Observation of the associated production of a top quark and a Z boson at 13 TeV with ATLAS

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on behalf of the ATLAS Collaboration

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Outline & Info

- Introduction to Standard Model (SM) tZq process
- Event topology
- Background estimation
- Analysis & fit strategy
- Results

Paper submitted for publication to JHEP
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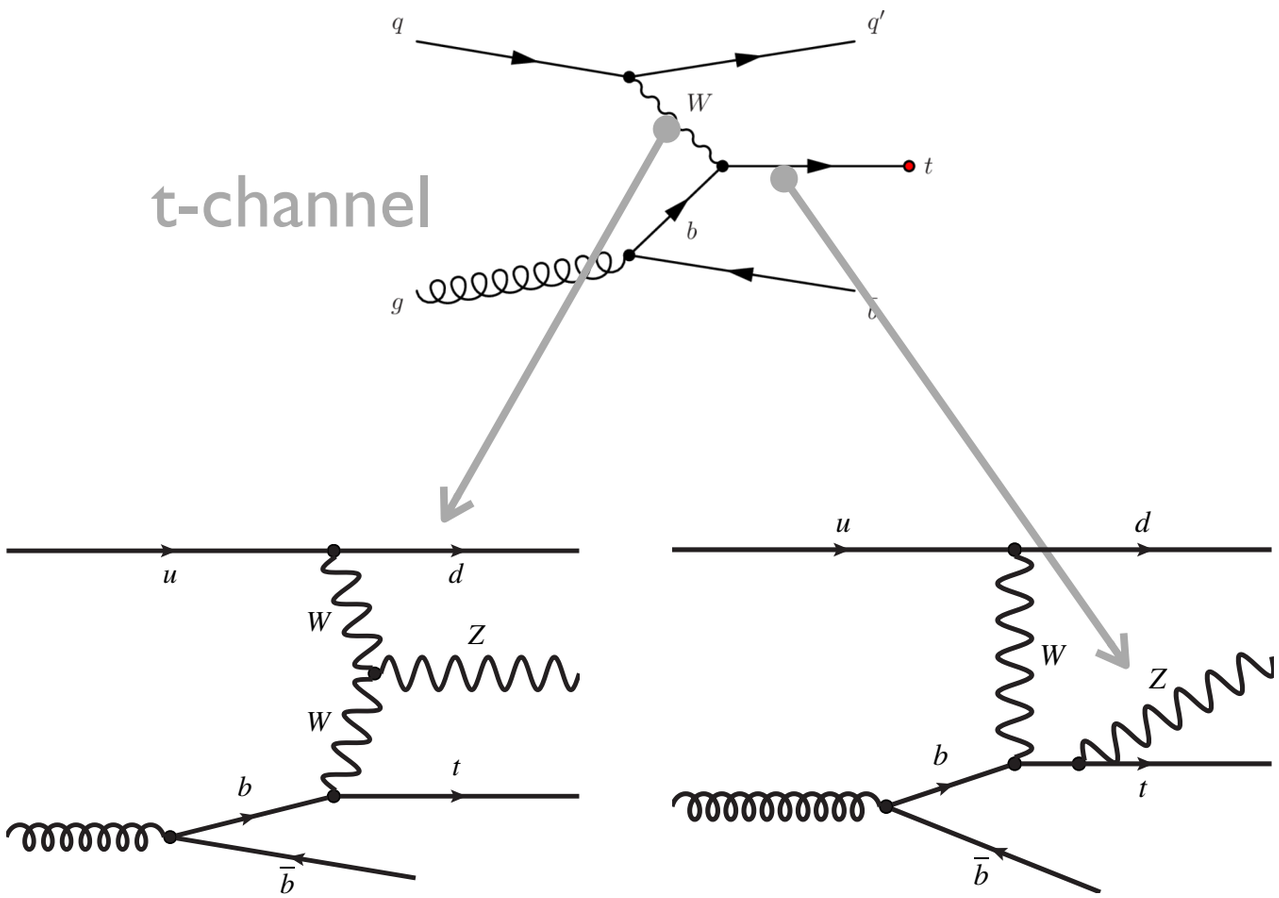
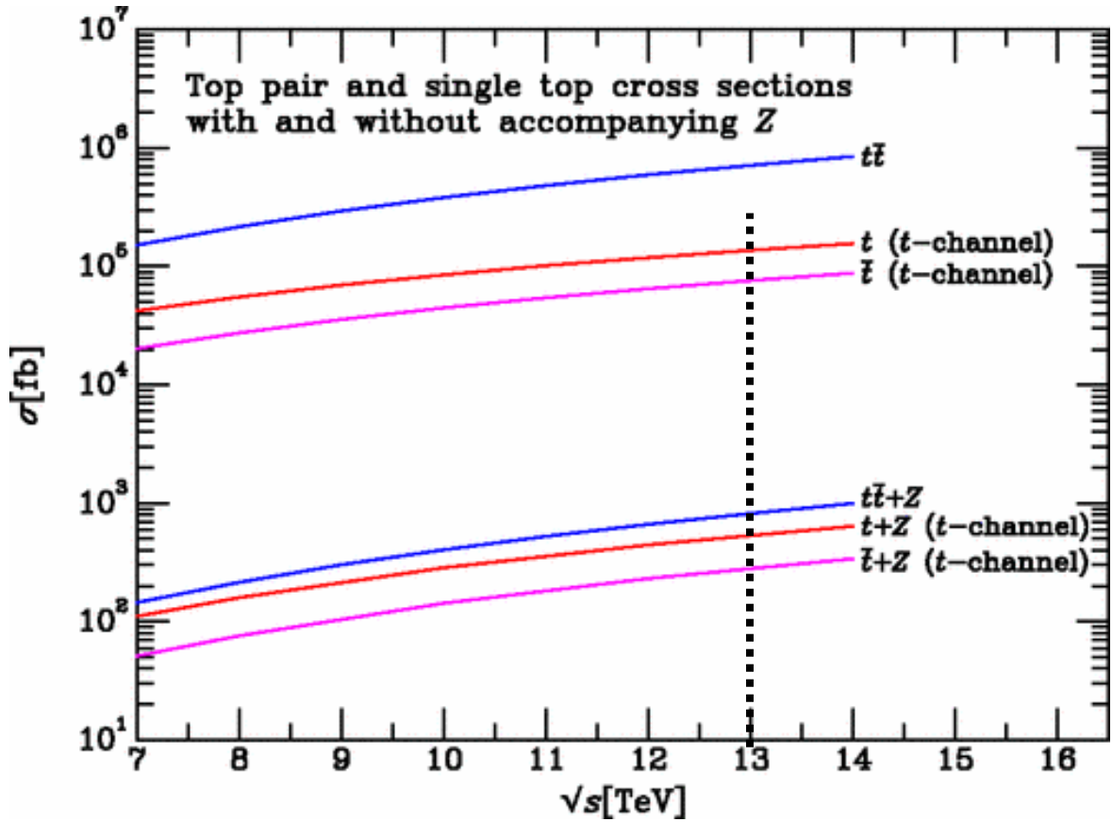
Auxiliary material at TOPQ-2018-01

Single top quark in association with a Z





from Phys. Rev. D 87 (2013) 114006

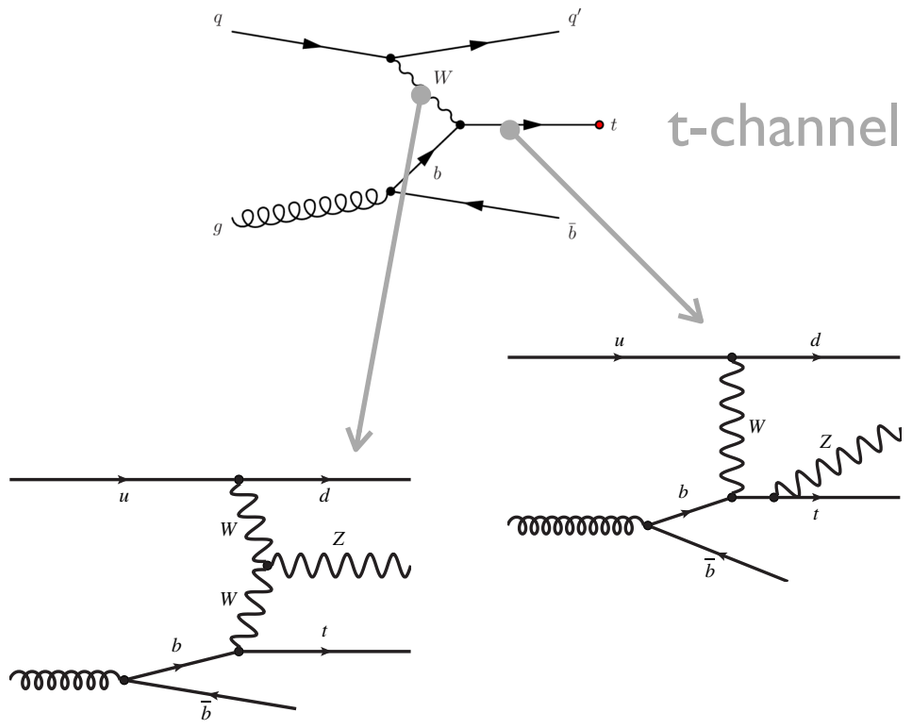
- SM single top-quark production in association with a Z boson (t-channel, tZq) not measured before Run 2

- CMS **observation** with 77 fb^{-1}
  - PRL 122 (2019) 132003
  - $\sigma(tllq) = 111 \pm 13(stat.)\ ^{+11}_{-9}$ (syst.) fb
    - 15% total uncertainty

- SM tZq probes both t-Z and W-Z couplings
- Useful for EFT extraction
- SM tZq background for:
  - Flavor Changing Neutral Current tZq production
  - SM tHq final state

The analysis in a nutshell

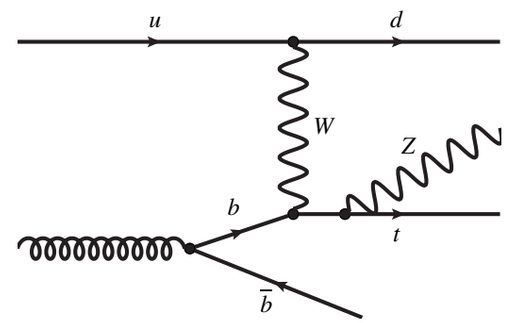
- Signal
  - Generated as tllq (with m_{ll} > 30 GeV) at NLO in 4FS
    - MadGraph5_aMC@NLO 2.6.0 with Pythia 8.230 (A14 tune)
    - PDF: NNPDF30_nlo_as_0118_nf_4
    - Scales: $4\sqrt{(m_b^2 + p_{T,b}^2)}$
  - Normalized to σ_{NLO}(tllq) = 102 fb $^{+5.2}_{-1.3}$% (scale) ±1% (PDF)
    - Cross section computed in 5FS
    - PDF: NNPDF30_nlo_as_0118
    - Scales: $(m_t + m_Z)/4$
- Data 2015-2018 used, integrated luminosity 139 fb^{-1}
- Event topology
  - 3 leptons + 2 or 3 jets (1 b-tagged)
  - t-channel: implies presence of a forward jet
- Main backgrounds
  - Diboson, mainly WZ: from Monte Carlo (MC)
  - $t\bar{t}Z$: from MC
  - Fakes (Z+jets and $t\bar{t}$): from MC enriched with b-jet replacement method (BJR)
- Analysis strategy: multivariate analysis (using Neural Networks)
- Fit strategy: simultaneous fit of signal regions and control regions

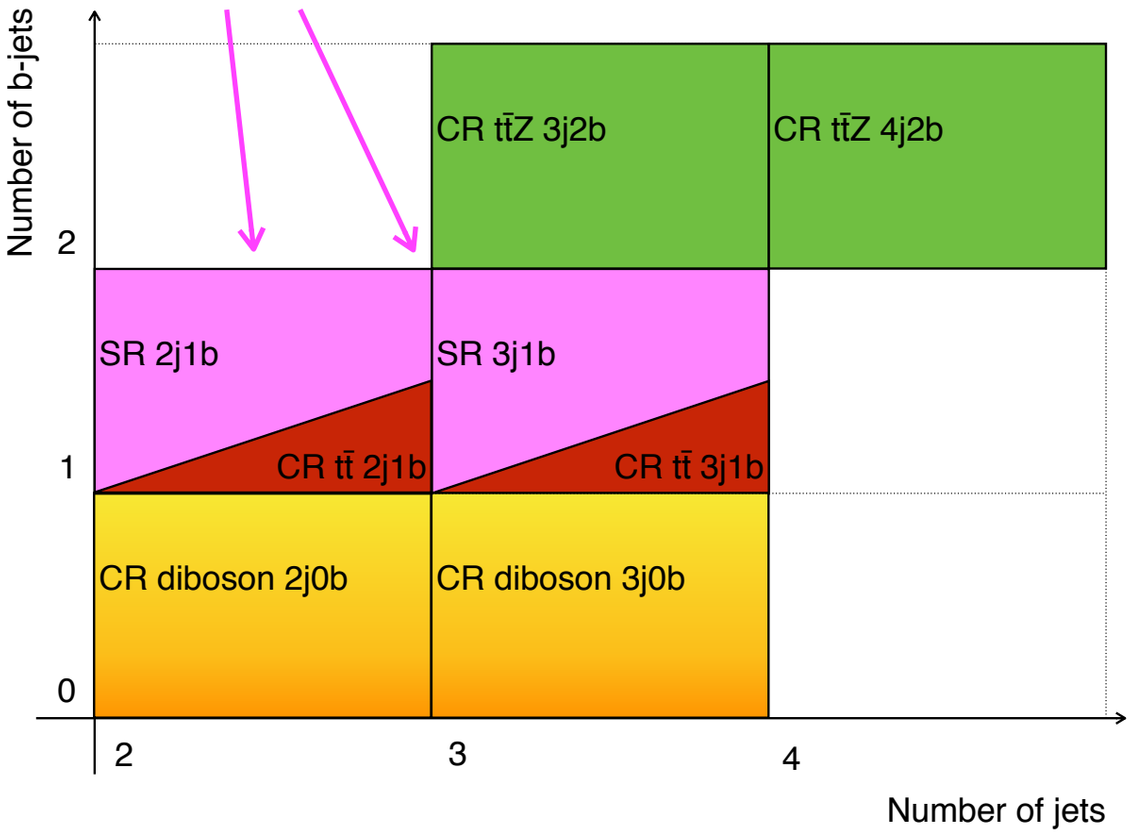


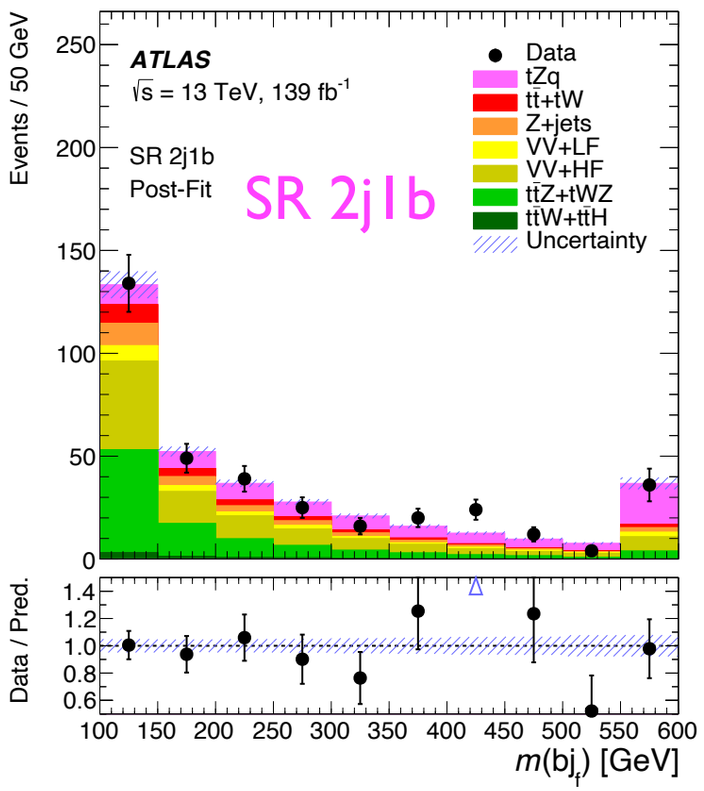
t-channel

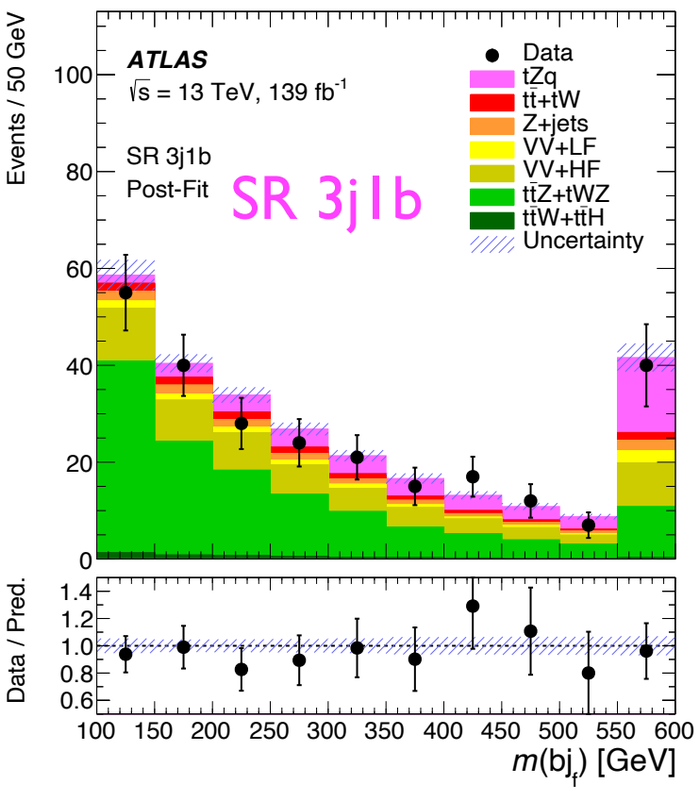
Event selection in Signal Regions

- Trigger
  - Single isolated lepton triggers
  - e: 26 GeV threshold (24 GeV in 2015)
  - μ: 26 GeV threshold (20 GeV in 2015)
- Leptons
  - Exactly 3 isolated leptons, e/μ
  - p_T > 28, 20, 20 GeV
- Jets
  - Exactly 2(3) jets
  - p_T > 35 GeV
  - $|\eta| < 4.5$
- b-tagging
  - Exactly 1 b-tagged jet
  - 70% efficiency WP
- In addition:
  - ≥1 OSSF lepton pair with $|m_{ll} - m_Z| < 10$ GeV



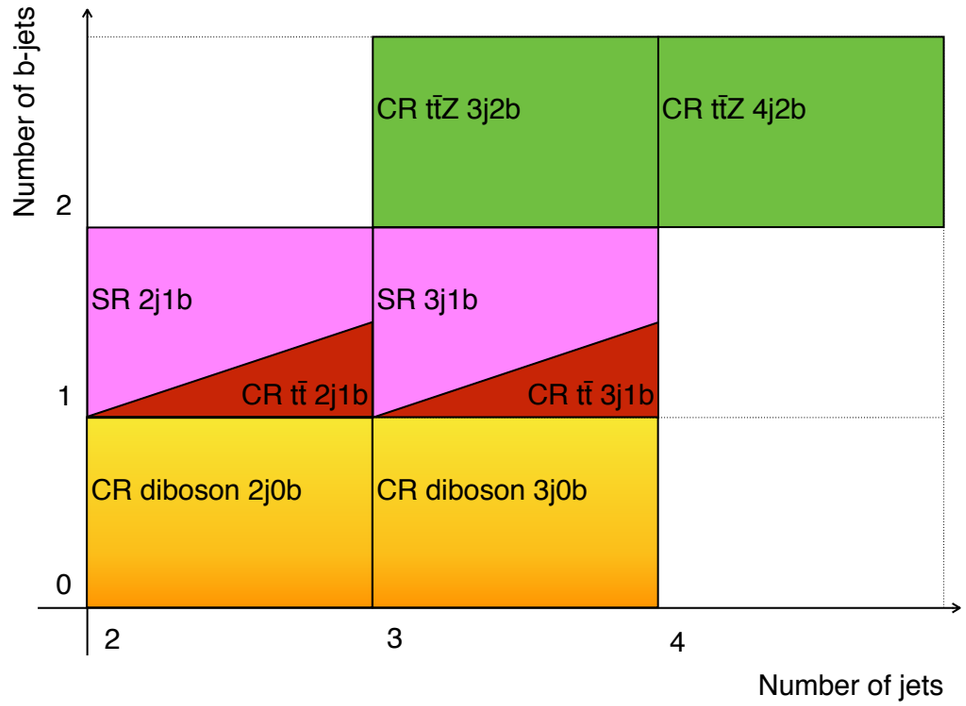






Background estimation

- Background sources from processes with:
  - three or more prompt leptons ($t\bar{t}V$, diboson, $t\bar{t}H$ and tWZ)
  - two prompt leptons and one additional non-prompt or fake lepton (Z+jets, $t\bar{t}$)

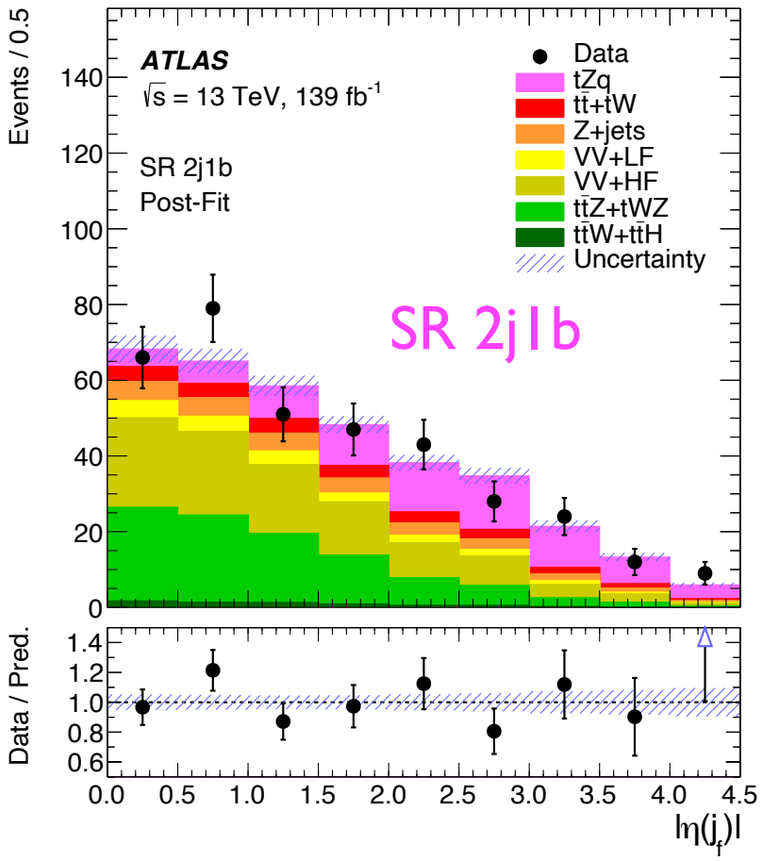


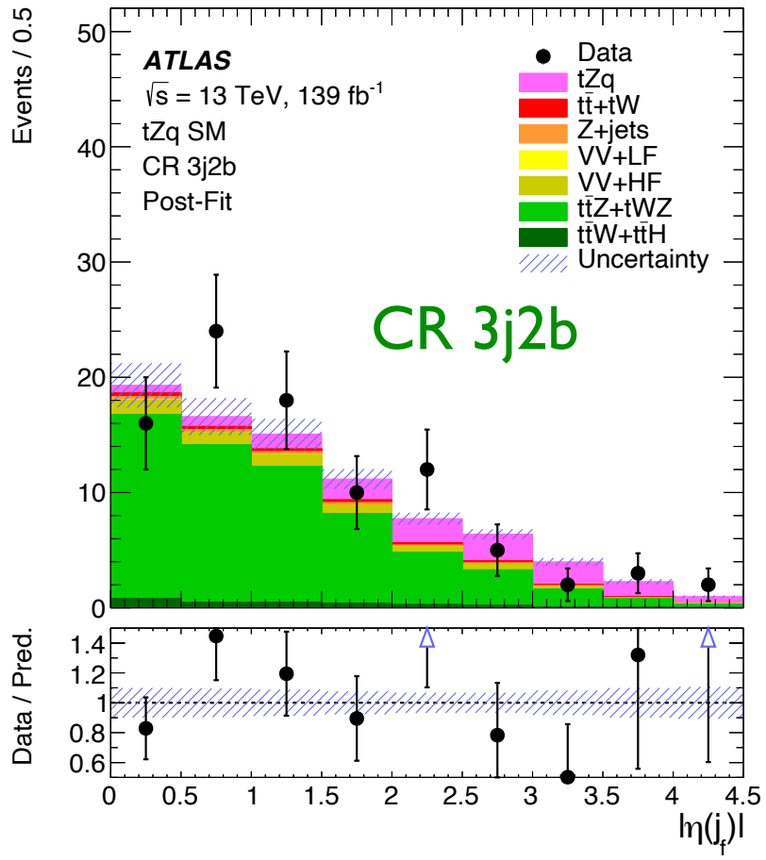
- Background MCs
  - $t\bar{t}V$: MadGraph5_aMC@NLO 2.3.3 (NNPDF3.0 NLO) with Pythia 8.230 (A14 tune, NNPDF2.3 LO)
    - Non resonant ll contributions included for $t\bar{t}Z$
  - Diboson: Sherpa 2.2.1 (2.2.2 for fully leptonic final states)
    - Up to one additional parton at NLO accuracy and up to three additional parton emissions at LO accuracy
  - $t\bar{t}$: Powheg-Box v2 (NNPDF3.0 NLO) with Pythia 8.230 (A14 tune, NNPDF2.3 LO)

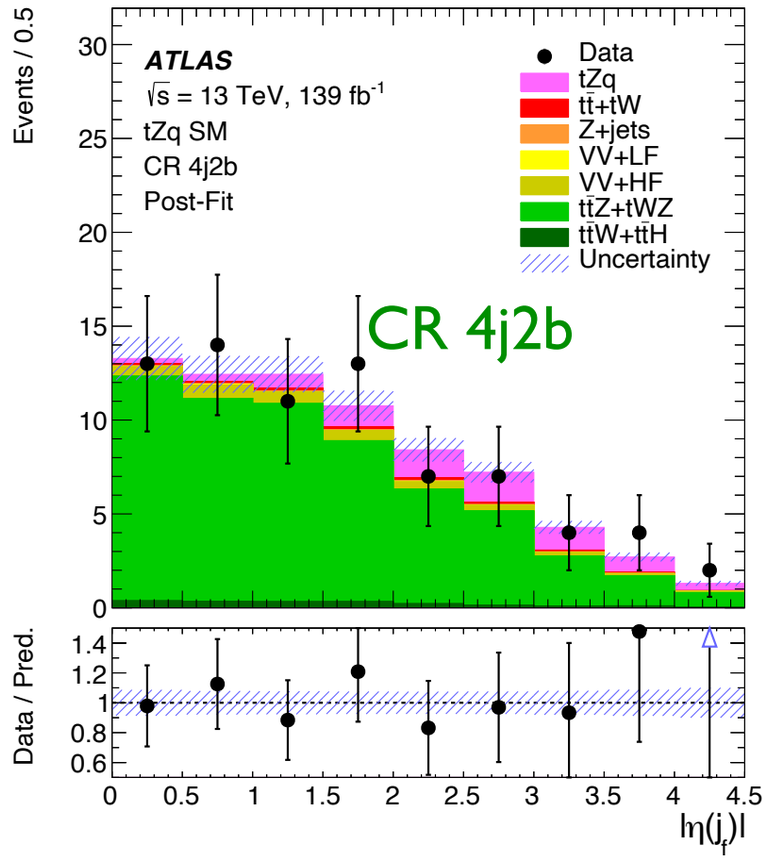
- Control Regions (CRs): used in the fit
  - $t\bar{t}Z$ CRs: one additional b-tagged jet (CR 3j2b and CR 4j2b)
  - Diboson CRs: no b-tagged jets (CR 2j0b and CR 3j0b)
    - Z+jets background extracted from these regions too
  - $t\bar{t}$ CRs: same jet multiplicities but with OSDF leptons (CR 2j1b and CR 3j1b)

Background estimation - $t\bar{t}Z$

- $t\bar{t}Z$ background extracted from CRs
- Good modeling of $t\bar{t}Z$ background

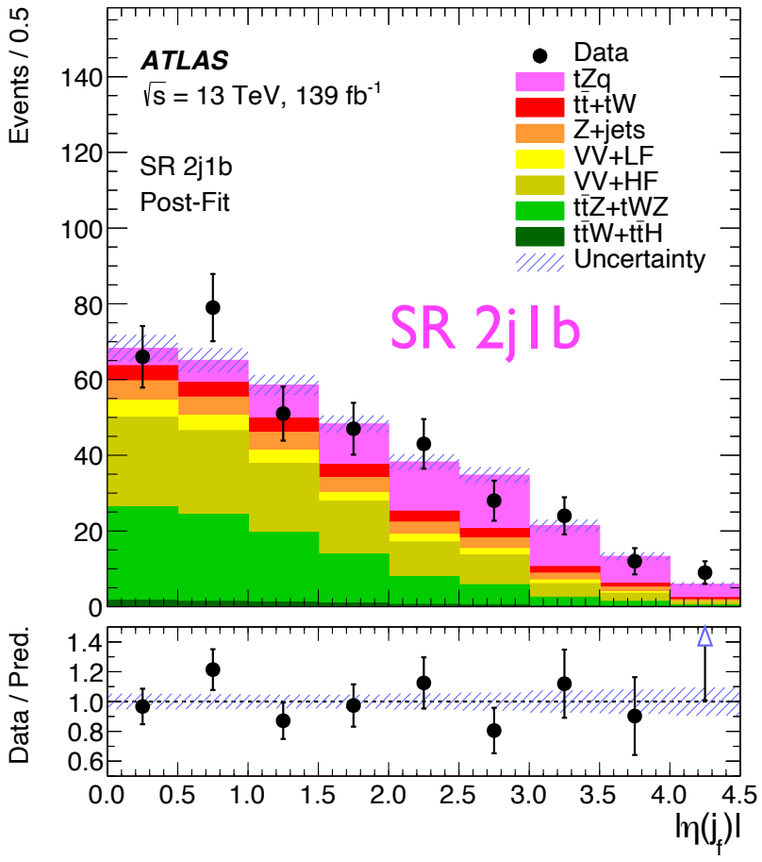


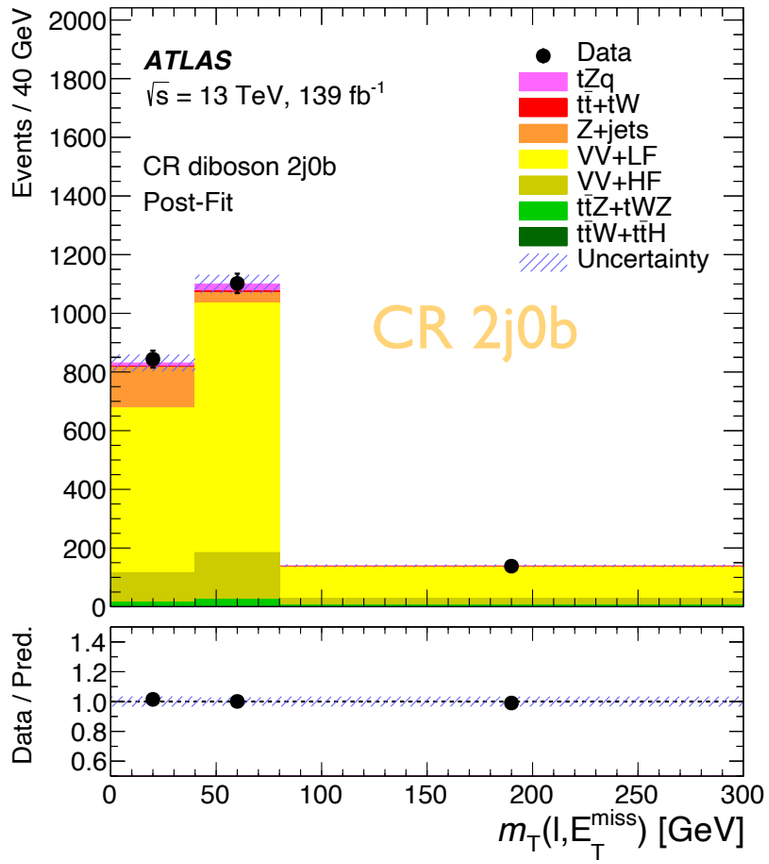


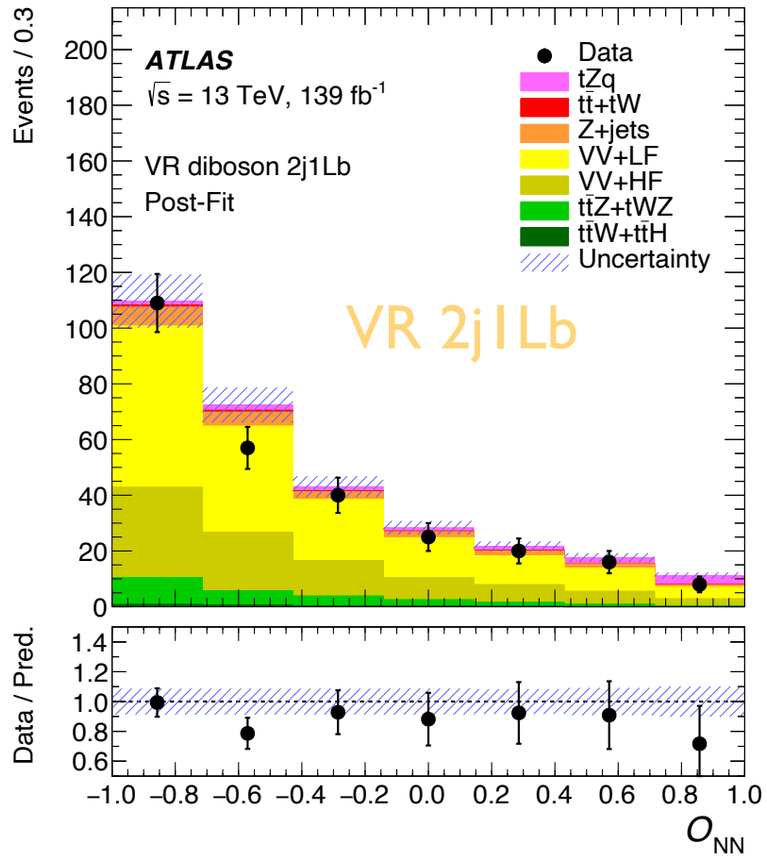


Background estimation - Diboson

- Contribution from diboson + b, c and light flavour
  - Diboson + b/c (HF) and diboson + light (LF) treated separately



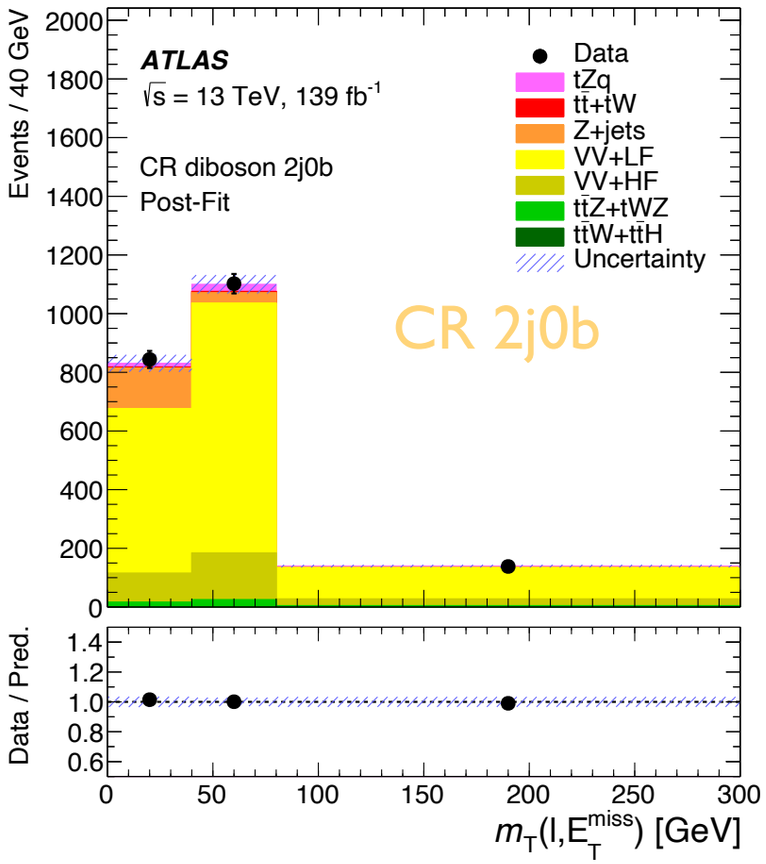


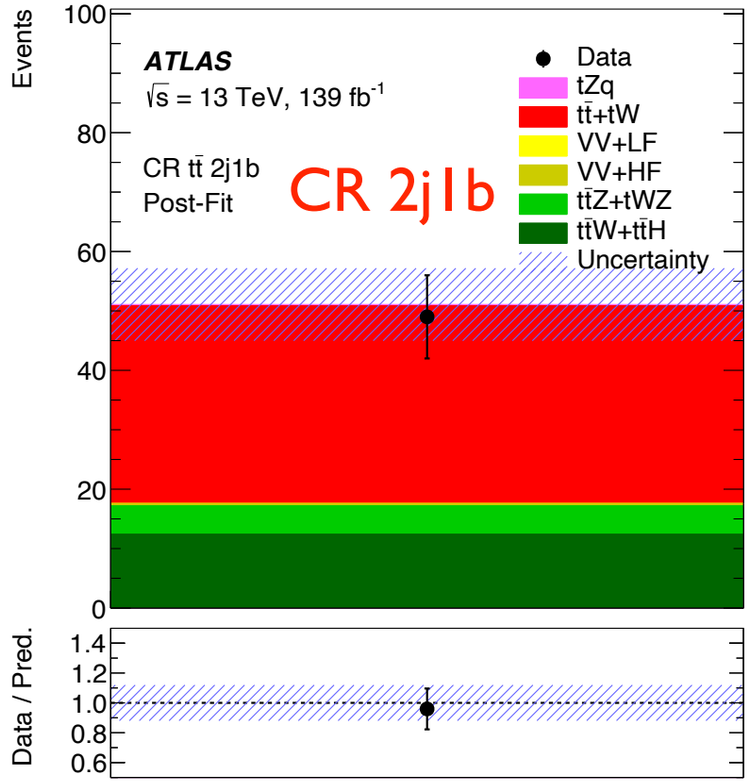


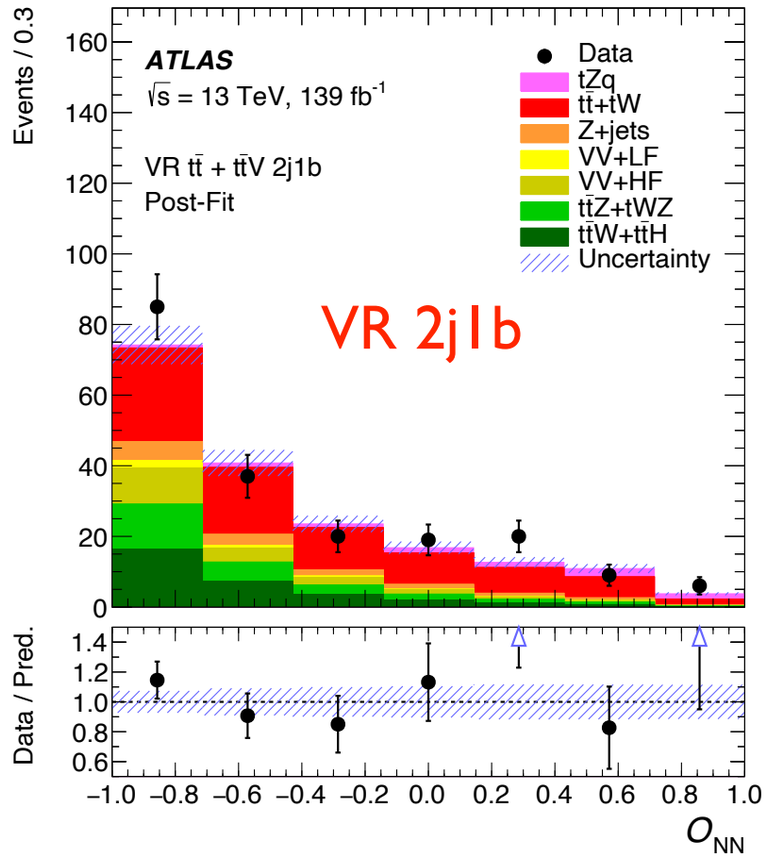
- Diboson background extracted from CRs
- Additional validation regions (VRs) to check background modeling
  - Diboson VRs: one loose b-tagged jet, i.e. passing 85% and not 70% WP (VR 2j1Lb and VR 3j1Lb)
- Different composition in SRs and CRs (and VRs)
- Good modeling of diboson background

Background estimation - Fakes

- Not enough $t\bar{t}$ and Z+jets MC events passing trilepton selection
- Use b-jet replacement method (BJR)
- Idea: extend dilepton sample into trilepton via forcing semileptonic b decay of a second b-jet
  - events are selected with one fewer lepton and one more b-tagged jet than in the SR
  - one of the b-jets (selected randomly) is then replaced by a lepton
- Assumption: b-hadron decays are the source of fakes
- Z+jets and $t\bar{t}$ background extracted from CRs
- Additional VRs to check $t\bar{t}$ background modeling
  - ttV+ $t\bar{t}$ VRs: same jet multiplicities but with reversed m_{ll} cut (VR 2j1b and VR 3j1b)
- Good modeling of fakes background







Neural Network

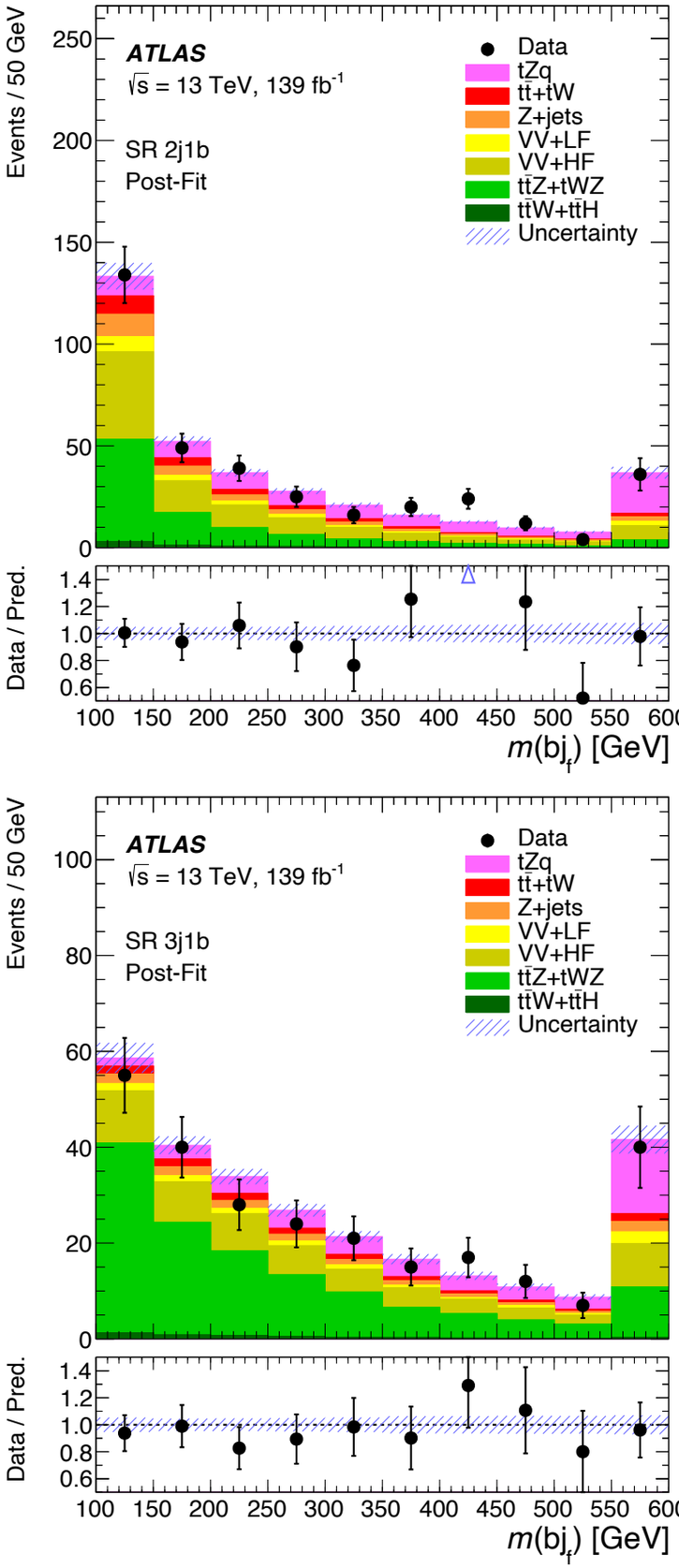
- To better separate the signal from the backgrounds, a Neural Network (NN) is trained, using NeuroBayes

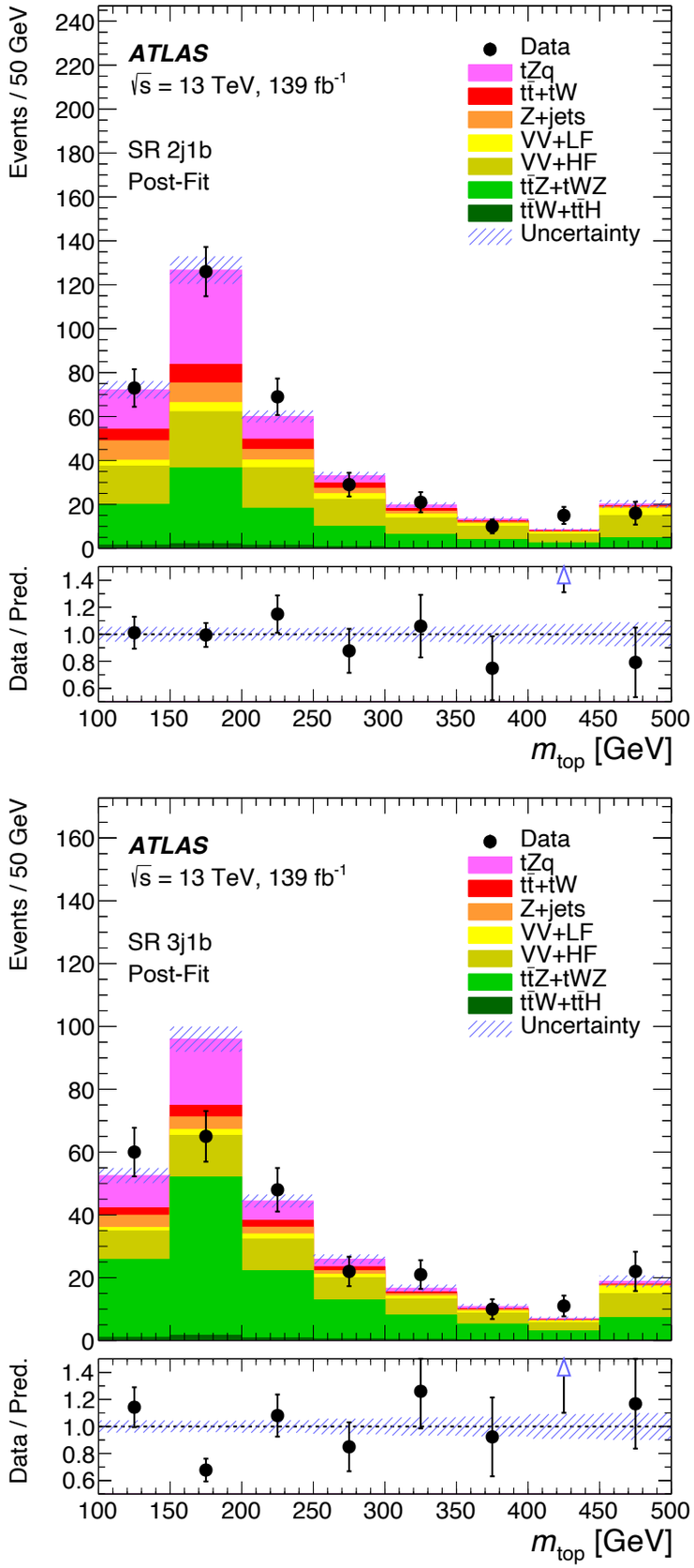
Variable	Rank		Definition
	SR 2j1b	SR 3j1b	
m_{bj_f}	1	1	(Largest) invariant mass of the b-jet and the untagged jet(s)
m_{top}	2	2	Reconstructed top-quark mass
$\lvert\eta(j_f)\rvert$	3	3	Absolute value of the η of the j_f jet
$m_T(\ell, E_T^{\text{miss}})$	4	4	Transverse mass of the W boson
b-tagging 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
$\lvert\eta(\ell_W)\rvert$	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
$\lvert\eta(Z)\rvert$	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
$\lvert\eta(j_r)\rvert$	–	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

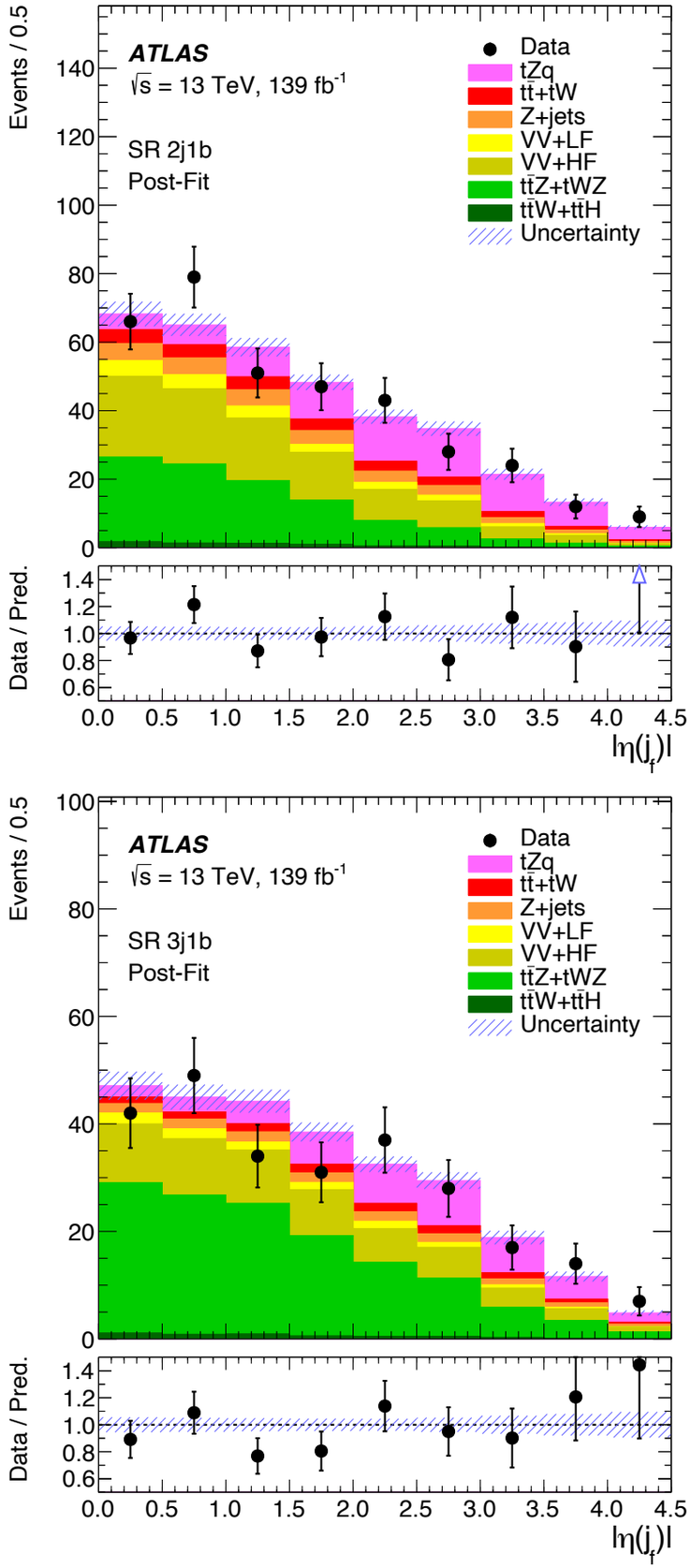
- NN trained in SR **2j1b** and SR **3j1b** separately
- All backgrounds included
- Same 4 variables are the highest ranked in the two SRs

NN input variables in SRs

SR 2j1b



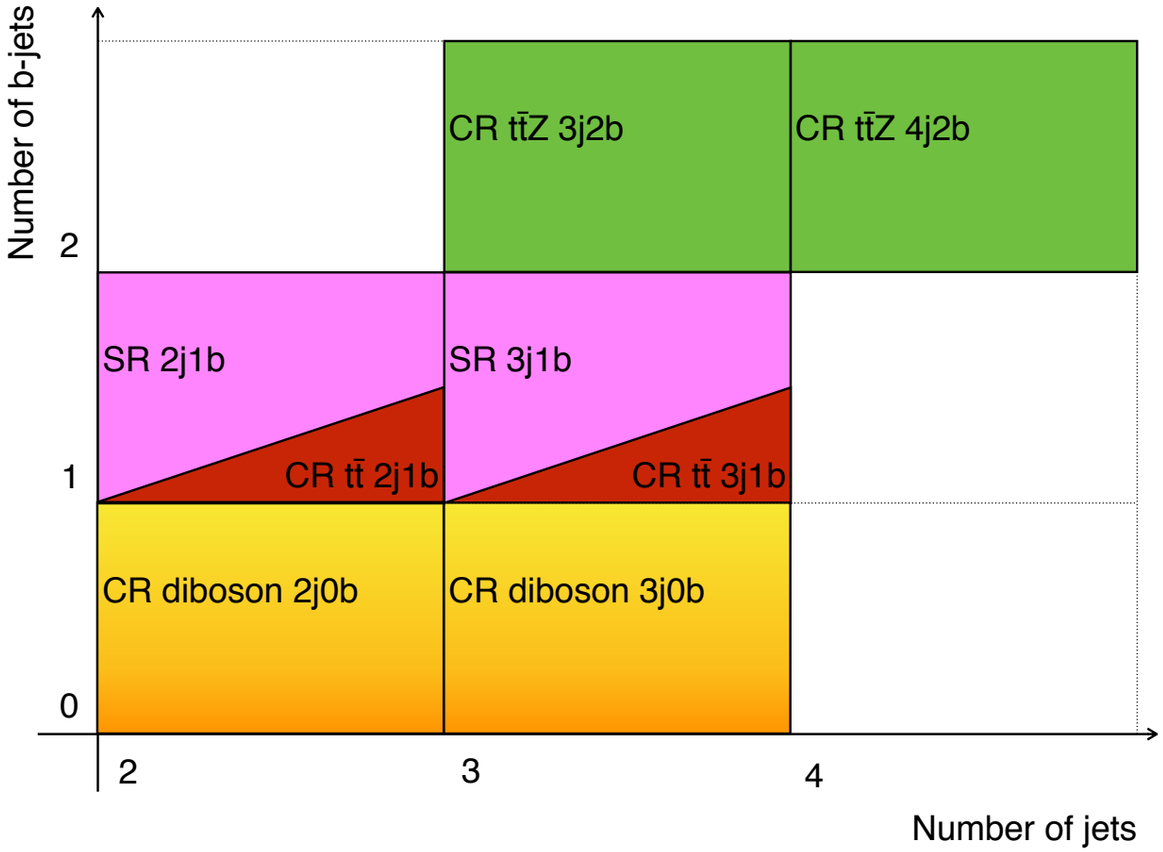




SR 3j1b

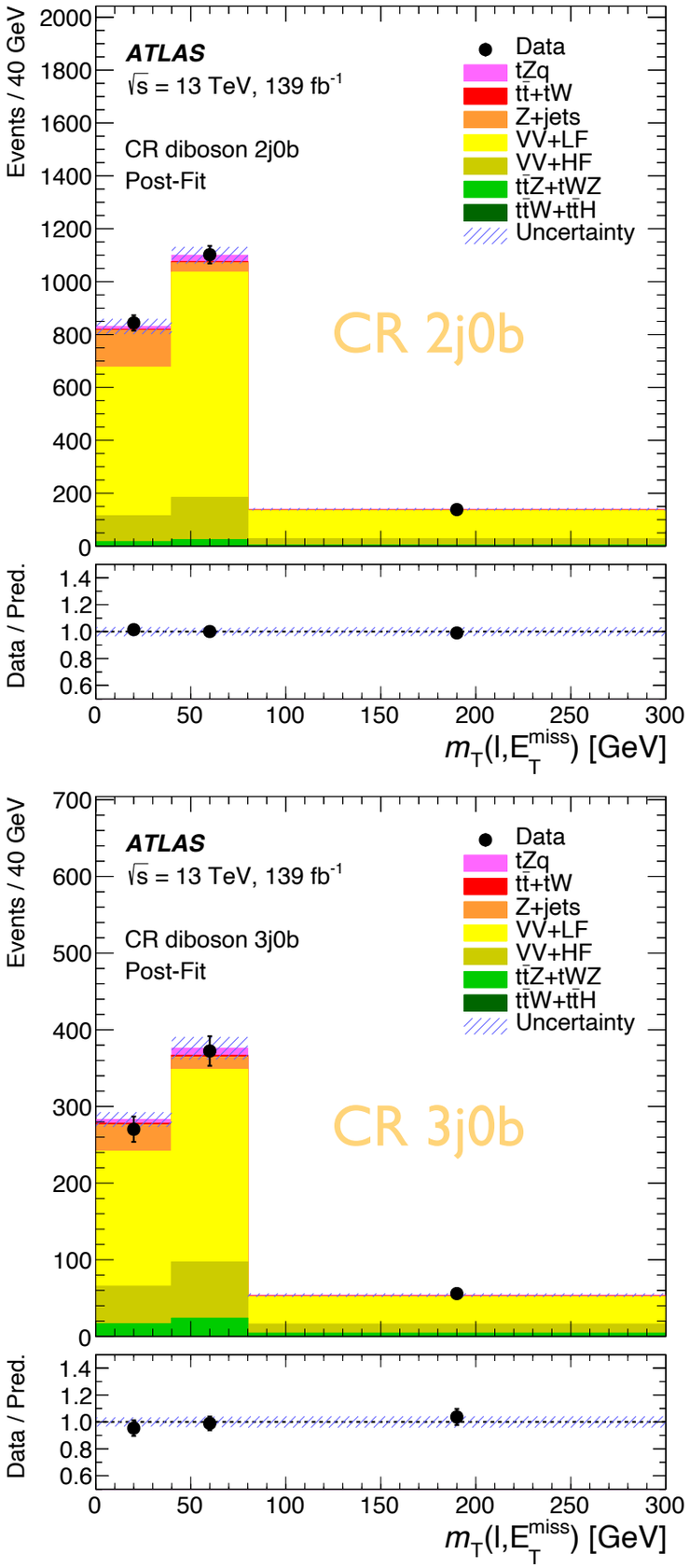
Fitting strategy

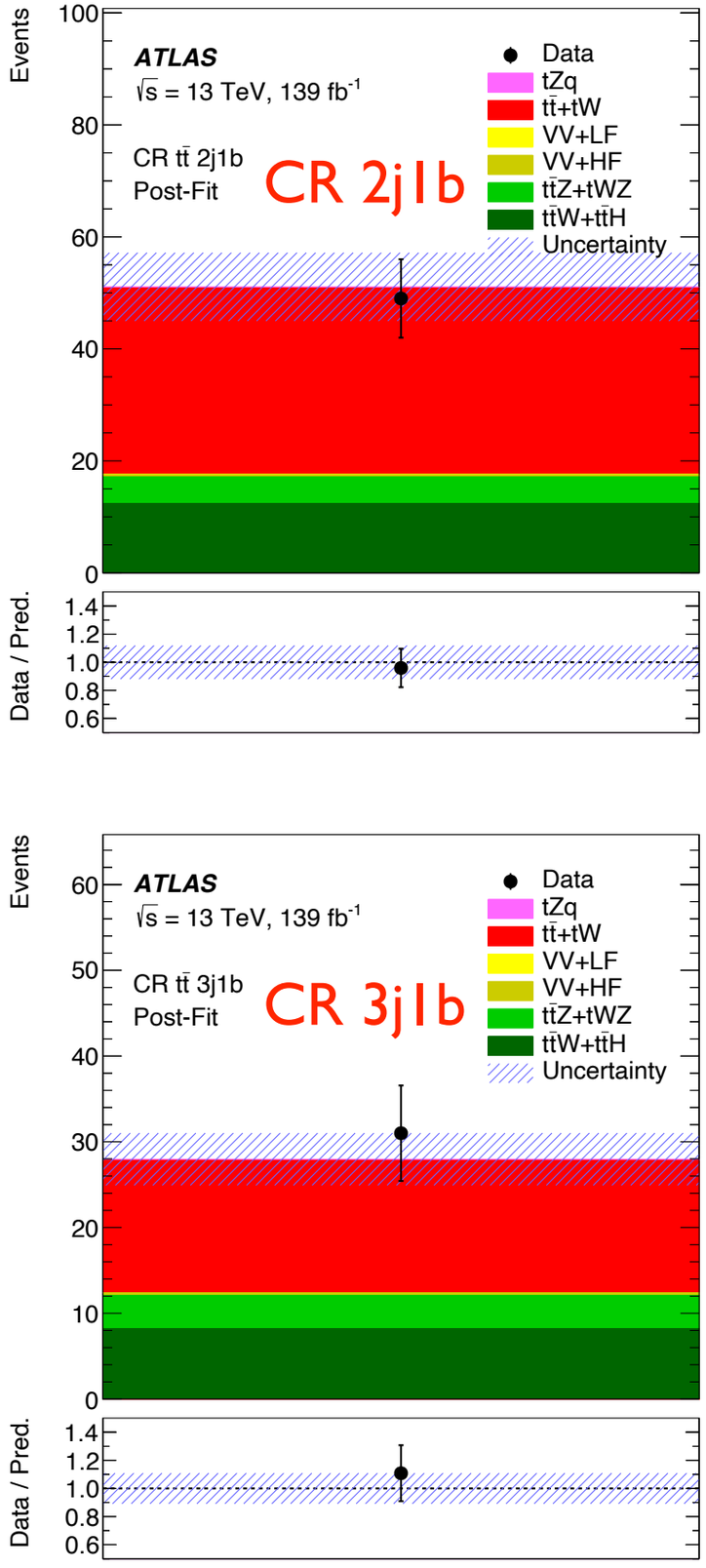
- Simultaneous binned maximum-likelihood fit of SRs and CRs
  - 2 SRs (O_{NN}) + 2 diboson CRs ($m_T(W)$) + 2 $t\bar{t}$ CRs (1bin) + $t\bar{t}Z$ CRs (O_{NN})
  - Fakes backgrounds (Z+jet and $t\bar{t}$) free floating in the fit

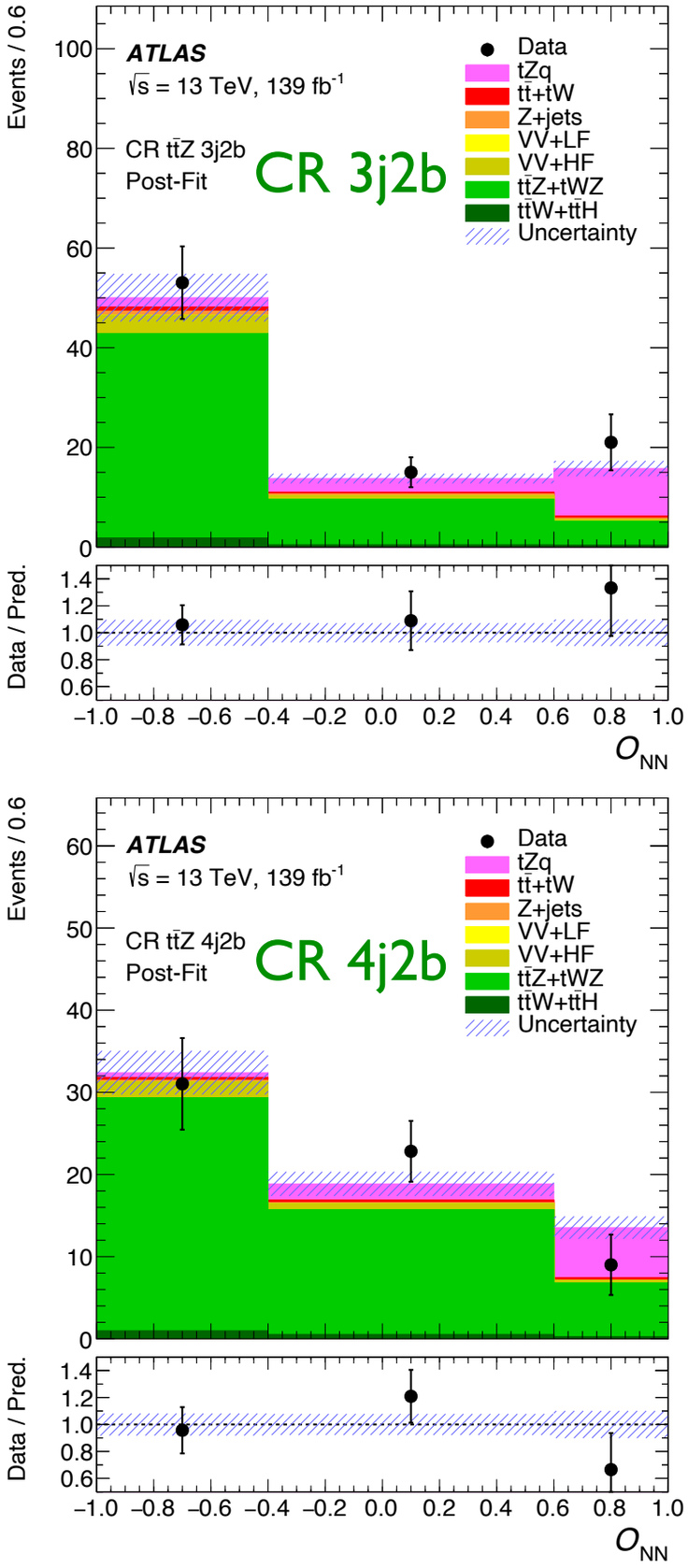


Region	Distribution	Additional info
2j1b SR	O_{NN}	–
3j1b SR	O_{NN}	–
2j0b diboson CR	$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$	–
3j0b diboson CR	$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$	–
2j1b $t\bar{t}$ CR	–	single bin
3j1b $t\bar{t}$ CR	–	single bin
3j2b $t\bar{t}Z$ CR	O_{NN}	–
4j2b $t\bar{t}Z$ CR	O_{NN}	–

Control Regions in the fit

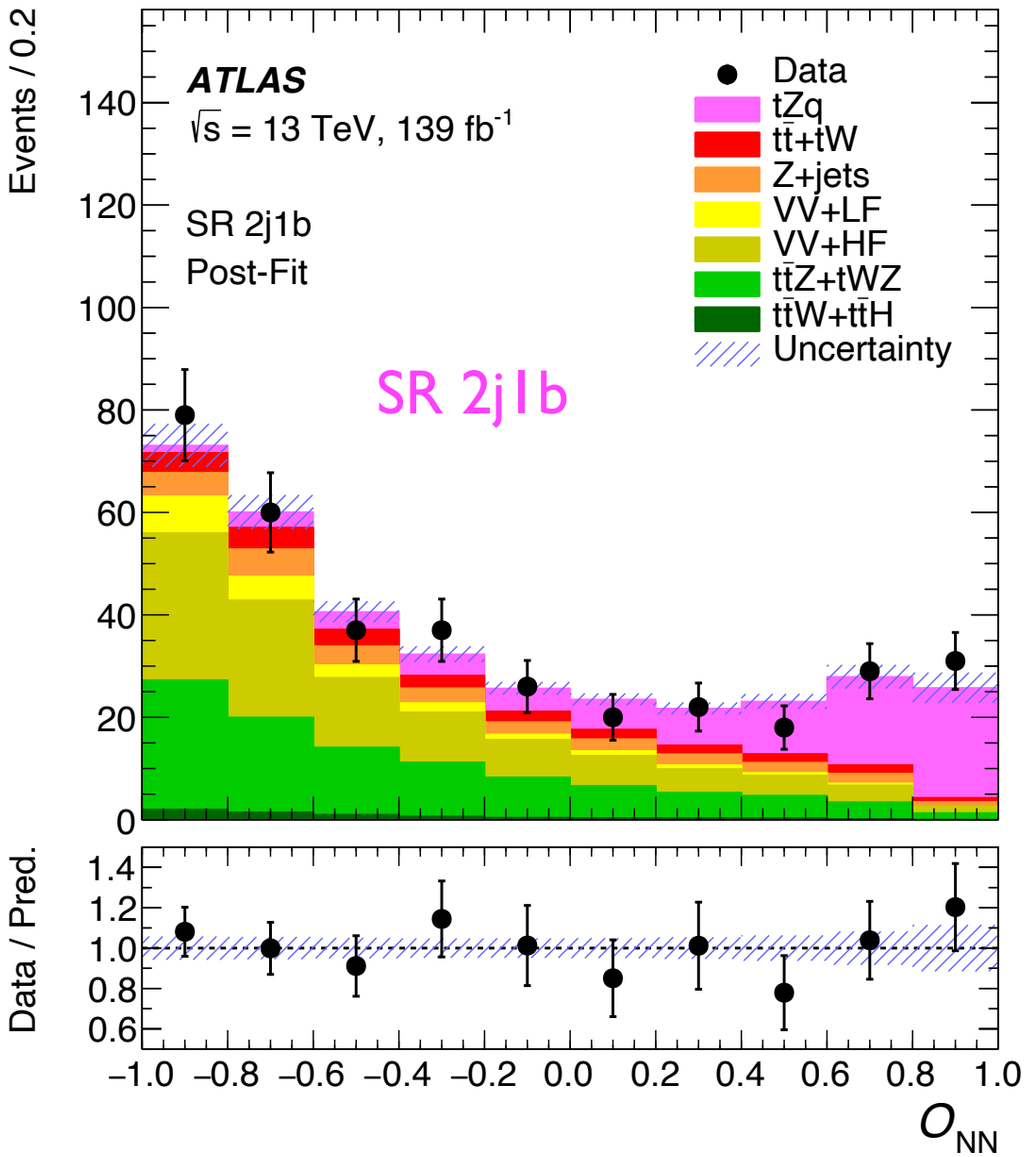


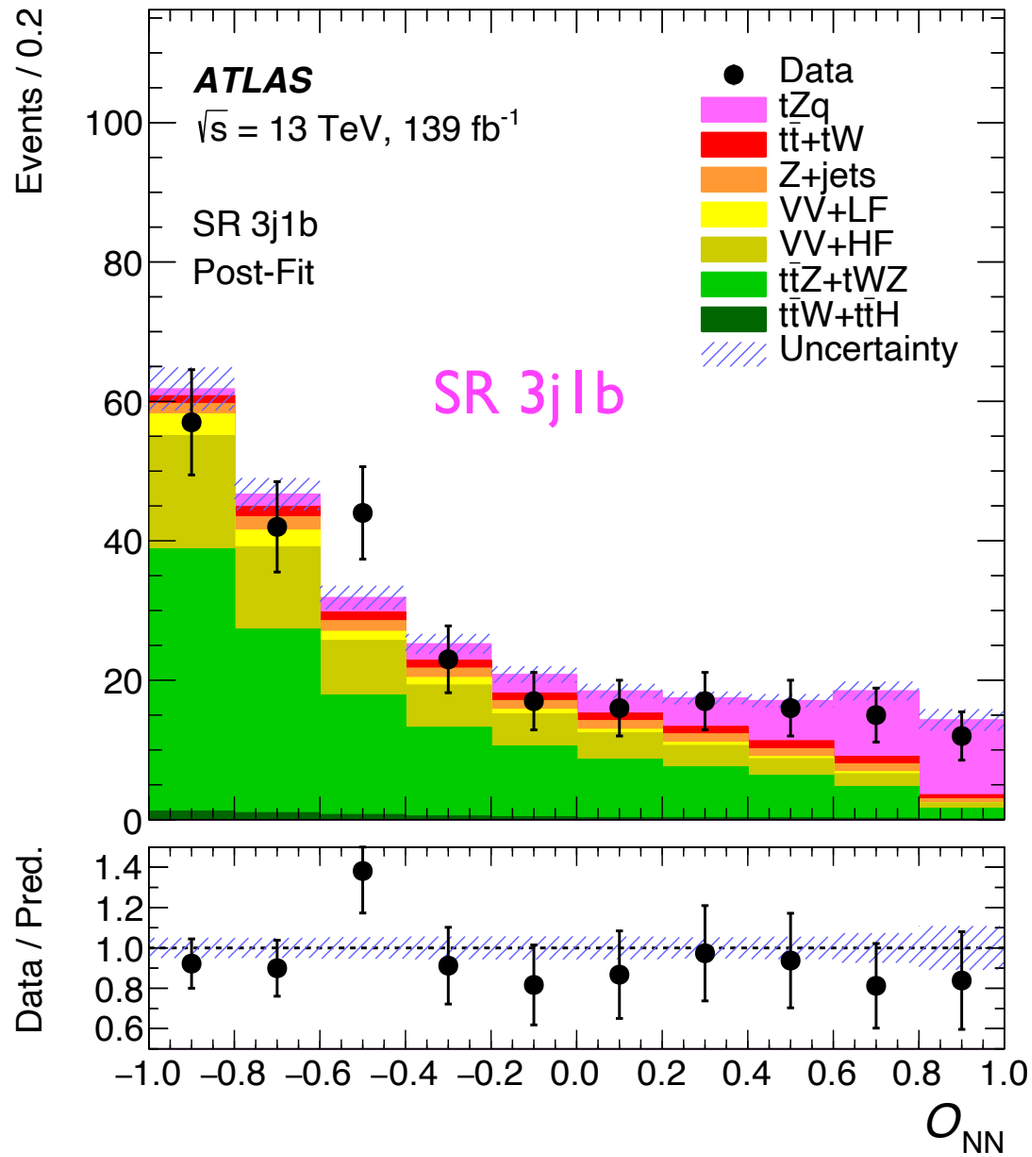




Results

- Observed significance well above 5σ
- $\sigma_{meas.}(tllq) = 97\ fb \pm 13\ (stat.) \pm 7\ (syst.)\ fb$
  - $\sigma_{NLO}(tllq) = 102\ fb\ ^{+5.2}_{-1.3}\%\ (scale) \pm 1\%\ (PDF)$

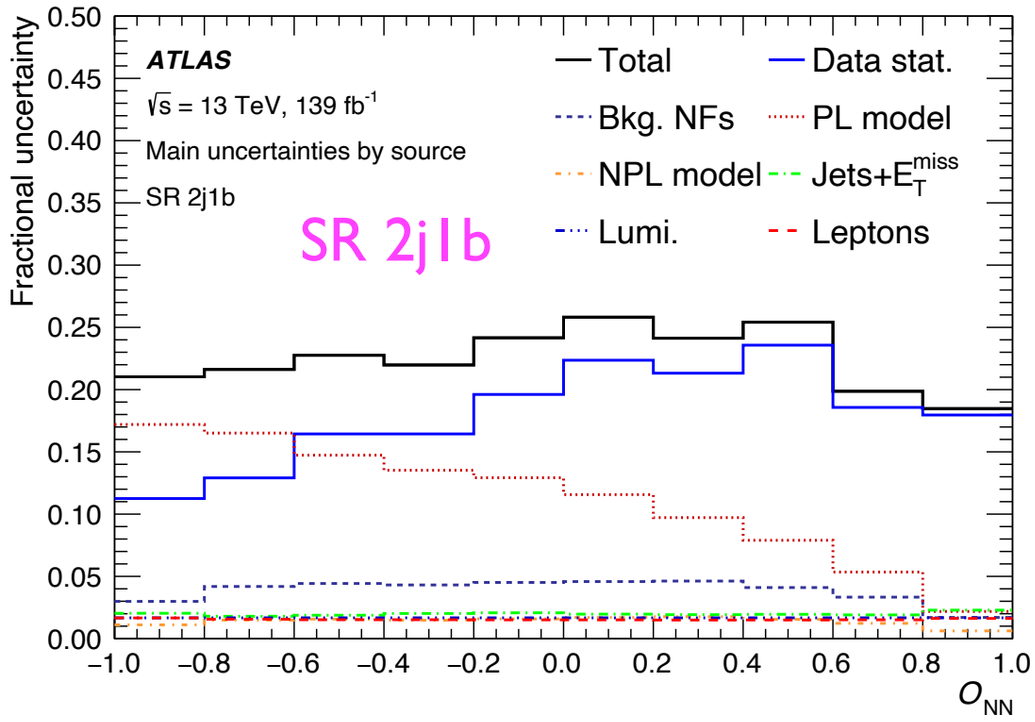


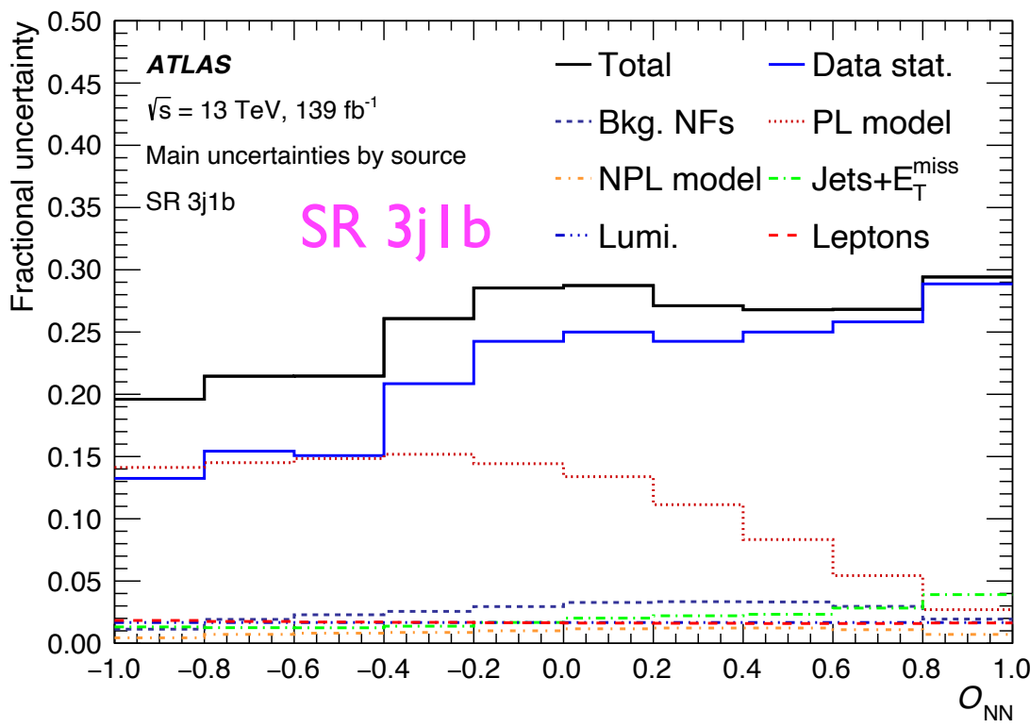


Results

- $\sigma_{meas.}(tllq)$ = 97 fb ±13 (stat.) ±7 (syst.) fb
  - $\sigma_{NLO}(tllq)$ = 102 fb $^{+5.2}_{-1.3}$% (scale) ±1% (PDF)

Uncertainty source	$\Delta\sigma/\sigma$ [%]
Prompt-lepton background modelling and normalisation	3.3
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction and calibration	2.0
Lepton reconstruction and calibration	2.0
Luminosity	1.7
Non-prompt-lepton background modelling	1.6
Pile-up modelling	1.2
MC statistics	1.0
tZq modelling (QCD radiation)	0.8
tZq modelling (PDF)	0.7
Jet flavour tagging	0.4
Total systematic uncertainty	7.0
Data statistical	12.6
$t\bar{t}$ and Z + jets normalisation	2.1
Total statistical uncertainty	12.9

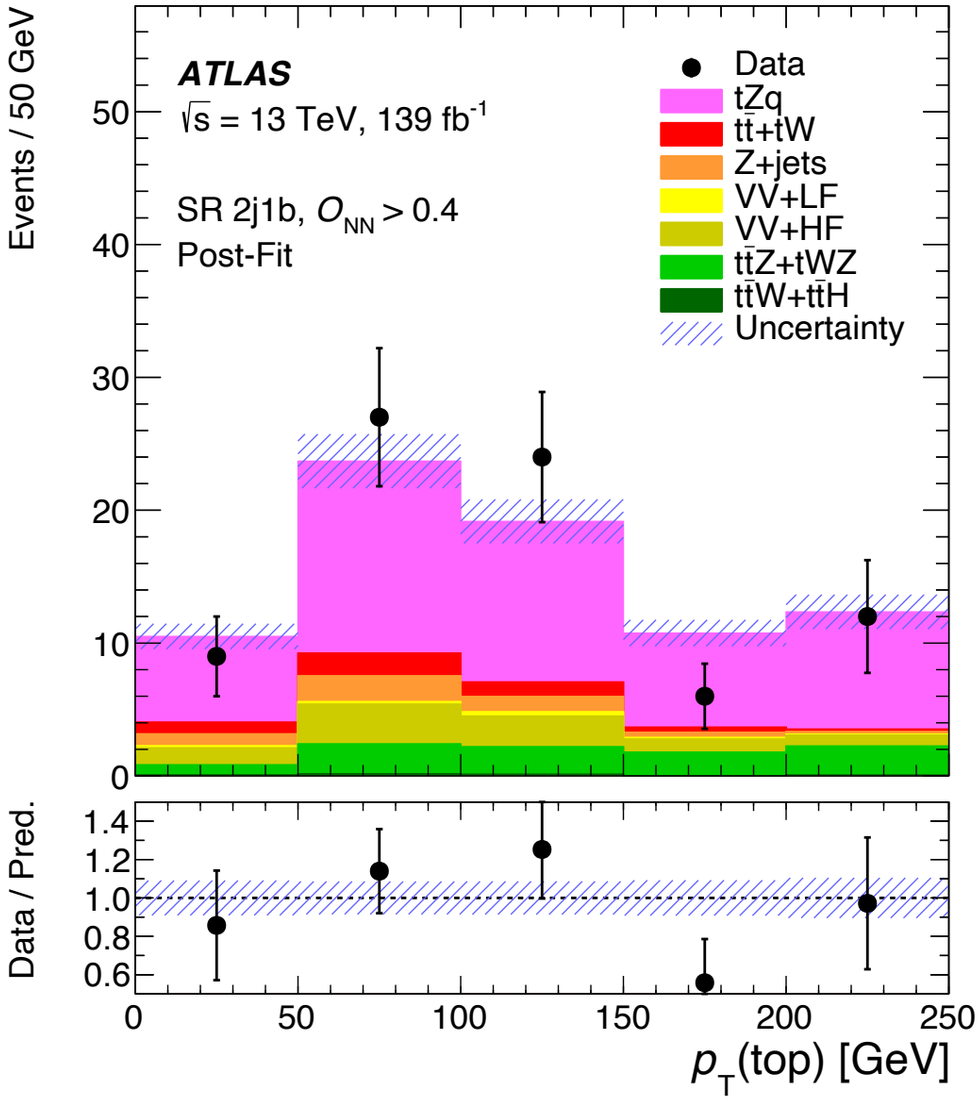


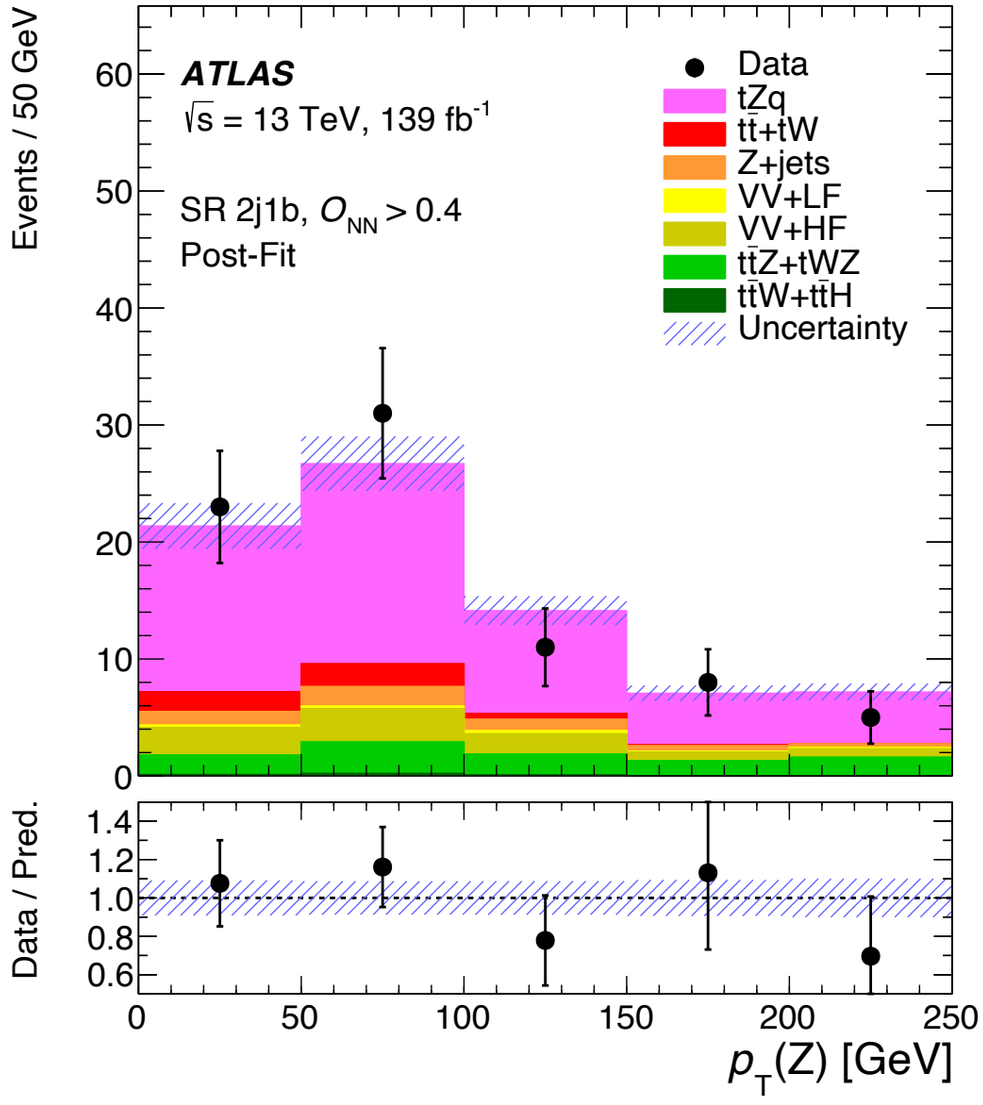


Conclusions

- Observation of Standard Model tZq process by ATLAS
  - Tri-lepton final state with 2 or 3 jets

- $\sigma_{meas.}(tllq) = 97$ fb ± 13 (stat.) ± 7 (syst.) fb
  - 14% uncertainty, dominated by statistical uncertainty
  - $\sigma_{NLO}(tllq) = 102$ fb $^{+5.2}_{-1.3}$% (scale) ± 1% (PDF)





BackUp

Event selection

Common selections			
Exactly 3 leptons with $\|\eta\| < 2.5$ $p_{\mathrm{T}}(\ell_1) > 28\,\mathrm{GeV}$, $p_{\mathrm{T}}(\ell_2) > 20\,\mathrm{GeV}$, $p_{\mathrm{T}}(\ell_3) > 20\,\mathrm{GeV}$ $p_{\mathrm{T}}(\mathrm{jet}) > 35\,\mathrm{GeV}$			
SR 2j1b	Diboson 2j0b CR	$t\bar{t}Z$ 3j2b CR	$t\bar{t}$ 2j1b CR
≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10\,\mathrm{GeV}$ 2 jets, $\|\eta\| < 4.5$ 1 b-jet, $\|\eta\| < 2.5$	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10\,\mathrm{GeV}$ 2 jets, $\|\eta\| < 4.5$ 0 b-jets	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10\,\mathrm{GeV}$ 3 jets, $\|\eta\| < 4.5$ 2 b-jets, $\|\eta\| < 2.5$	≥ 1 OSDF pair No OSSF pair 2 jets, $\|\eta\| < 4.5$ 1 b-jet, $\|\eta\| < 2.5$
	Diboson 2j1Lb VR	$t\bar{t}V + t\bar{t}$ 2j1b VR	
	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10\,\mathrm{GeV}$ 2 jets, $\|\eta\| < 4.5$ 1 'Loose' b-jet, $\|\eta\| < 2.5$	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| > 10\,\mathrm{GeV}$ 2 jets, $\|\eta\| < 4.5$ 1 b-jet, $\|\eta\| < 2.5$	
SR 3j1b	Diboson 3j0b CR	$t\bar{t}Z$ 4j2b CR	$t\bar{t}$ 3j1b CR
≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10\,\mathrm{GeV}$ 3 jets, $\|\eta\| < 4.5$ 1 b-jet, $\|\eta\| < 2.5$	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10\,\mathrm{GeV}$ 3 jets, $\|\eta\| < 4.5$ 0 b-jets	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10\,\mathrm{GeV}$ 4 jets, $\|\eta\| < 4.5$ 2 b-jets, $\|\eta\| < 2.5$	≥ 1 OSDF pair No OSSF pair 3 jets, $\|\eta\| < 4.5$ 1 b-jet, $\|\eta\| < 2.5$
	Diboson 3j1Lb VR	$t\bar{t}V + t\bar{t}$ 3j1b VR	
	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10\,\mathrm{GeV}$ 3 jets, $\|\eta\| < 4.5$ 1 'Loose' b-jet, $\|\eta\| < 2.5$	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| > 10\,\mathrm{GeV}$ 3 jets, $\|\eta\| < 4.5$ 1 b-jet, $\|\eta\| < 2.5$	

Post-fit event yields in SRs and CRs

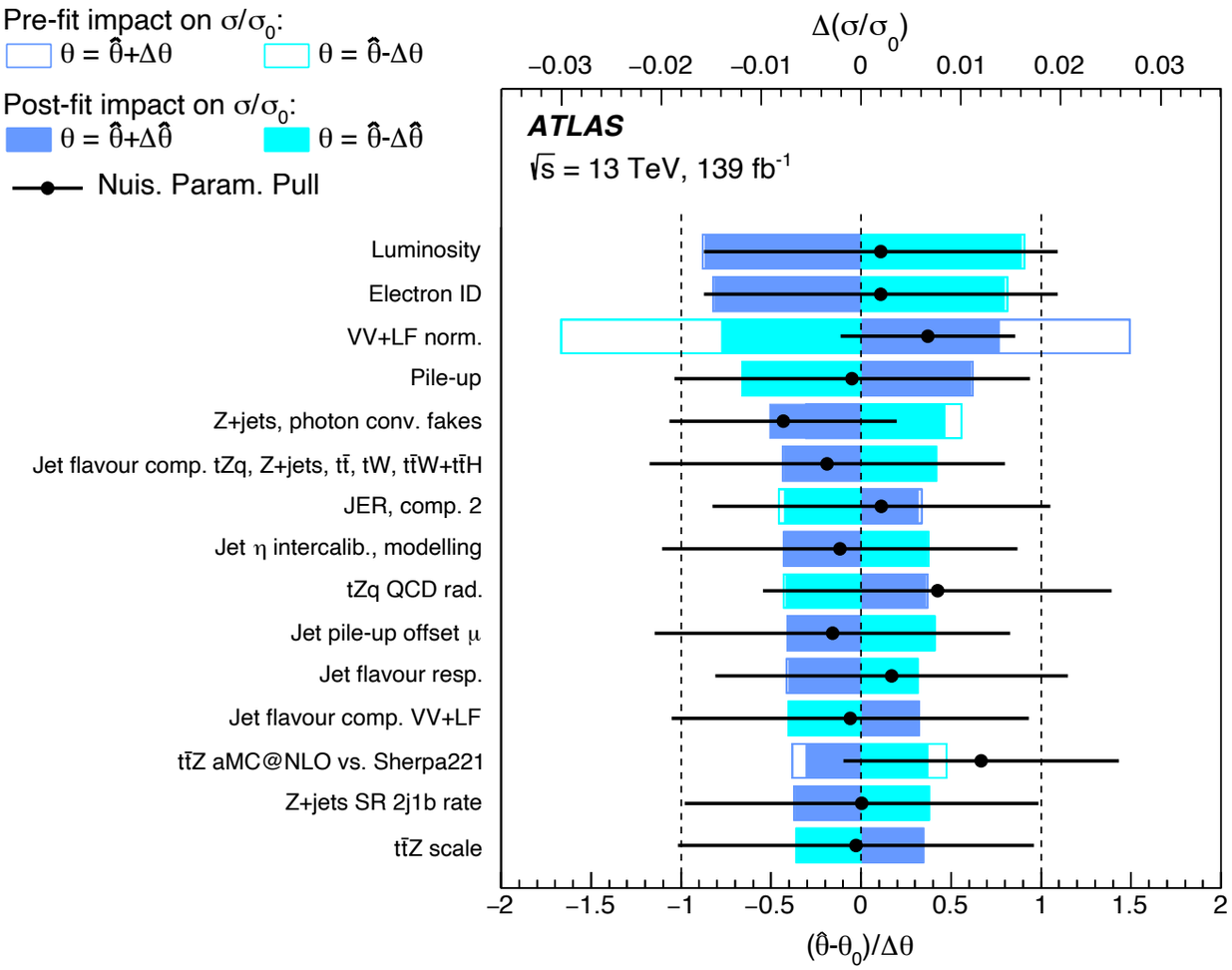
	SR 2j1b	CR diboson 2j0b	CR $t\bar{t}$ 2j1b	CR $t\bar{t}Z$ 3j2b
tZq	79 ± 11	53.1 ± 7.5	0.2 ± 0.1	12.9 ± 2.0
$t\bar{t} + tW$	23.8 ± 4.8	13.7 ± 2.7	33.3 ± 6.3	1.7 ± 0.3
Z + jets	28 ± 13	181 ± 82	< 0.1	1.4 ± 0.6
VV + LF	19.7 ± 7.9	2000 ± 100	< 0.1	0.1 ± 0.1
VV + HF	101 ± 22	383 ± 78	0.4 ± 0.1	5.2 ± 1.7
$t\bar{t}Z + tWZ$	96 ± 11	63.2 ± 7.0	4.8 ± 0.5	59.3 ± 7.1
$t\bar{t}H + t\bar{t}W$	6.5 ± 1.0	3.0 ± 0.5	12.4 ± 1.9	2.8 ± 0.5
Total	354 ± 16	2697 ± 56	51.1 ± 6.1	83.5 ± 6.4
Data	359	2703	49	92

	SR 3j1b	CR diboson 3j0b	CR $t\bar{t}$ 3j1b	CR $t\bar{t}Z$ 4j2b
tZq	43.4 ± 6.2	21.2 ± 3.3	0.2 ± 0.1	8.0 ± 1.3
$t\bar{t} + tW$	11.0 ± 2.2	6.9 ± 1.3	15.4 ± 3.1	1.0 ± 0.2
Z + jets	12.8 ± 6.0	53 ± 23	< 0.1	0.4 ± 0.2
VV + LF	10.1 ± 4.2	624 ± 53	< 0.1	0.1 ± 0.1
VV + HF	58 ± 17	186 ± 51	0.3 ± 0.1	3.4 ± 1.0
$t\bar{t}Z + tWZ$	132 ± 12	61.9 ± 6.2	3.9 ± 0.5	58.1 ± 5.3
$t\bar{t}H + t\bar{t}W$	4.7 ± 0.7	1.7 ± 0.3	8.2 ± 1.3	2.0 ± 0.3
Total	272 ± 12	955 ± 29	28.0 ± 3.0	72.8 ± 5.0
Data	259	949	31	75

Uncertainties

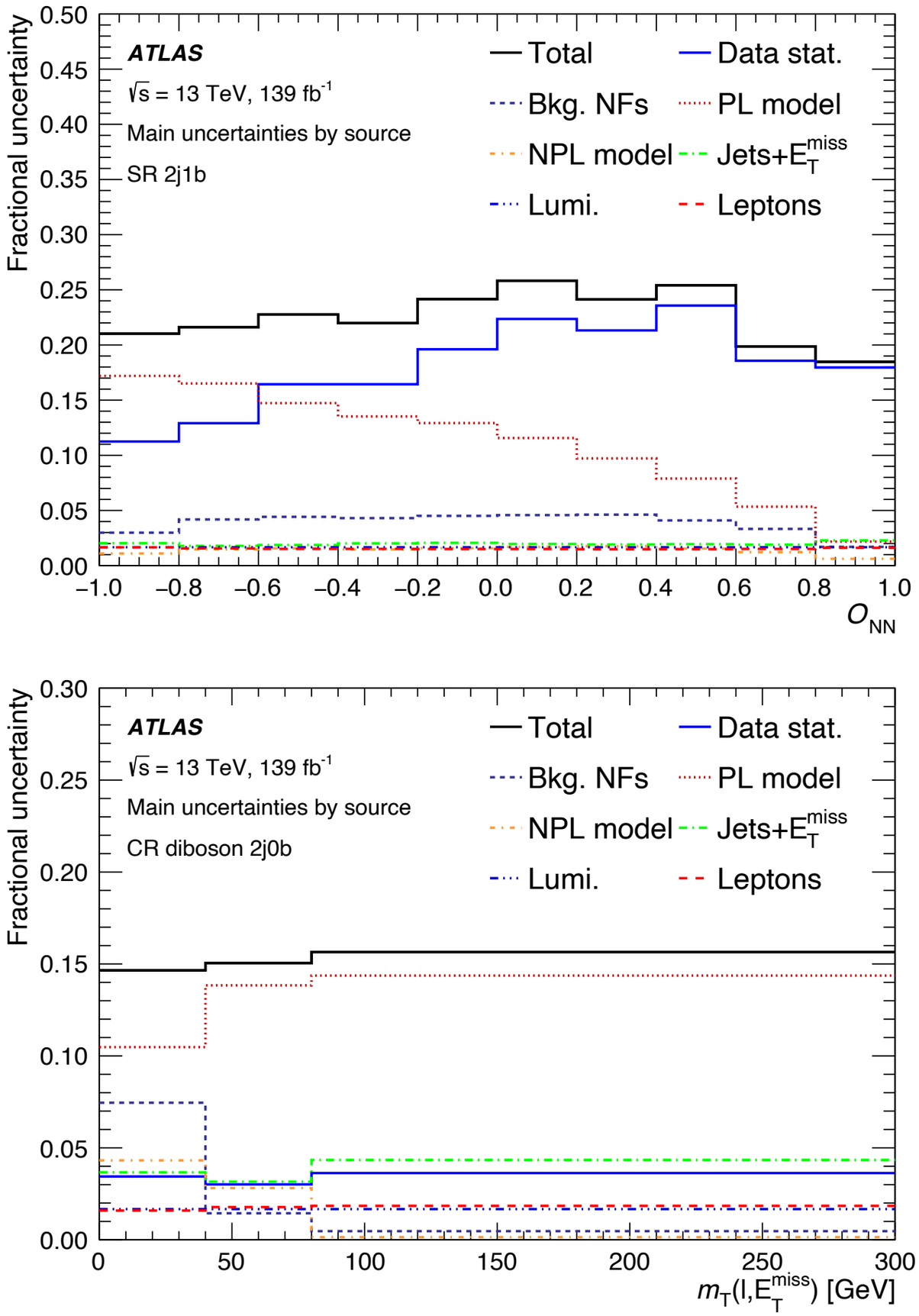
- Reconstruction efficiency and calibration uncertainties
- Signal modeling
  - Scale and radiation
- Background modeling
  - $t\bar{t}$
    - Generator: Powheg-Box vs MadGraph5_aMC@NLO
    - Parton shower and hadronisation: Pythia 8 vs Herwig 7
    - Scale and radiation
    - Pre-fit uncertainty (uncorrelated between regions): 7%
  - Z+jets
    - BJR shape uncertainty
    - Pre-fit uncertainty (uncorrelated between regions): 15%
  - Diboson
    - Generator: Sherpa vs Powheg-Box (separately for LF and HF)
    - Pre-fit uncertainty: 20% for LF and 30% for HF
  - $t\bar{t}Z$
    - Generator: MadGraph5_aMC@NLO vs Sherpa
    - Scale and radiation
    - $t\bar{t}Z$ / tWZ interference: DR1 vs DR2 (similarly to $t\bar{t}$ / tW)
    - Pre-fit uncertainty: 12%
- Luminosity: 1.7%

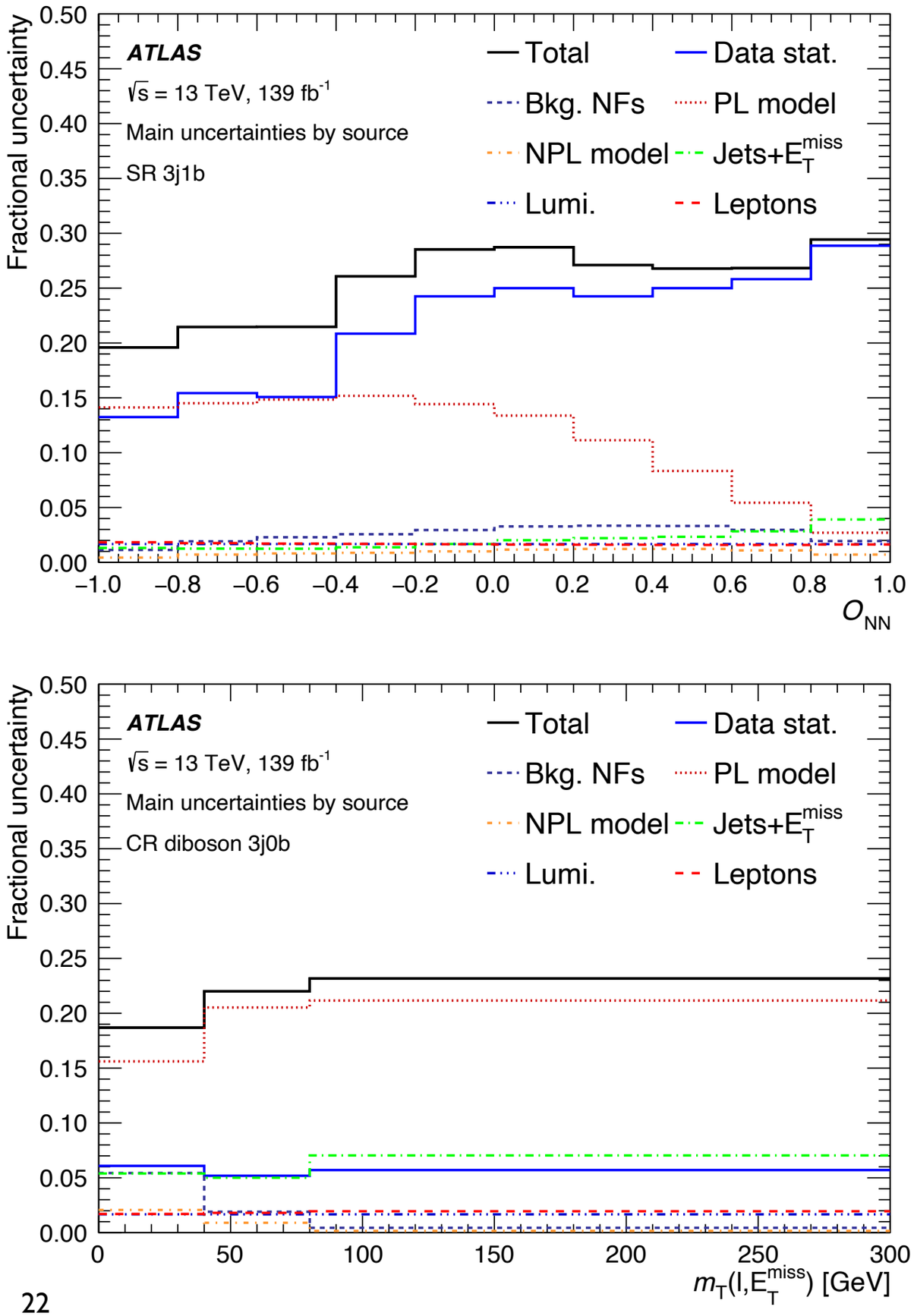
Uncertainties



Uncertainty source	$\Delta\sigma/\sigma$ [%]
Prompt-lepton background modelling and normalisation	3.3
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction and calibration	2.0
Lepton reconstruction and calibration	2.0
Luminosity	1.7
Non-prompt-lepton background modelling	1.6
Pile-up modelling	1.2
MC statistics	1.0
tZq modelling (QCD radiation)	0.8
tZq modelling (PDF)	0.7
Jet flavour tagging	0.4
Total systematic uncertainty	7.0
Data statistical	12.6
$t\bar{t}$ and Z + jets normalisation	2.1
Total statistical uncertainty	12.9

Fractional uncertainties





Fractional uncertainties