Associated productions with top ($t + X$, $tt + X$ with $X = W, Z, \gamma$, heavy-flavours, $t\bar{t}$) at the LHC

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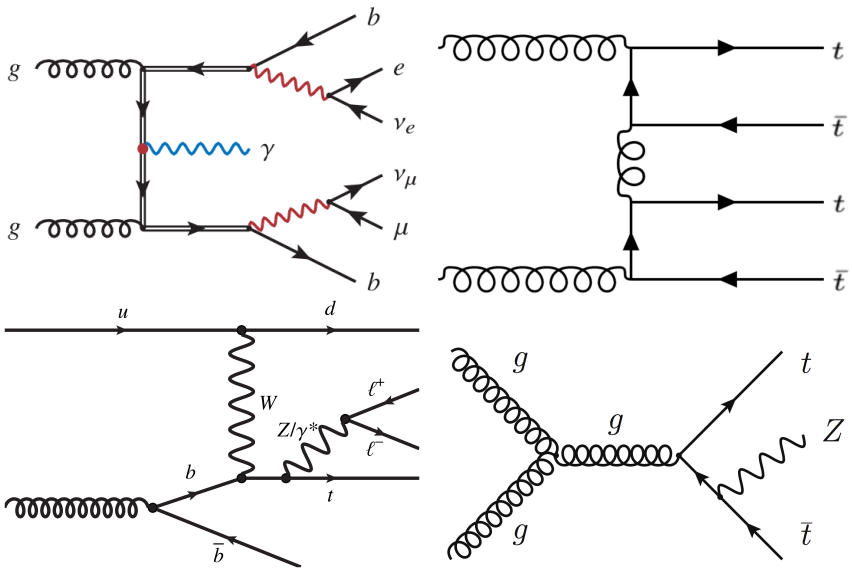
Introduction

Top quark

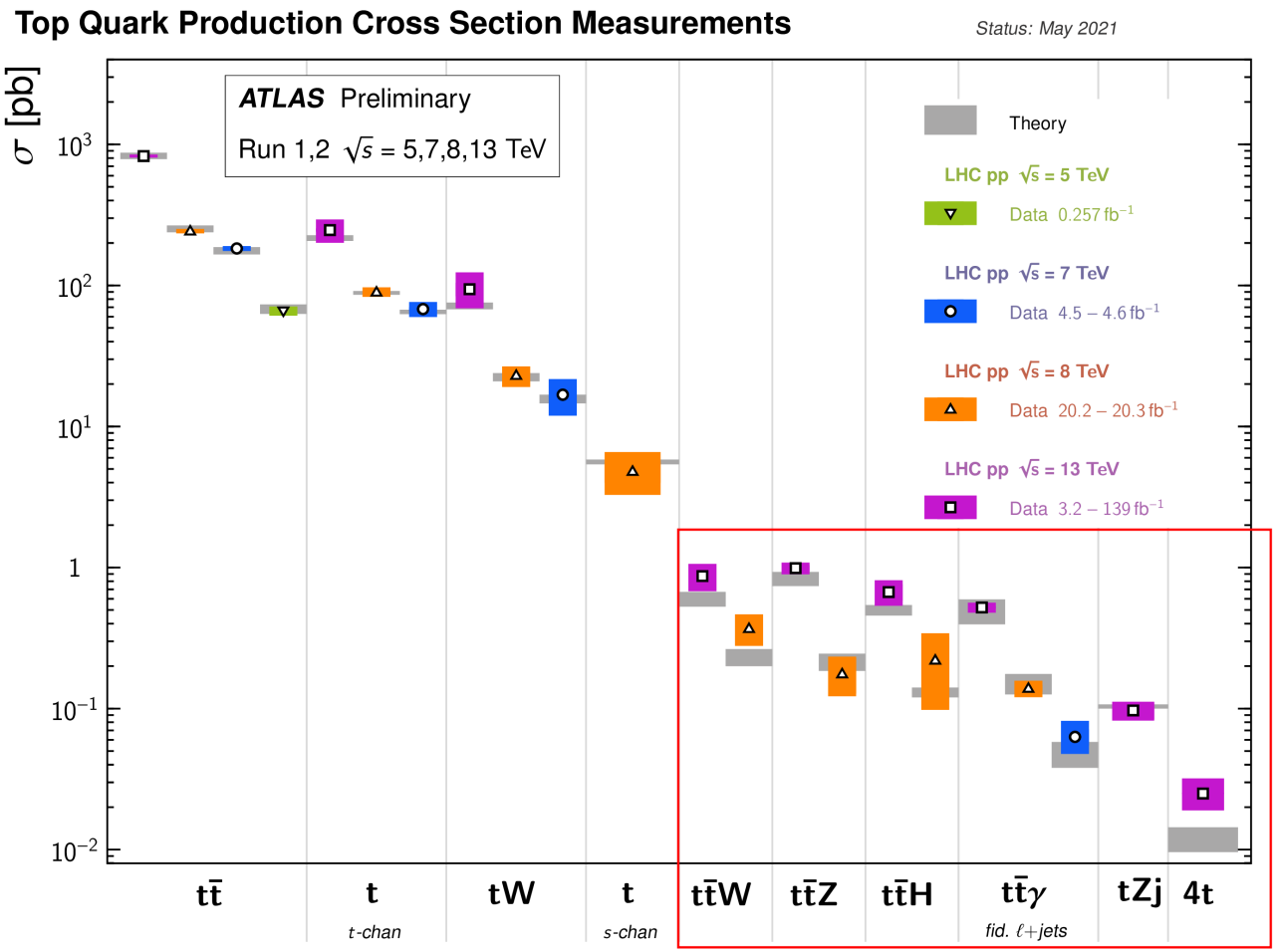
- **Heaviest** known elementary particle ($m_t \approx 173$ GeV)
- Extremely short mean lifetime ($\approx 10^{-25}$ s)
- Top quark decays before hadronisation



- In the SM top quark decays almost exclusively to W and b
- LHC = top factory
- Can study **top+X processes**!
  - $t(\bar{t}) + Z$
  - $t\bar{t} + \gamma$
  - $t\bar{t}t\bar{t}$
  - $t\bar{t} + c\bar{c}$

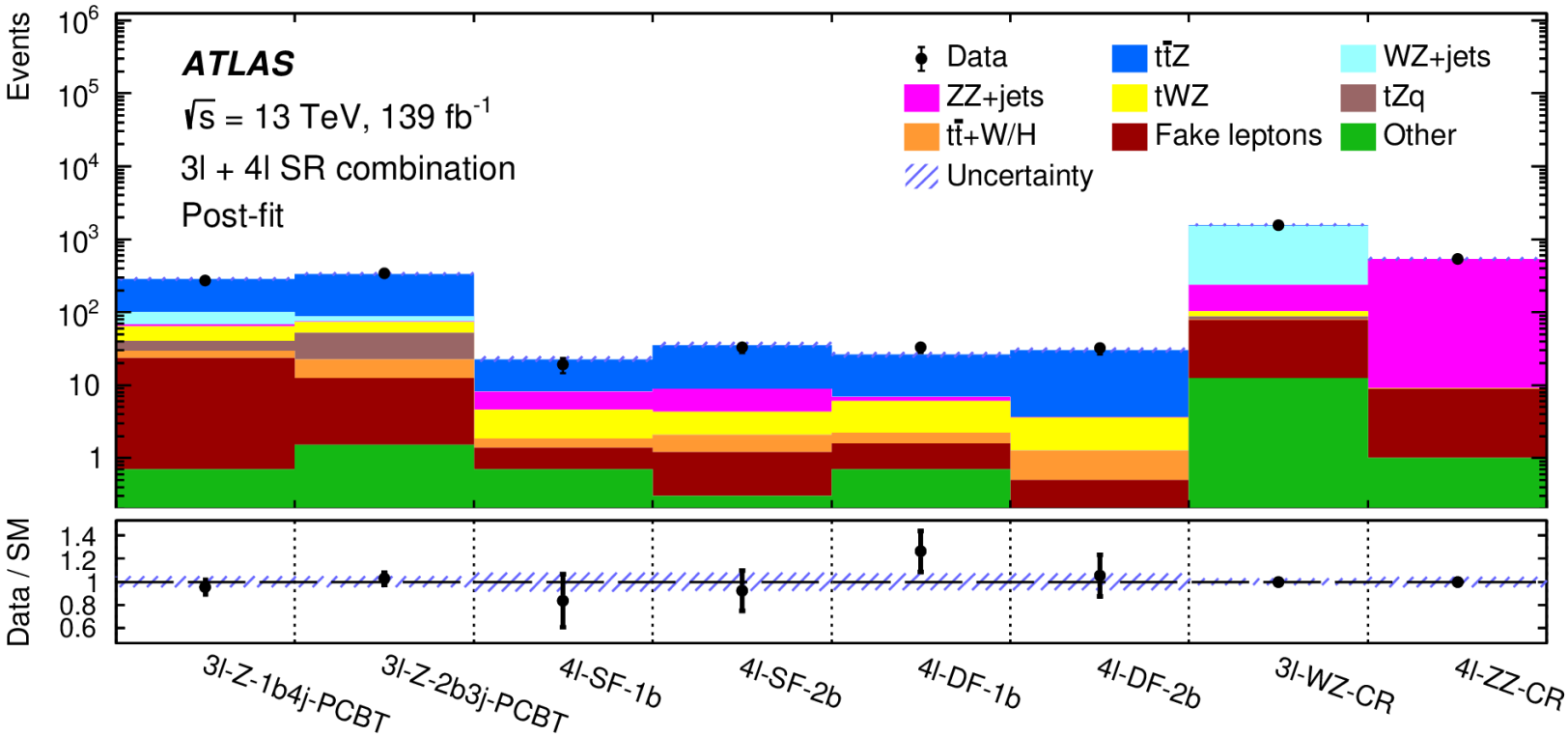
Top+X

- Top+X processes - one of the rarest at the LHC



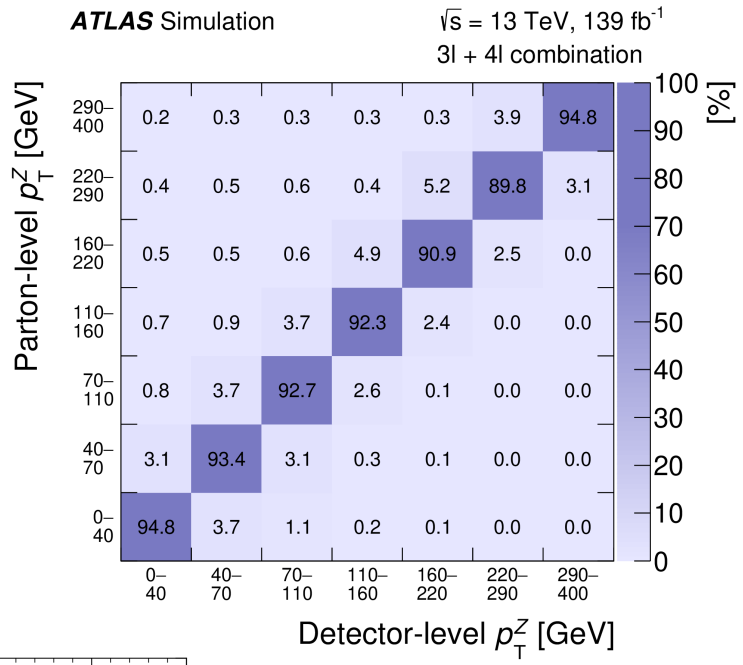
ATLAS $t\bar{t}Z$ - Eur. Phys. J. C 81, 737 (2021)

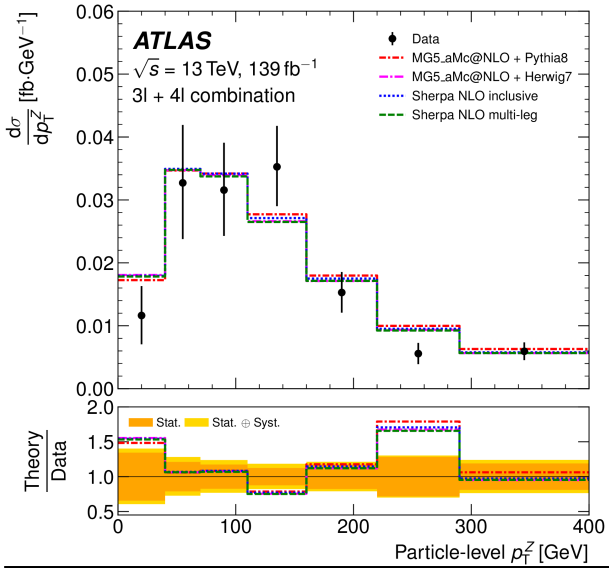
- **Inclusive** and **differential** measurement, targeting 3-lepton and 4-lepton channels (e or μ)
- $\geq$ 3 jets, $\geq$ 1 b-jet, 3 or 4 leptons, Z window
- Control regions for WZ and ZZ backgrounds (free-floating)
- Expected x-section: $\sigma^{\text{exp.}}_{t\bar{t}Z} = 0.84^{+0.09}_{-0.10}$ pb
- Measured x-section: $\sigma_{t\bar{t}Z} = 0.99 \pm 0.05(\text{stat.}) \pm 0.08(\text{syst.})$ pb

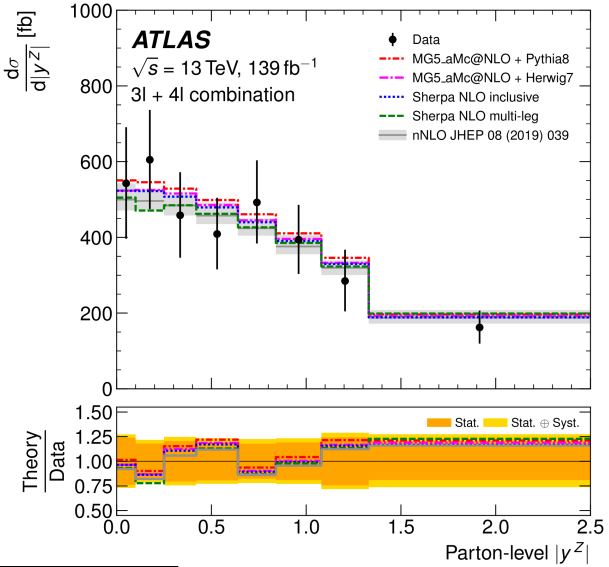


ATLAS $t\bar{t}Z$ - differential

- 10 observables unfolded to parton and particle level
- Sensitive to **BSM** effects and/or modelling
- Using IBU[1] technique
- Distributions compatible with predictions in most variables





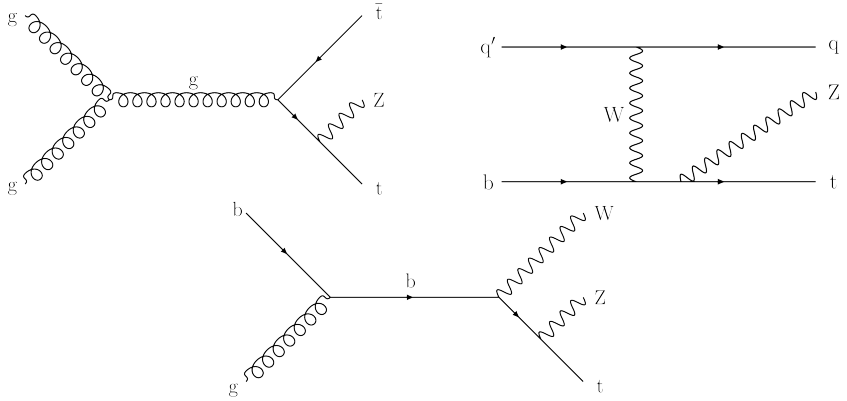


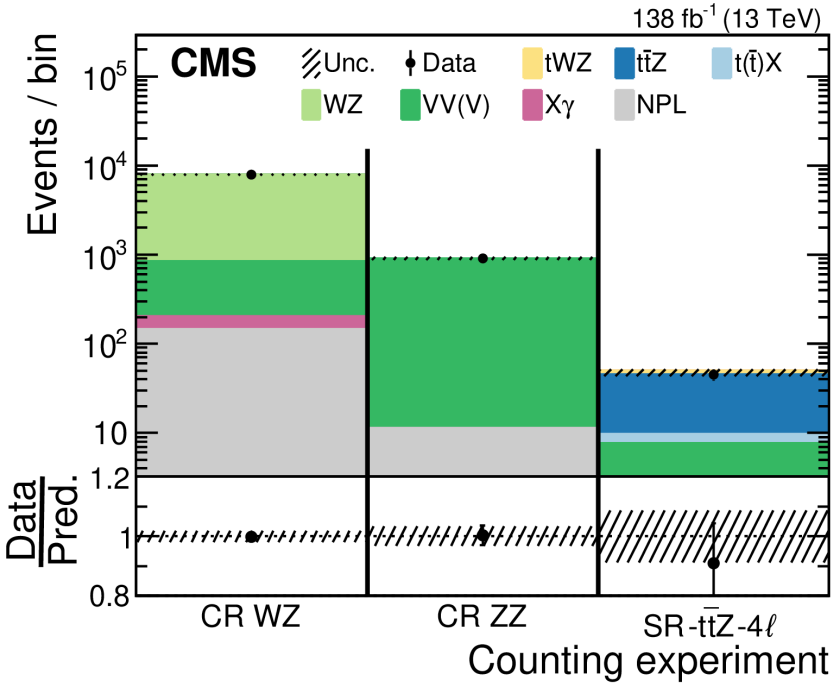
- **Dominates by stats**
- Dominant syst.:
  - Fake leptons
  - WZ modelling
  - $t\bar{t}Z$ modelling
  - b-tagging

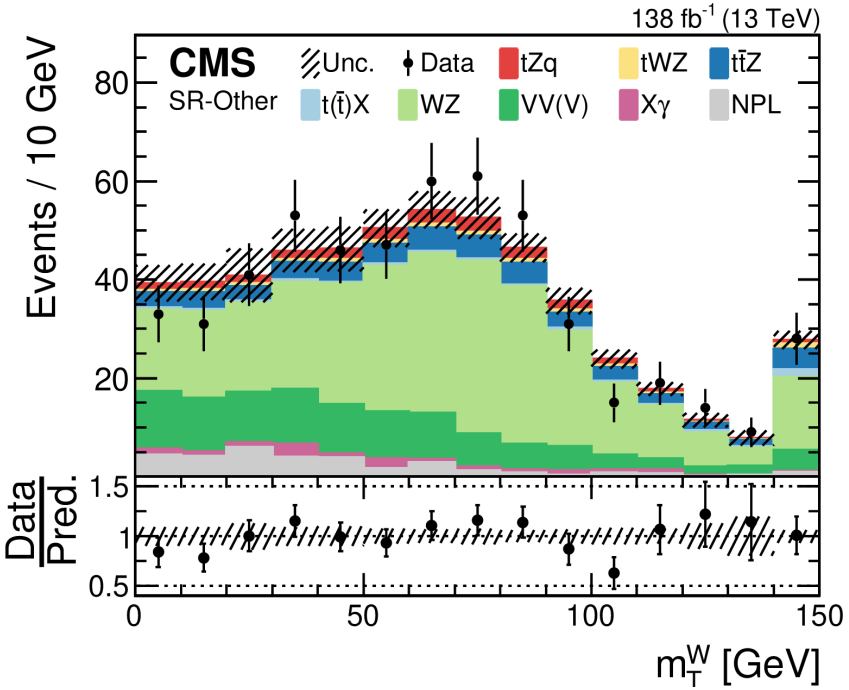
[1] Iterative Bayesian Unfolding

CMS $t(\bar{t}) + Z$ - arXiv:2107.13896 - submitted to JHEP

- Targets $t\bar{t}Z$, tZq and tWZ
- Using 3L or 4L channels
- Focuses on **EFT** - Wilson Coefficient sensitivity
- NN to separate $t\bar{t}Z$, tZq, other
- CR for WZ and ZZ

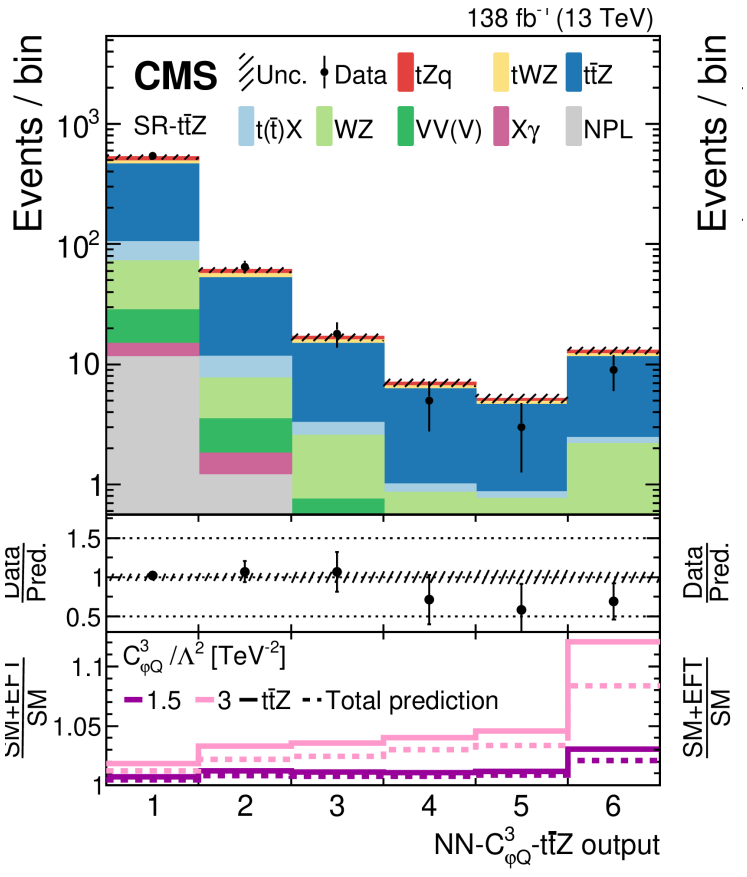






CMS $t(\bar{t}) + Z$ - EFT

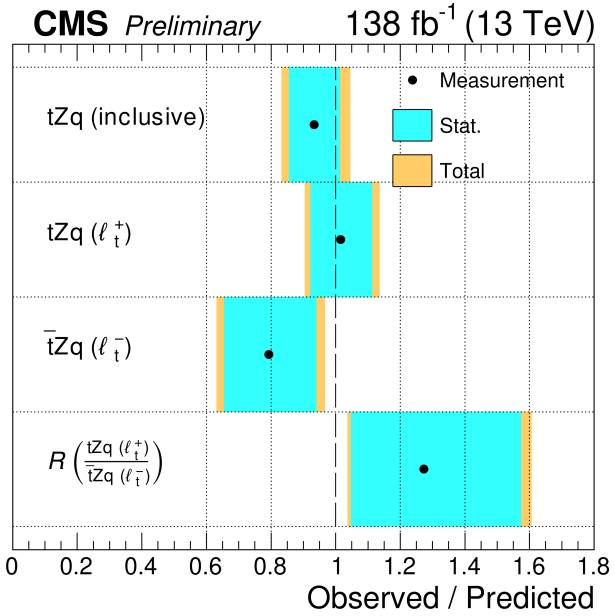
- Using dedicated NN to separate SM and EFT
- Used to build the SR variables
- **First time using the interference in the training**
- Five EFT operators

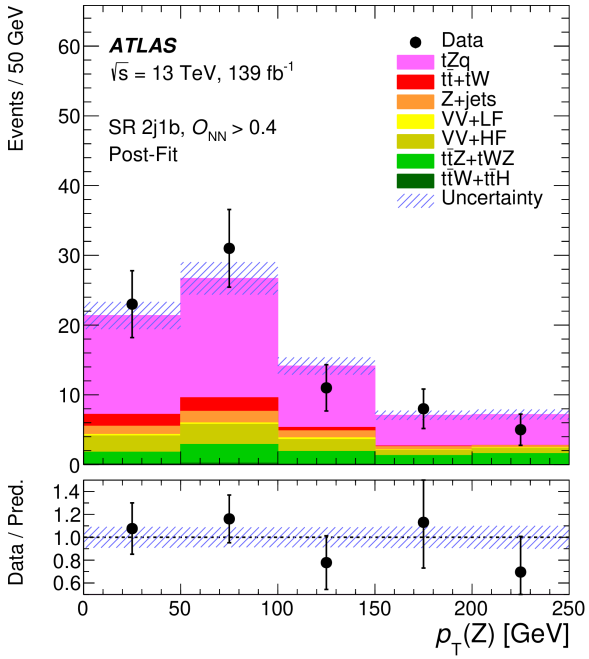


WC/Λ^2 $[TeV^{-2}]$	95% CL confidence intervals			
	Other WCs fixed to SM		5D fit	
	Expected	Observed	Expected	Observed
c_{tZ}	$[-0.97, 0.96]$	$[-0.76, 0.71]$	$[-1.24, 1.17]$	$[-0.85, 0.76]$
c_{tW}	$[-0.76, 0.74]$	$[-0.52, 0.52]$	$[-0.96, 0.93]$	$[-0.69, 0.70]$
$c^3_{\varphi Q}$	$[-1.39, 1.25]$	$[-1.10, 1.41]$	$[-1.91, 1.36]$	$[-1.26, 1.43]$
$c^-_{\varphi Q}$	$[-2.86, 2.33]$	$[-3.00, 2.29]$	$[-6.06, 14.09]$	$[-7.09, 14.76]$
$c_{\varphi t}$	$[-3.70, 3.71]$	$[-21.65, -14.61] \cup [-2.06, 2.69]$	$[-16.18, 10.46]$	$[-19.15, 10.34]$

tZq inclusive

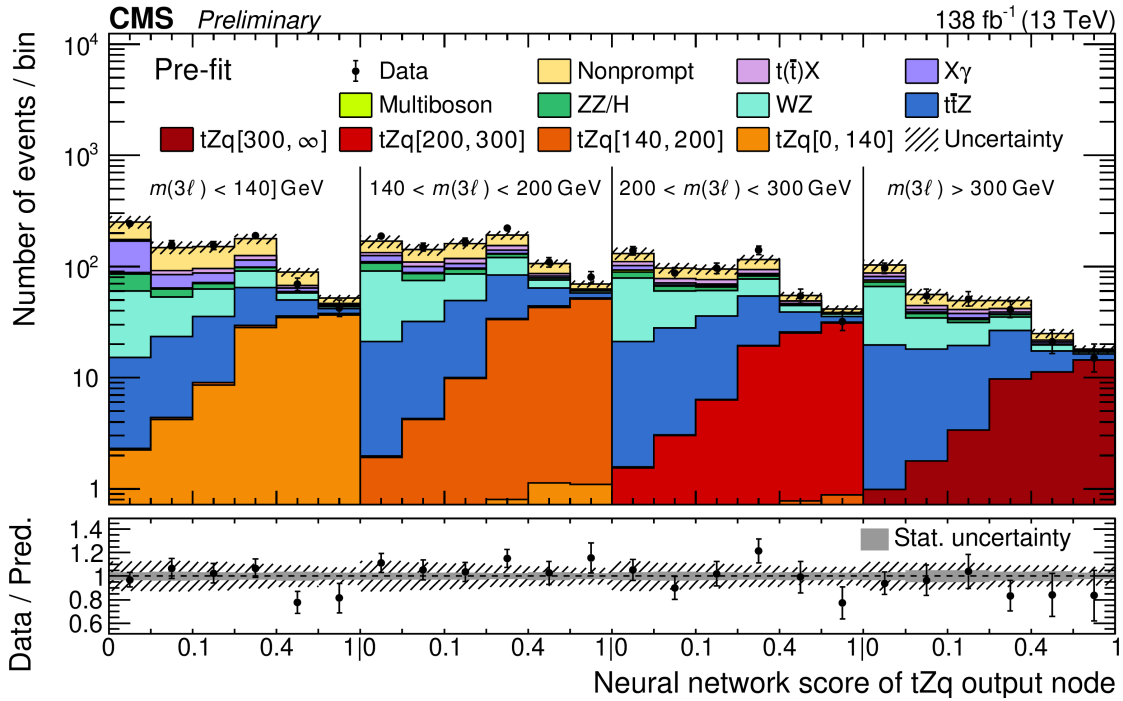
- ATLAS and CMS target 3L channel
- $\geq$ 2 jets, b-tagged jet for SRs
- CRs for $t\bar{t}Z$, diboson, WZ(CMS), $Z\gamma$(CMS), $t\bar{t}$(ATLAS) - free floating
- **MVA to suppress bkg.**, ATLAS: NN, CMS: BDT
- SM prediction: $\sigma_{tZq} = 102^{+5}_{-2}$ fb
- CMS PAS-TOP-20-010: $\sigma_{tZq} = 87.9^{+7.5}_{-7.3}(\text{stat.})^{+7.3}_{-6.0}(\text{syst.})$ fb
- ATLAS JHEP 07 (2020) 124: $\sigma_{tZq} = 97 \pm 13(\text{stat.}) \pm 7(\text{syst.})$ fb
- Good agreement with the SM

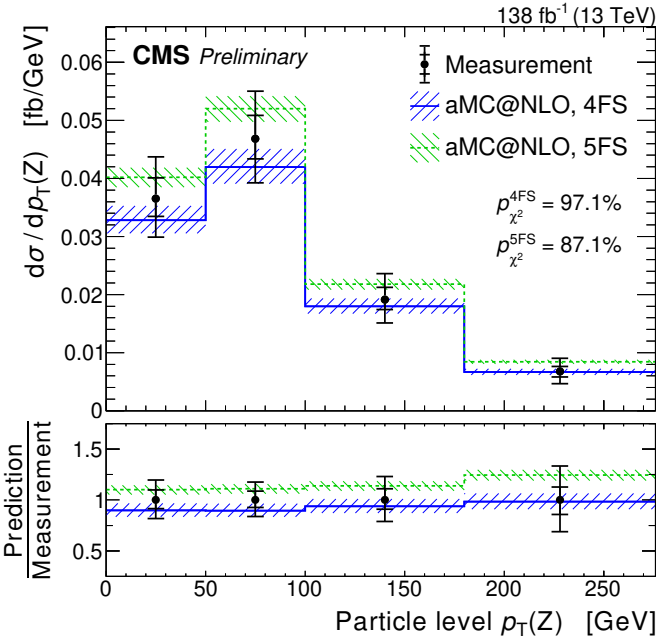




CMS *tZq* differential - PAS-TOP-20-010

- **Likelihood-based unfolding** to parton and particle level
- Differential: $\leq$ 4 jets
- Results mostly compatible with the MC predictions

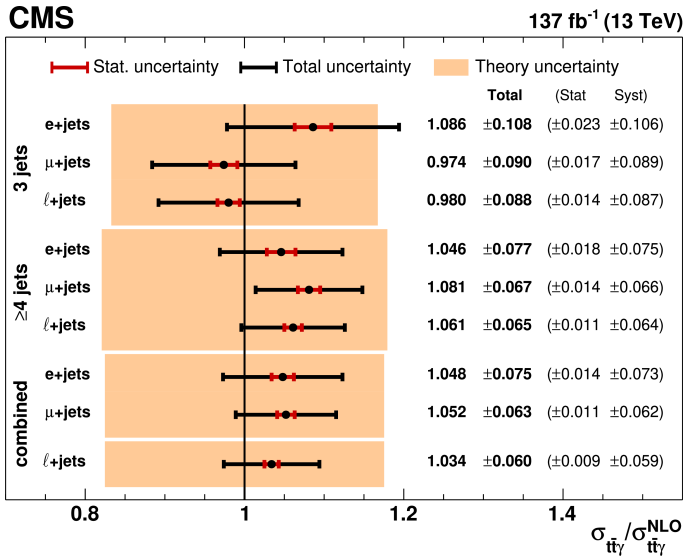


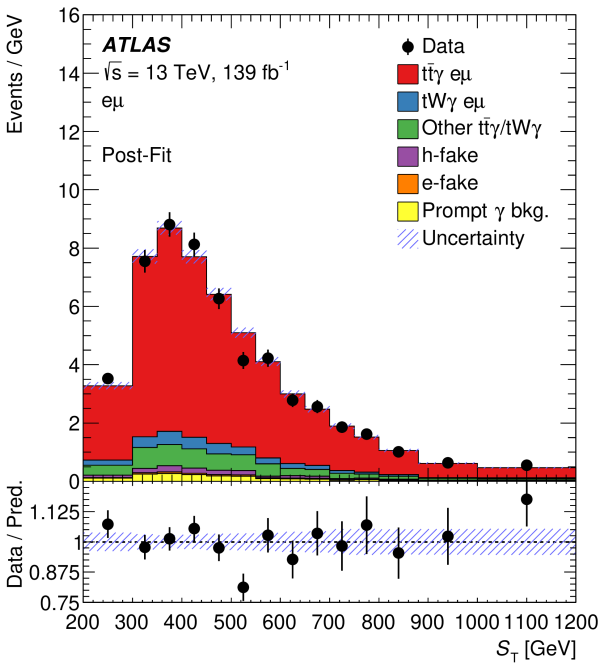


- Unfolding in each kinematic region separately
- **Multiclass NN** to isolate *tZq*

$t\bar{t}\gamma$ inclusive

- CMS[2]: lepton+jets
  - $\geq$ 3 jets
  - CRs for non-prompt γ
- ATLAS[3]: $e\mu$ only
  - $\geq$ 2 jets
  - $t\bar{t}\gamma$ and $tW\gamma$ combined
  - Fitting S_T (scalar sum of p_T)
- Inclusive **fiducial** cross-section
- $\sigma_{t\bar{t}\gamma}^{\text{l+jets}} = 800 \pm 7(\text{stat.}) \pm 46(\text{syst.})$ fb
- $\sigma_{t\bar{t}\gamma}^{e\mu} = 39.6 \pm 0.8(\text{stat.})^{+2.6}_{-2.2}(\text{syst.})$ fb
- Dominant uncertainties:
  - $e\mu$: $t\bar{t}\gamma$ modelling, lumi
  - l+jets: lepton/photon fakes, modelling, lumi

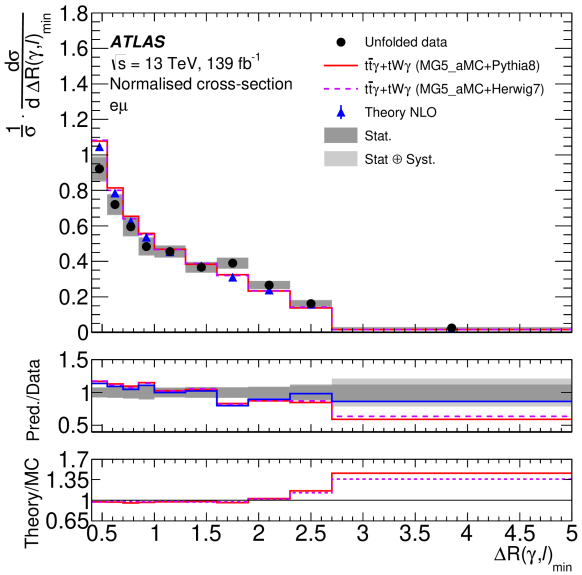


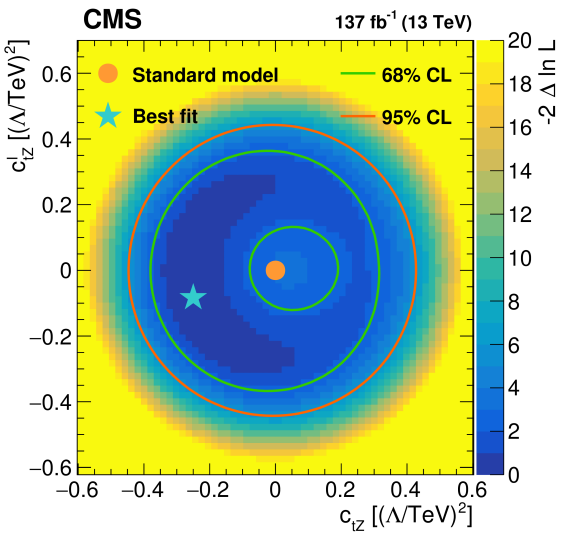


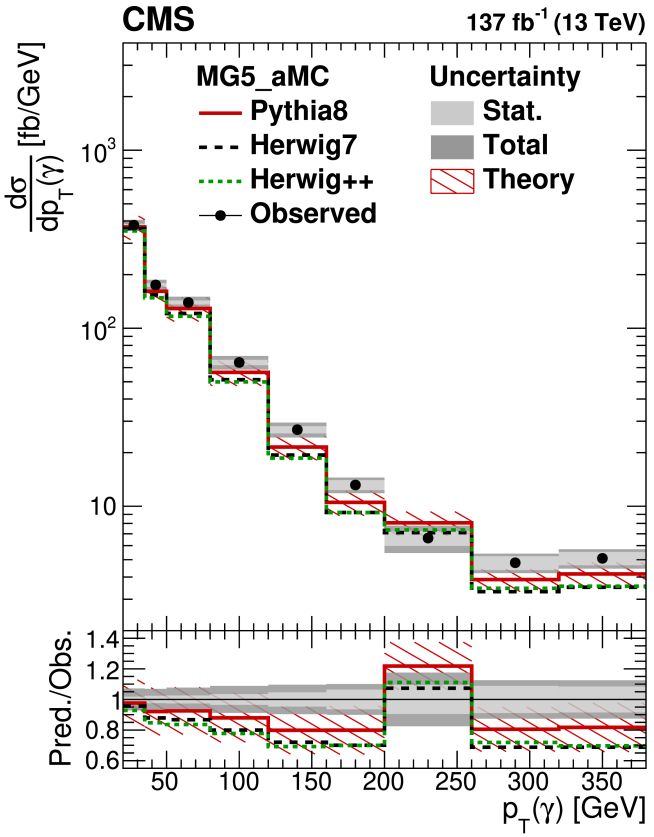
[2] arXiv:2107.01508 - submitted to JHEP, [3] JHEP 09 (2020) 049

$t\bar{t}\gamma$ differential

- Strongly diagonal migrations
- ATLAS: IBU unfolding
- CMS: TUnfold - matrix inversion
- **NLO theory prediction** describes data **better than LO generators**
- EFT fit (CMS) to detector level

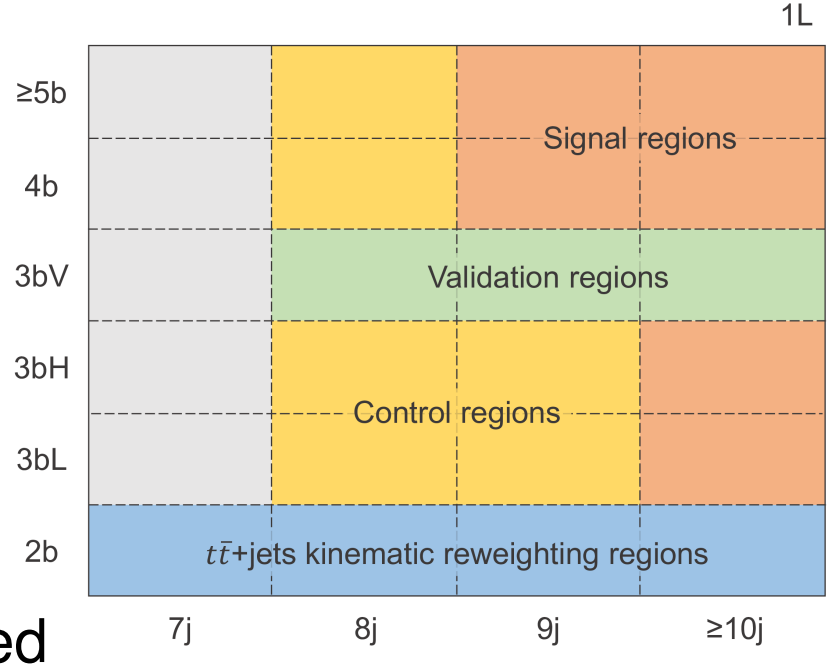




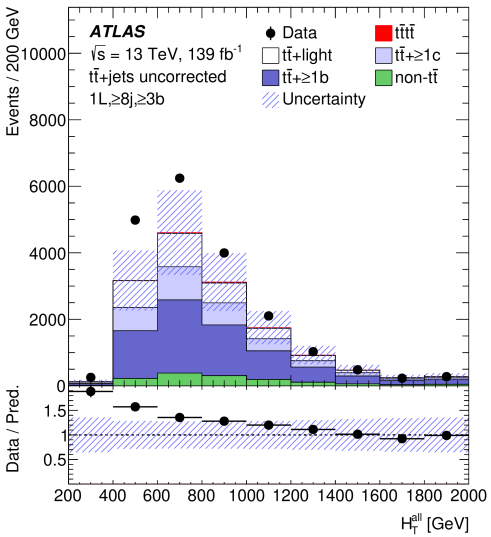


4 tops ($t\bar{t}t\bar{t}$) - arXiv:2106.11683 - submitted to JHEP

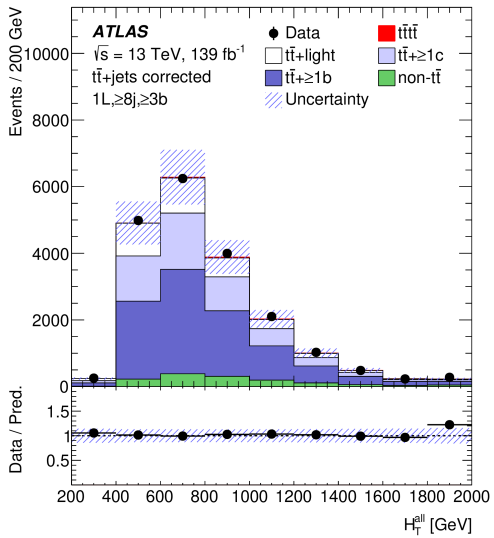
- Extremely **rare** process - 12 fb
- 1L and 2L opposite sign
- LO signature: $\geq$ 8 jets, $\geq$ 4 *b*-jets
- Dominant background: $t\bar{t}$+jets
  - Sequential reweighting using data - improves prediction
- Dom. unc.: modelling, *b*-tagging

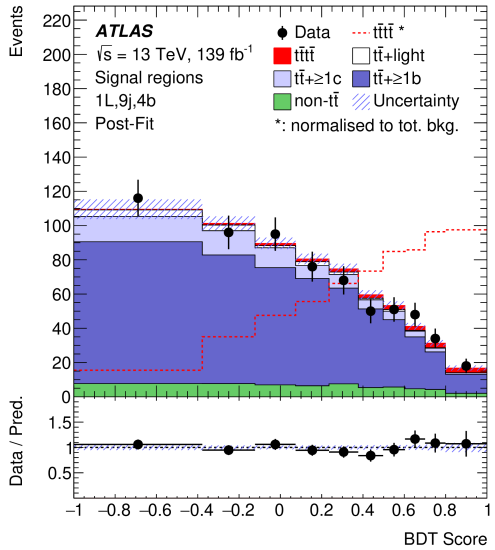


Uncorrected



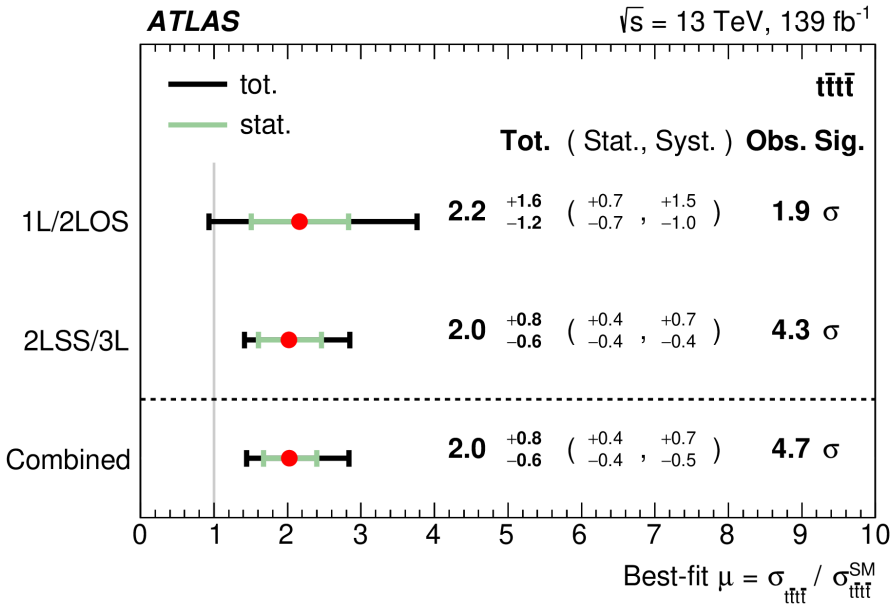
Corrected

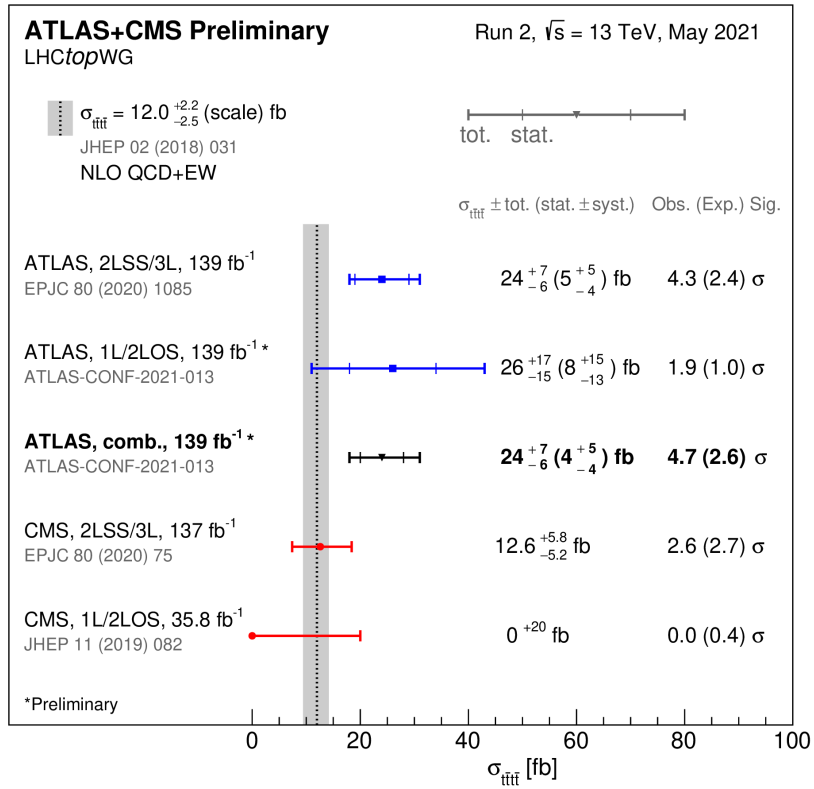




4 tops ($t\bar{t}t\bar{t}$) - results + combination

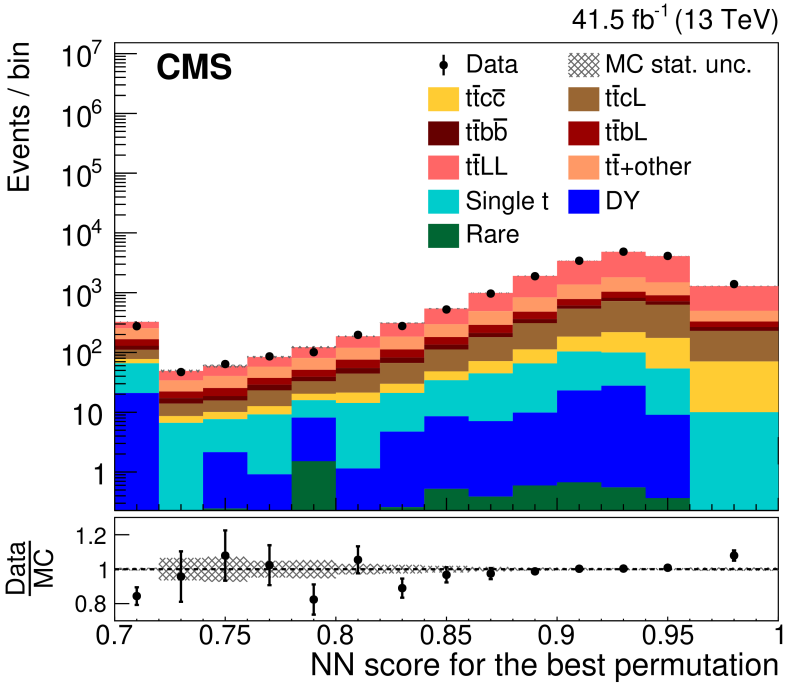
- Using **BDT** distribution in the SRs - to enhance signal
- 1LOS result: $\sigma_{t\bar{t}t\bar{t}} = 26^{+17}_{-15}$ fb - further evidence of 4tops process
- Combination with 2L SS and 3L channels - EPJC 80 (2020) 1085
- Combination: 2σ away from the SM prediction (exp: 12.0 ± 2.4 fb)

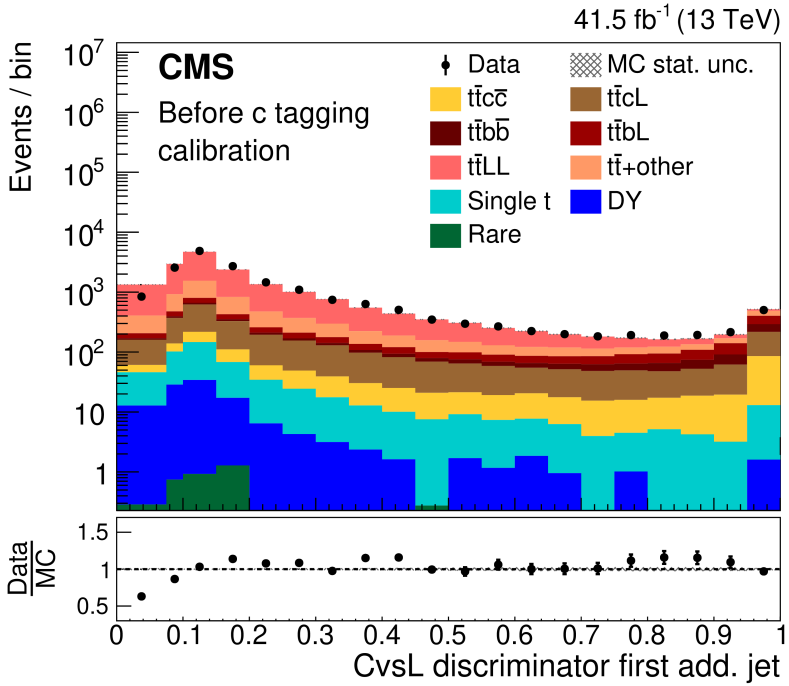




$t\bar{t} + c\bar{c}$ - Phys. Lett. B. 820 (2021) 136565

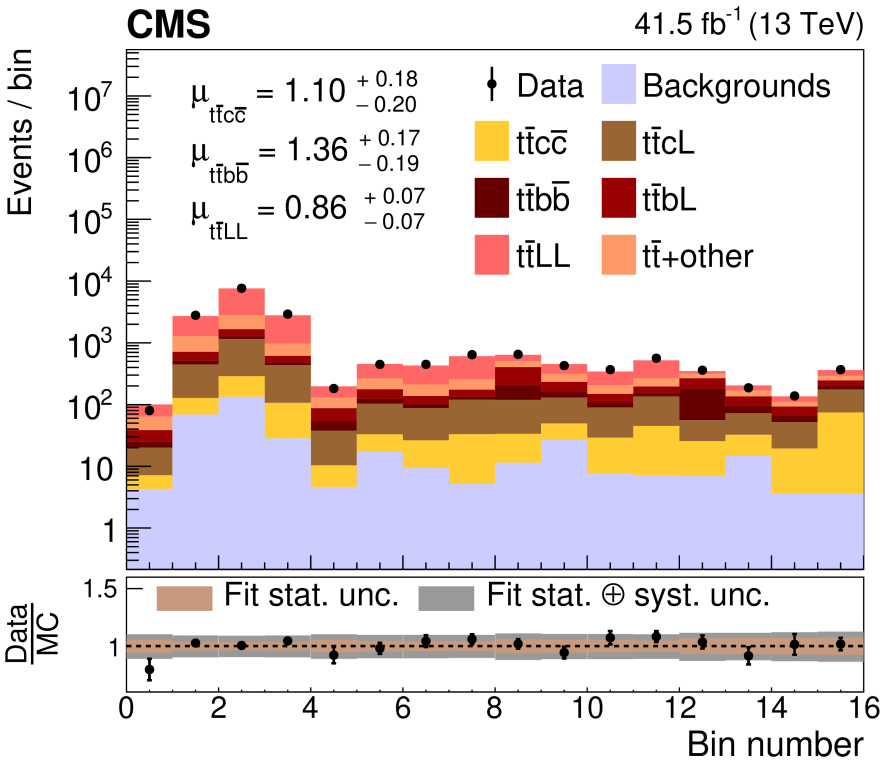
- Dilepton channel of $t\bar{t}$
- Main difficulty: separation from $t\bar{t} + b(\bar{b})$ and $t\bar{t}$+light
- Using *c*-tagger - exploiting multiclass flavour tagger
- **NN to match jets** to partons (permutations)
- Event-level NN - 5 classes for flavour of additional jets - projected onto two discriminators

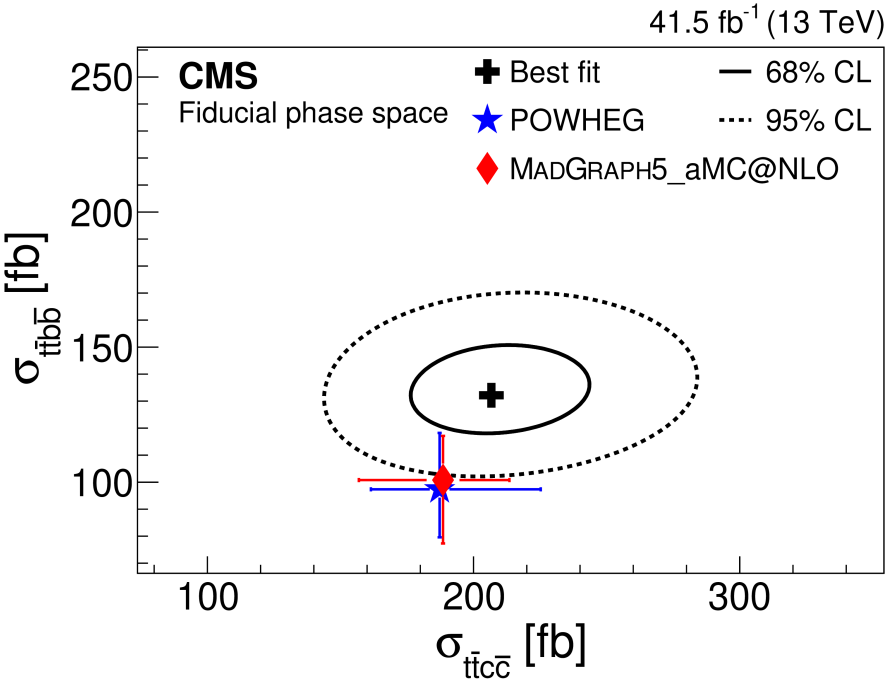




$t\bar{t} + c\bar{c}$

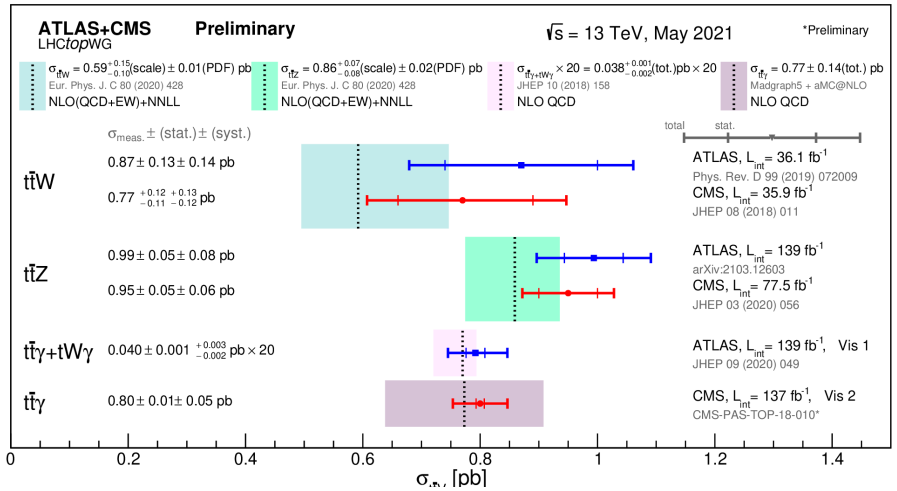
- **Template fit** (separate templates for ee, $e\mu$, $\mu\mu$)
- First fit to extract absolute cross-sections
- Second fit to extract fractions
- Dominant uncertainties: fragmentation, modelling, flavour tagging

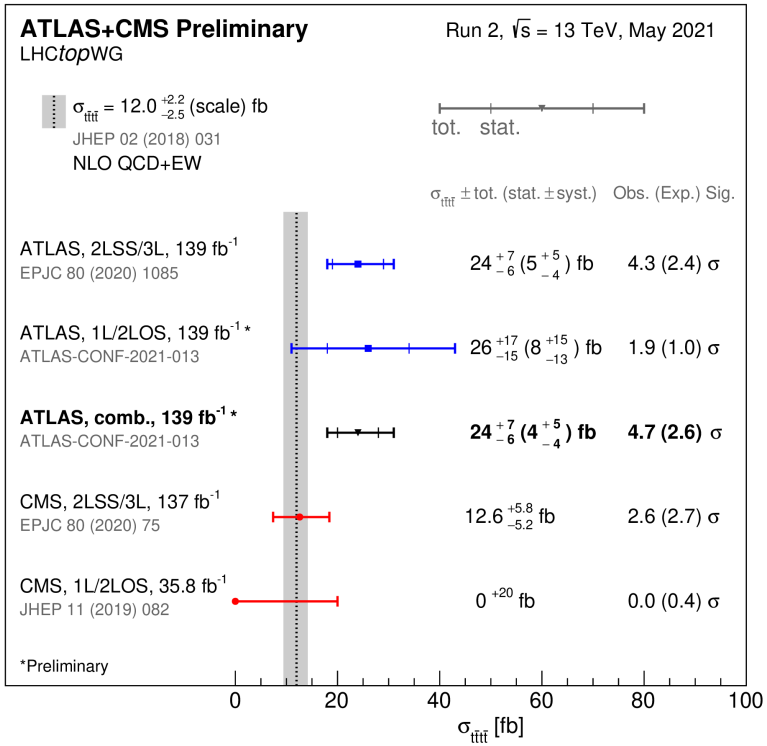




Summary

- Many new results for top+X in ATLAS and CMS
  - E.g. $t\bar{t}t\bar{t}$ or $t\bar{t} + c\bar{c}$
- Significantly improved results from previous iterations
- New EFT interpretations
- **More top-related results**: ATLAS and CMS





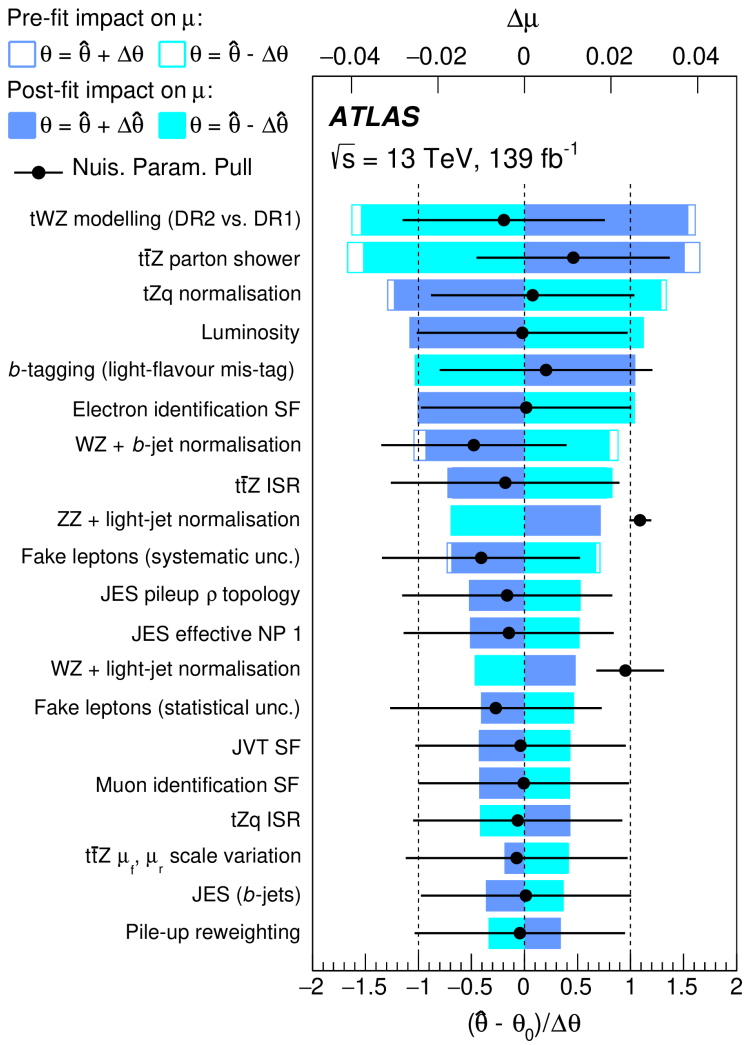
Outlook

- "Second wave" of analyses
  - More sophisticated tools - improved precision
  - More channels
- Combination of channels/measurements - EFT

BACK UP

ATLAS $t\bar{t}Z$ inclusive

- Systematic uncertainties dominated by modelling
- Diagram removal
- Pythia vs Herwig comparison
- Dominant detector uncertainty: flavour tagging



ATLAS $t\bar{t}Z$ differential

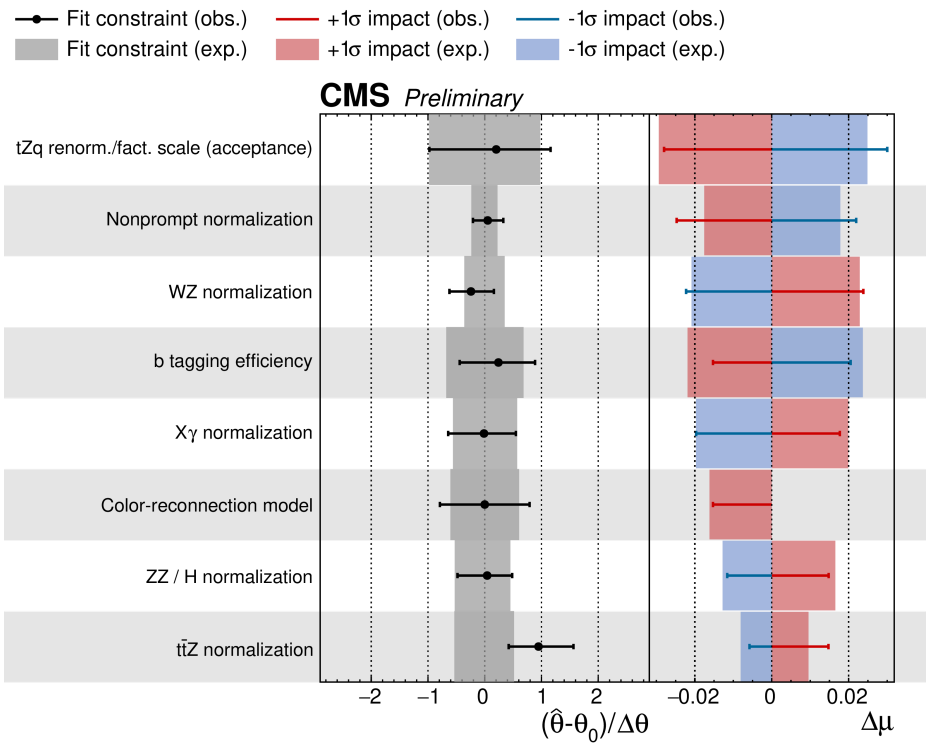
	Variable	Particle	Parton	Absolute	Normalised	Figure	MG5_aMC@NLO 2.3.3 + Pythia 8 χ^2/ndf	MG5_aMC@NLO 2.3.3 + Pythia 8 p-value	MG5_aMC@NLO 2.3.3 + Herwig 7 χ^2/ndf	MG5_aMC@NLO 2.3.3 + Herwig 7 p-value	Sherpa 2.2.1 NLO multi-leg χ^2/ndf	Sherpa 2.2.1 NLO multi-leg p-value	Sherpa 2.2.1 NLO inclusive χ^2/ndf	Sherpa 2.2.1 NLO inclusive p-value	Additional Theory χ^2/ndf	Additional Theory p-value
$3\ell + 4\ell$	p_{T}^{Z}	✓		✓		9(a)	12.8/7	0.08	12.0/7	0.10	11.6/7	0.11	12.1/7	0.10	/	/
	p_{T}^{Z}		✓	✓		9(b)	12.8/7	0.08	11.7/7	0.11	11.2/7	0.13	11.3/7	0.13	10.4/7	0.17
	p_{T}^{Z}	✓			✓	10(a)	11.0/6	0.09	10.8/6	0.09	10.6/6	0.10	10.7/6	0.10	/	/
	p_{T}^{Z}		✓		✓	10(b)	11.0/6	0.09	10.8/6	0.10	10.7/6	0.10	10.6/6	0.10	10.5/6	0.11
	$\lvert y^{Z}\rvert$		✓	✓		11(a)	2.8/8	0.95	2.9/8	0.94	4.0/8	0.85	2.7/8	0.95	2.9/8	0.94
3ℓ	N_{jets}	✓		✓		12(a)	0.8/3	0.85	0.6/3	0.90	0.3/3	0.95	0.5/3	0.92	/	/
	$p_{\mathrm{T}}^{\ell,\text{non-}Z}$		✓	✓		13(a)	7.6/4	0.11	8.8/4	0.07	8.3/4	0.08	8.6/4	0.07	/	/
	$\lvert\Delta\phi(Z, t_{\mathrm{lep}})\rvert$		✓	✓		13(b)	5.5/3	0.14	5.8/3	0.12	5.2/3	0.16	6.9/3	0.07	6.6/3	0.09
	$\lvert\Delta y(Z, t_{\mathrm{lep}})\rvert$		✓	✓		14(a)	0.9/3	0.82	0.7/3	0.88	0.2/3	0.98	0.5/3	0.92	0.3/3	0.96
4ℓ	N_{jets}	✓		✓		12(b)	1.4/4	0.84	1.7/4	0.79	2.8/4	0.59	2.8/4	0.59	/	/
	$\lvert\Delta\phi(\ell_t^+, \ell_{\bar{t}}^-)\rvert$		✓	✓		14(b)	2.1/4	0.72	2.3/4	0.69	2.7/4	0.62	2.6/4	0.63	/	/
	$\lvert\Delta\phi(t\bar{t}, Z)\rvert$		✓	✓		15(a)	5.2/3	0.16	4.7/3	0.19	3.5/3	0.32	3.4/3	0.33	4.9/3	0.18
	$p_{\mathrm{T}}^{t\bar{t}}$		✓	✓		15(b)	3.5/4	0.47	3.6/4	0.47	3.5/4	0.48	3.5/4	0.47	4.6/4	0.33

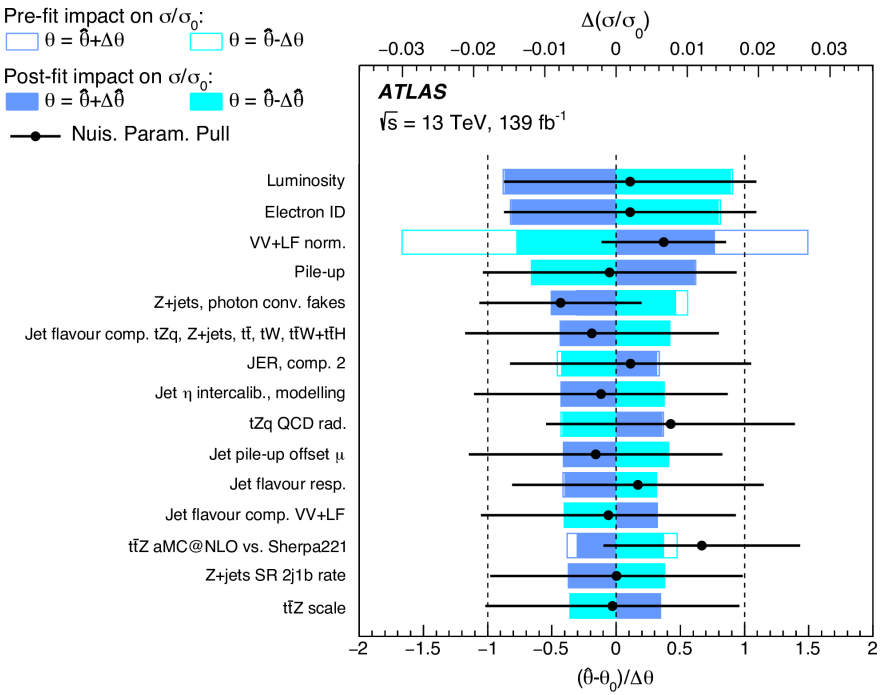
CMS $t(\bar{t}) + Z$ uncertainties

Source	c_{tZ}	c_{tW}	t	$c^{-}_{\varphi Q}$	$c_{\varphi t}$
tZq normalization	<0.1	<0.1	1.2	0.1	0.8
$t\bar{t}Z$ normalization	0.6	<0.1	0.4	37	38
tWZ normalization	0.1	0.1	<0.1	0.7	2.1
Background normalizations	<0.1	<0.1	6.9	3.6	6.8
NPL background estimation	1.4	0.2	5.6	0.3	3.8
Jet energy scale	<0.1	<0.1	0.8	0.7	2.3
Jet energy resolution	<0.1	<0.1	<0.1	<0.1	1.4
p_{T}^{miss}	<0.1	<0.1	<0.1	<0.1	0.2
b tagging	<0.1	<0.1	0.9	2.0	0.3
Other (experimental)	<0.1	<0.1	1.6	0.8	0.6
Lepton identification and isolation	0.4	0.4	1.2	2.2	0.8
Theory	2.1	1.1	0.4	0.9	0.9

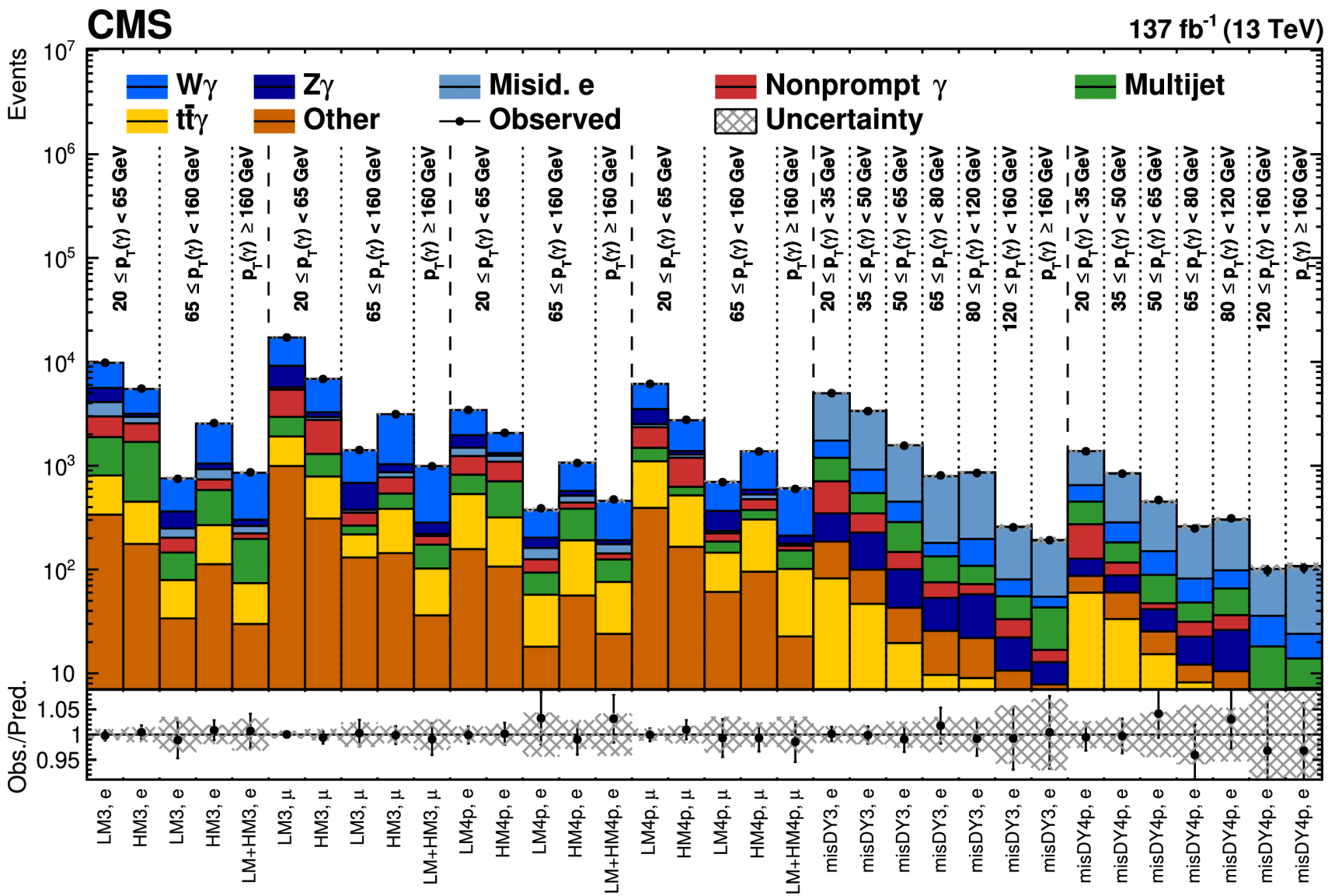
tZq systematic uncertainties

- Similar selection - can compare uncertainties
- **Dominant** systematic uncertainties
  - CMS: *tZq* modelling, non-prompt leptons, *WZ*
  - ATLAS: Luminosity, electron ID, *VV* normalisation



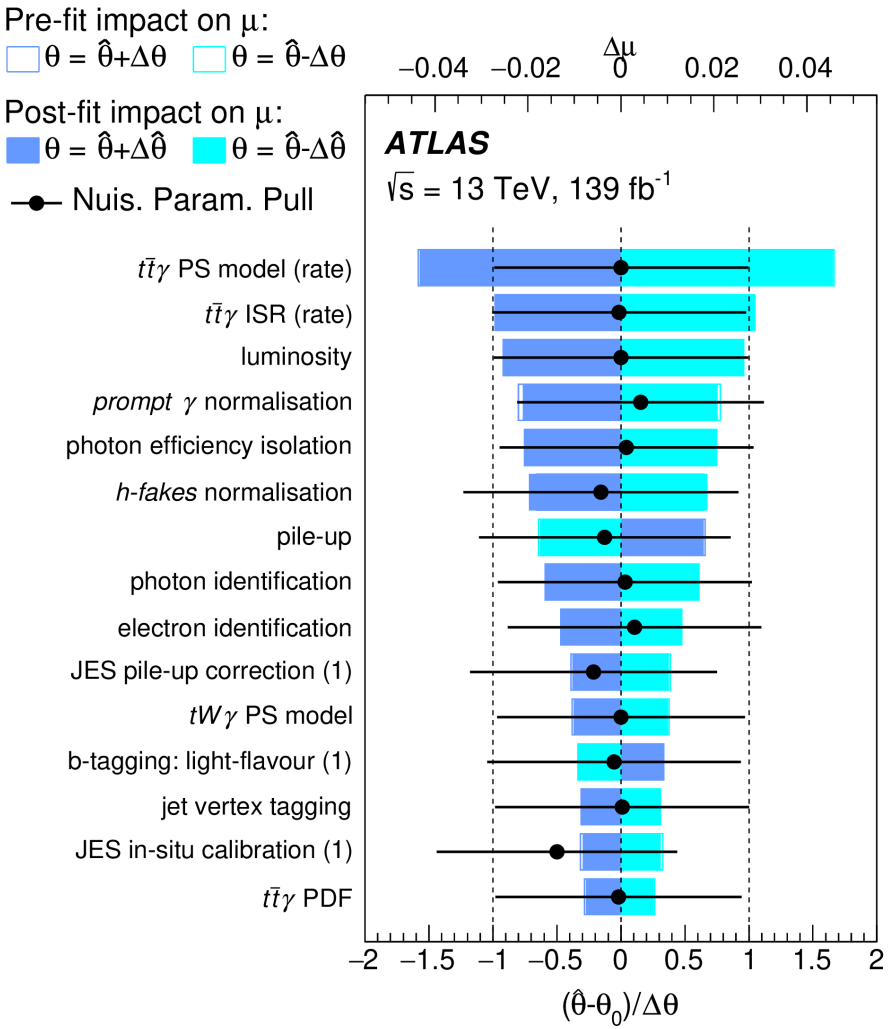


$t\bar{t}\gamma$ inclusive 1



$t\bar{t}\gamma$ inclusive 2

ATLAS



CMS

	Source	Correlation	Uncertainty [%] yield	Uncertainty [%] $\sigma(t\bar{t}\gamma)$
Experimental	Integrated luminosity	partial	2.3–2.5	1.8
	Pileup	100%	0.5–2.0	<0.5
	Trigger efficiency	—	<0.5	<0.5
	Electron reconstruction and identification	100%	0.2–1.7	<0.5
	Muon reconstruction and identification	partial	0.5–0.7	0.7
	Photon reconstruction and identification	100%	0.4–1.4	1.0
	p_T(e) and $p_T(\gamma)$ reconstruction	100%	0.1–1.2	<0.5
	JES	partial	1.0–4.1	1.9
	JER	—	0.4–1.6	0.6
	b tagging	100% (2017/2018)	0.8–1.6	1.1
	L1 prefiring	100% (2016/2017)	0.3–0.9	<0.5
Theoretical	Tune	100%	0.1–1.9	<0.5
	Color reconnection	100%	0.4–3.6	0.6
	ISR/FSR	100%	1.0–5.6	1.9
	PDF	100%	<0.5	<0.5
	ME scales μ_R, μ_F	100%	0.4–4.7	<0.5
Background	Multijet normalization	100%	1.3–6.5	0.9
	Nonprompt photon background	100%	1.2–2.7	2.0
	Misidentified e	—	2.5–8.0	1.8
	$Z\gamma$ normalization	100%	0.6–2.5	0.5
	$W\gamma$ normalization	100%	1.0–3.5	2.4
	DY normalization	100%	0.1–1.1	1.0
	$t\bar{t}$ normalization	100%	1.0–1.9	1.0
	"Other" bkg. normalization	100%	0.3–1.0	<0.5
	Total systematic uncertainty			5.7
	Statistical uncertainty			0.9
	Total			5.8

$t\bar{t}\gamma$ differential

ATLAS

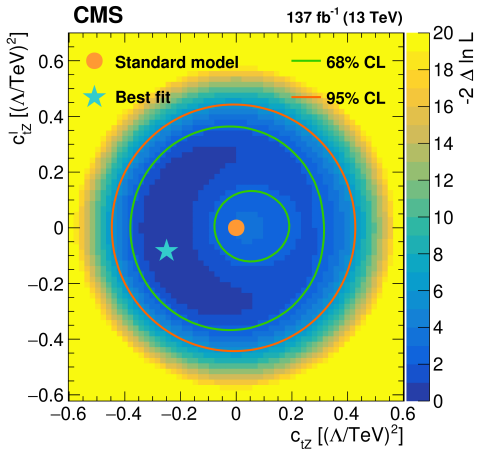
Predictions	$p_T(\gamma)$		$\lvert\eta(\gamma)\rvert$		$\Delta R(\gamma,\ell)_{min}$		$\Delta\phi(\ell,\ell)$		$\lvert\Delta\eta(\ell,\ell)\rvert$	
	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value
$t\bar{t}\gamma + tW\gamma$ (MG5_aMC+Pythia8)	6.3/10	0.79	7.3/7	0.40	20.1/9	0.02	30.8/9	<0.01	6.5/7	0.48
$t\bar{t}\gamma + tW\gamma$ (MG5_aMC+Herwig7)	5.3/10	0.87	7.7/7	0.36	18.9/9	0.03	31.6/9	<0.01	6.8/7	0.45
Theory NLO	6.0/10	0.82	4.5/7	0.72	13.5/9	0.14	5.8/9	0.76	5.6/7	0.59

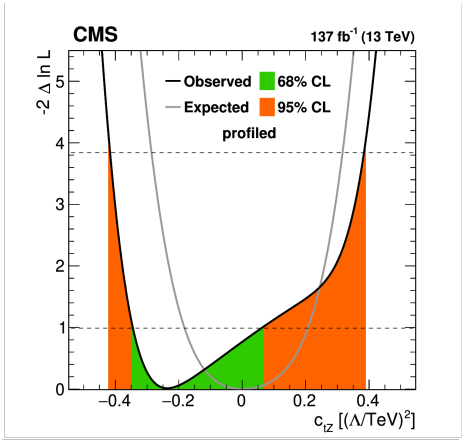
CMS

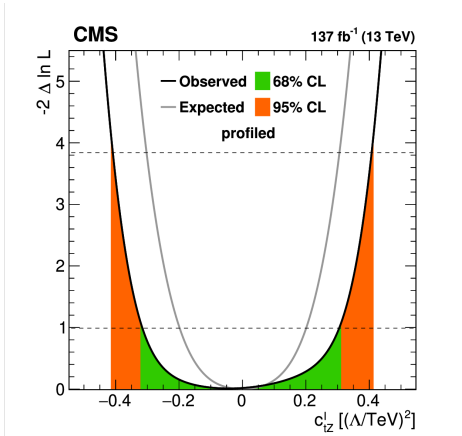
	Wilson coefficient		68% CL interval $(\Lambda/\text{ TeV})^2$	95% CL interval $(\Lambda/\text{ TeV})^2$
Expected	c_{tZ}	$c_{tZ}^I = 0$	$[-0.19, 0.21]$	$[-0.29, 0.32]$
		profiled	$[-0.19, 0.21]$	$[-0.29, 0.32]$
	c_{tZ}^I	$c_{tZ} = 0$	$[-0.20, 0.20]$	$[-0.30, 0.31]$
		profiled	$[-0.20, 0.20]$	$[-0.30, 0.31]$
Observed	c_{tZ}	$c_{tZ}^I = 0$	$[-0.35, -0.16]$	$[-0.42, 0.38]$
		profiled	$[-0.35, 0.07]$	$[-0.42, 0.39]$
	c_{tZ}^I	$c_{tZ} = 0$	$[-0.35, -0.16], [0.17, 0.35]$	$[-0.42, 0.42]$
		profiled	$[-0.32, 0.31]$	$[-0.41, 0.41]$

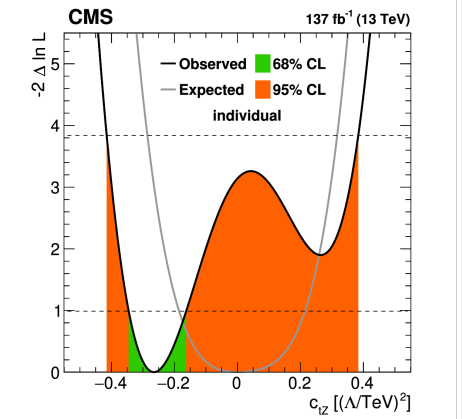
$t\bar{t}\gamma$ EFT interpretation

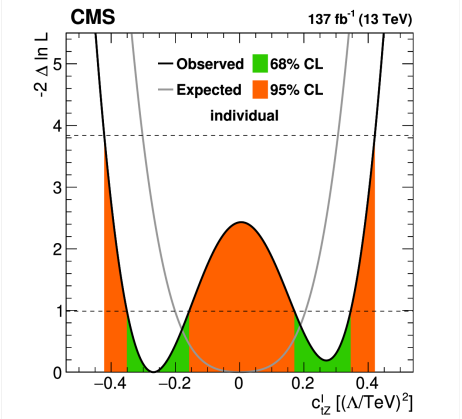
- **Detector level** distributions parametrised using EFT (Wilson) coefficients
- Fit to observed data - extract EFT
- Comparison with $t\bar{t}Z$ and $t\bar{t}$

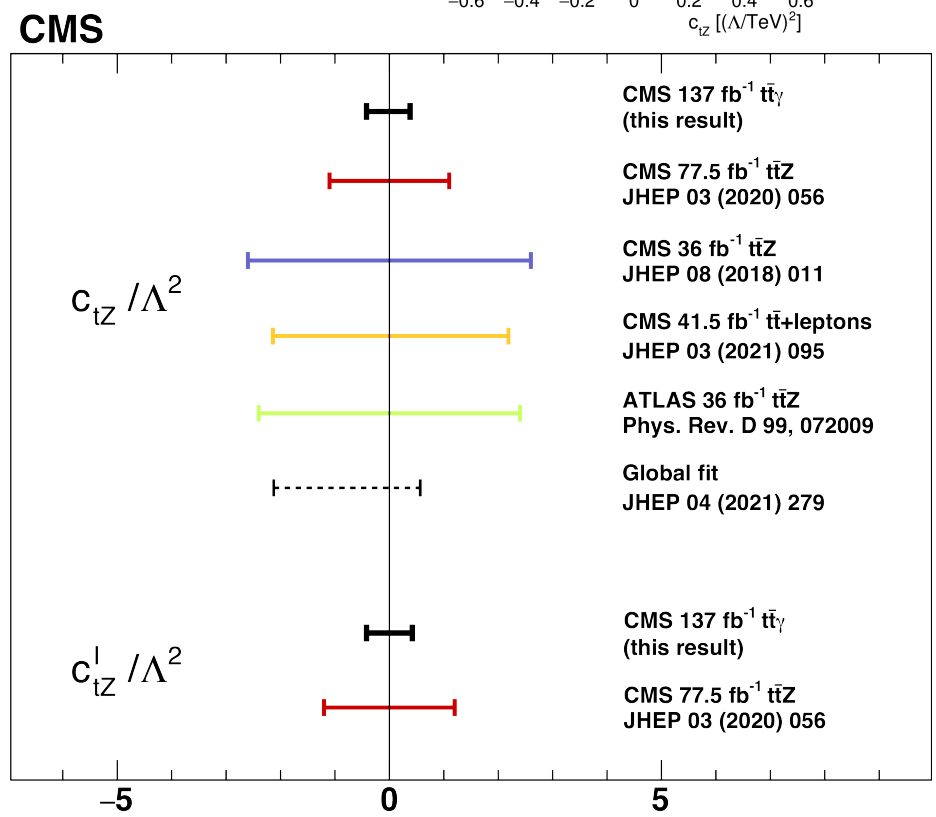






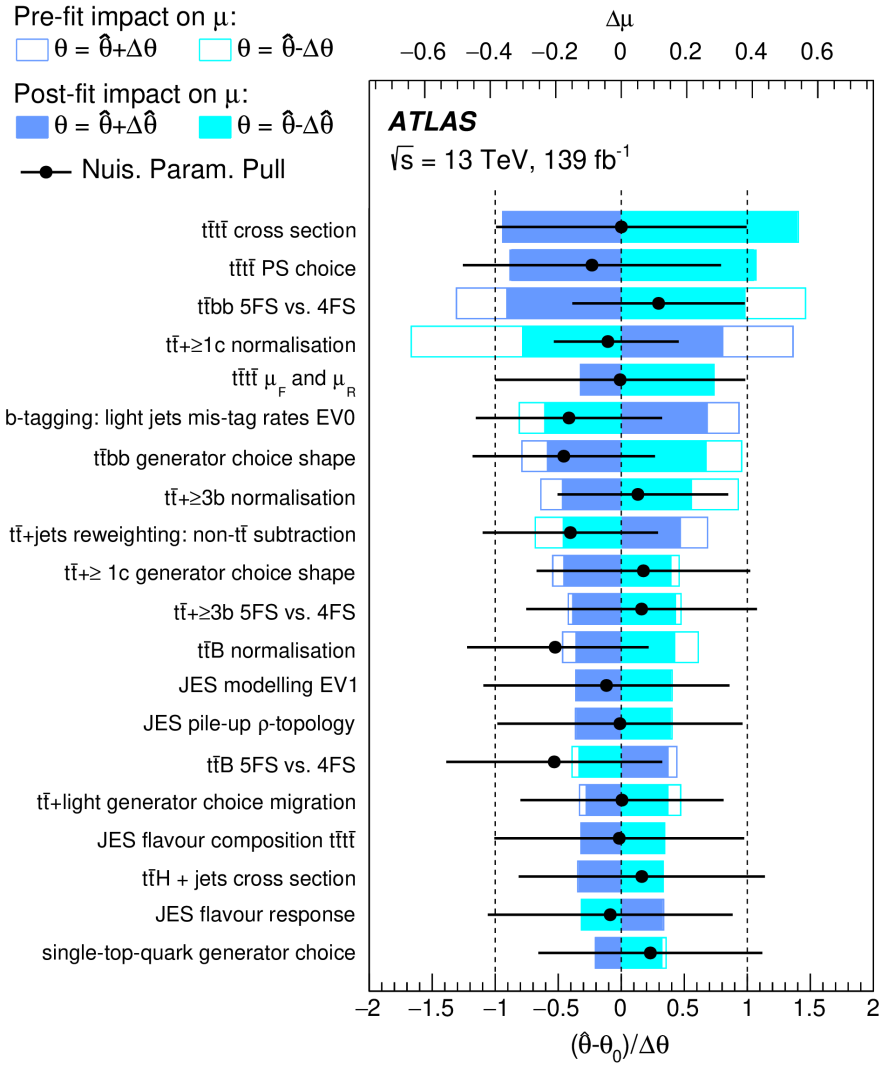






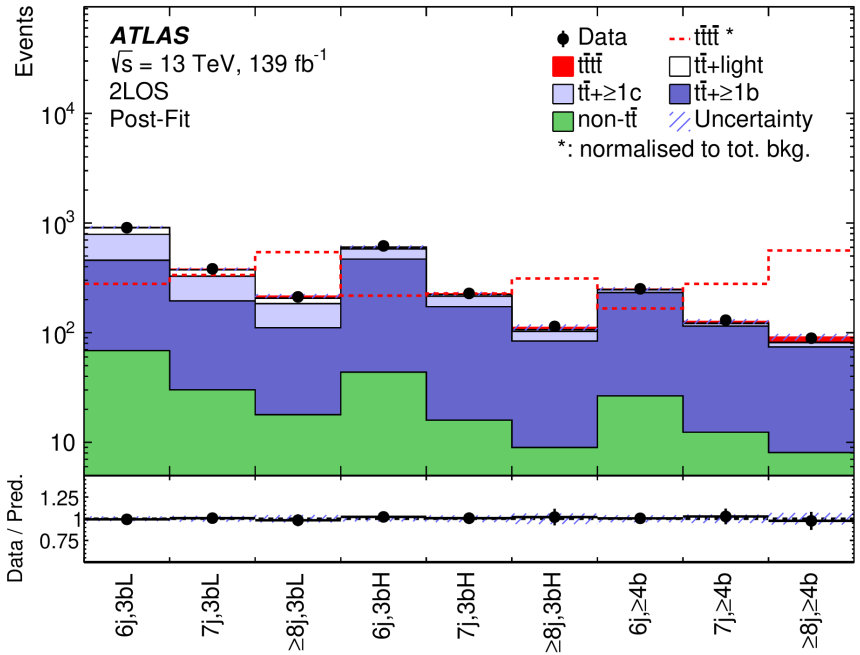
4 tops

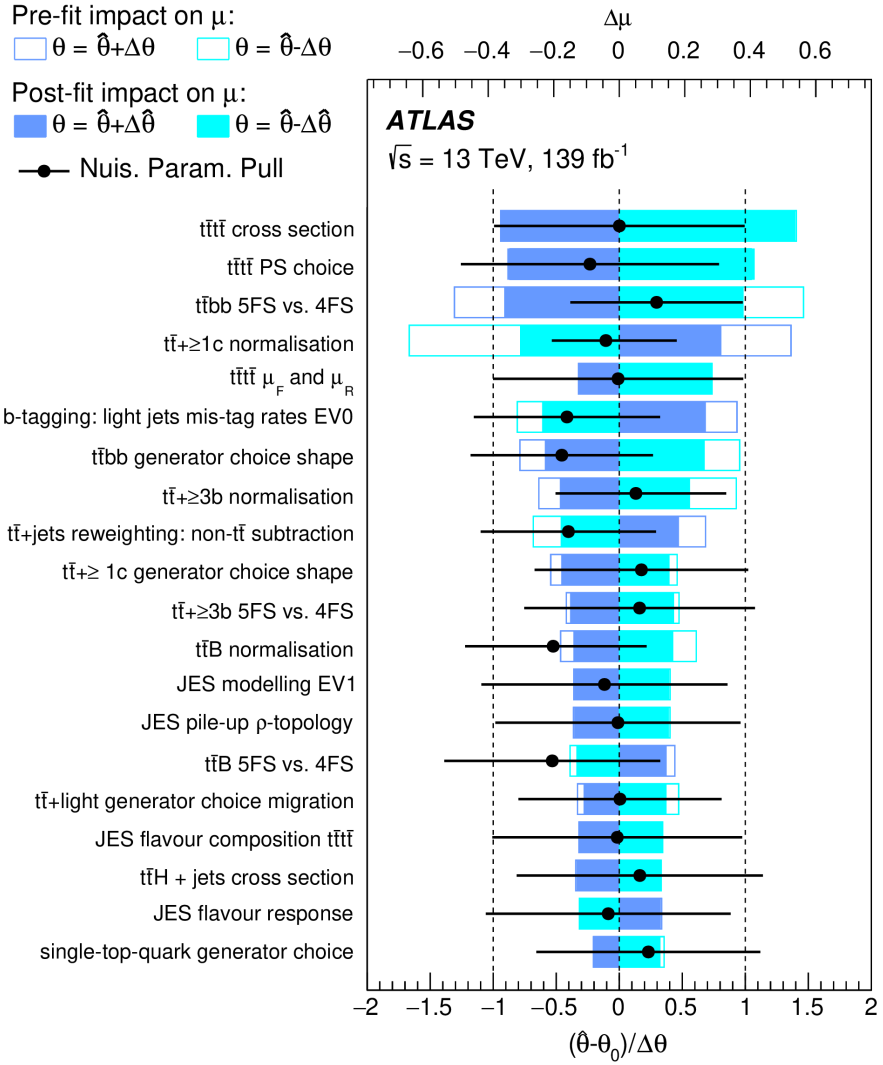
Uncertainty source	$\Delta\sigma_{t\bar{t}t\bar{t}}$ [fb]	
Signal Modelling		
$t\bar{t}t\bar{t}$ modelling	+8	−3
Background Modelling		
$t\bar{t}$+≥1b modelling	+8	−7
$t\bar{t}$+≥1c modelling	+5	−4
$t\bar{t}$+jets reweighting	+4	−3
Other background modelling	+4	−3
$t\bar{t}$+light modelling	+2	−2
Experimental		
Jet energy scale and resolution	+6	−4
b-tagging efficiency and mis-tag rates	+4	−3
MC statistical uncertainties	+2	−2
Luminosity	< 1	
Other uncertainties	< 1	
Total systematic uncertainty	+15	−12
Statistical uncertainty	+8	−8
Total uncertainty	+17	−15



4 tops ($t\bar{t}t\bar{t}$)

- Dominant systematic uncertainties
  - 4tops PS and hadronisaton model (Pythia vs Herwig)
  - $t\bar{t}bb/t\bar{t}+c$ modelling
  - 4tops scales
  - *b*-tagging





$t\bar{t} + c\bar{c}$

Sources	Systematic uncertainty (%)				
	$\Delta\sigma_{t\bar{t}c\bar{c}}$	$\Delta\sigma_{t\bar{t}b\bar{b}}$	$\Delta\sigma_{t\bar{t}LL}$	ΔR_c	ΔR_b
Jet energy scale	4.0	3.2	4.7	2.8	2.1
Jet energy resolution	2.3	1.0	0.9	2.5	1.3
c tagging calibration	7.0	3.2	2.5	7.3	3.5
Lepton identification and isolation	0.8	1.0	1.3	0.6	0.3
Trigger	2.0	2.0	2.0	< 0.1	< 0.1
Pileup	0.3	0.2	0.3	0.5	< 0.1
Total integrated luminosity	2.3	2.4	2.3	< 0.1	< 0.1
μ_R and μ_F scales in ME	3.3	6.2	2.1	3.8	6.8
PS scale	0.4	1.6	0.3	0.5	1.6
PDF	0.3	0.1	0.1	0.2	0.1
ME-PS matching	7.1	5.7	3.5	2.6	1.5
Underlying event	1.9	2.3	1.1	0.5	0.9
b fragmentation	0.4	1.9	0.8	0.3	2.4
c fragmentation	4.6	< 0.1	< 0.1	3.9	0.7
$t\bar{t}bL(cL)/t\bar{t}b\bar{b}(c\bar{c})$ and $t\bar{t}$+other/$t\bar{t}LL$	2.4	1.8	1.1	1.8	1.5
Efficiency (theoretical)	2.4	2.1	2.0	< 0.1	< 0.1
Simulated sample size	3.2	2.6	1.1	3.1	2.5
Background normalization	0.5	0.7	0.6	0.1	0.1
Total	13.7	11.4	8.2	10.9	9.2