Rare top quark production in ATLAS

tqγ, tqZ and 4tops

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on behalf of the ATLAS Collaboration

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Top Physics session
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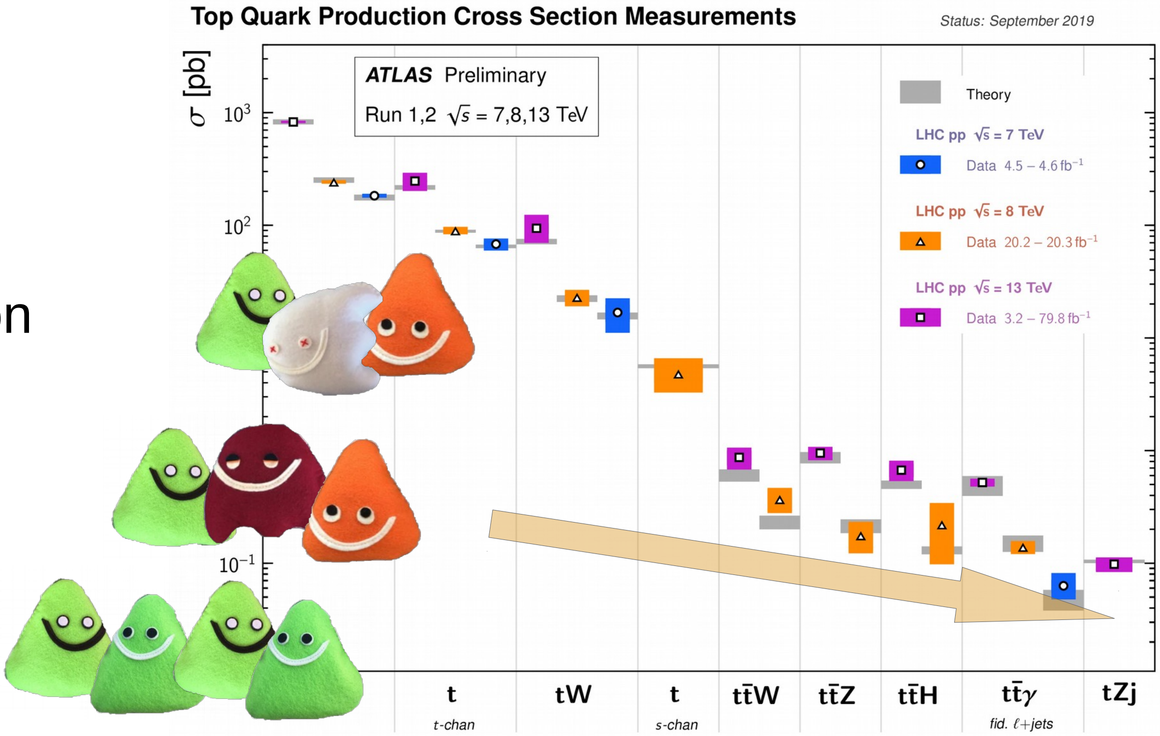
Outline

The exceptional dataset collected in Run 2 paves the way to test the Standard Model at higher and higher precision..

.. but also to measure very tiny signals from rare processes.

ATL-PHYS-PUB-2019-035



Processes covered in this talk:

- FCNC Top to qγ coupling
- Standard-Model tqZ production
- Four-top quarks production

The tqγ FCNC coupling

Phys. Lett. B 800 (2020) 135082

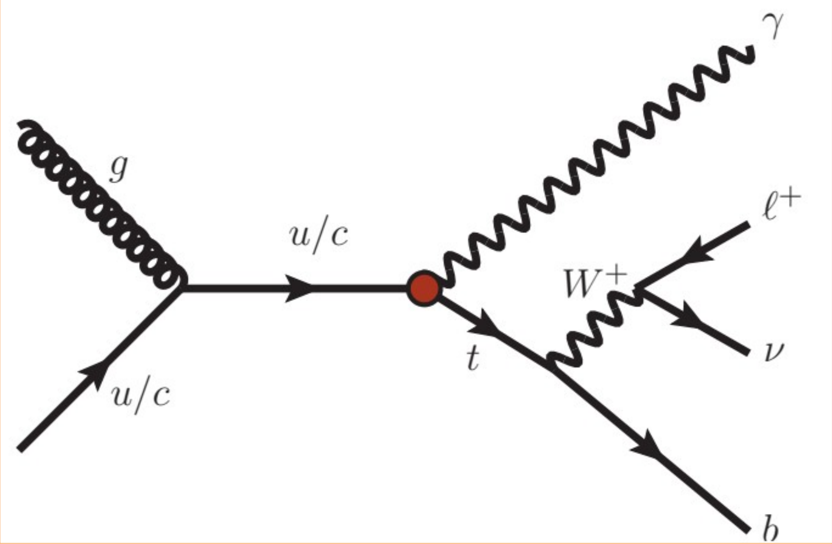
SM branching ratio t → qγ is tiny (10^{-14}), possible deviations from BSM.

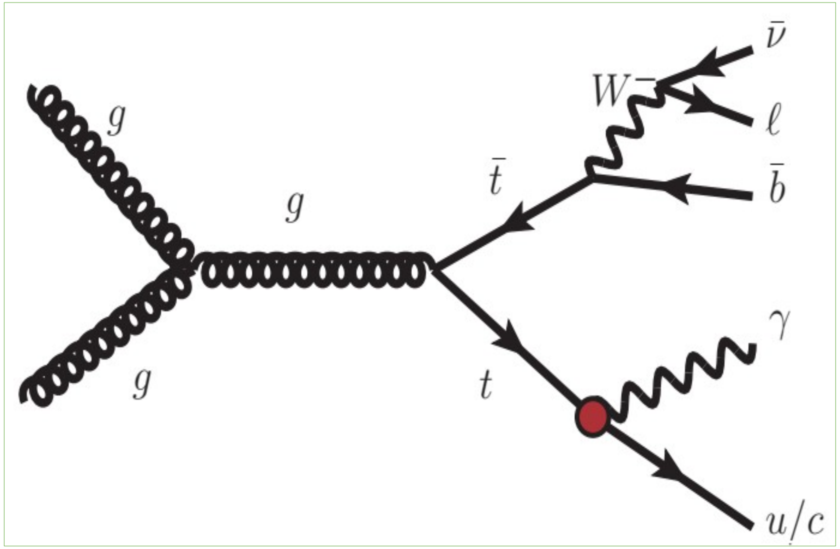
Observed in two final states:

- q → tγ in single top production
- t → qγ in top pair production

NLO (QCD) EFT operators:

- O^{ij}_{uW}, O^{ij}_{uB}
- Right/Left-Handed couplings

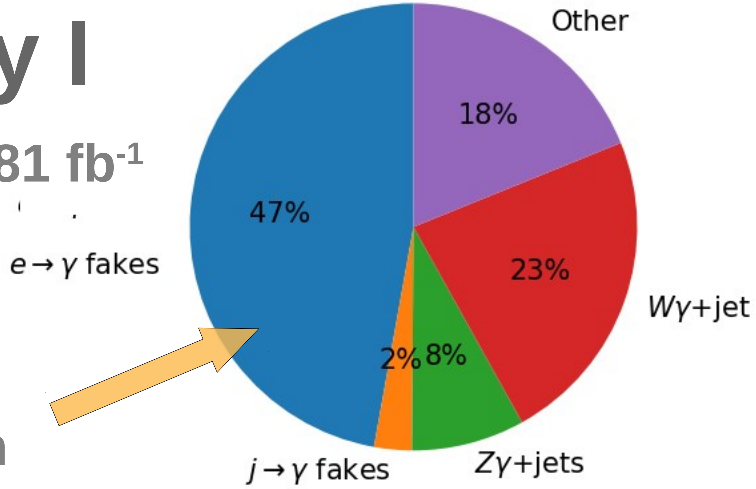




Analysis strategy I

Phys. Lett. B 800 (2020) 135082

Dataset at √s = 13 TeV, using **81 fb^{-1}**

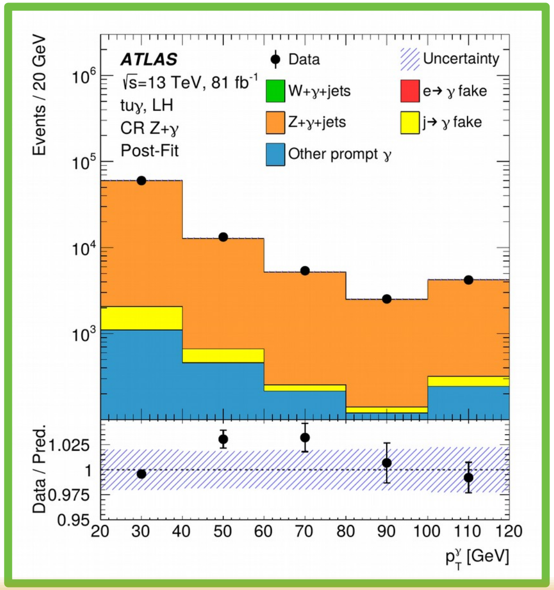


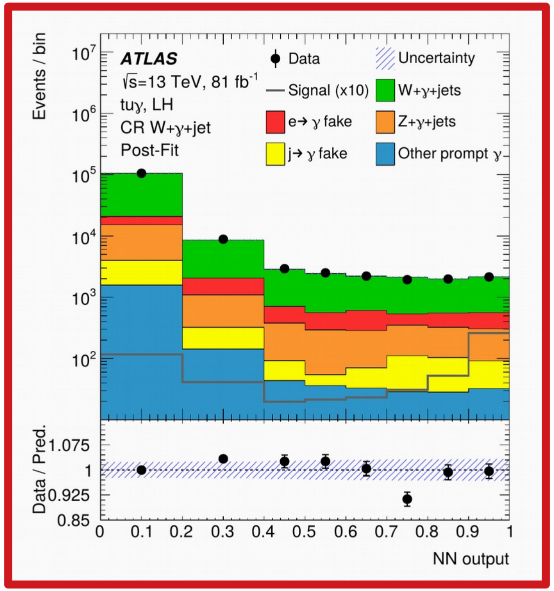
Single top topology + photon

- 1 lepton (e,μ)
- 1 photon
- Exactly one b-jet (MV2c10 60%)
- E_T^{miss} > 30 GeV

Ratios q → tγ/t → qγ

- tuγ LH (RH) ~ 4.2 (5.3)
- tcγ LH (RH) ~ 0.9 (0.7)





Normalisations of:

- Wγ+jets
- Zγ+jets

Measured in the fit.

Analysis strategy II

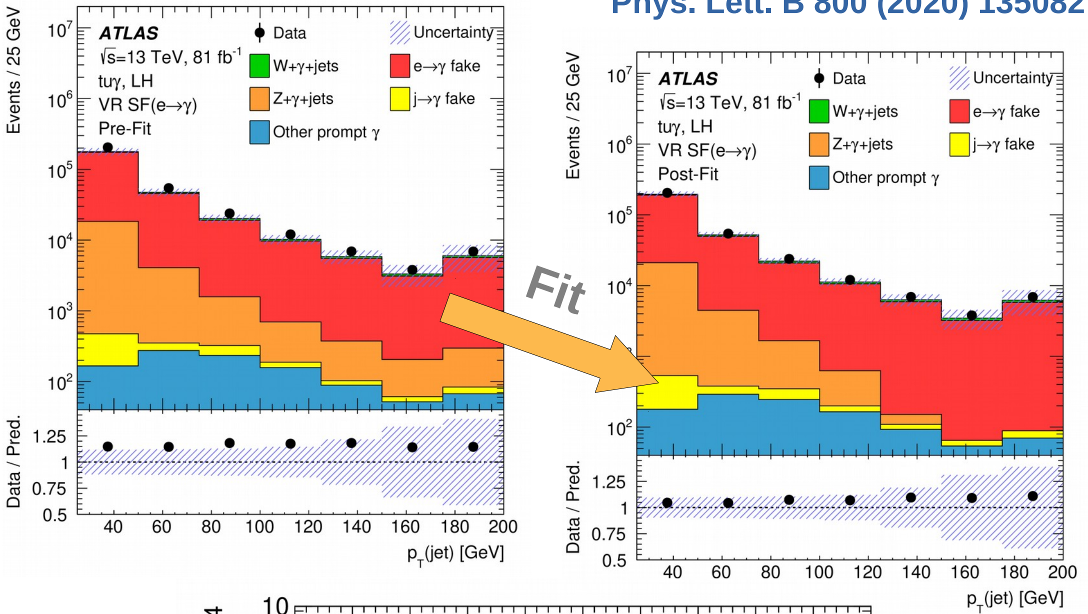
Phys. Lett. B 800 (2020) 135082

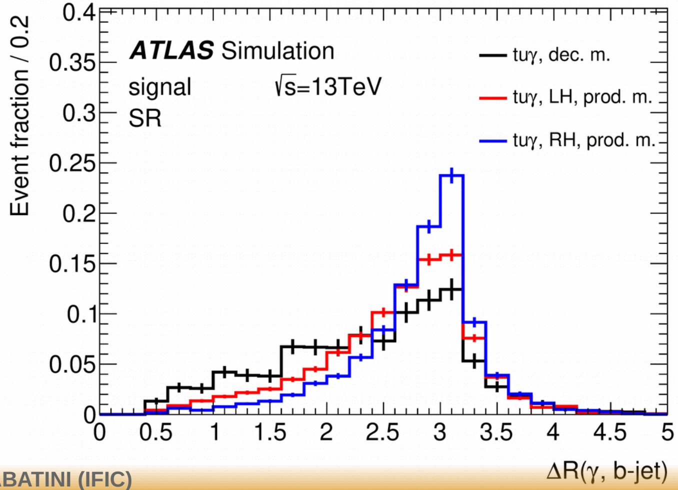
Large contribution from **e → γ fakes**:

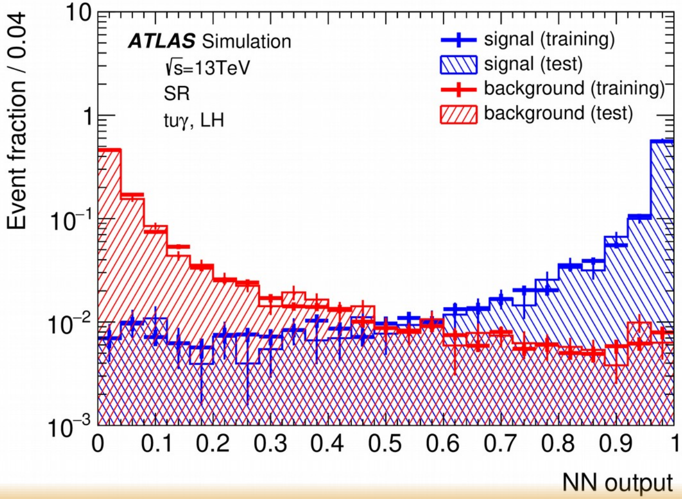
- Estimation of Data/MC e → γ efficiency
- Application is validated in a VR

Discriminant: **Neural Network**

- Output used in the SR
- A NN trained for each studied coupling







Results

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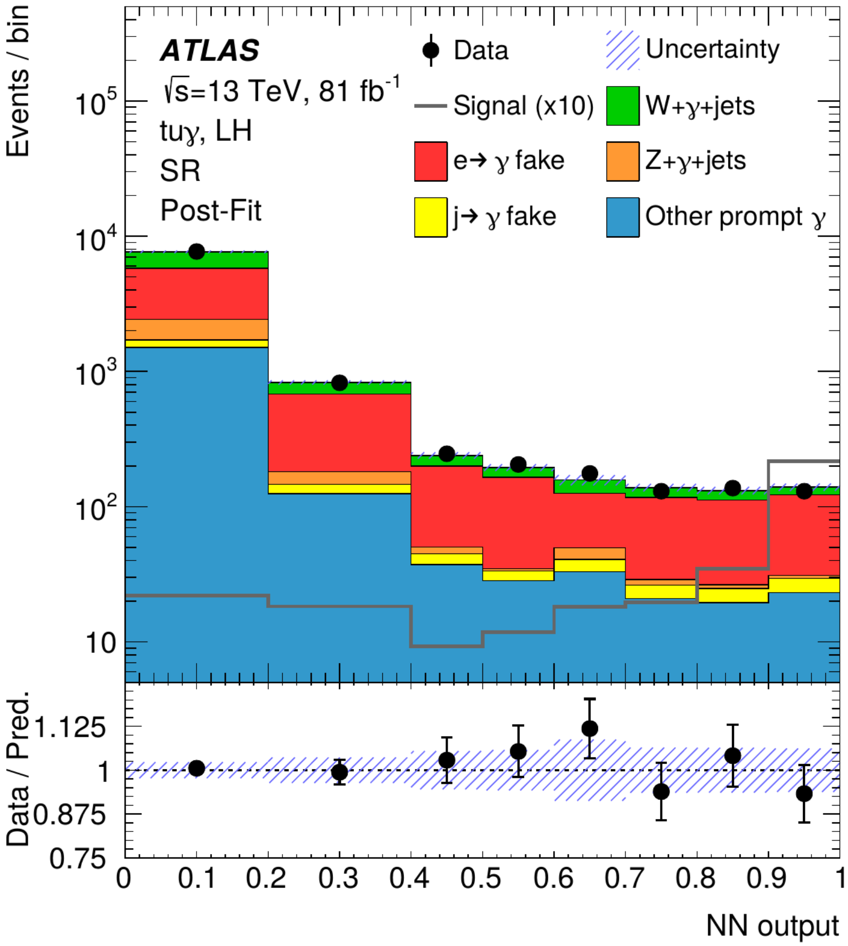
Profile likelihood fit in Control and Signal regions.

Limits at 95% CL for different assumed couplings:

➔ **>2x improvement than past results!**

Observable	Vertex	Coupling	Obs.	Exp.
$\left\|C_{uW}^{(13)*} + C_{uB}^{(13)*}\right\|$	$tu\gamma$	LH	0.19	$0.22^{+0.04}_{-0.03}$
$\left\|C_{uW}^{(31)} + C_{uB}^{(31)}\right\|$	$tu\gamma$	RH	0.27	$0.27^{+0.05}_{-0.04}$
$\left\|C_{uW}^{(23)*} + C_{uB}^{(23)*}\right\|$	$tc\gamma$	LH	0.52	$0.57^{+0.11}_{-0.09}$
$\left\|C_{uW}^{(32)} + C_{uB}^{(32)}\right\|$	$tc\gamma$	RH	0.48	$0.59^{+0.12}_{-0.09}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	LH	2.8	$4.0^{+1.6}_{-1.1}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	RH	6.1	$5.9^{+2.4}_{-1.6}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	LH	22	27^{+11}_{-7}
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	RH	18	28^{+12}_{-8}



Limiting factors:

Stats, JER, Scale Factor on $p_T(\gamma)$, $\mu_{F/R}$ scales, modelling of tt and single-top processes.

The tZq production

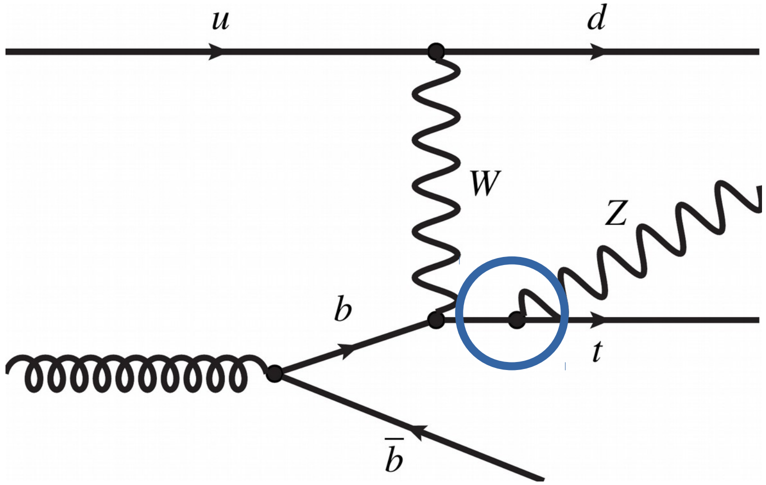
arXiv:2002.07546

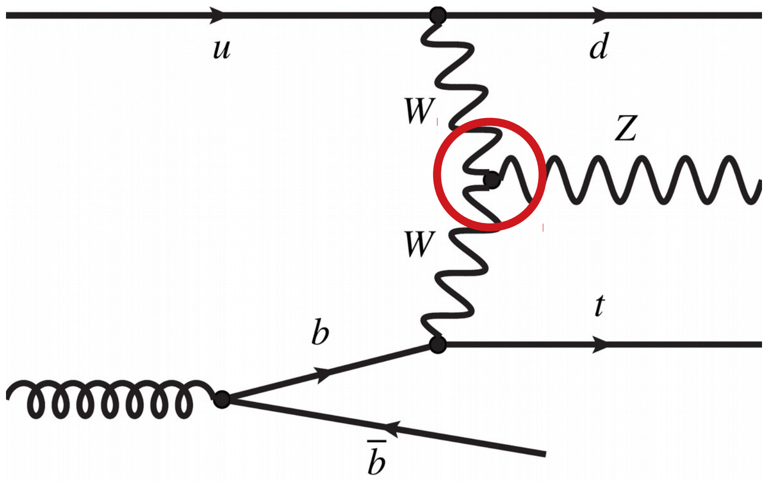
Production of single-top associated with a Z-boson:

$$\sigma_{tZq}^{\text{NLO QCD}}(m_{ll} > 30\ \text{GeV}) = 102^{+5}_{-2}\ \text{fb}$$

More sensitive to tZ coupling than $t\bar{t}Z$

Sensitive both to tZ and WZ couplings





arXiv:2002.07546

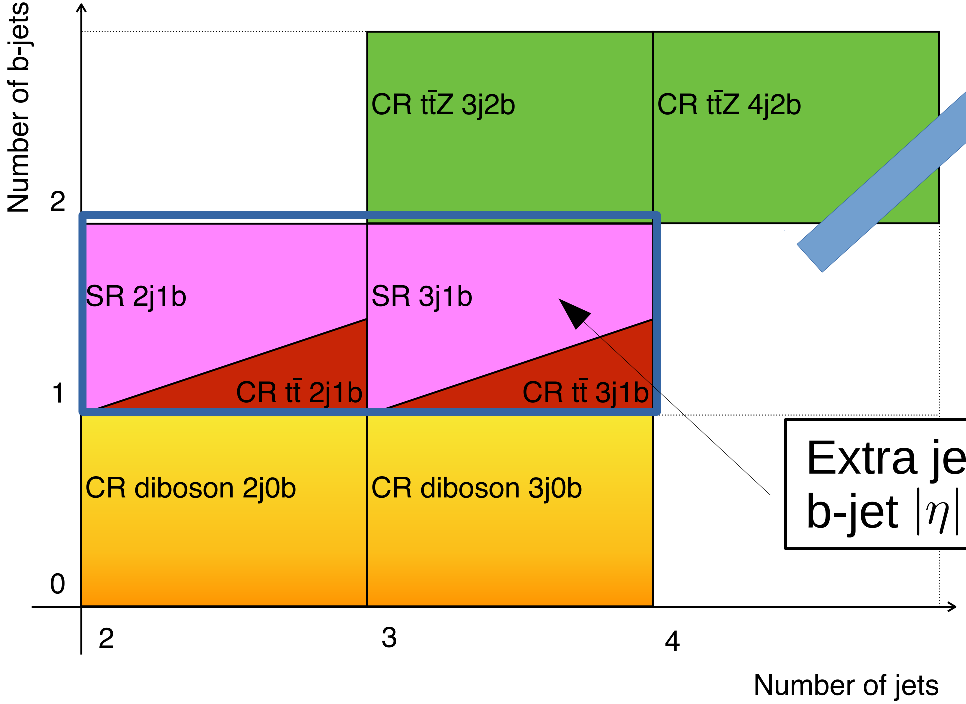
Analysis strategy

Dataset at $\sqrt{s}$ = 13 TeV, using **139 fb^{-1}**

Selection – Leptonic top decay + $Z(l^+l^-)$

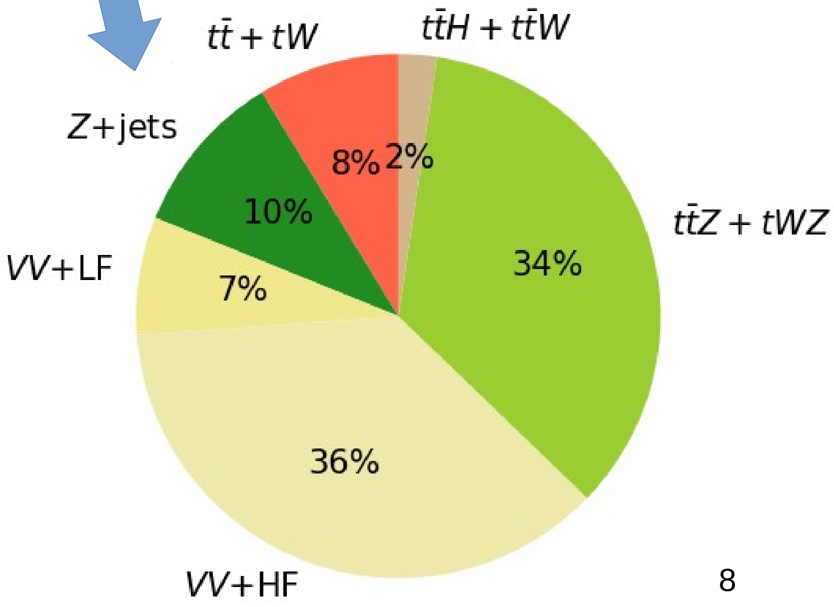
Three leptons:

- 3 jets for QCD radiation
- $m(l^+l^-)$ within Z peak
- **SR** : contains $e^+e^-/\mu^+\mu^-$ pair
- $t\bar{t}$ **CR**: contains $e^{\mp}\mu^{\pm}$ pair



Extra jet $|\eta| < 4.5$
b-jet $|\eta| < 2.5$

Background composition in SRs



Fit setup

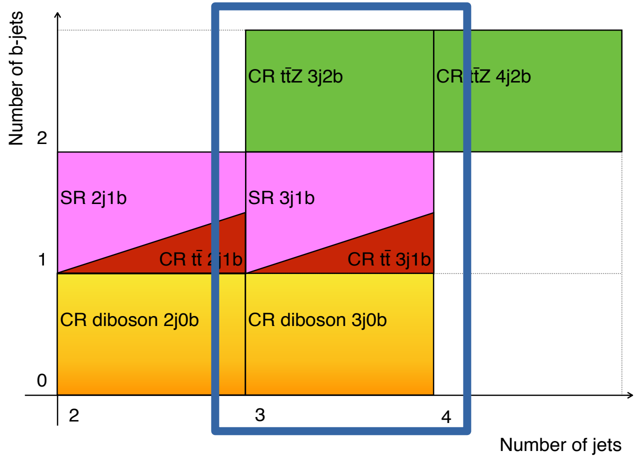
arXiv:2002.07546

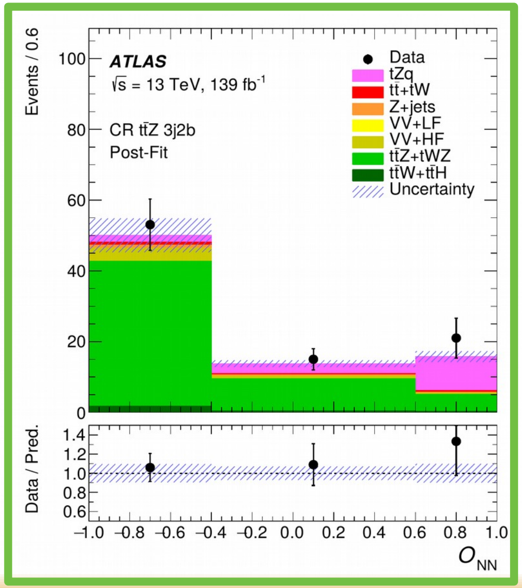
SR and $t\bar{t}Z$ CRs based on output of Neural Network

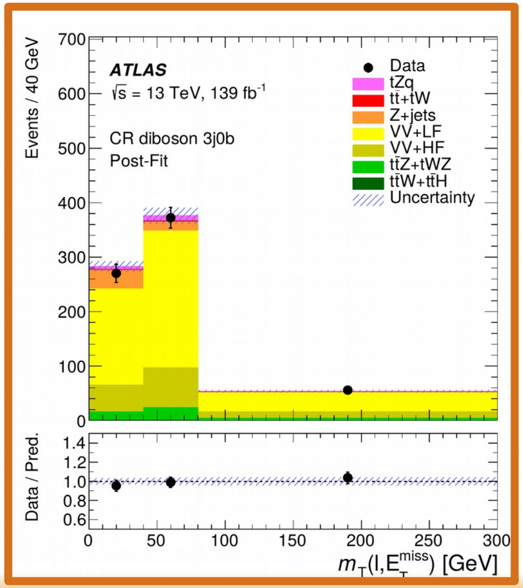
- Most important variables: m_{bj}, m_{top}, $|\eta(j)|$

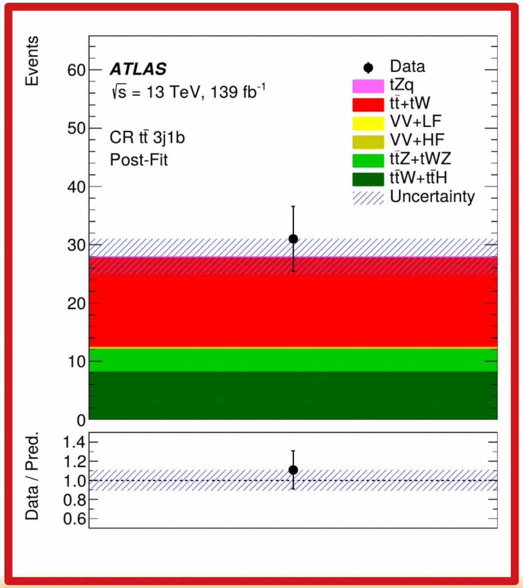
Non-prompt leptons from HF (tW, $t\bar{t}$ and Z+jets):

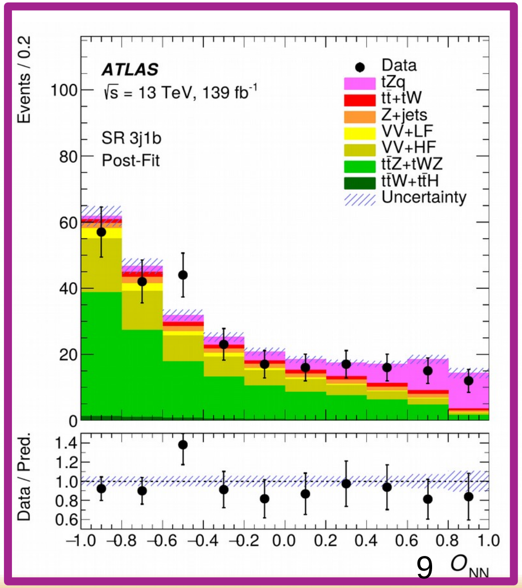
- *replacement method*
- free-floating normalisation in the fit











arXiv:2002.07546

Results

Fitted fiducial cross-section:

$$\sigma_{tZq}(m_{ll} > 30\ \mathrm{GeV}) = 97\ \pm 13\ (\mathrm{stat.})\ \pm 7\ (\mathrm{syst.})\ \mathrm{fb}$$

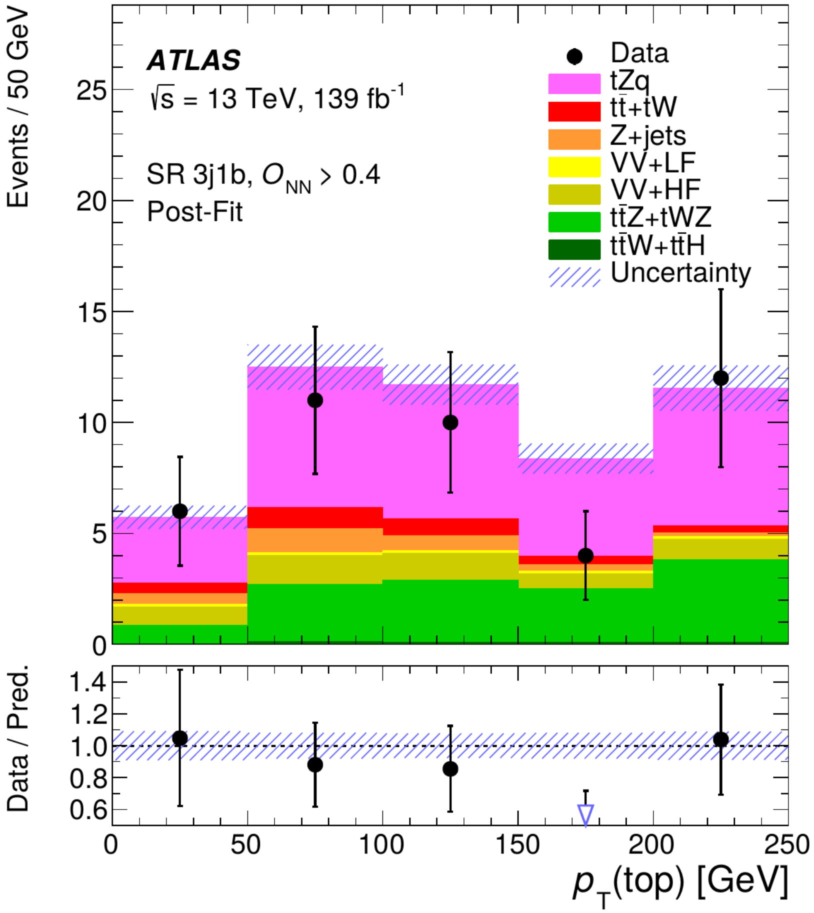
Measured at 14% accuracy, dominated by statistical uncertainty.

Expected and observed significance: **>5σ**

Observation of the tZq production!

Limiting factors:

- Data statistics
- Jet/E_T^{miss}/lepton reco. and calib.
- Luminosity
- Prompt-lepton modelling



Production of $t\bar{t}t\bar{t}$

ATLAS-CONF-2020-013

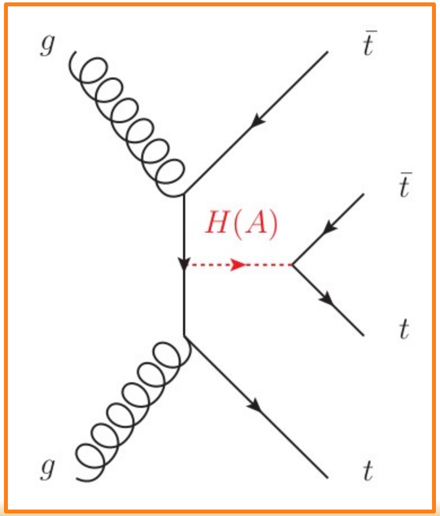
Standard Model process with $\sigma_{t\bar{t}t\bar{t}}^{\text{NLO QCD+EW}} = 12 \pm 20\%\ \text{fb}$ [JHEP02(2018) 031]

Very sensitive to many BSM scenarios that strongly enhance the cross-sections

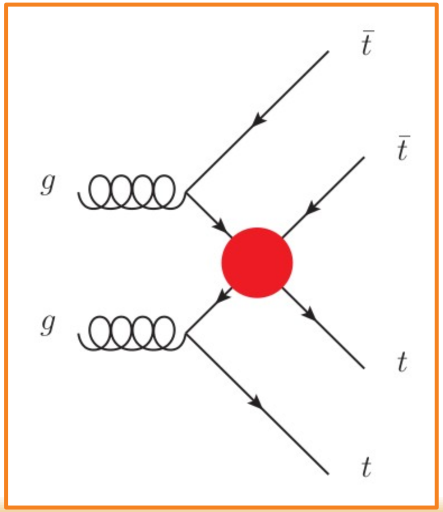
Latest ATLAS results using 2015/16 dataset [Phys. Rev. D 99 052009]

- Observed (expected) limit on $t\bar{t}t\bar{t}$ cross-section @ 95% CL = $5.3\ (2.1)\ \sigma_{t\bar{t}t\bar{t}}^{\text{NLO QCD+EW}}$

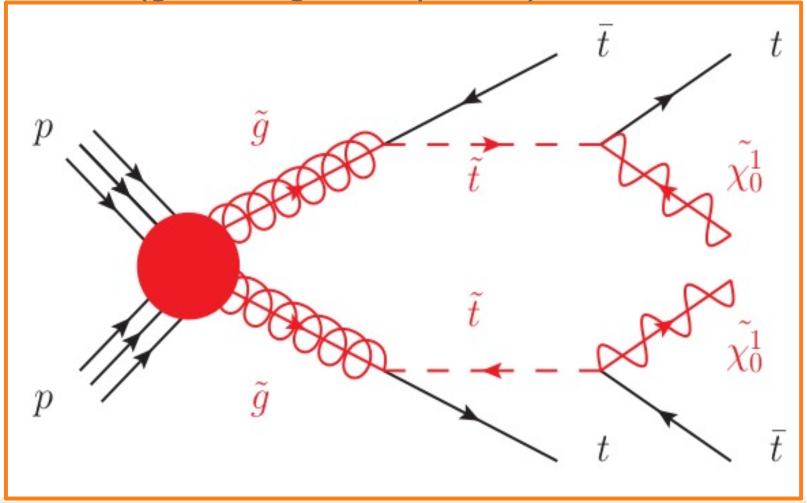
2HDM



Contact Interaction



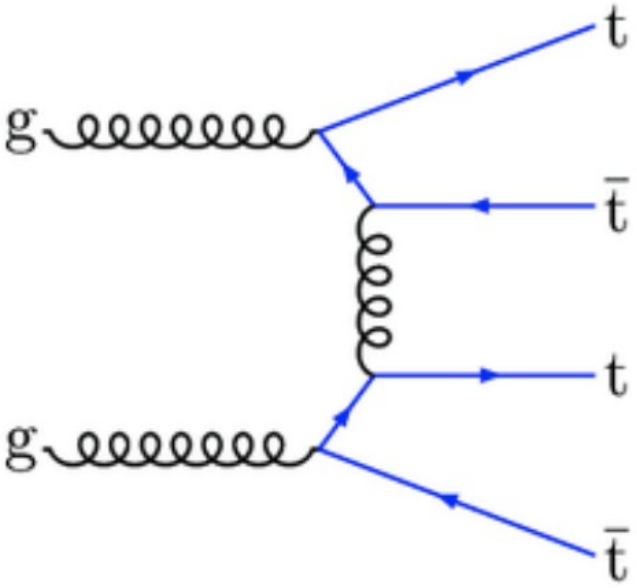
SUSY (gluino/sgluons pair ...)



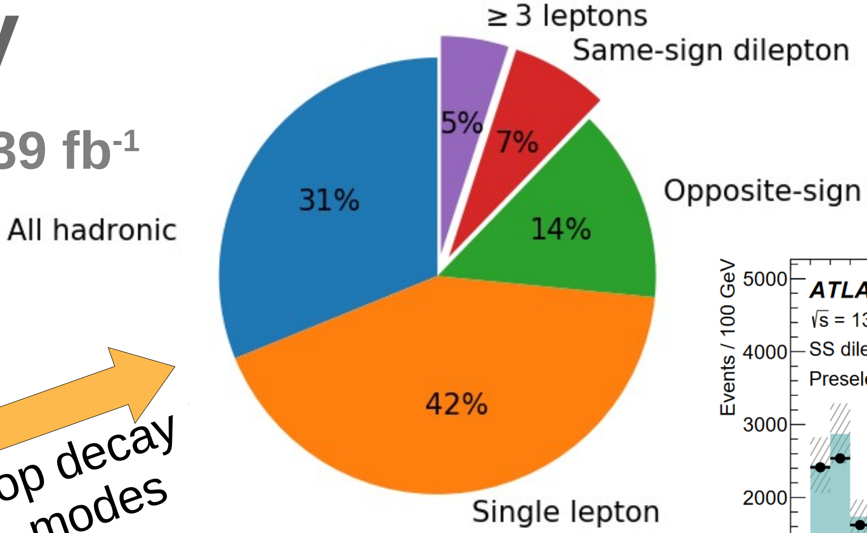
ATLAS-CONF-2020-013

Analysis strategy

Dataset at √s = 13 TeV, using **139 fb^{-1}**



Top decay modes



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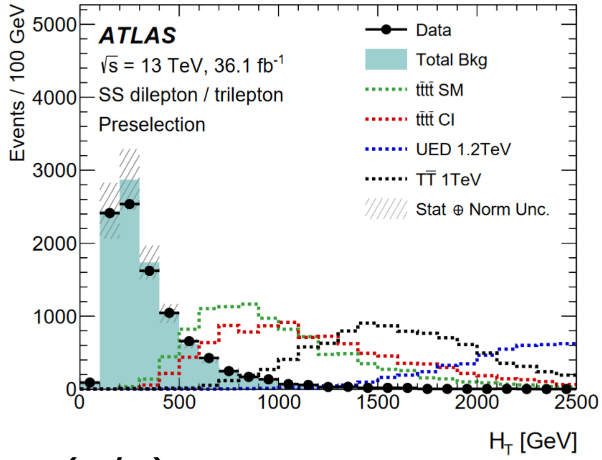
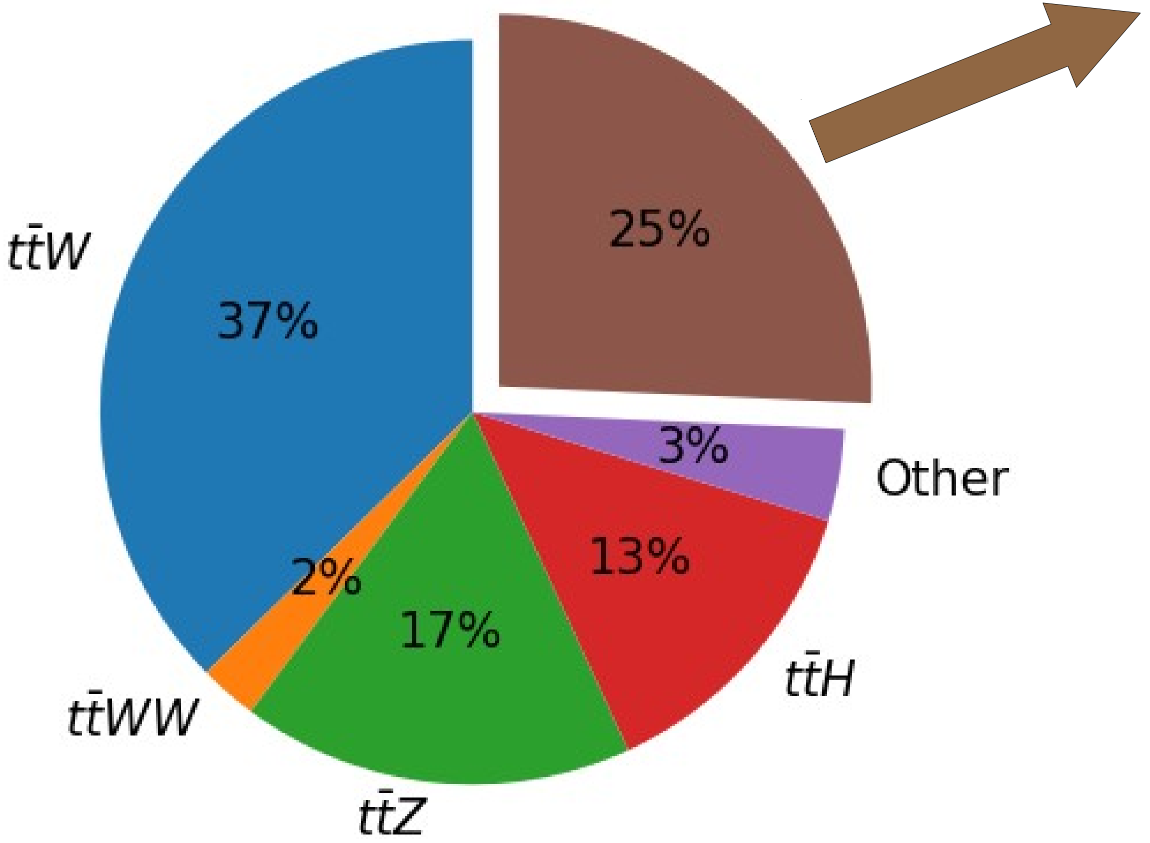


Signal region definition

- Two same-sign or ≥3 leptons (e/μ)
- ≥ 6 jets
- ≥ 2 b-jets (MV2c10 77%)
- $H_{\mathrm{T}} = \sum_{i \in \text{jets, leptons}} p_{\mathrm{T},i} > 500\ \mathrm{GeV}$

Background composition



Fake/Non-prompt leptons background composition

- Charge mis-identification [QmisID]
- Non-prompt leptons originating from HF decay [HFe/μ]
- Non-prompt from photon conversion in material [MatCO]
- Non-prompt from virtual photons [Low-mass e^+e^-]

Non-prompt lepton background

Charge misidentification

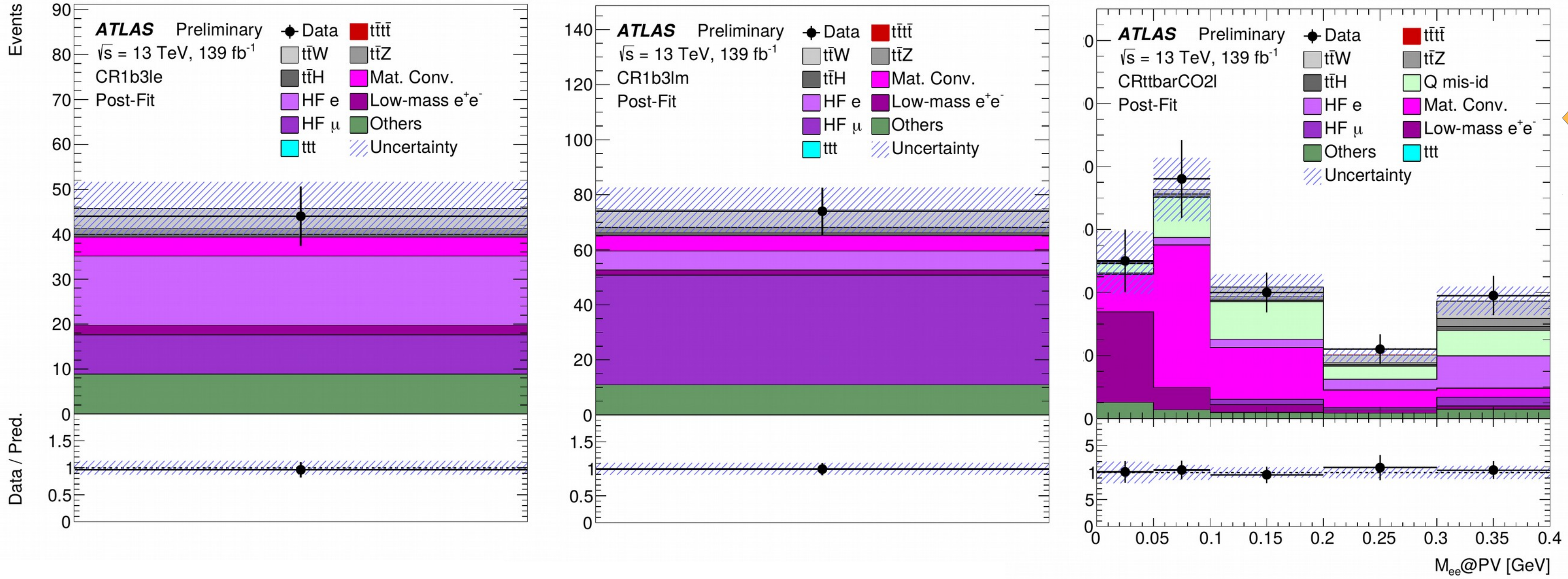
Data-Driven method based on $Z \rightarrow e^+e^-$:

- Efficiencies QmisID = Z (SS) / Z (OS)
- Apply efficiencies on OS to estimate SS

Template method

- MC shapes assumed
- Normalisation fitted

HFe HFm MatCO & Low mass e^+e^-



$t\bar{t}W$ background modelling

ATLAS-CONF-2020-013

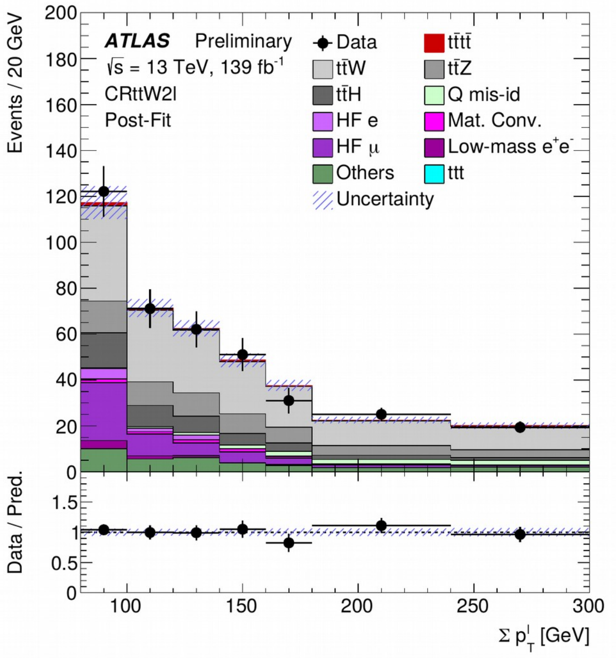
Template method

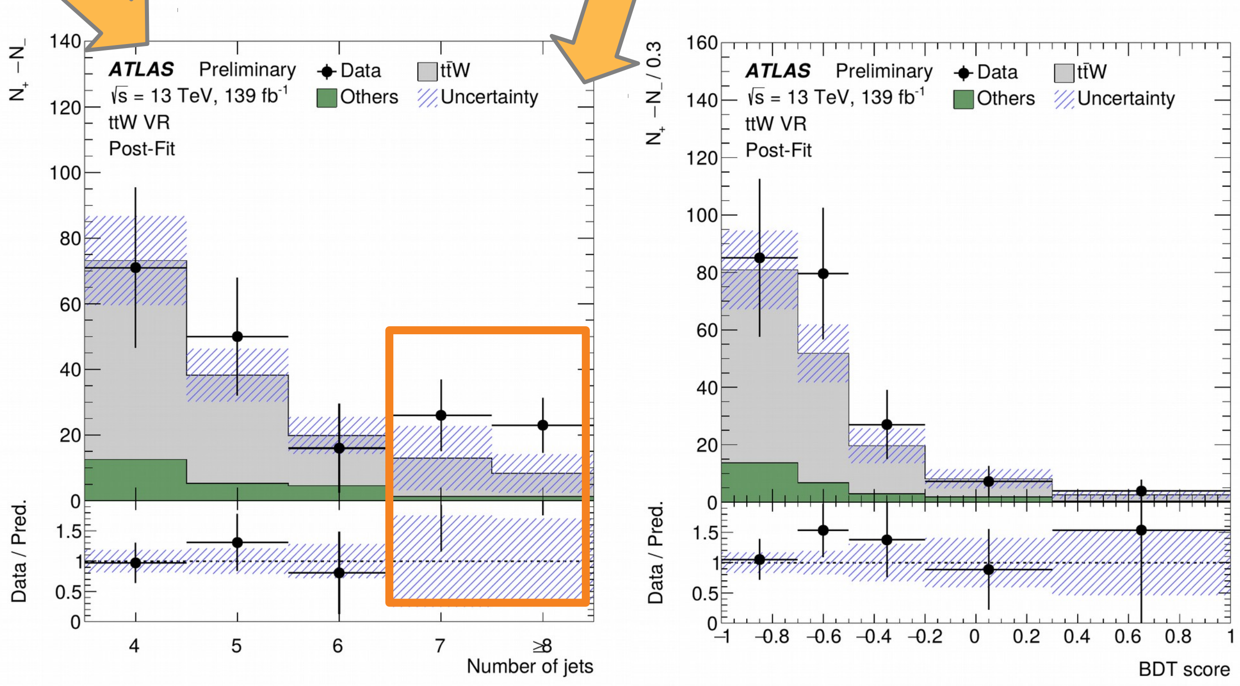
Additional uncertainties on:

- $t\bar{t}W$ w/ 7 (8) jets: **125 (300) %**
- $t\bar{t}W$ w/ 3/≥4 b-jets: **50 %**

Validation region

- Exploiting $t\bar{t}W$ charge asymmetry
- $\sum(q_l > 0) - \sum(q_l < 0)$
- $N_{jets} \geq 4$ and $N_{b\text{-}jets} \geq 2$

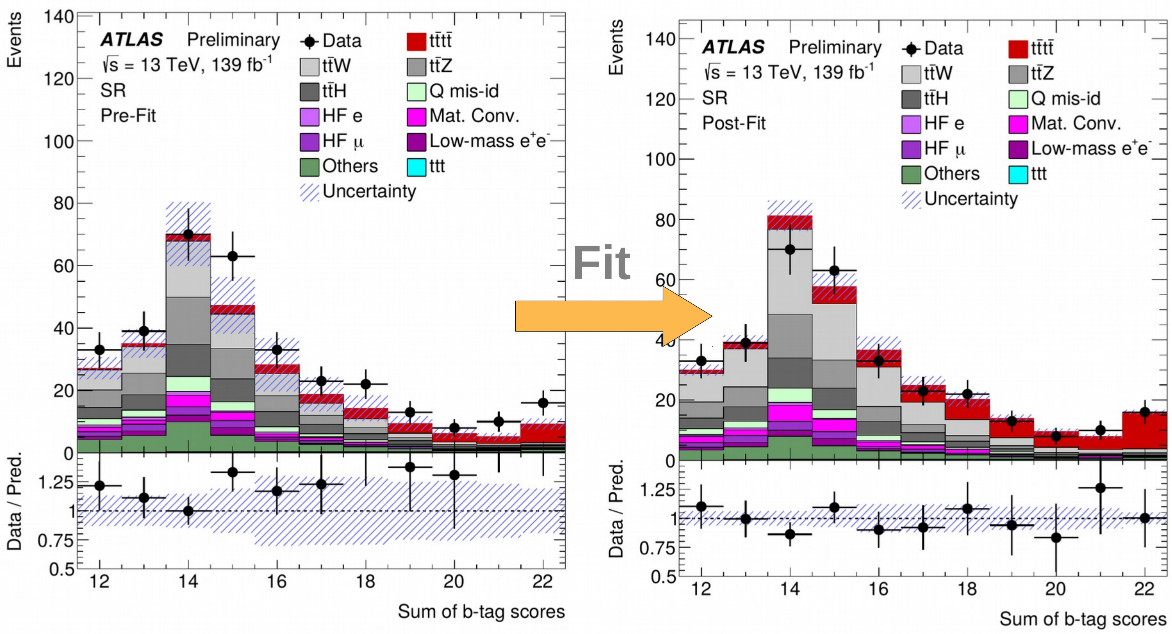




Signal discrimination

A BDT is trained to separate signal from the total background.

Optimised to maximise the separation as Receiver-Operator-Characteristics curve integral.



Input variables

- Lepton and jets p_T
- Jet/lepton topologies
- E_T^{miss}
- **B-tagging information of jets**

Sum over the b-tagging score of jets in the event

Fit to data

Profile-likelihood fit in CRs and SRs.

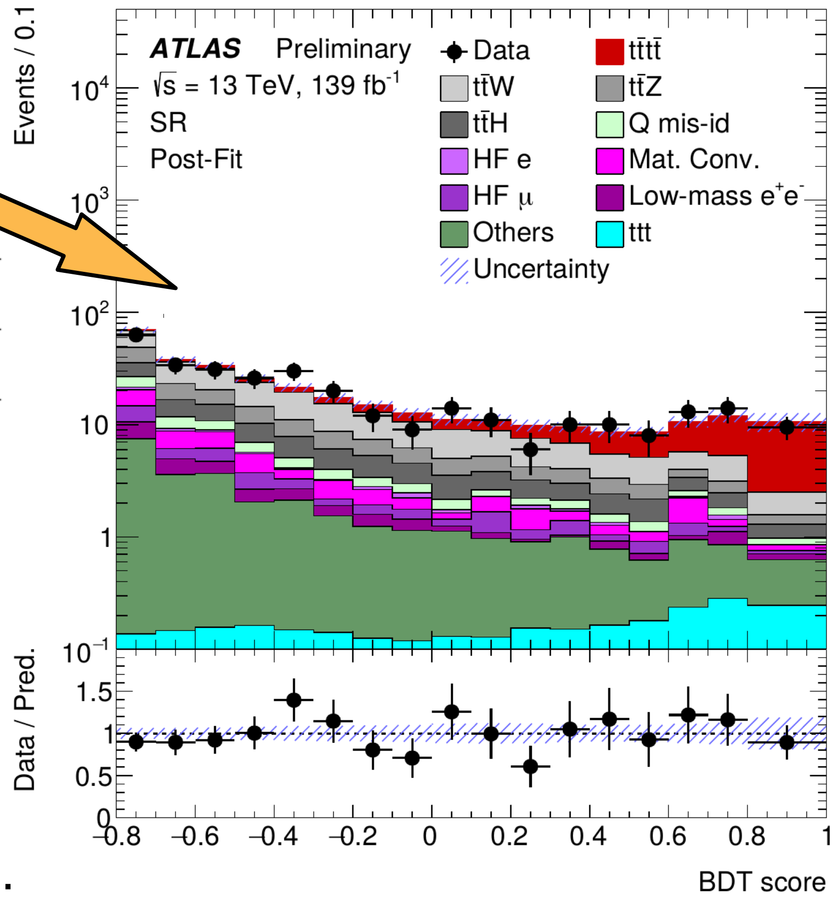
Normalisations factors fitted:

Parameter	$NF_{t\bar{t}W}$	$NF_{\text{Mat. Conv.}}$	$NF_{\text{Low } M_{ee}}$	$NF_{\text{HF } e}$	$NF_{\text{HF } \mu}$
Value	1.6 ± 0.3	1.6 ± 0.5	0.9 ± 0.4	0.8 ± 0.4	1.0 ± 0.4

The value of the $t\bar{t}t\bar{t}$ signal strength $\mu_{t\bar{t}t\bar{t}}$

$$\mu_{t\bar{t}t\bar{t}} = 2.0\,^{+0.4}_{-0.4}(\text{stat.})\,^{+0.7}_{-0.5}(\text{syst.}) = 2.0^{+0.8}_{-0.6}$$

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



Observed (expected) significance over background:

➔ **4.3 (2.4) std. dev.**

Fit to data

Profile-likelihood fit in CRs and SRs.

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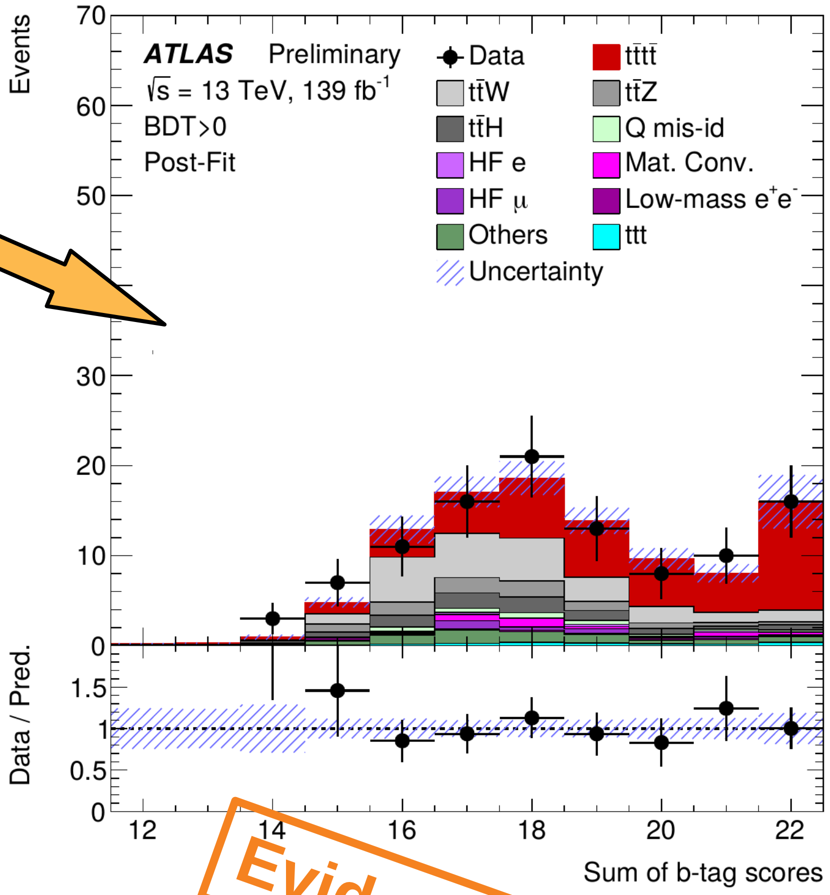
$$\sigma_{t\bar{t}t\bar{t}} = 24\,^{+5}_{-5}(\text{stat.})\,^{+5}_{-4}(\text{syst.}) = 24^{+7}_{-6}\ \text{fb}$$



Evidence!!

Observed (expected) significance over background:

➔ **4.3 (2.4) std. dev.**

Conclusions

An overview over ATLAS **latest** results on rare top quark processes is given.

FCNC tqγ coupling

- Production of single top quark via $q \rightarrow t\gamma$ vertex
- **Best limits** on EFT operators and branching ratios

SM production of tZq

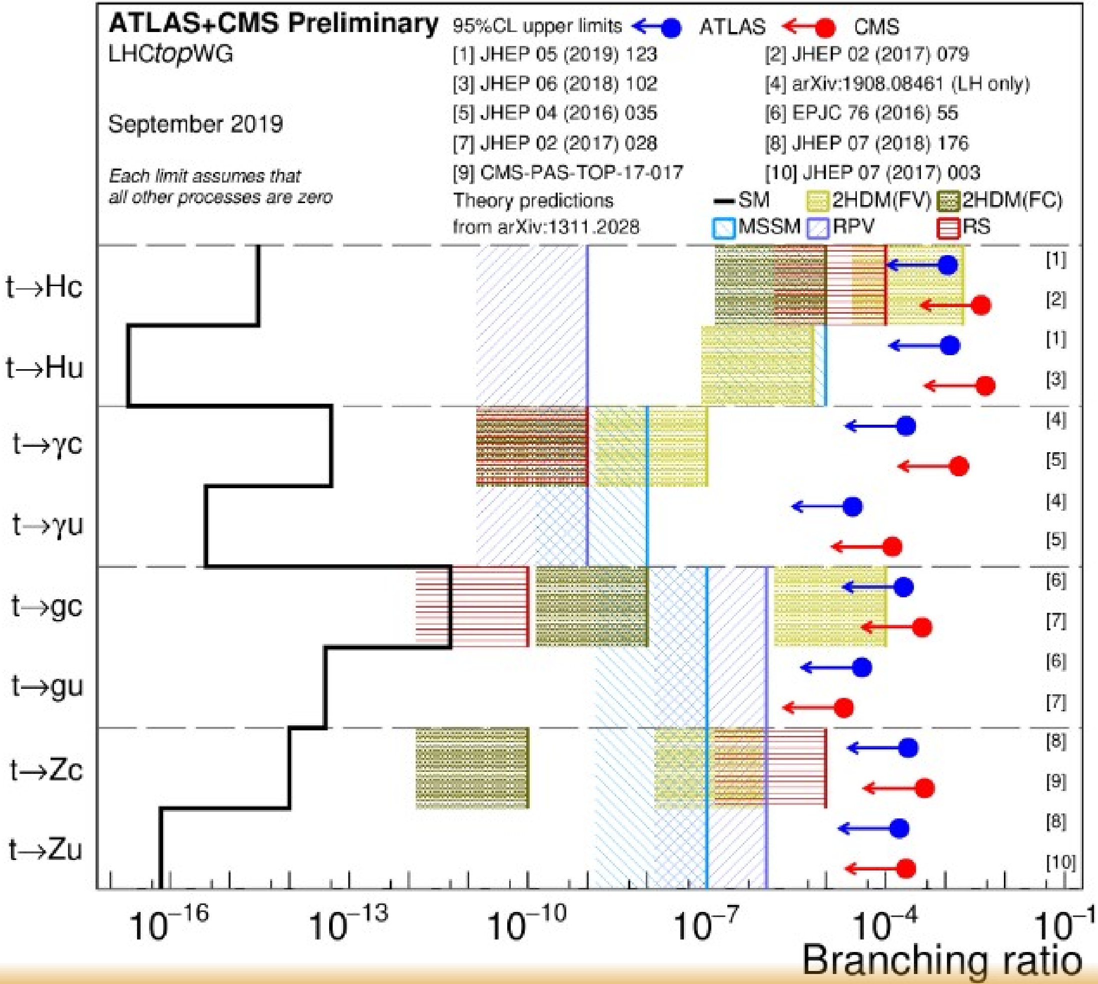
- Sensitive to tZ coupling (but also to WZ)
- **Observation!** Cross-section compatible with SM within 1σ

SM four top quarks production

- Same-sign dilepton and multilepton channel
- **Evidence of $t\bar{t}t\bar{t}$** – significance of 4.3 (2.4) std. dev.
- **Cross-section compatible with SM within 1.7σ**

Backup

tqγ – FCNC Summary



tqγ – Systematics impact

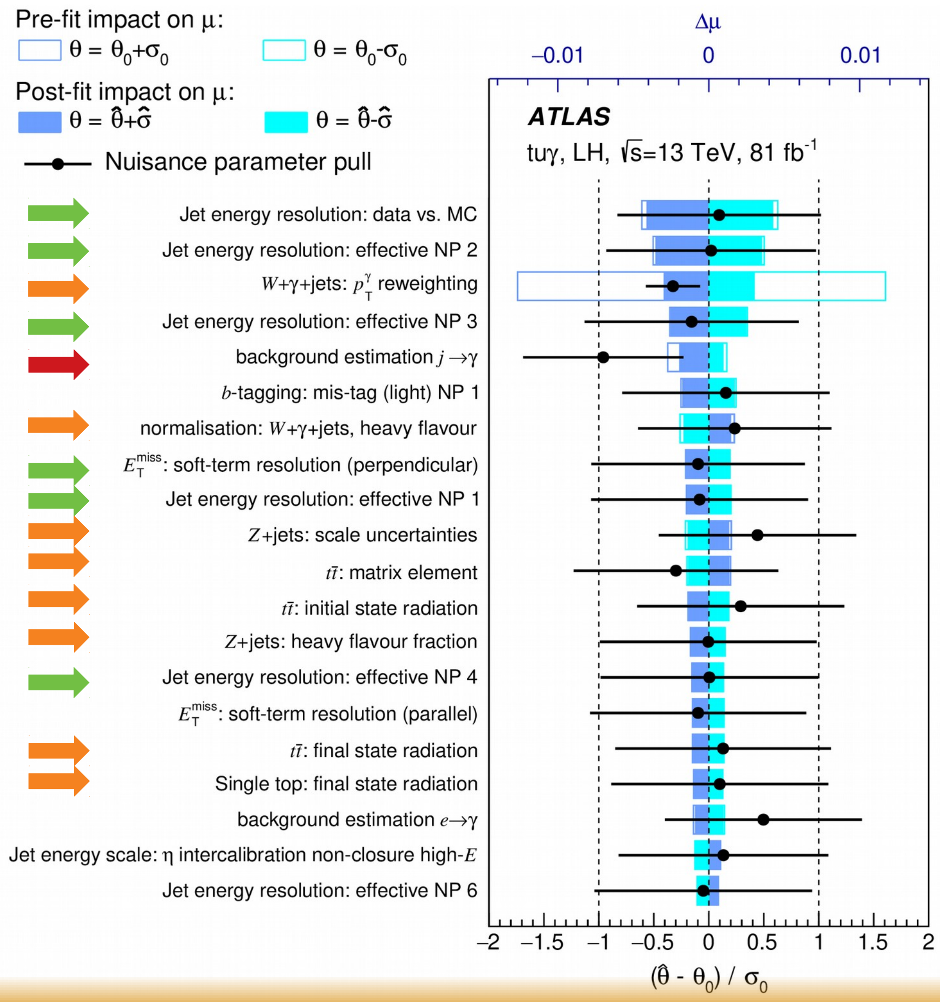
JER

Prompt-photon modeling

j→γ estimation

Data driven method

- Iso/ID efficiencies on looser photon
- Applied to loose photon to tight

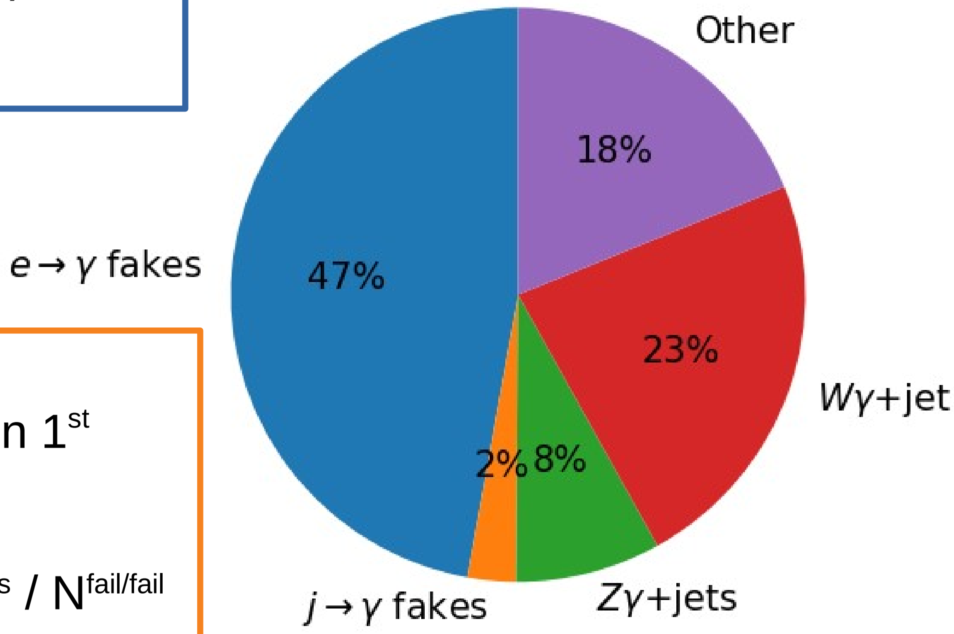


tqγ – Background estimation

DD estimation
- Fit of Z peak
- $f_{e\gamma}$ from M(eγ) / M(ee)
- SF from Data/MC

MC-based

SF measured in CR
- Same as SR
- No b-jets
- $M_{let\text{-}photon}$ not in Z peak

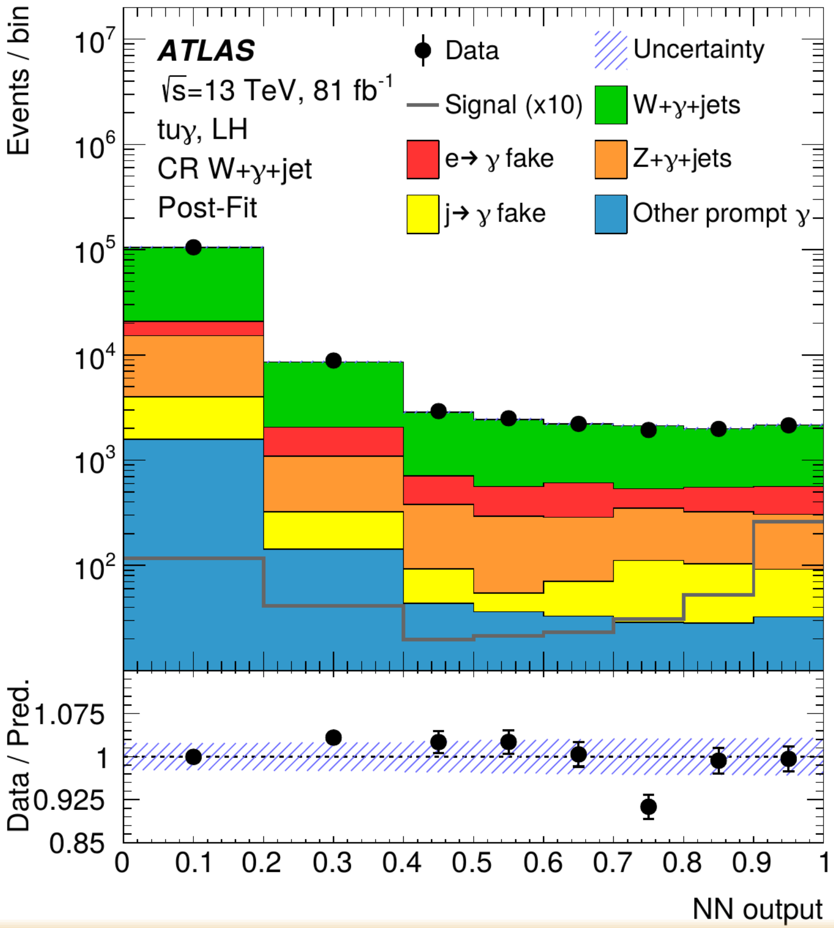


SF measured in CR
- Same as SR
- No b-jets
- Dilepton Same-Flavour
- M_{ll} in Z peak

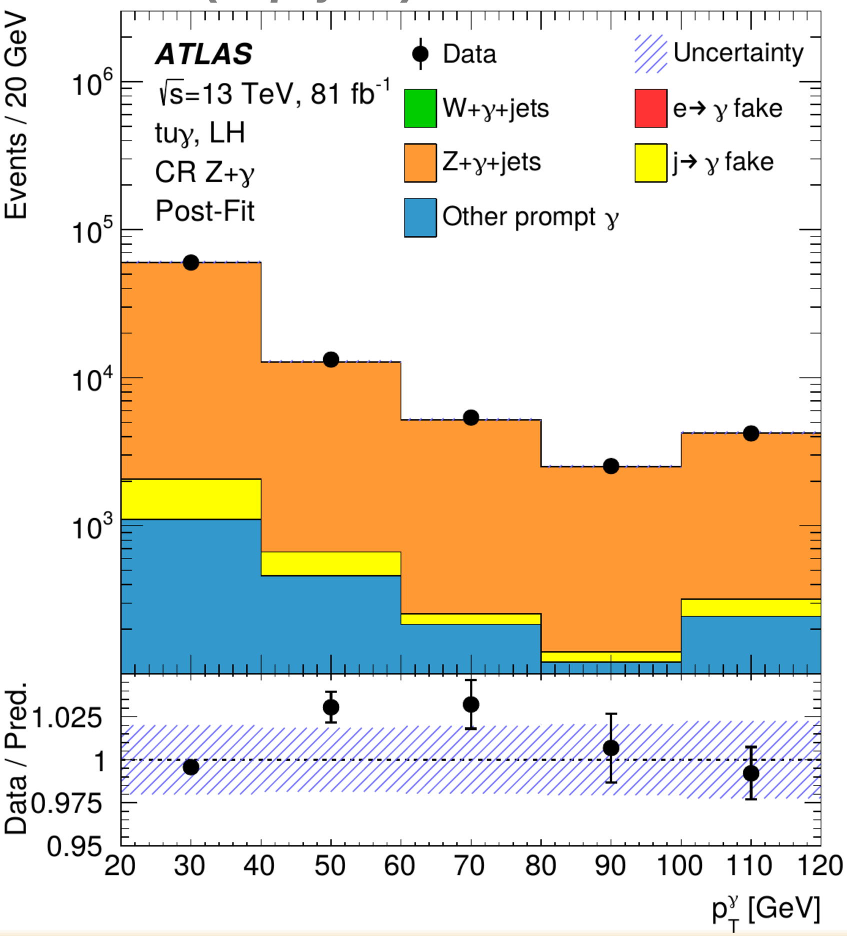
DD estimation
- Index 1: ID criteria on 1st layer
- Index 2: Iso
- SF = $N^{pass|fail}$ x $N^{fail|pass}$ / $N^{fail/fail}$ Data/MC

tqγ – Control regions

SF (Zγ+jets) = 1.12 ± 0.12



SF (Wγ+jets) = 1.25 ± 0.09



tZq – Control regions definition

Common selections			
Exactly 3 leptons (e or μ) with $\lvert\eta\rvert < 2.5$ $p_T(\ell_1) > 28$ GeV, $p_T(\ell_2) > 20$ GeV, $p_T(\ell_3) > 20$ GeV $p_T(\text{jet}) > 35$ GeV			
SR 2j1b	CR diboson 2j0b	CR $t\bar{t}$ 2j1b	CR $t\bar{t}Z$ 3j2b
≥ 1 OSSF pair $\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV 2 jets, $\lvert\eta\rvert < 4.5$ 1 b-jet, $\lvert\eta\rvert < 2.5$	≥ 1 OSSF pair $\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV 2 jets, $\lvert\eta\rvert < 4.5$ 0 b-jets	≥ 1 OSDF pair No OSSF pair 2 jets, $\lvert\eta\rvert < 4.5$ 1 b-jet, $\lvert\eta\rvert < 2.5$	≥ 1 OSSF pair $\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV 3 jets, $\lvert\eta\rvert < 4.5$ 2 b-jets, $\lvert\eta\rvert < 2.5$
SR 3j1b	CR diboson 3j0b	CR $t\bar{t}$ 3j1b	CR $t\bar{t}Z$ 4j2b
≥ 1 OSSF pair $\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV 3 jets, $\lvert\eta\rvert < 4.5$ 1 b-jet, $\lvert\eta\rvert < 2.5$	≥ 1 OSSF pair $\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV 3 jets, $\lvert\eta\rvert < 4.5$ 0 b-jets	≥ 1 OSDF pair No OSSF pair 3 jets, $\lvert\eta\rvert < 4.5$ 1 b-jet, $\lvert\eta\rvert < 2.5$	≥ 1 OSSF pair $\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV 4 jets, $\lvert\eta\rvert < 4.5$ 2 b-jets, $\lvert\eta\rvert < 2.5$

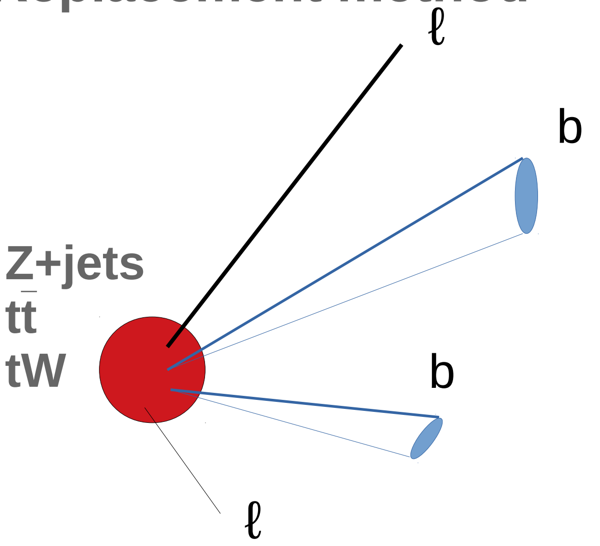
tZq – non-prompt leptons

arXiv:2002.07546

Events from tW, $t\bar{t}$ and Z+jets enter SR only with a ‘’fake’’ lepton.
Main source: non-prompt e/μ from heavy-flavour hadrons.
MC-simulation with poor statistics → **how to enhance it?**

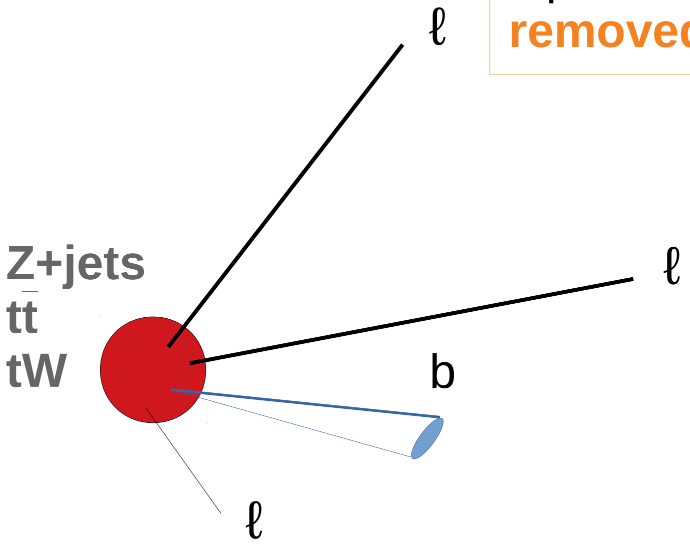
If b-jet too close to new lepton → **removed**

Replacement method

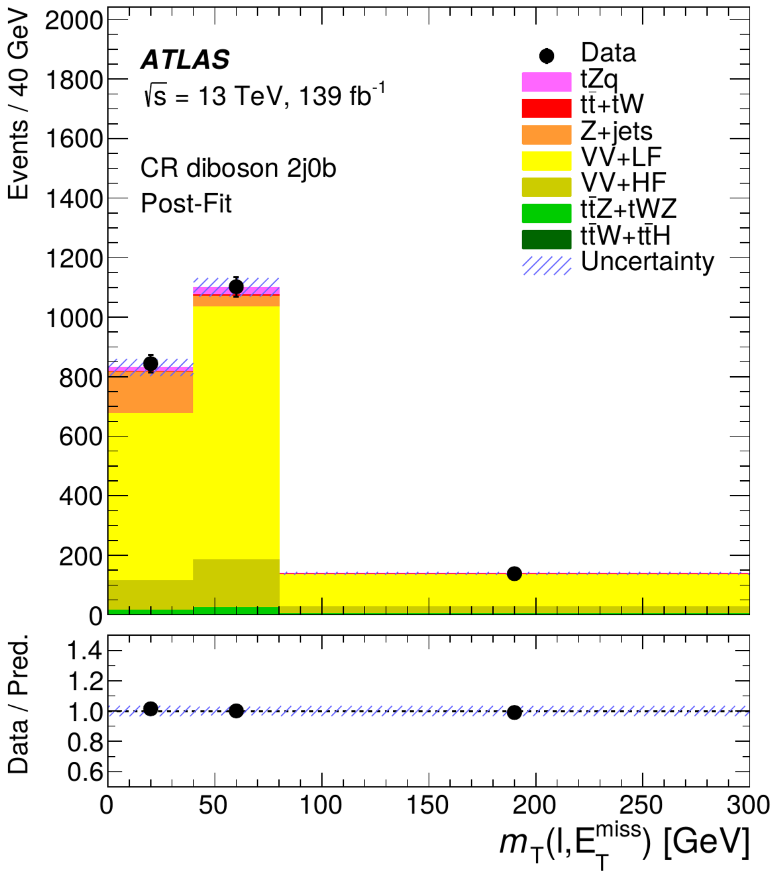


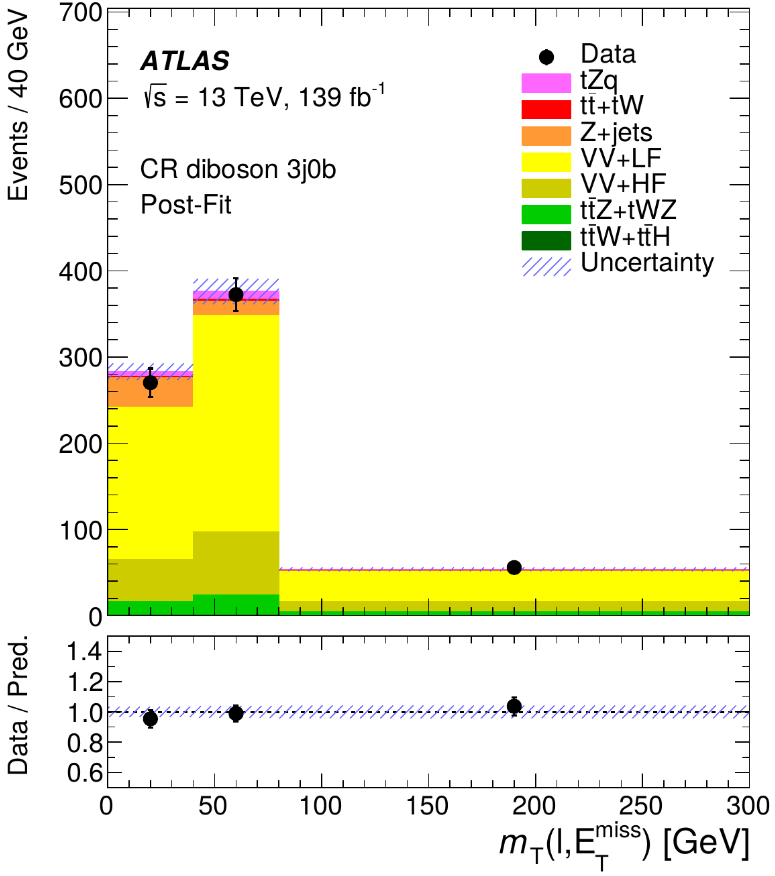
B-jet → lepton

Lepton kinematics
Assigned from truth
wrt b-jet

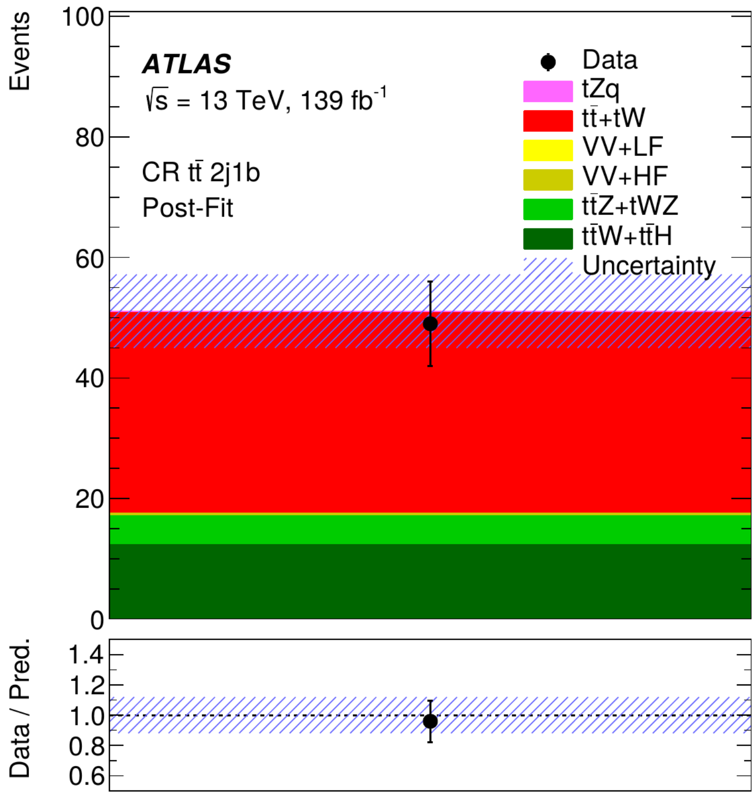


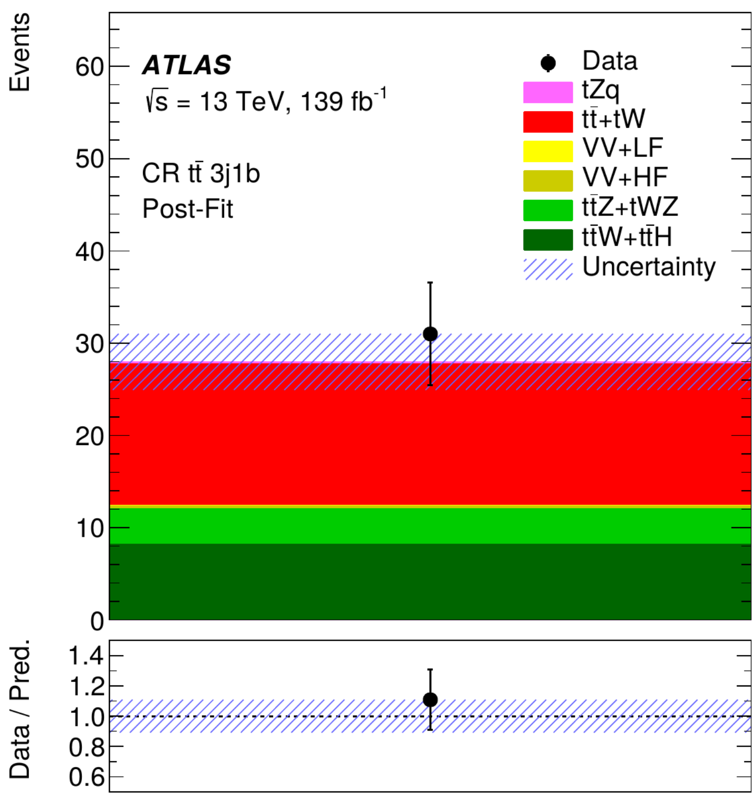
tZq – Diboson control regions



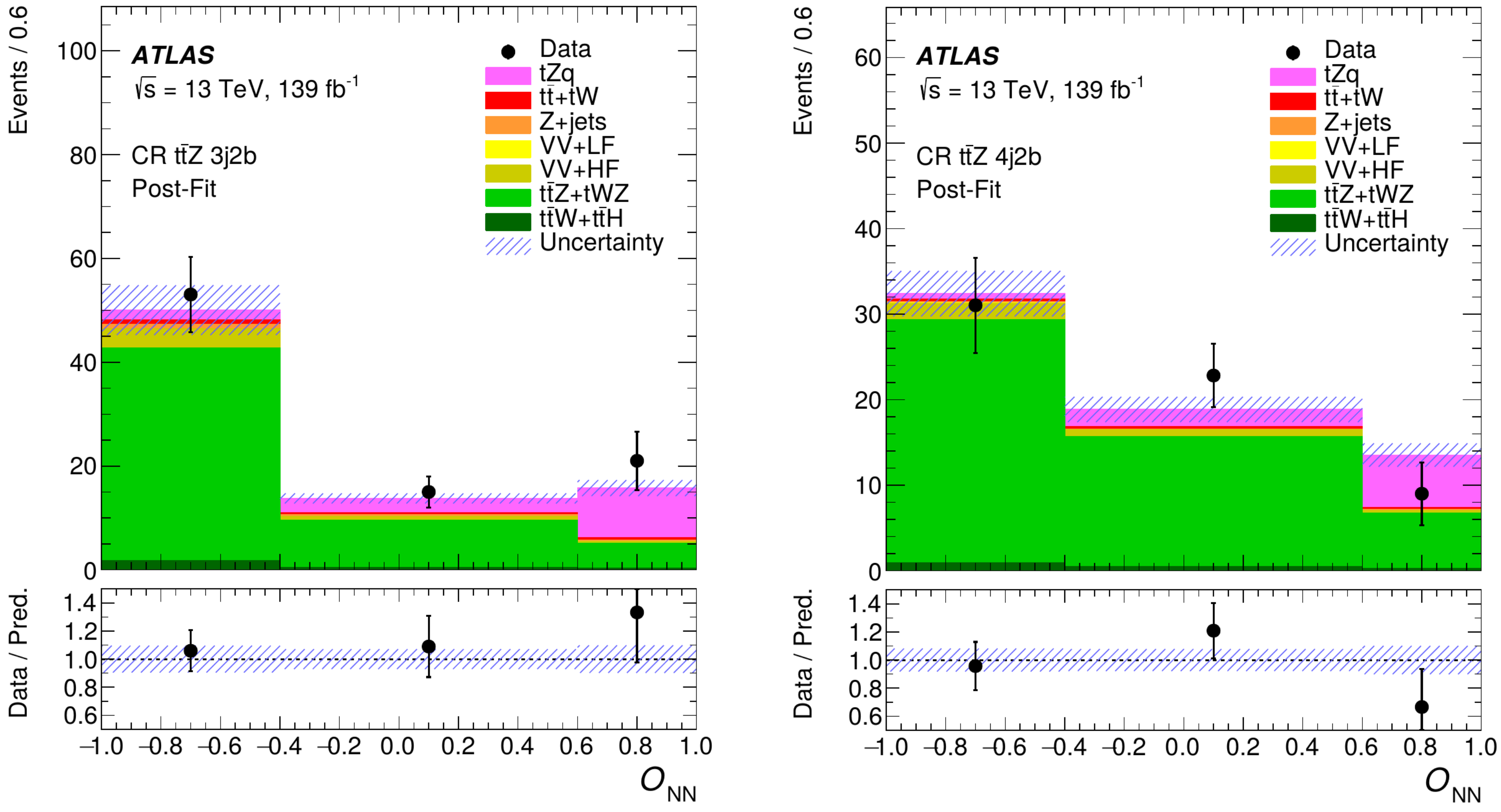


tZq – $t\bar{t}$ control regions

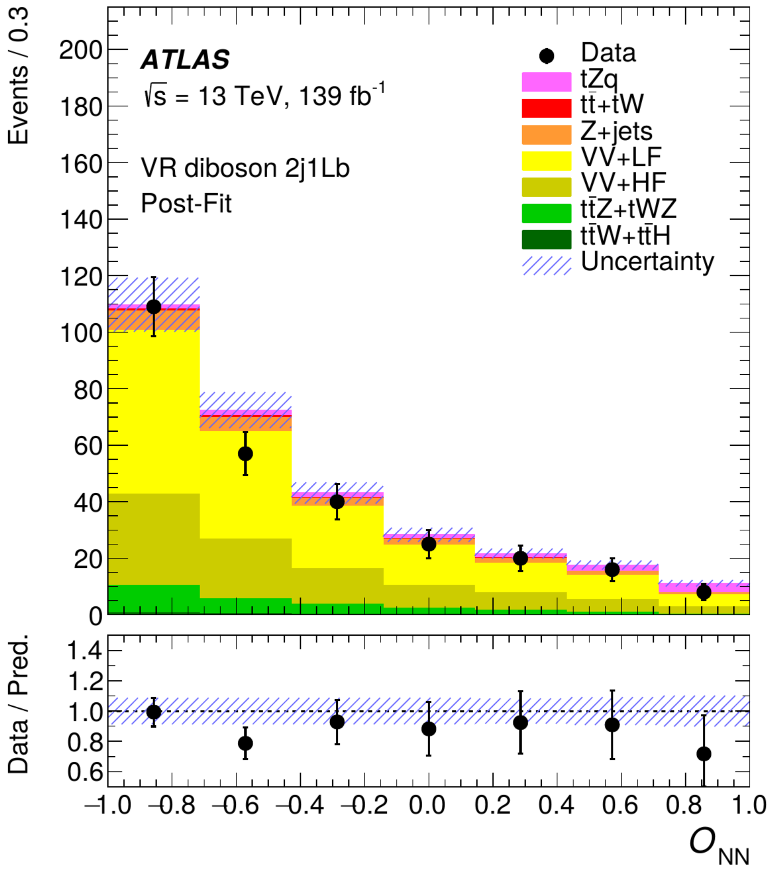


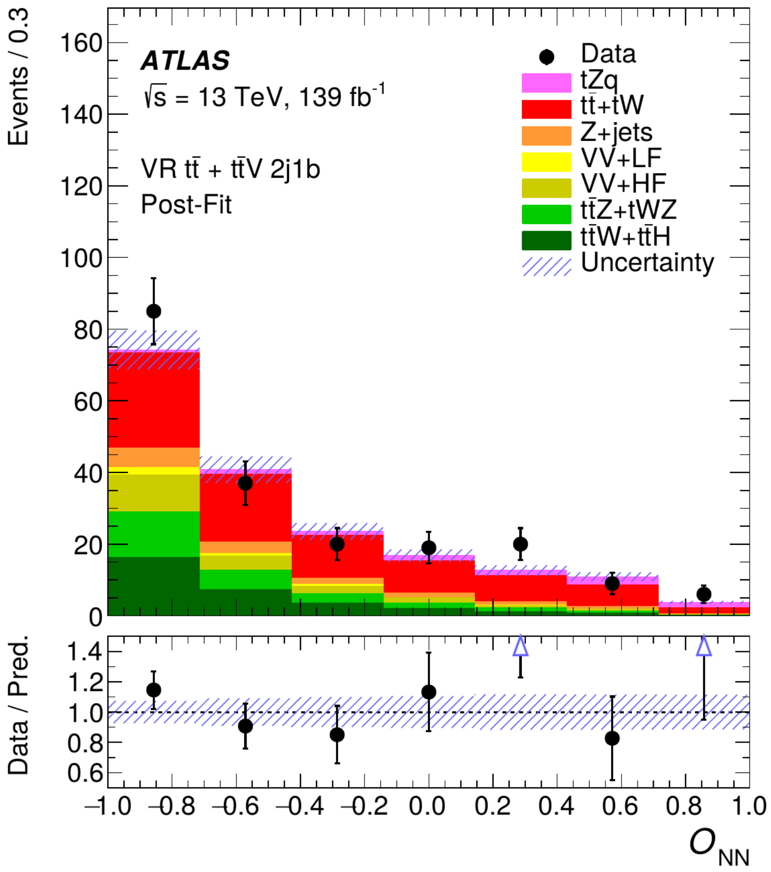


tZq – $t\bar{t}Z$ control regions

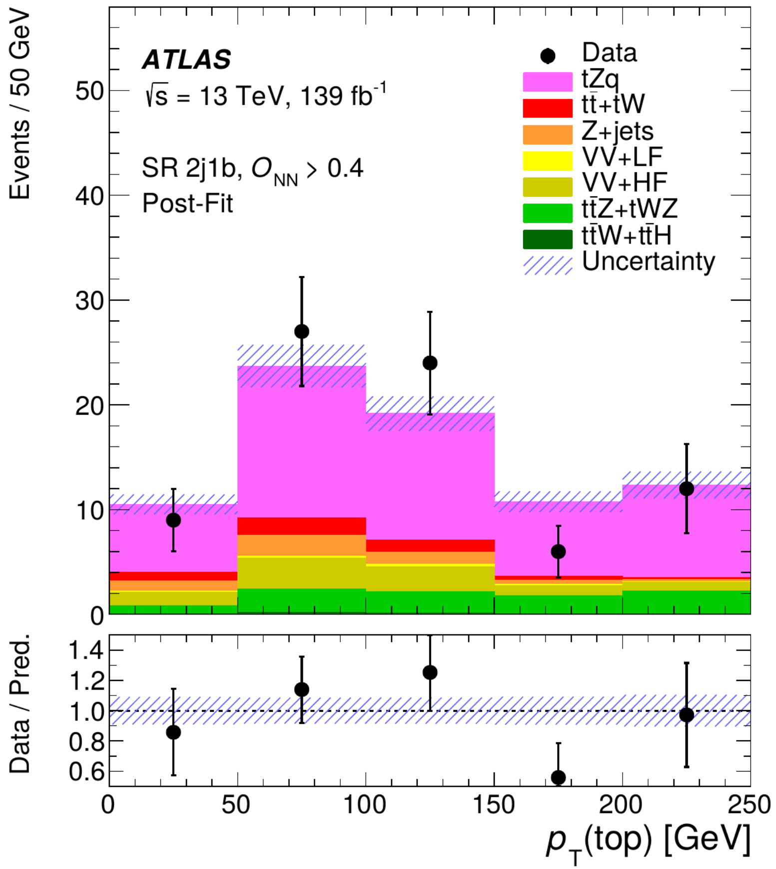


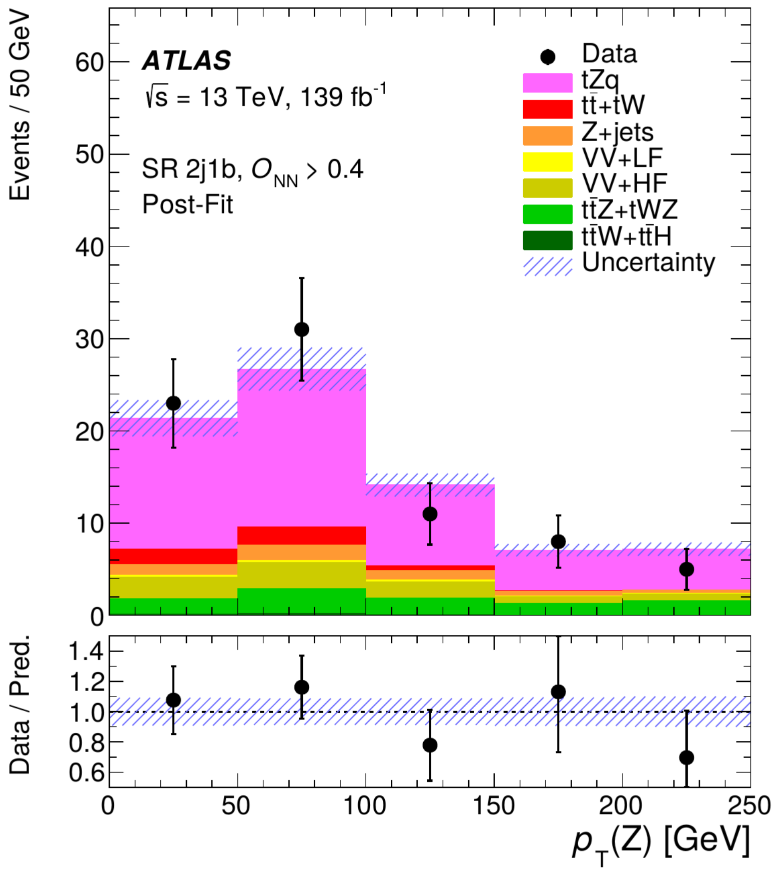
tZq – Validation regions



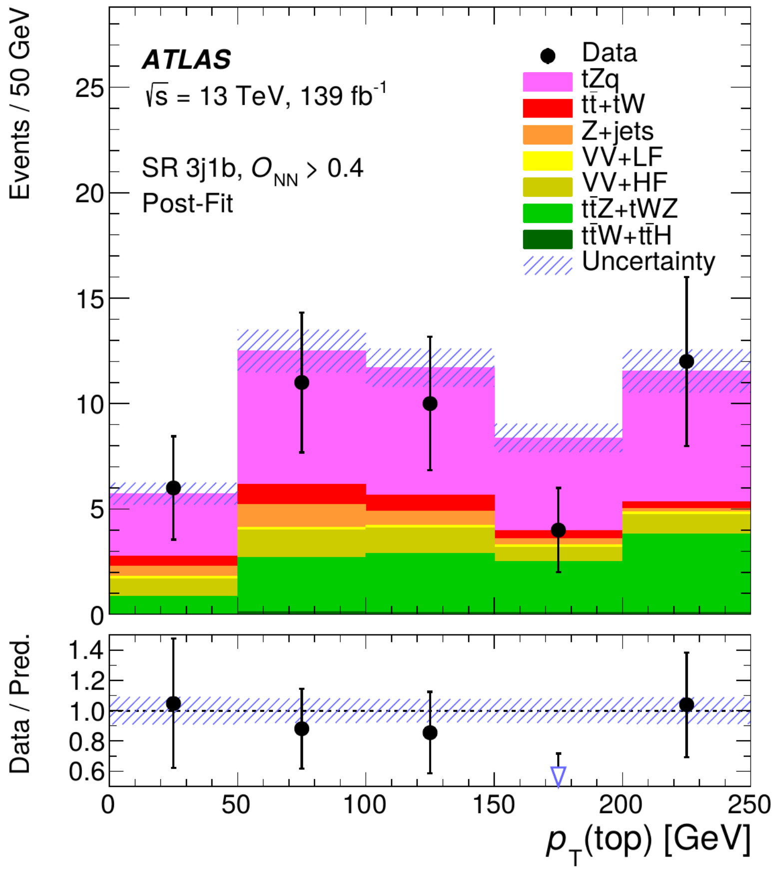


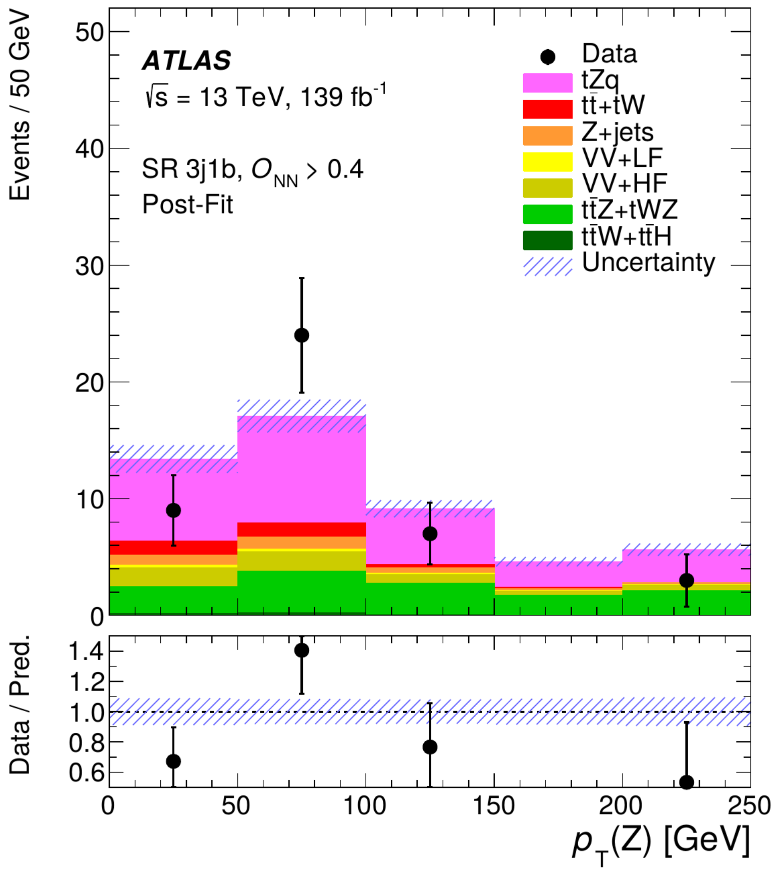
tZq – Signal modelling in SR





tZq – Signal modelling in SR





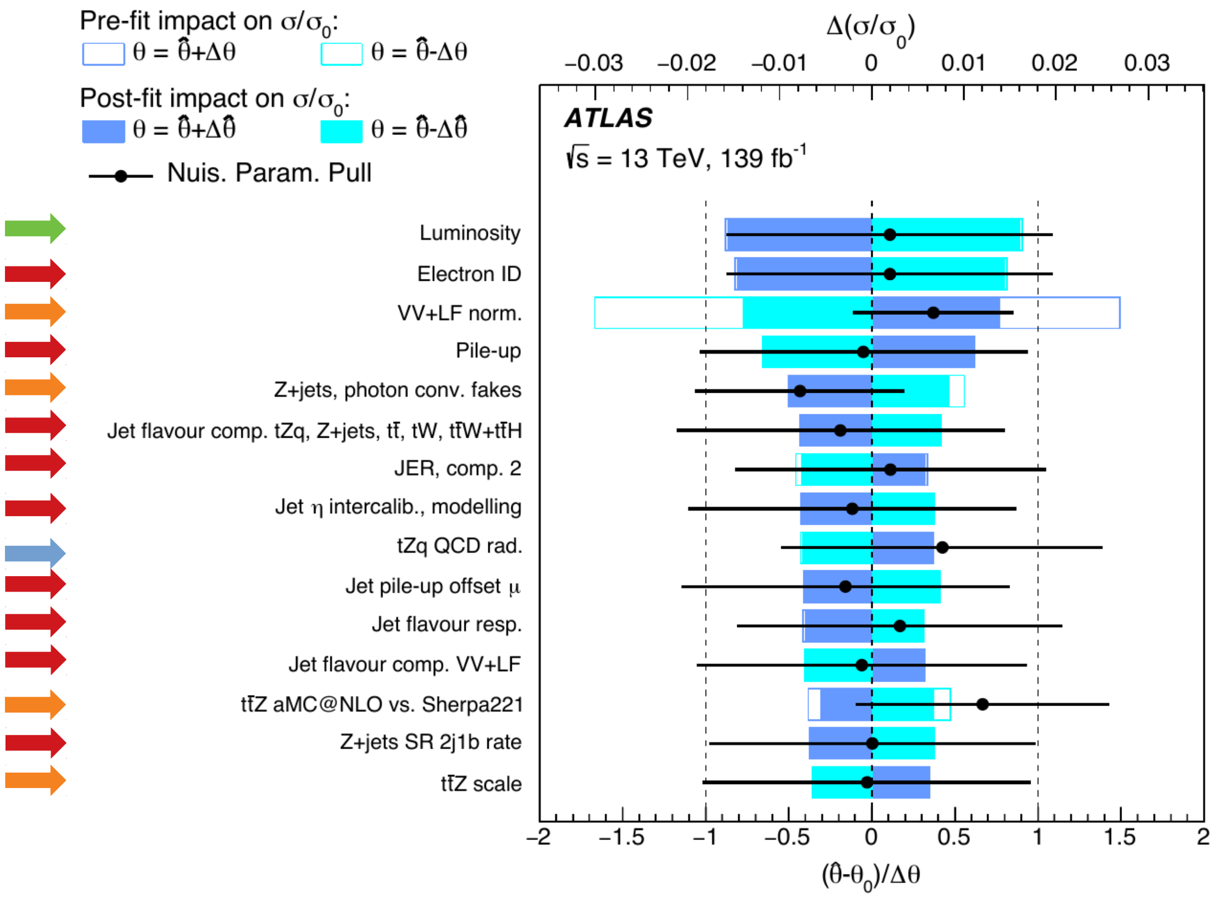
tZq – Systematics impact

Luminosity

Prompt-lepton

Instrumental

Signal modeling



tZq – NN settings/training

A different NN trained in each signal region.

NeuroBayes
Same input variables
→ used the best 15

Variable	Rank SR 2j1b	Rank SR 3j1b	Definition
m_{bj_f}	1	1	(Largest) invariant mass of the b-jet and the untagged jet(s)
m_{top}	2	2	Reconstructed top-quark mass
$\|\eta(j_f)\|$	3	3	Absolute value of the η of the j_f jet
$m_T(\ell, E_T^{miss})$	4	4	Transverse mass of the W boson
b-tagging score	5	11	b-tagging score of the b-jet
H_T	6	–	Scalar sum of the p_T of the leptons and jets in the event
$q(\ell_W)$	7	8	Electric charge of the lepton from the W-boson decay
$\|\eta(\ell_W)\|$	8	12	Absolute value of the η of the lepton from the W-boson decay
$p_T(W)$	9	15	p_T of the reconstructed W boson
$p_T(\ell_W)$	10	14	p_T of the lepton from the W-boson decay
$m(\ell\ell)$	11	–	Mass of the reconstructed Z boson
$\|\eta(Z)\|$	12	13	Absolute value of the η of the reconstructed Z boson
$\Delta R(j_f, Z)$	13	7	ΔR between the j_f jet and the reconstructed Z boson
E_T^{miss}	14	–	Missing transverse momentum
$p_T(j_f)$	15	10	p_T of the j_f jet
$\|\eta(j_r)\|$	–	5	Absolute value of the η of the j_r jet
$p_T(Z)$	–	6	p_T of the reconstructed Z boson
$p_T(j_r)$	–	9	p_T of the j_r jet

Forward+central jets

Against VV

Forward untagged jet

Against VV

Against VV/ttZ

4tops – Signal discrimination

Input variables:

- Leading lepton p_T
- E_T^{miss}
- Leading and sub-leading jet p_T
- 6^{th} highest jet p_T
- Leading b-jet p_T
- Sum over lepton and jet p_T (except leading)
- $\sum \Delta R_{ll}$
- Max (ΔR_{bl})
- Min (ΔR_{bj})
- Sum of b-tagging score
- Min (ΔR_{ll})

Validation:

- Three-fold validation
- 2 sets for the evaluation (input variables)
- 1 set to test different configurations

Hyperparameters tested:

- Depth of the three
- Number of trees
- Learning rate...

4tops – Systematics impact

4tops modeling

ttW modeling

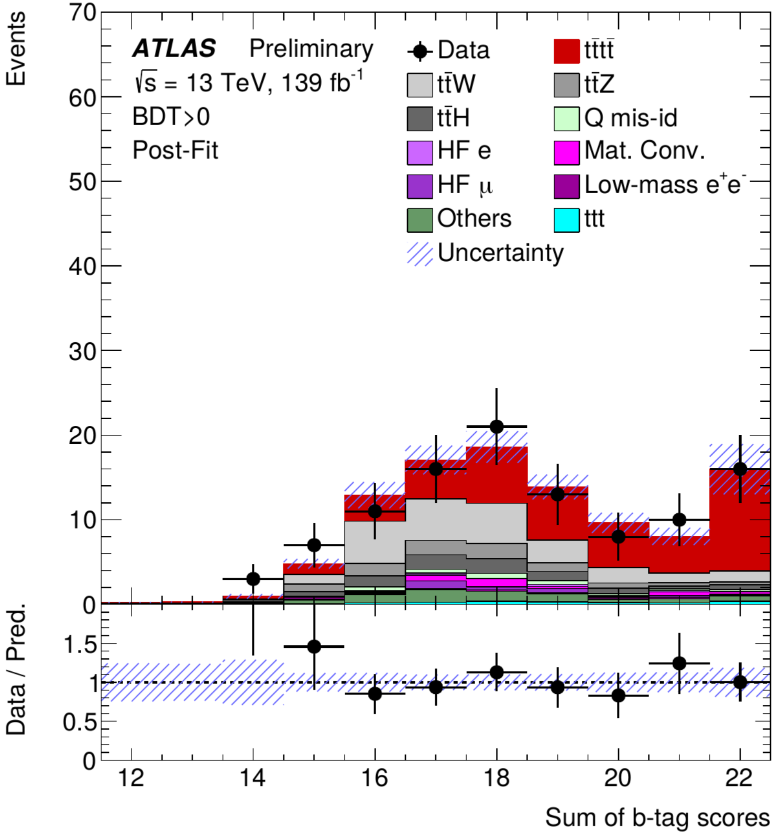
ttt modeling

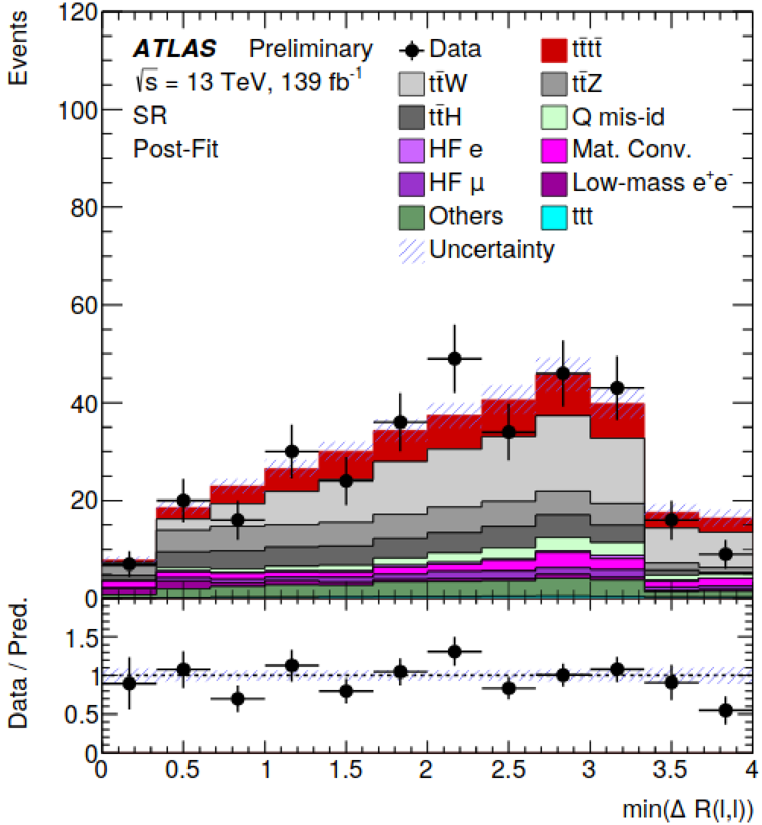
JES

B-tagging

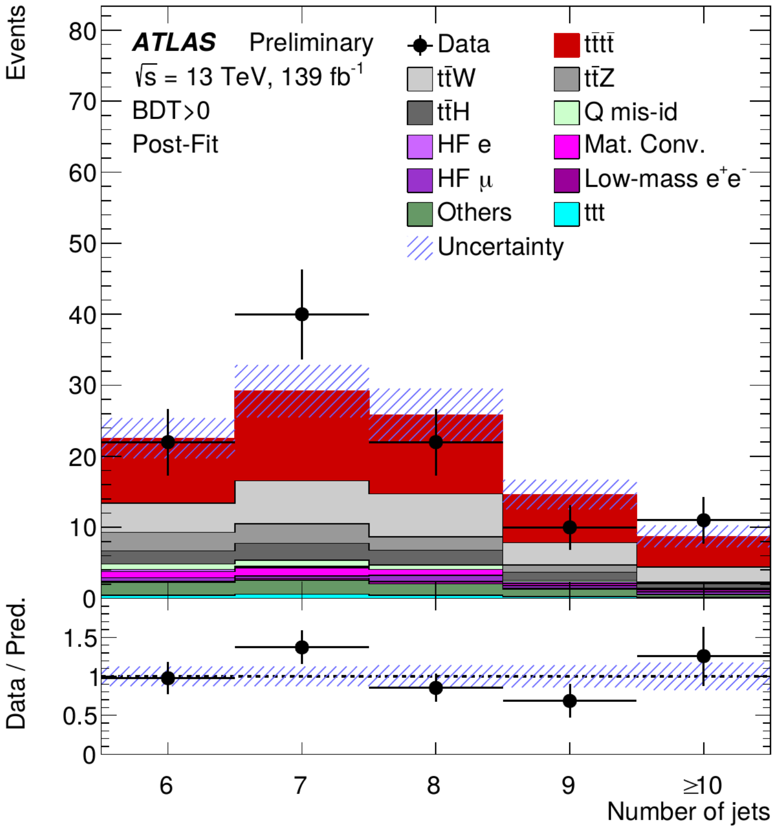
Uncertainty source	$\Delta\mu$	
Signal modelling		
$t\bar{t}t\bar{t}$ cross section	+0.56	−0.31
$t\bar{t}t\bar{t}$ modelling	+0.15	−0.09
Background modelling		
$t\bar{t}W$ modelling	+0.26	−0.27
$t\bar{t}t$ modeling	+0.10	−0.07
Non-prompt leptons modeling	+0.05	−0.04
$t\bar{t}H$ modelling	+0.04	−0.01
$t\bar{t}Z$ modelling	+0.02	−0.04
Charge misassignment	+0.01	−0.02
Instrumental		
Jet uncertainties	+0.12	−0.08
Jet flavour tagging (light-jets)	+0.11	−0.06
Simulation sample size	+0.06	−0.06
Luminosity	+0.05	−0.03
Jet flavour tagging (b-jets)	+0.04	−0.02
Other experimental uncertainties	+0.03	−0.01
Jet flavour tagging (c-jets)	+0.03	−0.01
Total systematic uncertainty	+0.69	−0.46
Statistical	+0.42	−0.39
Non-prompt leptons normalisation(HF, material conversions)	+0.05	−0.04
$t\bar{t}W$ normalisation	+0.04	−0.04
Total uncertainty	+0.82	−0.62

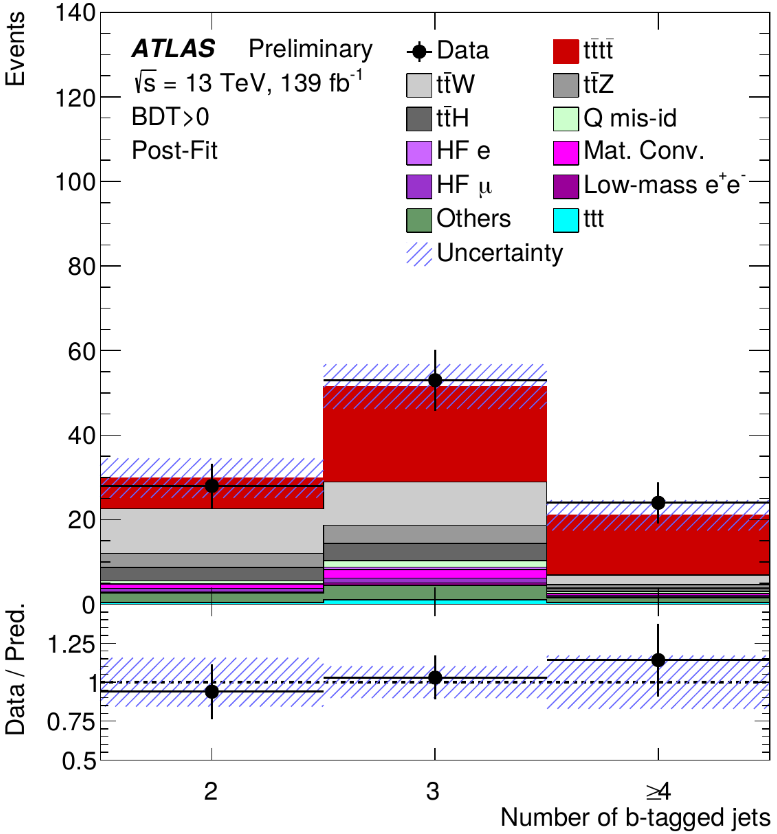
4tops – Signal modelling in SR I





4tops – Signal modelling in SR II



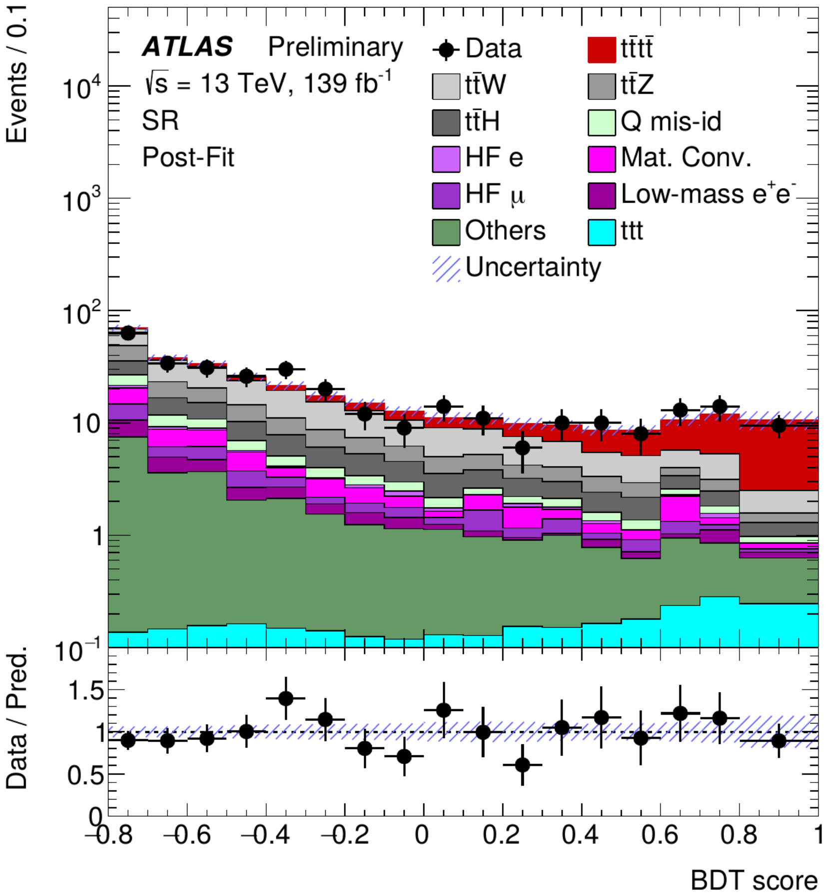


4tops – ttt/ttZ uncertainties

The ttt process share similar features with the 4tops signal.

Modeling uncertainties:
- Ad-hoc 100% on cross-section
- ttt with 3b or ≥4b: 50%

Additional uncertainties on ttZ:
- ttt with 3b or ≥4b: 50%



4tops – Non-prompt leptons unc.

QmisID
- Statistics of the Z mass peak fit
- Fit range
- Discrepancy of MC/Data efficiencies

Non-prompt from HF (e/m)
- Normalisation from the fit
- Shape: Data/MC comparison in the regions with looser lepton definition

Material/virtual photon conversion
- Selecting Z(μμ)+γ events
- Shape from Data/MC
- Normalisation from the fit

4tops – Control regions

Region	Channel	N_j	N_b	Other requirements	Fitted variable
CRttbarCO2l	$e^{\pm}e^{\pm}\|\|e^{\pm}\mu^{\pm}$	$4 \leq N_j < 6$	≥ 1	$M_{ee}@CV \in [0, 0.1\text{ GeV}]$ $200 < H_{\mathrm{T}} < 500$ GeV	$M_{ee}@\mathrm{PV}$
CR1b3Le	$eee \;\|\|\; ee\mu$	-	$= 1$	$100 < H_{\mathrm{T}} < 250$ GeV	counting
CR1b3Lm	$e\mu\mu \;\|\|\; \mu\mu\mu$	-	$= 1$	$100 < H_{\mathrm{T}} < 250$ GeV	counting
CRttW2l	$e^{\pm}\mu^{\pm}\|\|\mu^{\pm}\mu^{\pm}$	≥ 4	≥ 2	$M_{ee}@CV \notin [0, 0.1\text{ GeV}]$, $\|\eta(e)\| < 1.5$ for $N_b = 2$, $H_{\mathrm{T}} < 500$ GeV or $N_j < 6$ for $N_b \geq 3$, $H_{\mathrm{T}} < 500$ GeV	$\Sigma p_{\mathrm{T}}^{\ell}$

4tops – ttH ML results

ATLAS-CONF-2019-045

Channel	Selection criteria
Common	$N_{\text{jets}} \geq 2$ and $N_{b\text{-jets}} \geq 1$
2ℓSS	Two same-charge (SS) very tight (T*) leptons, $p_T > 20$ GeV
	No τ_{had} candidates
	$m(\ell^+\ell^-) > 12$ GeV for all SF pairs
	13 categories: enriched with $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}$, mat. conv, int. conv.,
	split by lepton flavour, charge, jet and b-jet multiplicity
3ℓ	Three loose (L) leptons with $p_T > 10$ GeV; sum of light-lepton charges = ±1
	Two SS very tight (T*) leptons, $p_T > 15$ GeV
	One OS (w.r.t the SS pair) loose-isolated (L*) lepton, $p_T > 10$ GeV
	No τ_{had} candidates
	$m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert > 10$ GeV for all SFOS pairs
	$\lvert m(3\ell) - 91.2\text{ GeV}\rvert > 10$ GeV
	7 categories: enriched with $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$, VV, $t\bar{t}$, mat. conv, int. conv

SF on ttW XS on Y:

- NLO QCD ttW+1jet: 1.11
- NLO EW ttW+1jet: 1.09

= **1.20**

Fitted NF for ttW XS:

$$\hat{\lambda}^{2\ell\text{LJ}}_{t\bar{t}W} = 1.56^{+0.30}_{-0.28},\ \hat{\lambda}^{2\ell\text{HJ}}_{t\bar{t}W} = 1.26^{+0.19}_{-0.18},\text{ and } \hat{\lambda}^{3\ell}_{t\bar{t}W} = 1.68^{+0.30}_{-0.28}.$$