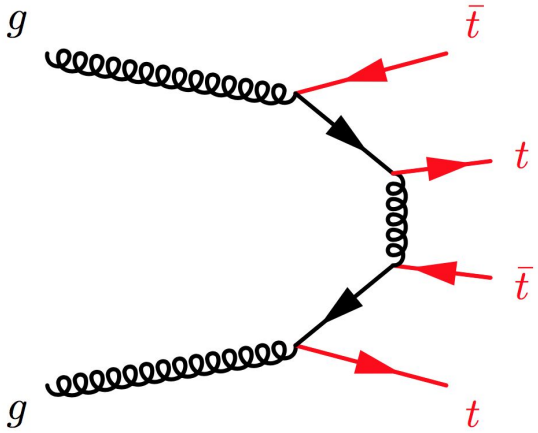
units of 1/TeV²

- Previous measurements:
  - 3.2 fb^{-1} with 13 TeV: ATLAS-CONF-2016-020
    - Observed (expected) upper limit of:
      21 (16) x four-top SM σ at 95% CL.
    - Single lepton channel only.

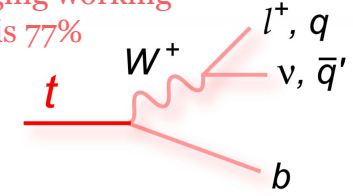
- Today, presenting measurements with 36.1 fb^{-1} (2015+2016) with 13 TeV.
  - Single lepton and dilepton opposite-sign channels: EXOT-2017-11
  - Dilepton same-sign, and three-lepton channels: arXiv:1807.11883

$t\bar{t}t\bar{t}$ Signal

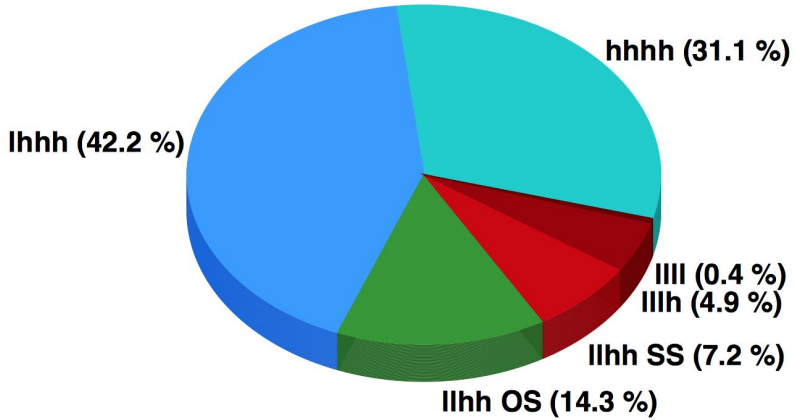
- Very busy signal with no narrow resonance.
- Many b-jets and jets in the final state.
- Channels split into:
  - **l+jets & OS dilepton**
  - **SS dilepton & ML**
- Expected total cross-section:
  9.2 fb at NLO.



B-tagging working point is 77%



Channels depend on W decays from the top.



l+jets

Signature (selection): 1-lepton (e or μ), $N_j = 10$ (≥5), $N_b = 4$ (≥2), MET

OS dilepton

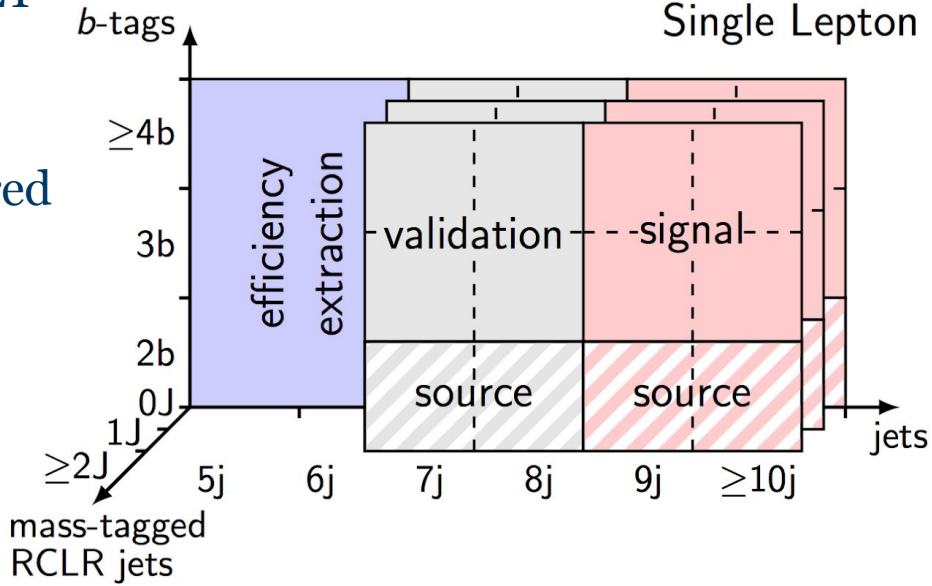
Signature (selection): 2-leptons, opposite-sign (e+e−, μ+μ−, $\mu^{\pm}e^{\mp}$), $N_j = 8$ (≥4), $N_b = 4$ (≥2), MET

Events categorized according to jet, *b*-tagged jet and mass-tagged reclustered large-*R* jet multiplicities.

Dominated by $t\bar{t}b\bar{b}$ background

Not expected to be modelled well

➢ Data-driven estimation



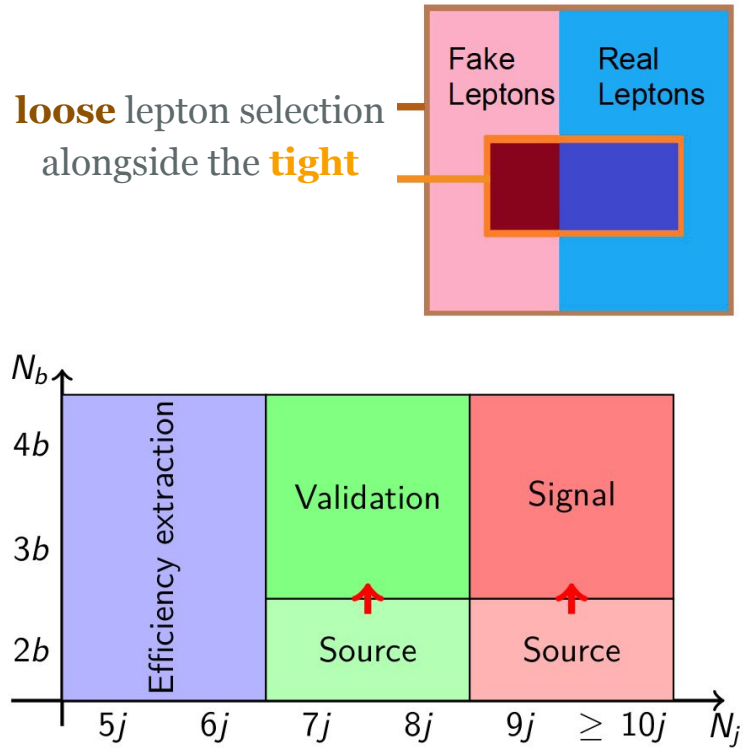
$t\bar{t}t\bar{t}$ l+jets/OS2L

1L:

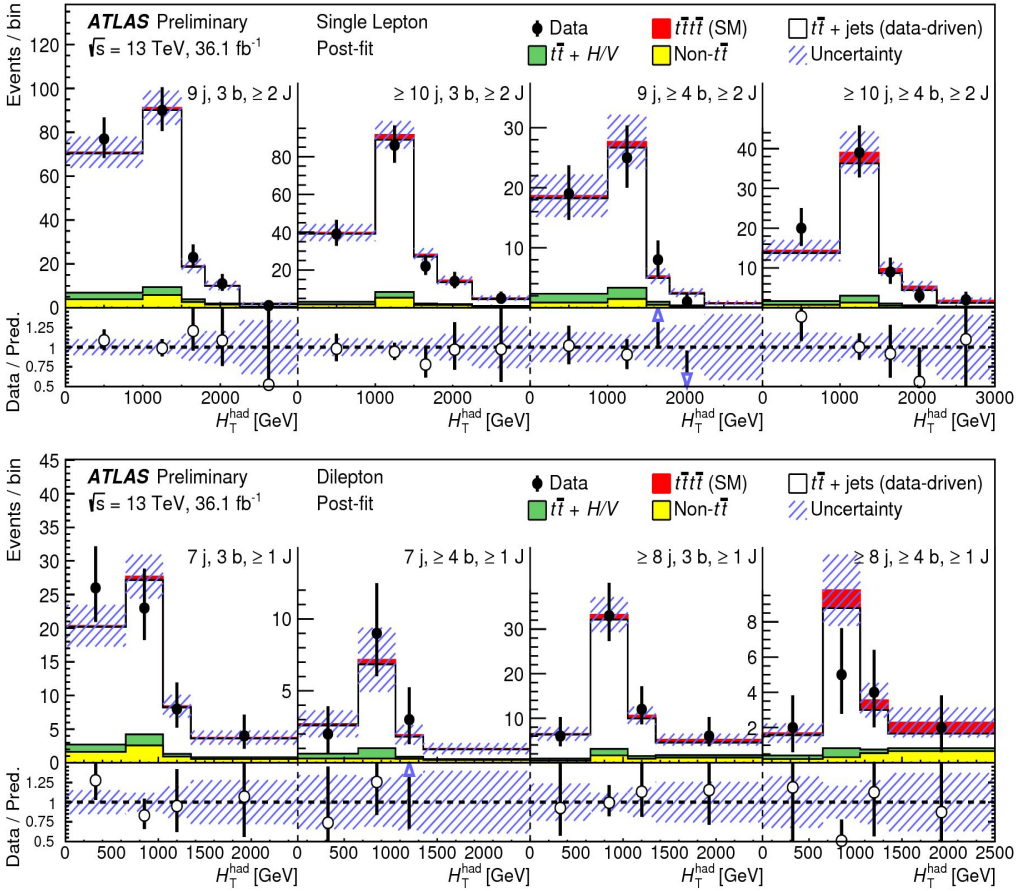
- Background from events with a fake or non-prompt lepton estimated directly from data using matrix method.
- tt Tag Rate Function to estimate $t\bar{t}$ + jets: ttTRF gives the probability that a jet is b-tagged
  - Three phases: extraction, validation, application.
  - Reweight data in low # b-jet bins with weights from low # jet bins.
  - Implement MC-correction factors.

OS2L:

- Background is estimated from MC.
  - Less than 8% of total background in signal region.



$t\bar{t}t\bar{t}$ l+jets / 2LOS fit



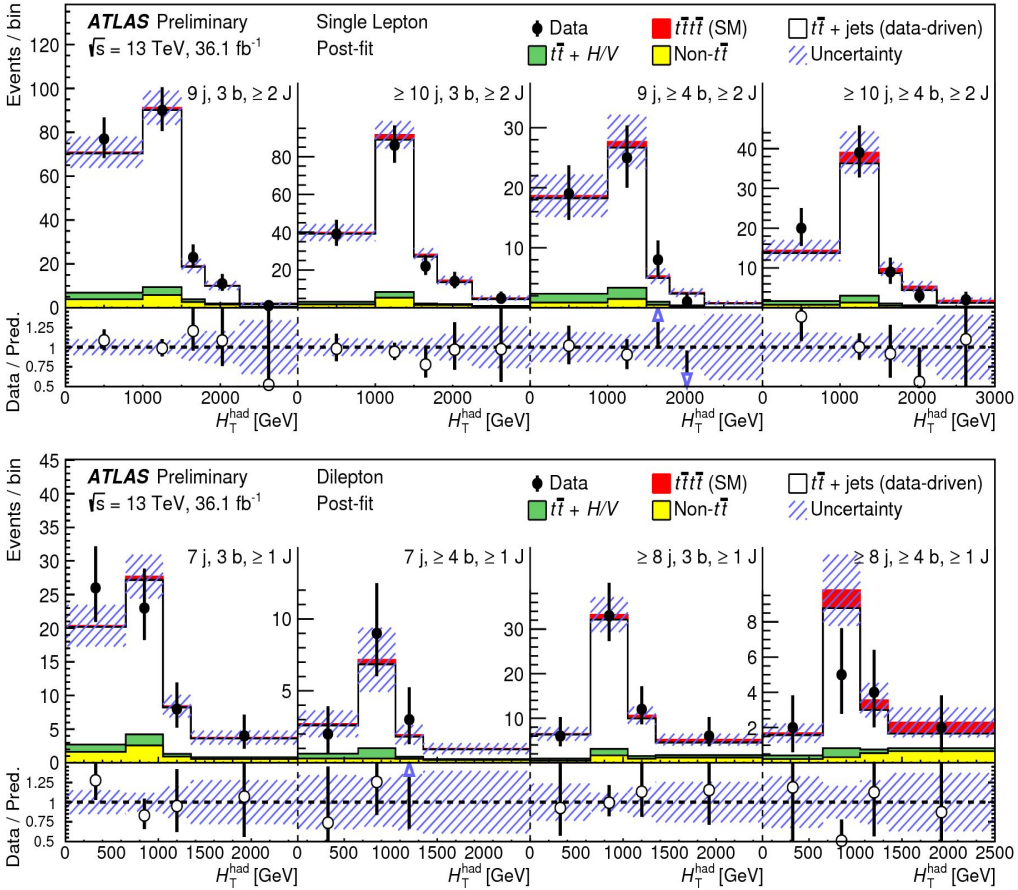
Simultaneous fit in 20 signal regions

- Non-$t\bar{t}$
  - W/Z+jets, single top, diboson productions and multijet backgrounds.
- Uncertainty stat & syst.

Observed (expected) 95% CL upper limit on $\sigma(t\bar{t}t\bar{t})$ of 47 fb (33 fb).

➢ Upper limit on $\sigma(t\bar{t}t\bar{t})$:
5.1 (3.6) x SM.

$t\bar{t}t\bar{t}$ l+jets / 2LOS fit



For four-top production via an EFT model with a four-top-quark contact interaction:

an observed (expected) 95% CL upper limit on σ of

21 fb (22 fb).

(SM four-top is considered as a background)

This is lower than SM as the contact interaction tends to result in final state objects with larger momenta.

SS dilepton

Signature: 2-leptons (ee, μμ, eμ), $N_j = 8$, $N_b = 4$, MET

Multilepton

Signature: #l=3, $N_j > 6$, $N_b = 4$, MET

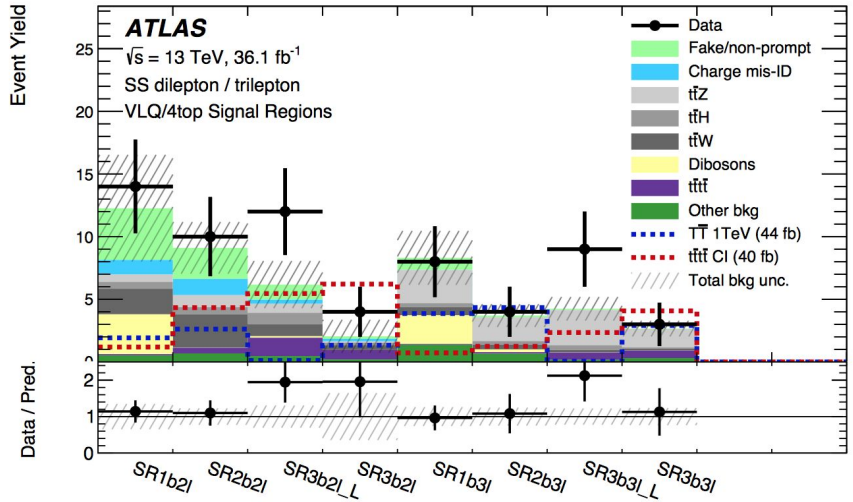
Cut and count analysis in 8 signal regions and 6 validation regions.

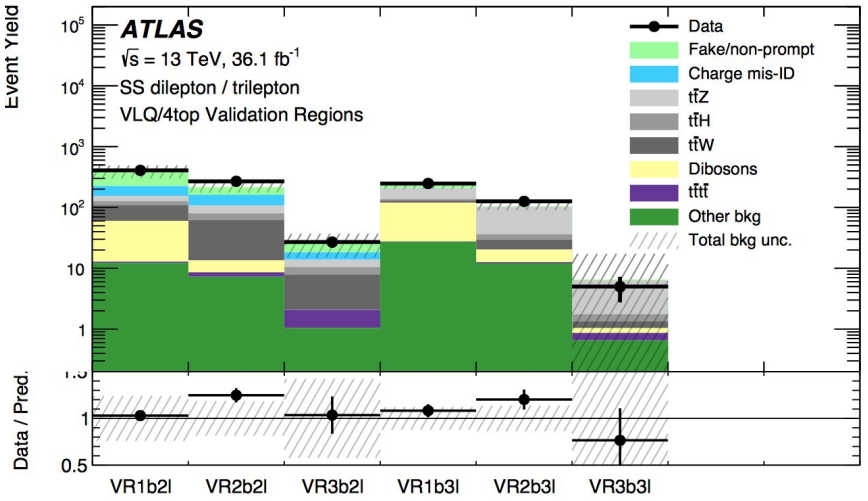
- The SM $\sigma(t\bar{t}t\bar{t})$ upper limit is (expected) 69 (29) fb.

Dominated by fakes and $t\bar{t}V$ background. Data driven techniques for

- Fake/non-prompt lepton backgrounds from matrix method
- 2LSS: charge misidentification

Irreducible backgrounds (e.g. $t\bar{t}V$) modelled by MC.

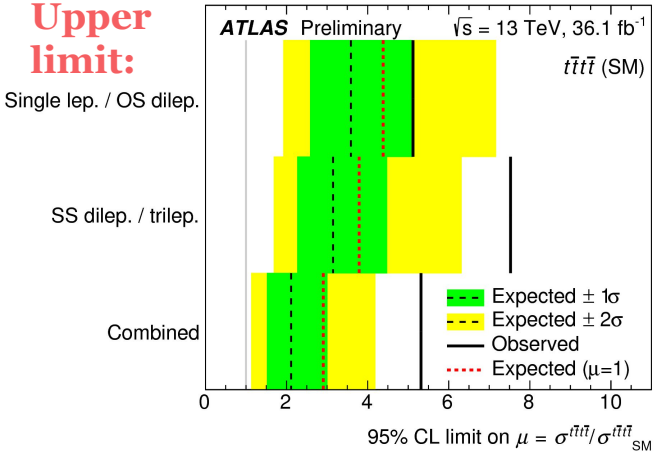




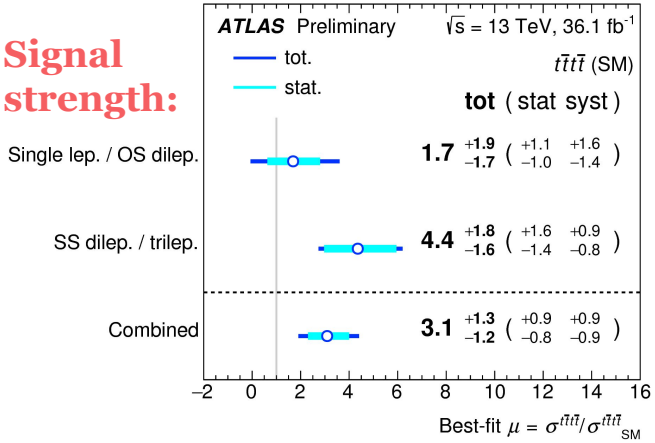
$t\bar{t}t\bar{t}$ Combination

- Uncertainties treatment:
  - All experimental systematic uncertainties treated as fully correlated between channels.
  - Background modelling uncertainties treated as uncorrelated.
- An excess of events over the SM background prediction, excluding the SM $t\bar{t}t\bar{t}$ production, is observed at 2.8 σ (1.0 σ).
- Observed (expected) 95% CL upper limit on σ($t\bar{t}t\bar{t}$) of 49 fb (19 fb).
  - Corresponding to an upper limit on σ(*tttt*), of 5.3 (2.1) x SM.

Upper limit:



Signal strength:



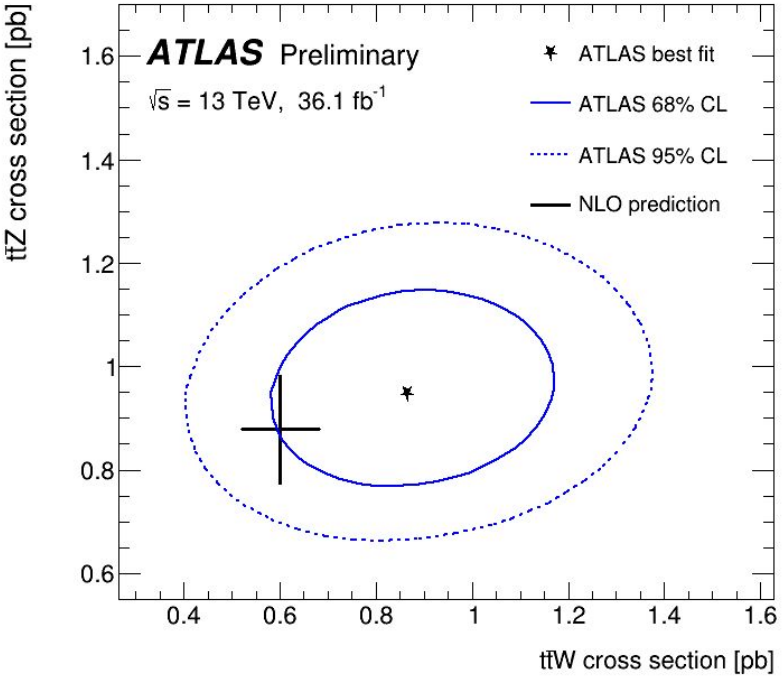
Summary

$t\bar{t}V$ ATLAS-CONF-2018-047

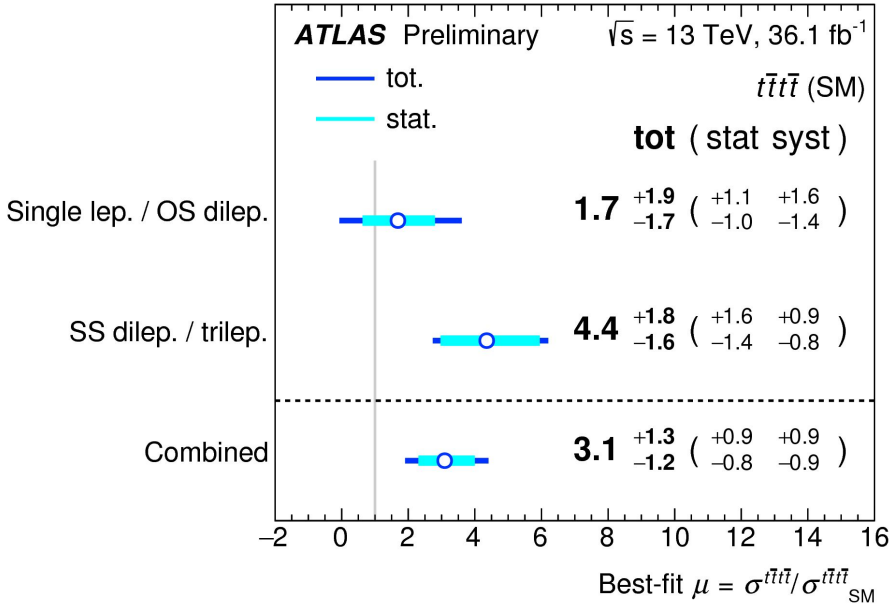
- Measurement with 36 fb^{-1} 13 TeV data.
- Combined fit measured
  - $\sigma(t\bar{t}Z) = 0.95 \pm 0.13$ pb
  - $\sigma(t\bar{t}W) = 0.87 \pm 0.19$ pb

  and yields significance of:
  - $t\bar{t}W$: 4.3σ (4.3σ) observed (expected)
  - $t\bar{t}Z$ has a significance > 5σ.
- No significant excess above the SM expectation is observed.
- Limits set on EFT coefficients:
  - Matched or exceeded previous measurements.

ATLAS-CONF-2018-047



Summary



$t\bar{t}t\bar{t}$ arXiv:1807.11883

- Combined result with all channels using 36 fb^{-1} of 13 TeV data.
- Observed (expected) upper limit of:
  5.3 (2.1) x 4-top SM σ at 95% CL.
- A slight excess above the SM expectation is observed at 2.8 σ (1.0 σ expected), which is driven by the 2LSS / 3L channel.
- The kinematic properties of the 2LSS / 3L channel events were compared with expectations from BSM four-tops and found to agree poorly.
- Analysis is still statistically dominated.

Summary

$t\bar{t}V$ ATLAS-CONF-2018-047

- Measurement with 36 fb^{-1} 13 TeV data.
- Combined fit measured
  $\sigma(t\bar{t}Z) = 0.95 \pm 0.13$ pb
  $\sigma(t\bar{t}W) = 0.87 \pm 0.19$ pb
  and yields significance of:
  $t\bar{t}W$: 4.3σ (4.3σ) observed (expected)
  $t\bar{t}Z$ has a significance > 5σ.
- No significant excess above the SM expectation is observed.
- Limits set on EFT coefficients:
  - Matched or exceeded previous measurements.

$t\bar{t}t\bar{t}$ arXiv:1807.11883

- Combined result with all channels using 36 fb^{-1} of 13 TeV data.
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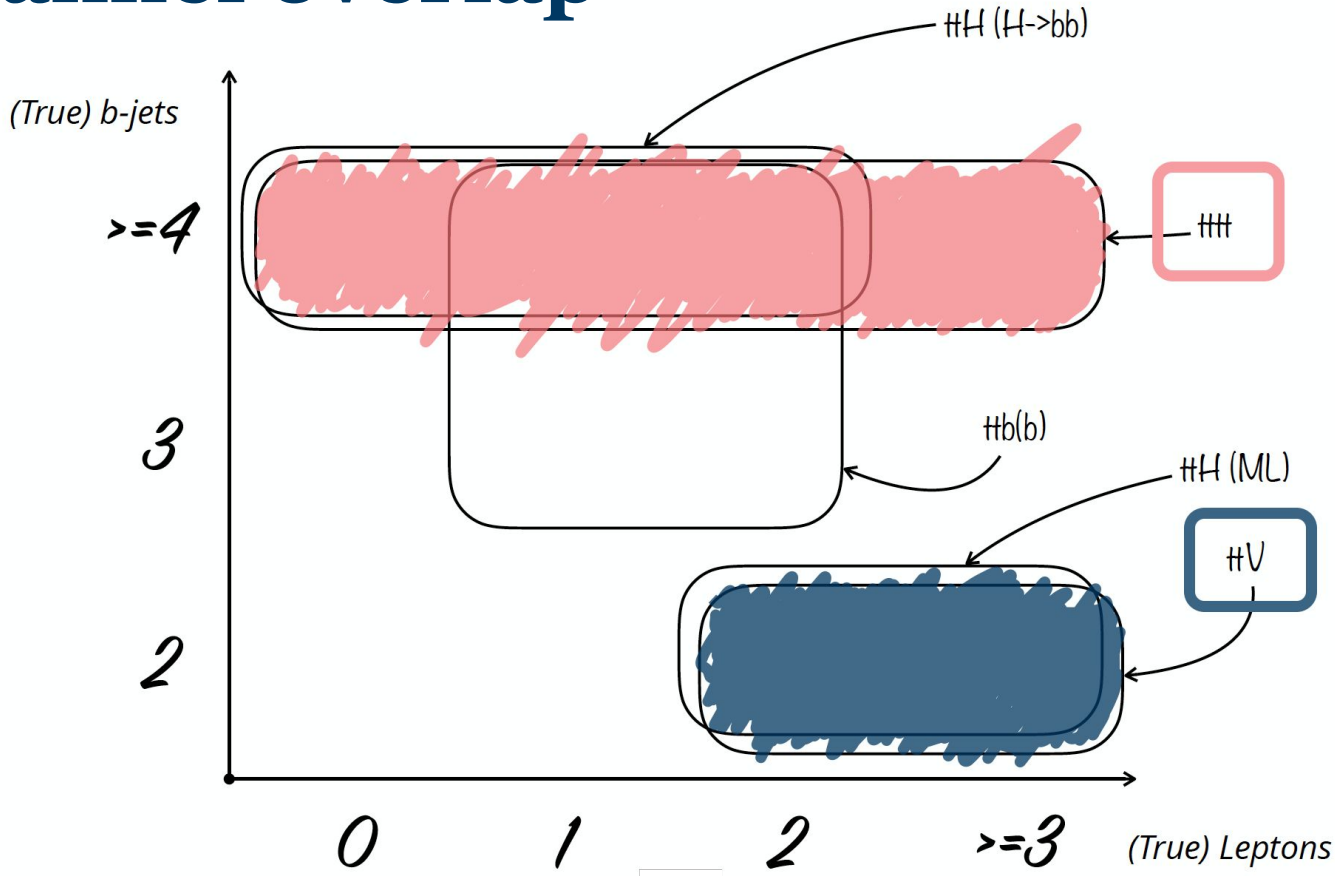
- The kinematic properties of the 2LSS / 3L channel events were compared with expectations from BSM four-tops and found to agree poorly.

Thank you for your attention!

Backup

Channel overlap



13 TeV 3.2 fb^{-1} uncertainties:

Table 5 List of dominant and total uncertainties in the measured cross sections of the $t\bar{t}Z$ and $t\bar{t}W$ processes from the fit. All uncertainties are symmetrised

Uncertainty	$\sigma_{t\bar{t}Z}$ (%)	$\sigma_{t\bar{t}W}$ (%)
Luminosity	2.6	3.1
Reconstructed objects	8.3	9.3
Backgrounds from simulation	5.3	3.1
Fake leptons and charge misID	3.0	19
Signal modelling	2.3	4.2
Total systematic	11	22
Statistical	31	48
Total	32	53

BDT distributions for the OS dilepton signal regions

2L: OSSF

Variable	2ℓ-Z-6j1b-SR	2ℓ-Z-5j2b-SR	2ℓ-Z-6j2b-SR
Event cleaning		Common to all SR	
Leptons		$= 2$	
Leptons		same-flavour	
Leptons		opposite-sign	
M_{ll}		$\lvert M_{ll} - M_Z \rvert < 10$ GeV	
p_{T} (1st lepton)		> 30 GeV	
p_{T} (2nd lepton)		> 15 GeV	
$n_{b\text{–jets}}$	$=1$	≥ 2	≥ 2
n_{jets}	≥ 6	$=5$	≥ 6
(BDT output	> 0.4	> 0.4	> 0)

BDT distributions for the OS dilepton signal regions

ttV

3L

Variable	3ℓ-Z-1b4j	3ℓ-Z-2b3j	3ℓ-Z-2b4j	3ℓ-noZ-2b4j
Event cleaning	Common to all SR			
Leptons	=3			
Leading lepton p_T	> 27 GeV			
Second and third lepton p_T	> 20 GeV			
One OSSF lepton pair	required			required
Z-like OSSF pair	required			vetoed
Sum of lepton charges	± 1			
n_{jets}	≥ 4	$= 3$	≥ 4	≥ 4
$n_{b-\text{jets}}$	$= 1$	≥ 2	≥ 2	≥ 2

ttV

4L

Region	Z_2 leptons	p_{T4}	p_{T34}	$\lvert m_{\ell\ell} - m_{Z_2}\rvert$	E_T^{miss}	N_{jets}	$N_{b\text{-jets}}$
4ℓ-DF-1b	$e^{\pm}\mu^{\mp}$	> 7 GeV	> 35 GeV	-	-	-	1
4ℓ-DF-2b	$e^{\pm}\mu^{\mp}$	> 10 GeV	-	-	-	-	≥ 2
4ℓ-SF-1b	$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}$	> 7 GeV	> 25 GeV	> 10 GeV < 10 GeV	> 40 GeV > 80 GeV	-	1
4ℓ-SF-2b	$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}$	> 10 GeV	-	> 10 GeV < 10 GeV	- > 40 GeV	-	≥ 2

ttV control region:

Z+jets background in the 2l OS ttZ channel

Table 19: Summary of the event selection in the Z+jets control region.

Variable	2ℓ-Z-6j1b-CR	2ℓ-Z-5j2b-CR	2ℓ-Z-6j2b-CR
Event cleaning	Common to all SR		
Leptons	$= 2$		
Leptons	same-flavour		
Leptons	opposite-sign		
M_{ll}	$\lvert M_{ll} - M_Z \rvert < 10$ GeV		
p_{T} (1st lepton)	> 30 GeV		
p_{T} (2nd lepton)	> 15 GeV		
$n_{b-\mathrm{jets}}$	$=1$	≥ 2	≥ 2
n_{jets}	≥ 6	$=5$	≥ 6
BDT output	< 0.4	< 0.4	< 0

ttV control region:

WZ background in the 3L ttZ channel

- To define a control region dominated by the *WZ* background with a small signal contamination.
- In addition to the preselection, exactly three reconstructed jets are required, including a veto on *b*-tagged jets. MET > 40 GeV.
- In this region fakes are estimated using the Fake Factor Method
  - due to the lack of a data-driven estimate (with MM) for events with zero *b*-jets.

ttV control region:

ZZ background in the 4L ttZ channel

- Exactly four reconstructed leptons (mediumLH electrons, medium track quality muons)
- The Z_2 pair must have opposite charge and same flavour leptons
- The value of m_{Z_1} and m_{Z_2} must be within 10 GeV of the mass of the Z boson, *i.e.*, $|m_{Z_1} - m_Z| < 10$ GeV and $|m_{Z_2} - m_Z| < 10$ GeV
- $20\ \text{GeV} < E_{\text{T}}^{\text{miss}} < 40\ \text{GeV}$

ttV validation region:

tt background in the 2L OS ttZ channel

Table 21: Summary of the event selection in the $t\bar{t}$ validation regions.

Variable	$e\mu$-Z-6j1b-VR	$e\mu$-Z-5j2b-VR	$e\mu$-Z-6j2b-VR
Event cleaning	Common to all SR		
Leptons	$= 2$		
Leptons	$e\mu$		
Leptons	opposite-sign		
M_{ll}	$\lvert M_{ll} - M_Z \rvert < 10$ GeV		
p_{T} (1st lepton)	> 30 GeV		
p_{T} (2nd lepton)	> 15 GeV		
$n_{b-\mathrm{jets}}$	$=1$	≥ 2	≥ 2
n_{jets}	≥ 6	$=5$	≥ 6

ttV validation region:

backgrounds in the 3L ttZ channel

Table 23: Summary of the validation region definition. The term lepton is used in the table to refer to signal electrons and muons. Jets are labeled with an index corresponding to their order in p_{T}.

Variable	3ℓ-Z-2j-VR	3ℓ-1b-VR
Event cleaning	Common to both region	
Leptons	==3	
Leading lepton p_T	> 27 GeV	
Second and third lepton p_T	> 20 GeV	
One OSSF lepton pair	required	not required
Z-like OSSF pair	required	not required
n_{jets}	≥ 2	2 or 3
$n_{b-\mathrm{jets}}$	—	== 1

ttV: Constraints on BSM

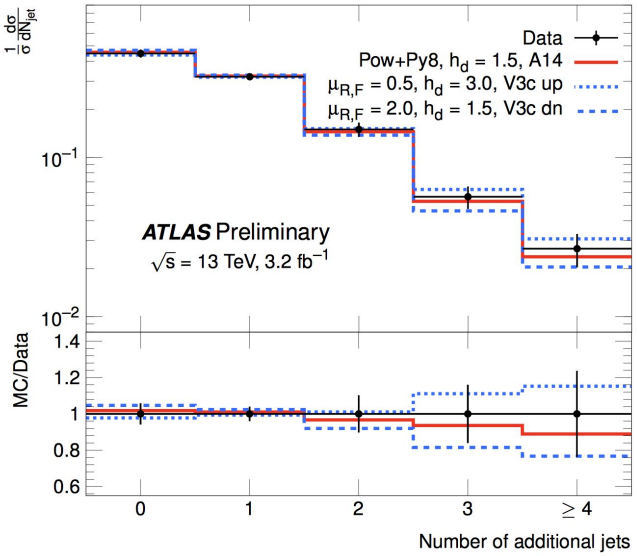
- Effective field theory operators considered and their form in terms of SM fields.

Operator	Expression
$\mathcal{O}_{\phi Q}^{(3)}$	$i\frac{1}{2}(\phi^\dagger \overleftrightarrow{D}_\mu^I \phi)(\bar{Q}\gamma^\mu \tau^I Q)$
$\mathcal{O}_{\phi Q}^{(1)}$	$i\frac{1}{2}(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{Q}\gamma^\mu Q)$
$\mathcal{O}_{\phi t}$	$i\frac{1}{2}(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{t}\gamma^\mu t)$
$\mathcal{O}_{tW}$	$y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W_{\mu\nu}^I$
$\mathcal{O}_{tB}$	$y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\phi}B_{\mu\nu}$

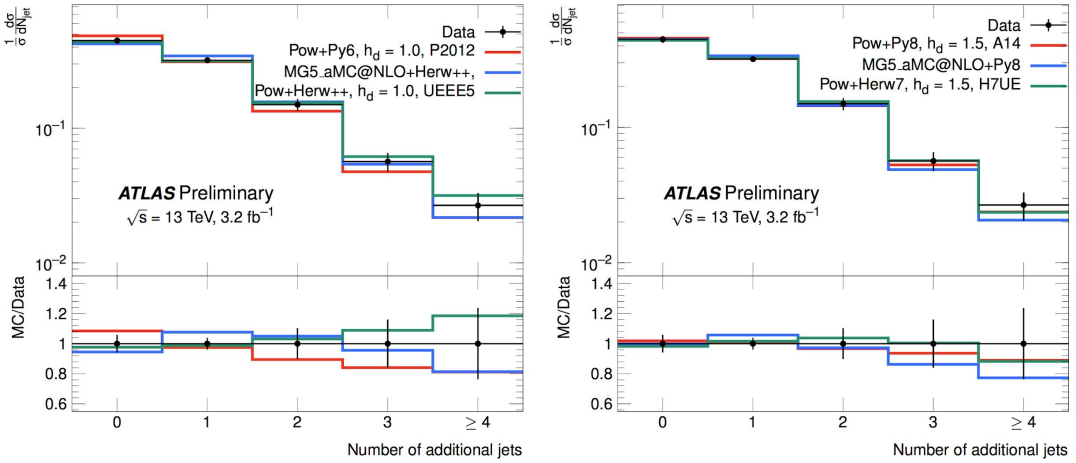
Both the linear and quadratic terms are considered together for one operator at a time.

Notation from O. Bessidskaia Bylund, et. al, *Probing top quark neutral couplings in the Standard Model Effective Field Theory at NLO in QCD*, JHEP **05** (2016) 052, arXiv: 1601.08193 [hep-ph].

tttt: Large # jets mismodelling



The impact of parameter variations that lead to additional radiation.



Comparison of different generator setups used to assess the NLO+PS matching as well as the PS and hadronisation uncertainty as defined for early Run 2 analyses (left) and after optimisation (right)

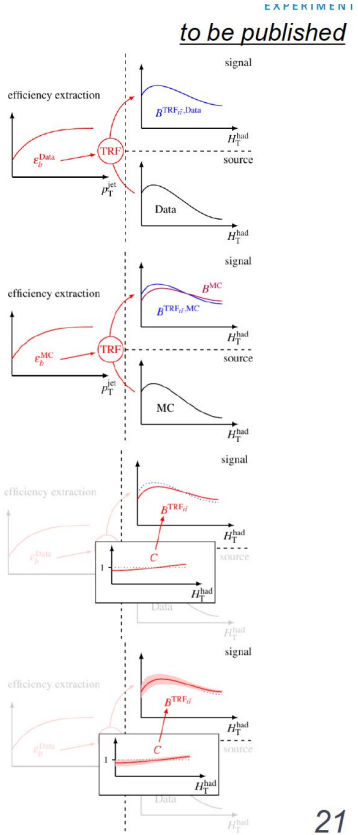
Improvements in tttt modelling using NLO+PS Monte Carlo generators for Run2:
https://cds.cern.ch/record/2630327

Tttt: ttTRF

Prepared by Leonid Serkin

GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

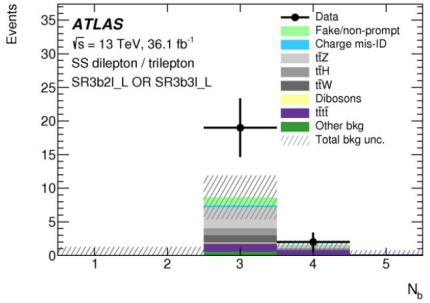
- Search for four-top-quark production in 1L / 2OSL final states: small signal on top of large tt+jets bkg
- Categorise in number of jets (Nj), b-jets (Nb), reclustered large-R jets (NJ) and HT
- MC simulation not expected to model well the high multiplicity regions: data-driven tt+jets
  - ✓ assume probability of b-tagging a jet in tt+jets event is independent of number of extra jets
  - ✓ extract effective b-tagging efficiencies from low Nj, reweight the data and predict tt+jets in signal regions with same Nj/NJ, but larger Nb
  - ✓ correction factor C for each considered bin
  - ✓ full set of syst. uncert. by repeating the procedure on MC simulated events with syst. variations applied

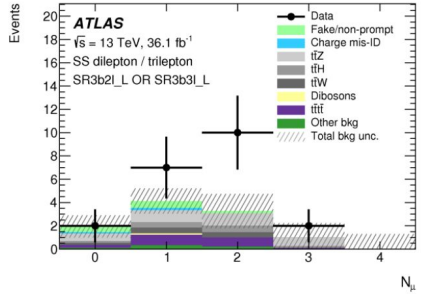
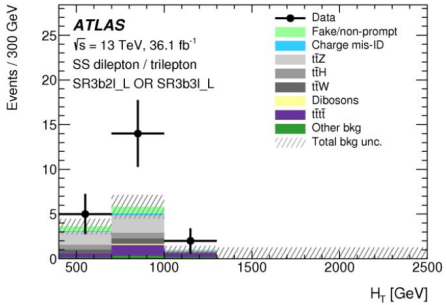


21

- Excess info: More than half of the excess is observed in events with two muons, three b-tagged jets and HT around 700 GeV.

- the kinematic properties of the events were compared with the expectations from the BSM four-top-quark production benchmark models, and found to agree poorly with all of them, particularly in the b-tagged jet multiplicity





Region name	N_j	N_b	N_ℓ	Lepton charges	Kinematic criteria
VR1b2ℓ	≥ 1	1	2	++ or −−	$400 < H_T < 2400$ GeV or $E_T^{miss} < 40$ GeV
SR1b2ℓ	≥ 1	1	2	++ or −−	$H_T > 1000$ GeV and $E_T^{miss} > 180$ GeV
VR2b2ℓ	≥ 2	2	2	++ or −−	$H_T > 400$ GeV
SR2b2ℓ	≥ 2	2	2	++ or −−	$H_T > 1200$ GeV and $E_T^{miss} > 40$ GeV
VR3b2ℓ	≥ 3	≥ 3	2	++ or −−	$400 < H_T < 1400$ GeV or $E_T^{miss} < 40$ GeV
SR3b2ℓ_L	≥ 7	≥ 3	2	++ or −−	$500 < H_T < 1200$ GeV and $E_T^{miss} > 40$ GeV
SR3b2ℓ	≥ 3	≥ 3	2	++ or −−	$H_T > 1200$ GeV and $E_T^{miss} > 100$ GeV
VR1b3ℓ	≥ 1	1	3	any	$400 < H_T < 2000$ GeV or $E_T^{miss} < 40$ GeV
SR1b3ℓ	≥ 1	1	3	any	$H_T > 1000$ GeV and $E_T^{miss} > 140$ GeV
VR2b3ℓ	≥ 2	2	3	any	$400 < H_T < 2400$ GeV or $E_T^{miss} < 40$ GeV
SR2b3ℓ	≥ 2	2	3	any	$H_T > 1200$ GeV and $E_T^{miss} > 100$ GeV
VR3b3ℓ	≥ 3	≥ 3	3	any	$H_T > 400$ GeV
SR3b3ℓ_L	≥ 5	≥ 3	3	any	$500 < H_T < 1000$ GeV and $E_T^{miss} > 40$ GeV
SR3b3ℓ	≥ 3	≥ 3	3	any	$H_T > 1000$ GeV and $E_T^{miss} > 40$ GeV