Top highlights from ATLAS

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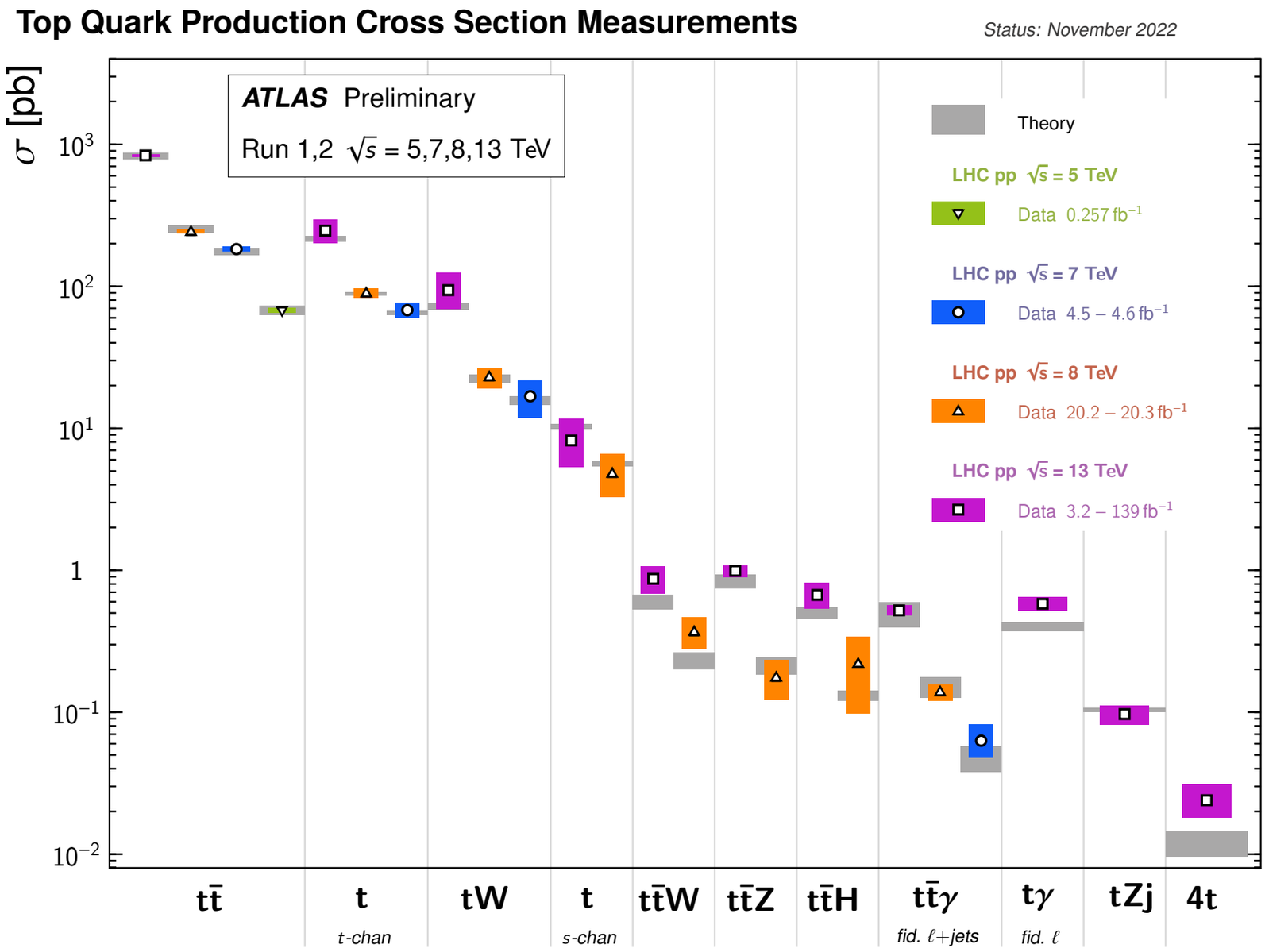
for the ATLAS collaboration

Why rare top processes?

- No signs of new physics beyond the SM brought by searches at LHC
- Further test SM by measuring more precisely rare processes which are not yet well measured



- More information in the talk by Soureek Mitra

ttW production

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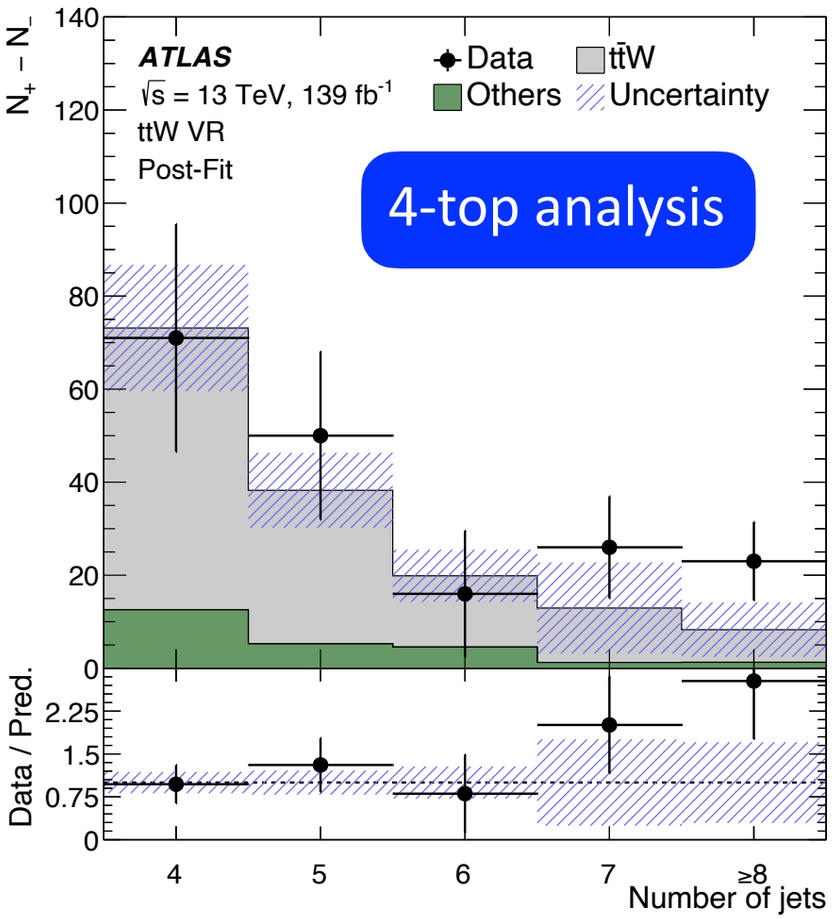

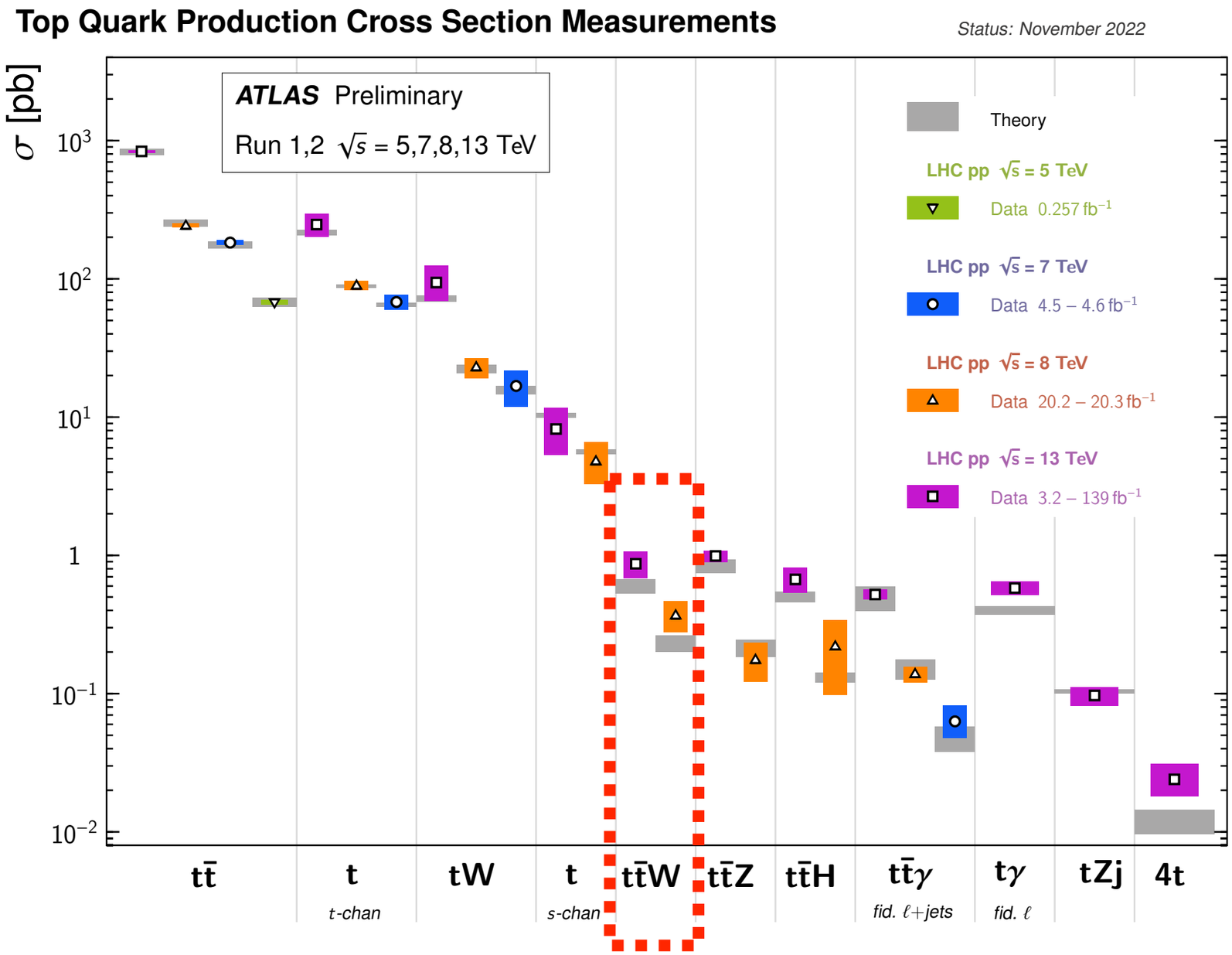

- Dominant background for searches and other measurements: $t\bar{t}H$, $t\bar{t}t\bar{t}$
- Provides irreducible source of same-sign dilepton pairs

ttW production

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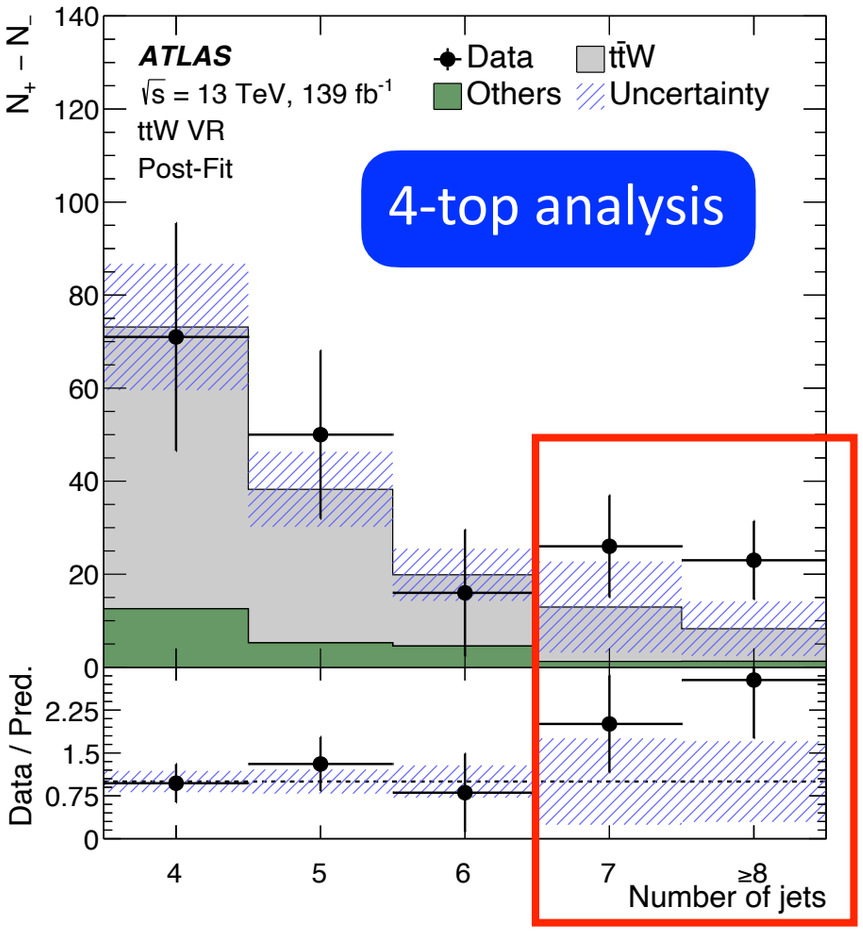

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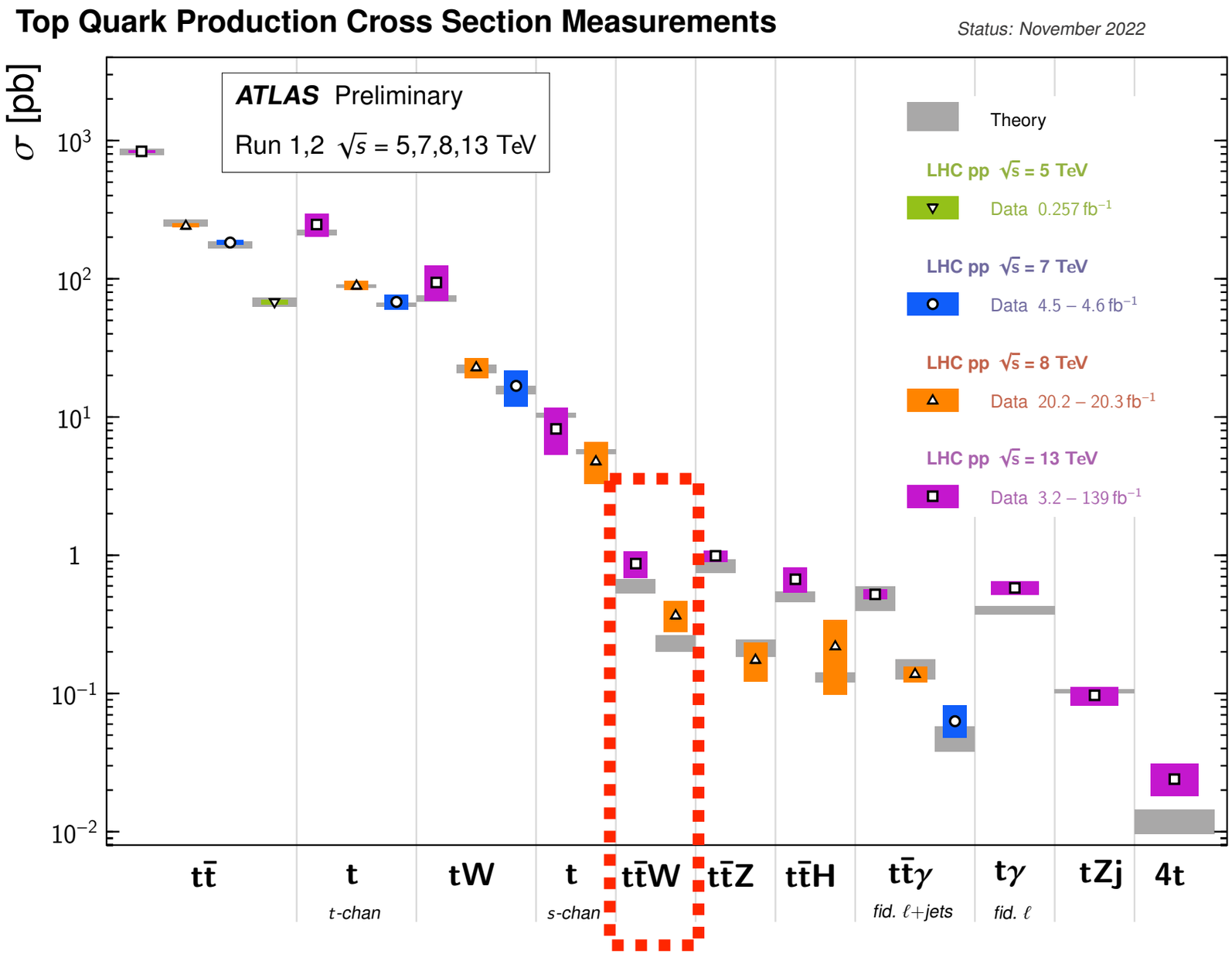


- Largest source of systematic uncertainty in ATLAS 4-top evidence analysis due to N_{jets} mismodelling

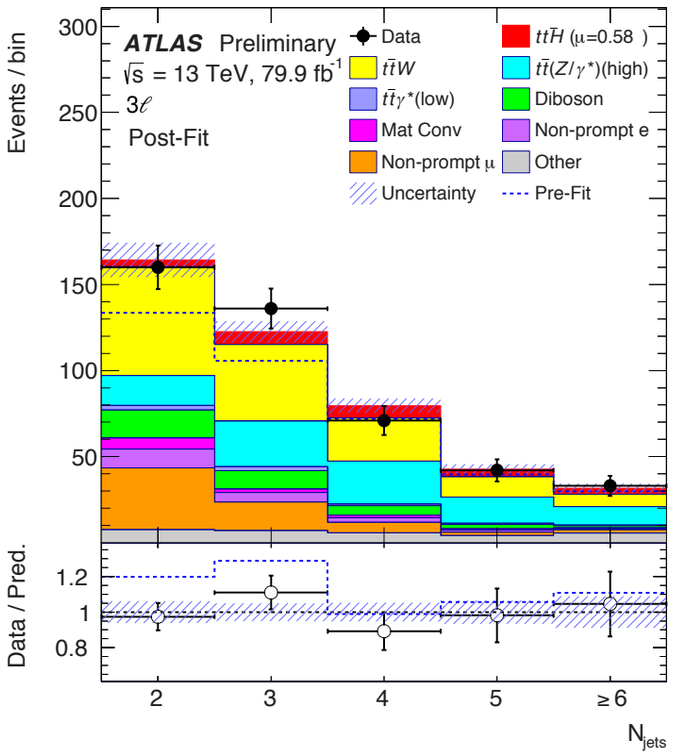
Not so simple…

- $t\bar{t}W$ mismodelling observed in $t\bar{t}H$ ATLAS analysis

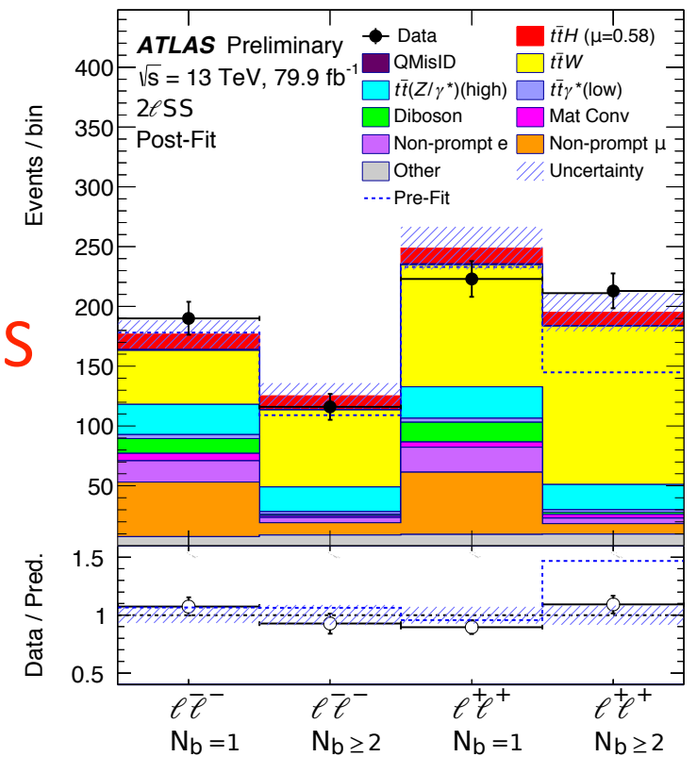
$\mu = 1.67^{+0.20}_{-0.19}$ wrt to YR4 of 600 fb

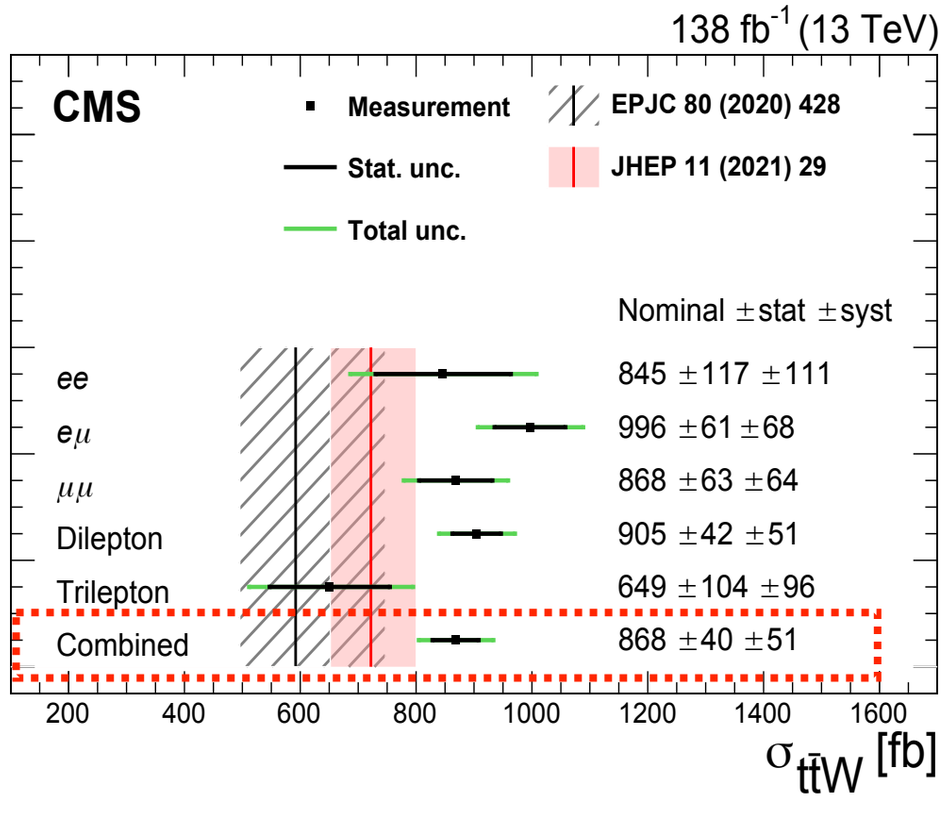
ATLAS-CONF-2019-045

arXiv:2208.06485



2ℓSS





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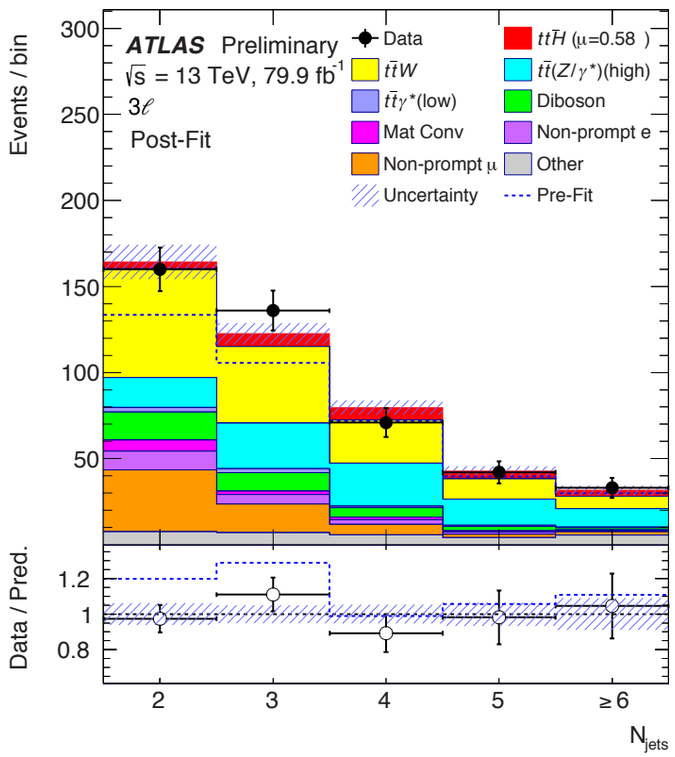

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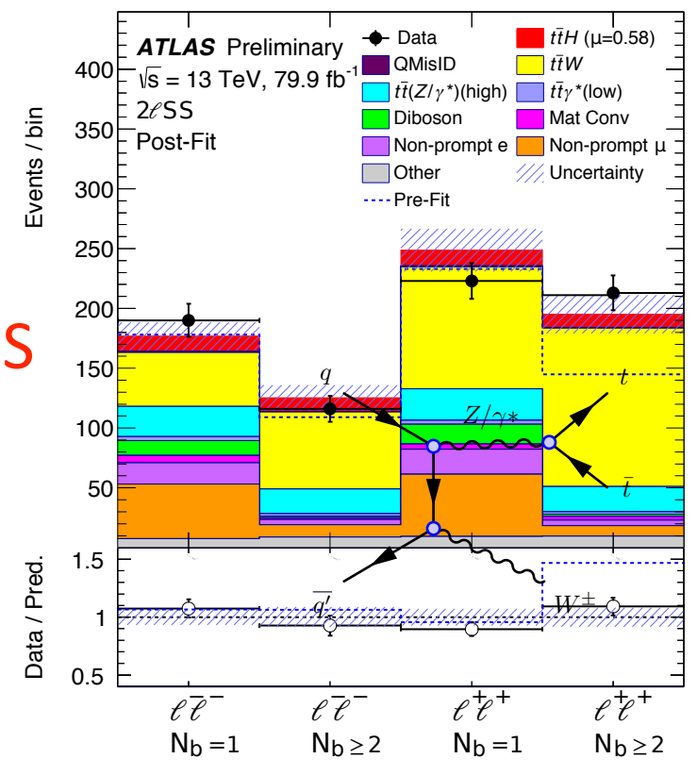
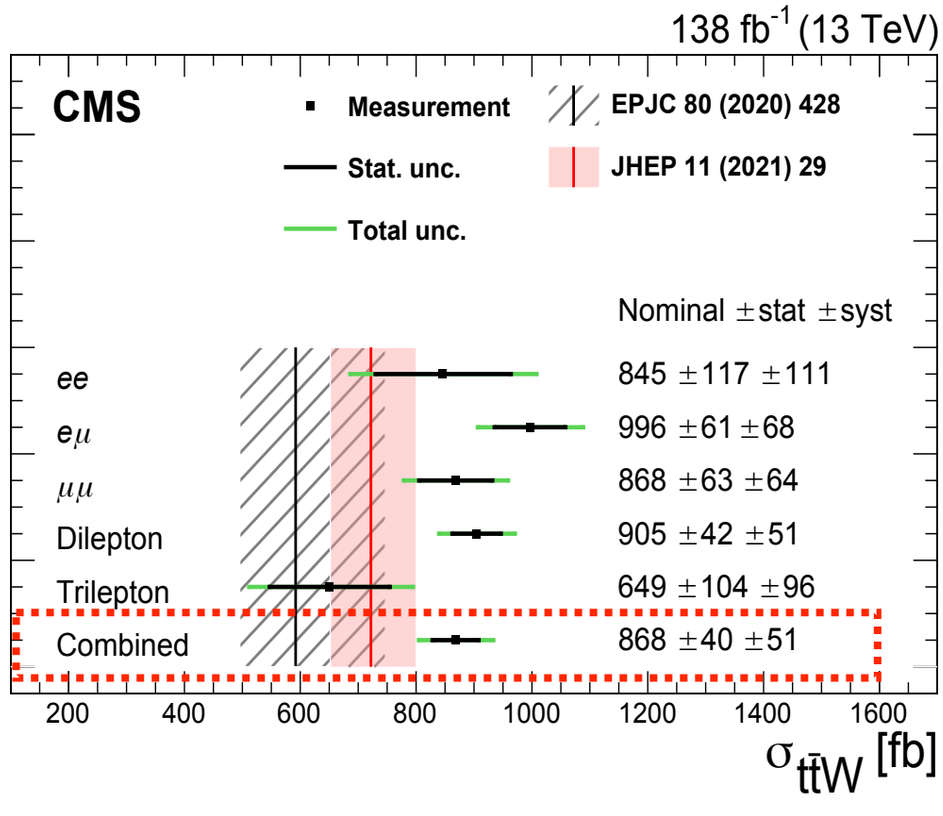
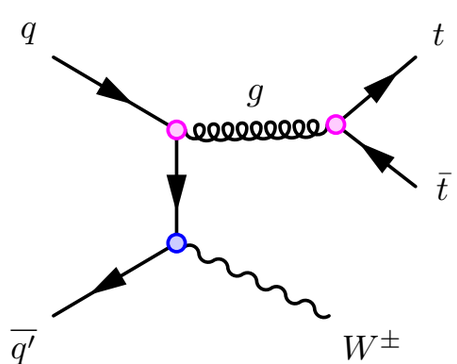
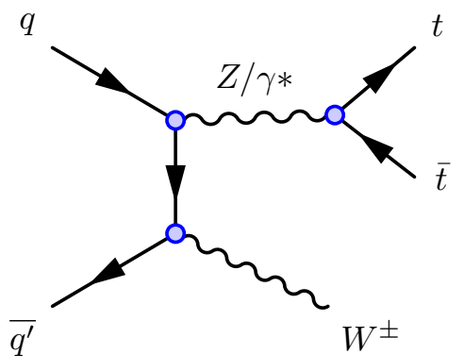




Charge-asymmetric production from PDF

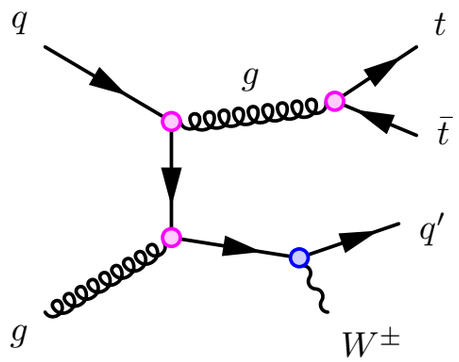


$O(\alpha\alpha_S^2)$

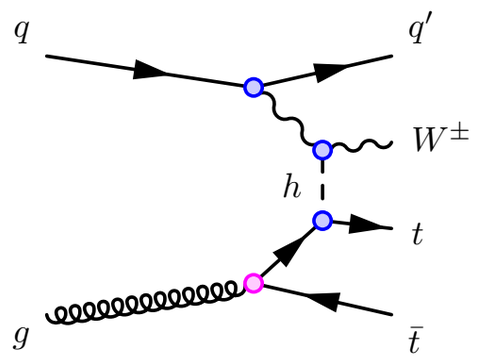


$O(\alpha^3)$

Complex NLO QCD and EW corrections



$O(\alpha\alpha_S^3)$



$O(\alpha^3\alpha_S)$

ttW measurement

- Selection
  - 1 SS lepton pair or 3L
  - $N_{jets} \geq 2$
  - $\geq$1b-jet 60% or $\geq$2b-jets 77%
  - exclude OSSF and 3L pairs with mass in Z peak

- Inclusive measurement
  - split according to N_{jets}, N_b and lepton charge
  - in SS split by lepton flavour
  - 48 SS + 8 3L signal regions
- Measured parameters
  - inclusive and fiducial ttW cross section
  - cross sections for $t\bar{t}W^+$, $t\bar{t}W^-$ and their ratio
  - charge asymmetry

ttW measurement

- Differential measurement
  - events split by lepton charge SS (++/--) and 3L (+/-)
- Measured distributions
  - absolute and normalised cross sections at particle level
- 9 observables:
  - N_{jets}, HT(jets), HT(lep)
  - ΔR(lb,lead), |Δφ(ll,SS)| Δη(ll,SS)|
  - M(jj,lead), M(ll,SS), M(lb,lead)
  - Assess compatibility between data and predictions via χ^2 test

- Inclusive measurement
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- Main backgrounds
  - irreducible: diboson, $t\bar{t}Z$, $t\bar{t}H$
  - reducible: fake/non-prompt leptons mainly from $t\bar{t}$ production, charge misID (electron)

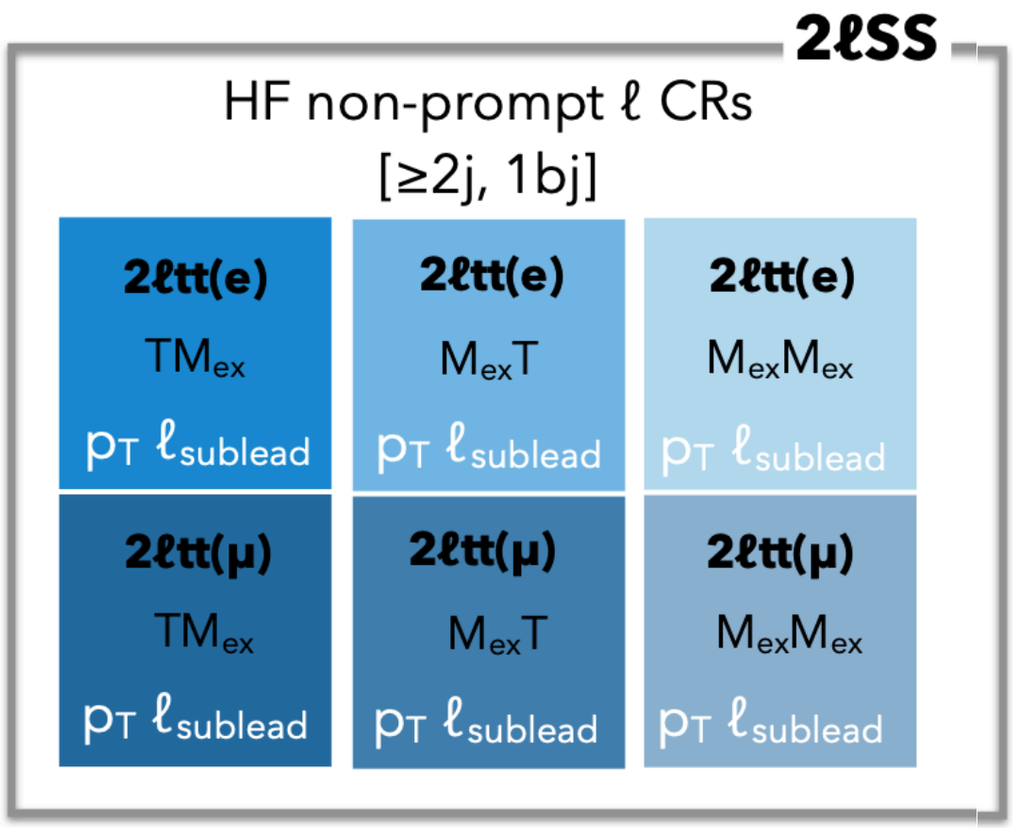
Reducible background

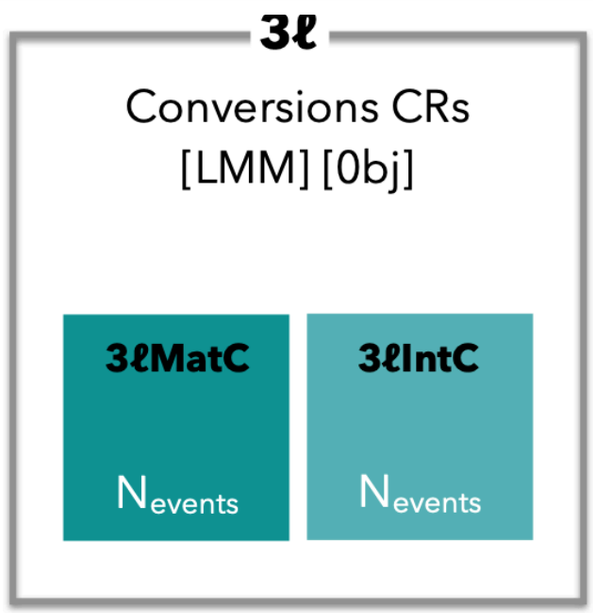
Template method

- Shapes from simulation
- Categorise non-prompt/fake leptons into 4 classes
  - HF electron, HF muon
  - material conversions
  - virtual photon conversions (internal conversions)
- 4 free parameters in the signal extraction fit to determine normalisation

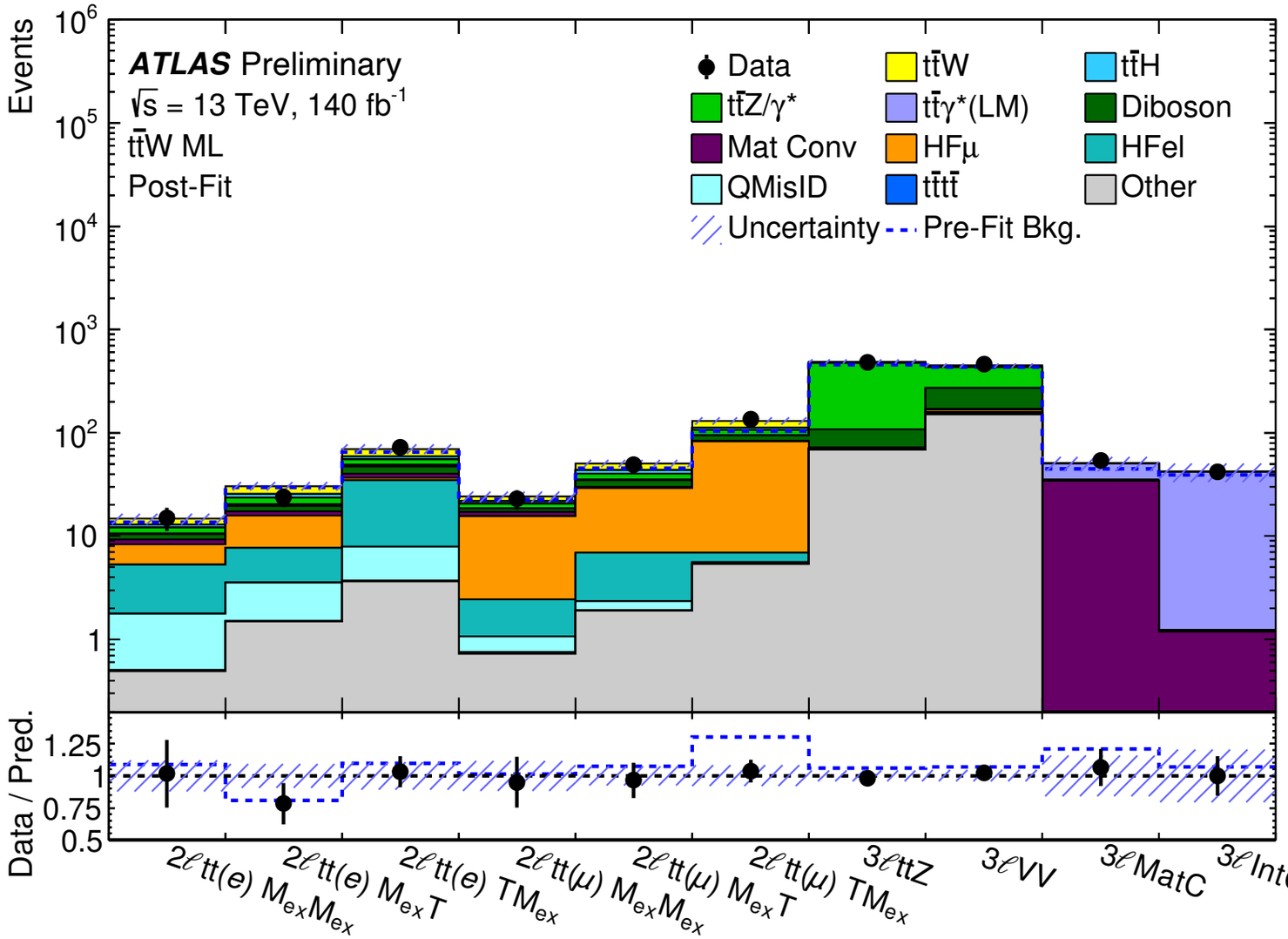
- Charge mis-identification:
  - negligible for muons
  - data-driven from $Z \to e^{\pm}e^{\pm}/e^{\pm}e^{\mp}$

6 regions defined by exclusive BDT-based isolation working points M_{ex}

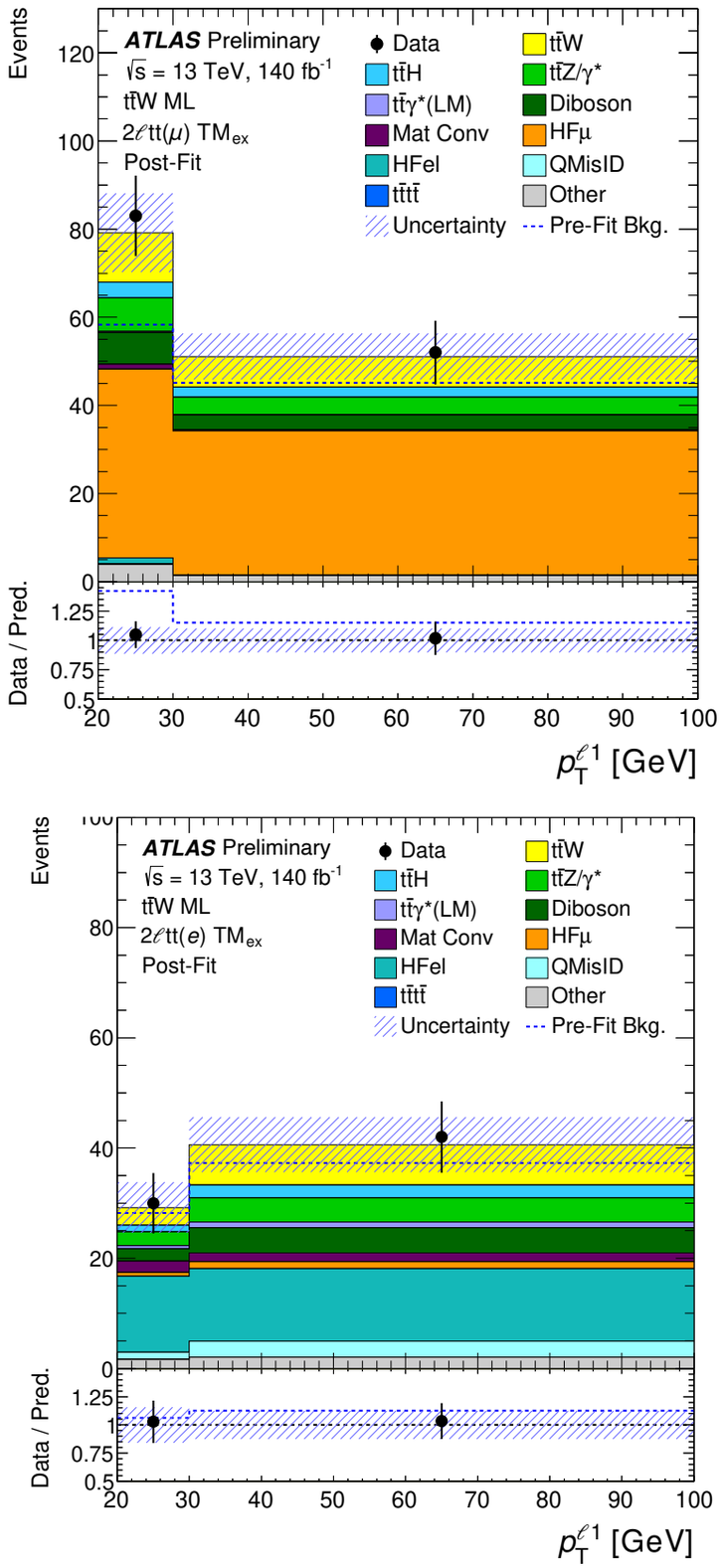




Control regions



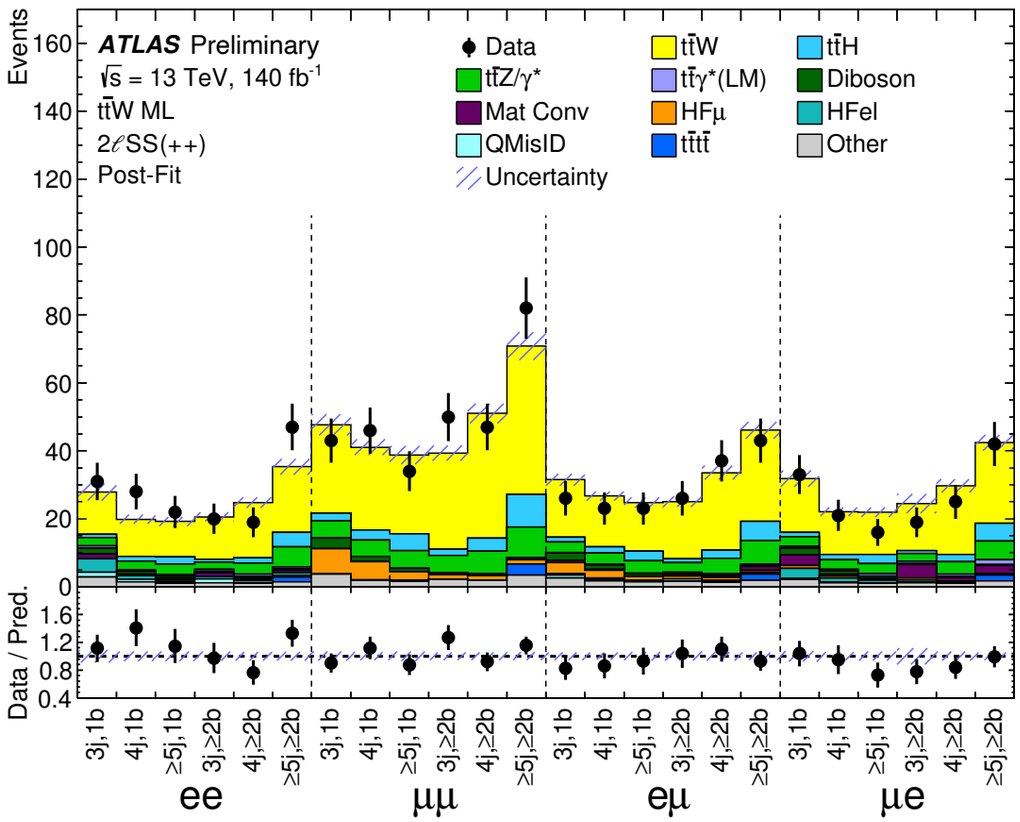
$NF_{Mat.\ Conv.}$	$NF_{Low\ m_{\gamma^*}}$	$NF_{HF\ e}$	$NF_{HF\ \mu}$
1.15 ± 0.31	1.07 ± 0.24	0.83 ± 0.31	1.01 ± 0.21

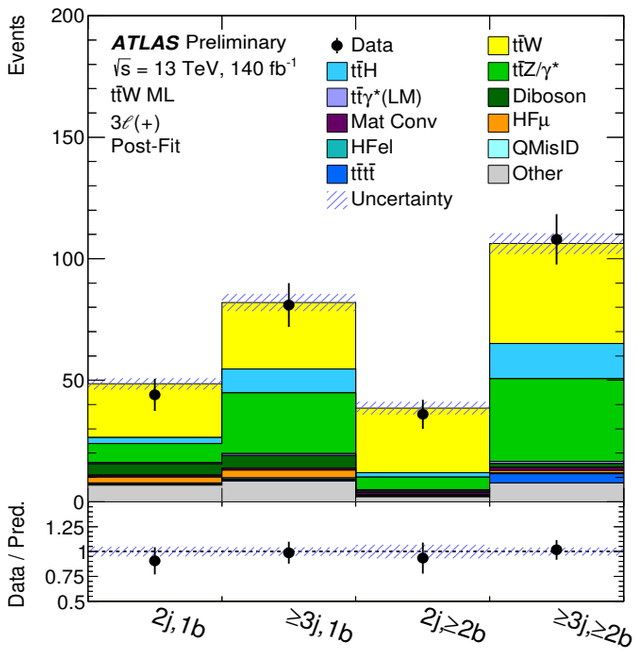


subleading lepton pT

Inclusive results

- Simultaneous profile likelihood fit to data using event yields in 56 SR and 10 CR with 6 free parameters (4 for fake/non-prompt, diboson and $t\bar{t}Z$ normalisation)





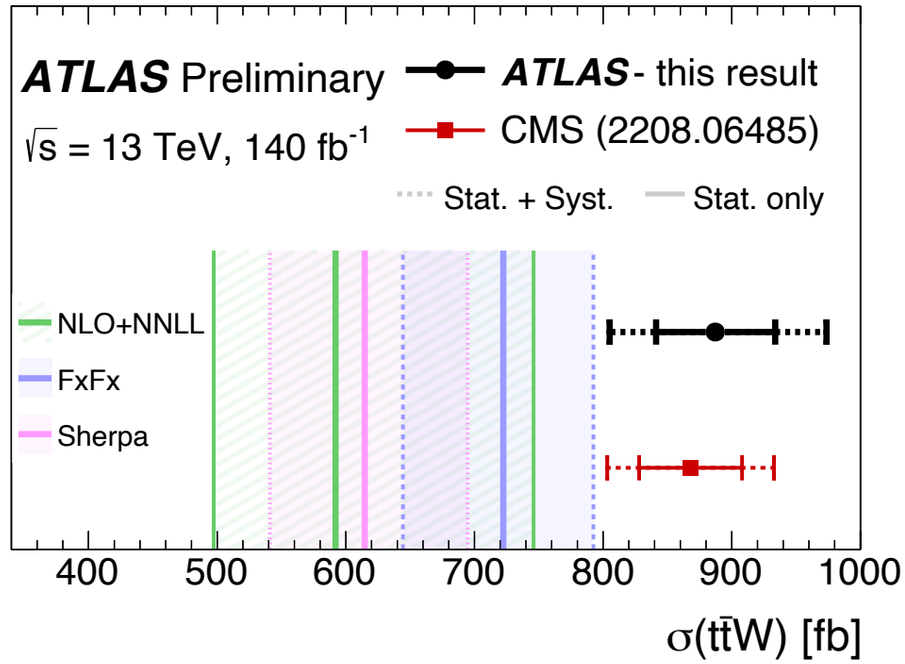
$$\sigma_{t\bar{t}W} = 890 \pm 50\ (\text{stat}) \pm 70\ (\text{syst})\ \text{fb}$$

9% relative uncertainty

- Largest systematic uncertainties:
  - ttW modelling
  - ttH, four-top background normalisation
  - b-tagging and
  - non-prompt isolation BDT calibration

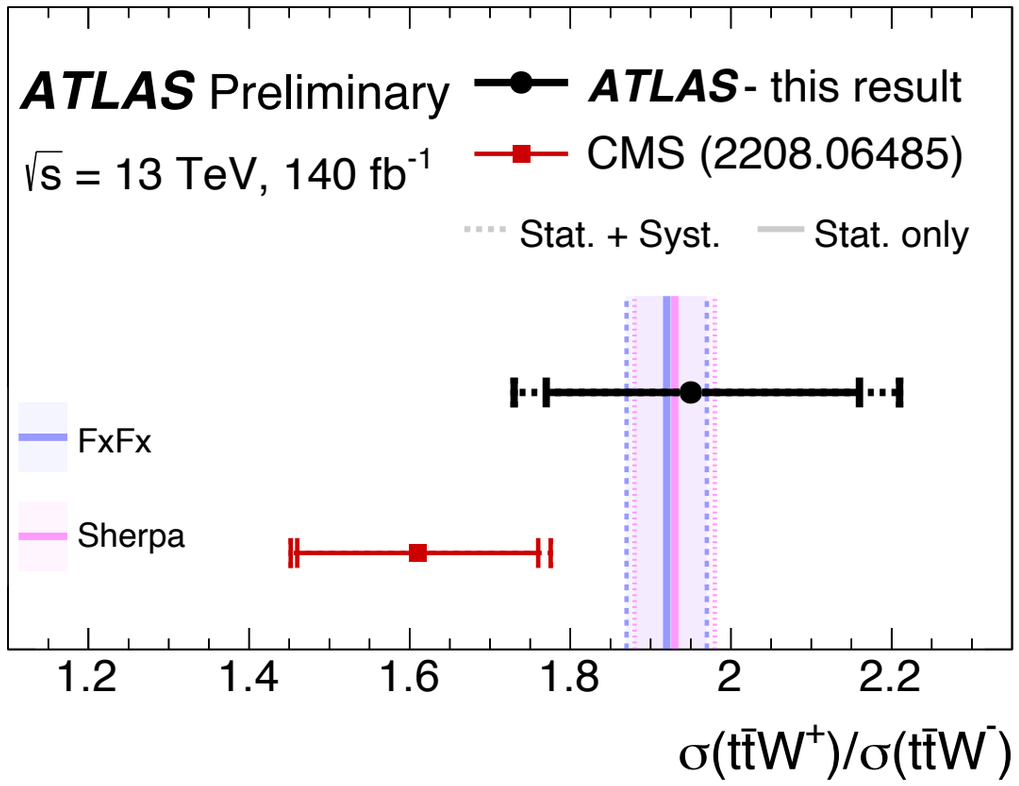
consistent at 1.5σ with theory calculation

$\sigma_{t\bar{t}W} = 722^{+70}_{-78}\ (\text{scale}) \pm 7\ (\text{PDF})\ \text{fb}$ JHEP 11 (2021) 029



Ratios and asymmetry

- Ratio of $t\bar{t}W^+$ to $t\bar{t}W^-$ production rate



$$\frac{\sigma_{t\bar{t}W^+}}{\sigma_{t\bar{t}W^-}} = 1.95 \pm 0.21\ (\text{stat}) \pm 0.16\ (\text{syst})$$

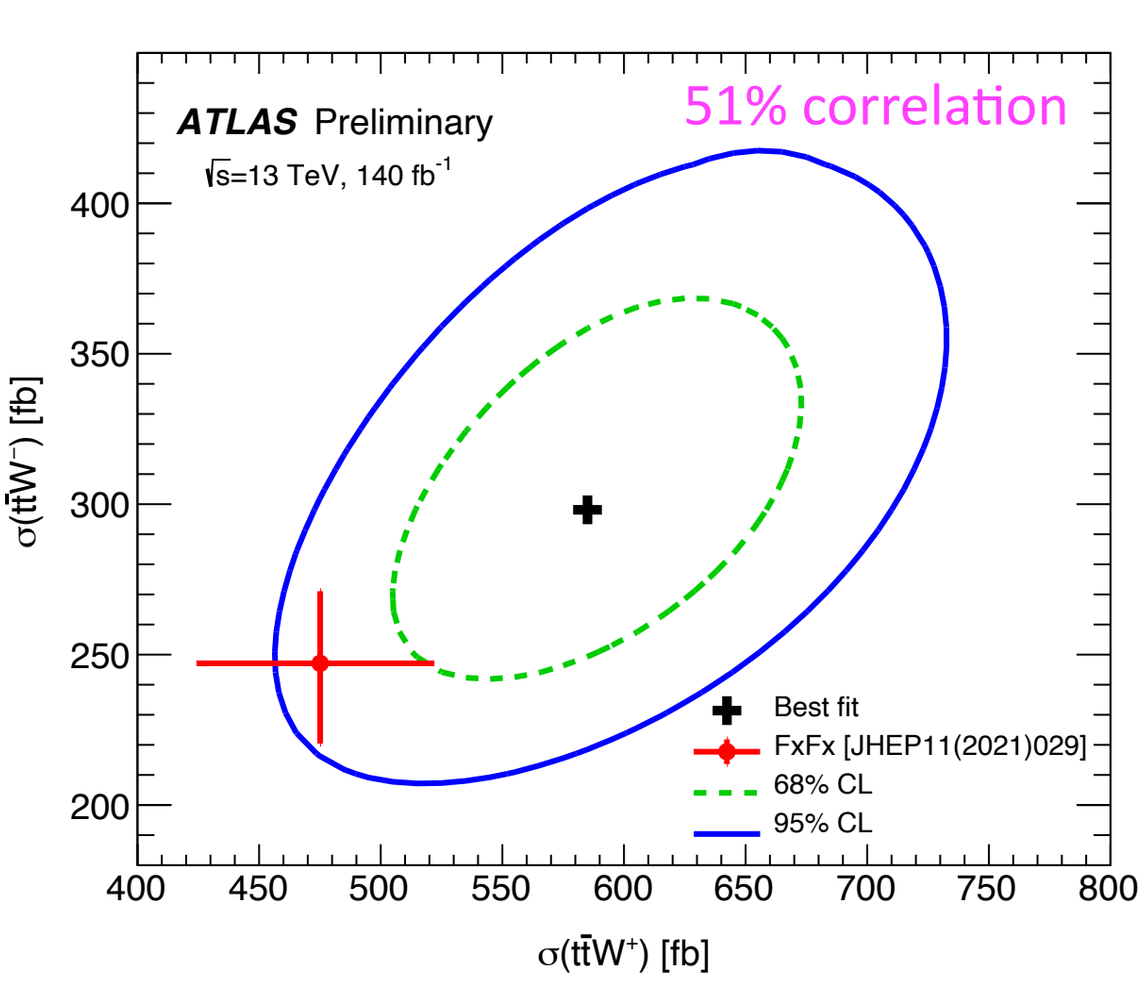
consistent with MC predictions

$$A_C^{rel} = \frac{\sigma(t\bar{t}W^+) - \sigma(t\bar{t}W^-)}{\sigma(t\bar{t}W^+) + \sigma(t\bar{t}W^-)}$$

$$A_C^{rel} = 0.32 \pm 0.05\ (\text{stat}) \pm 0.03\ (\text{syst})$$

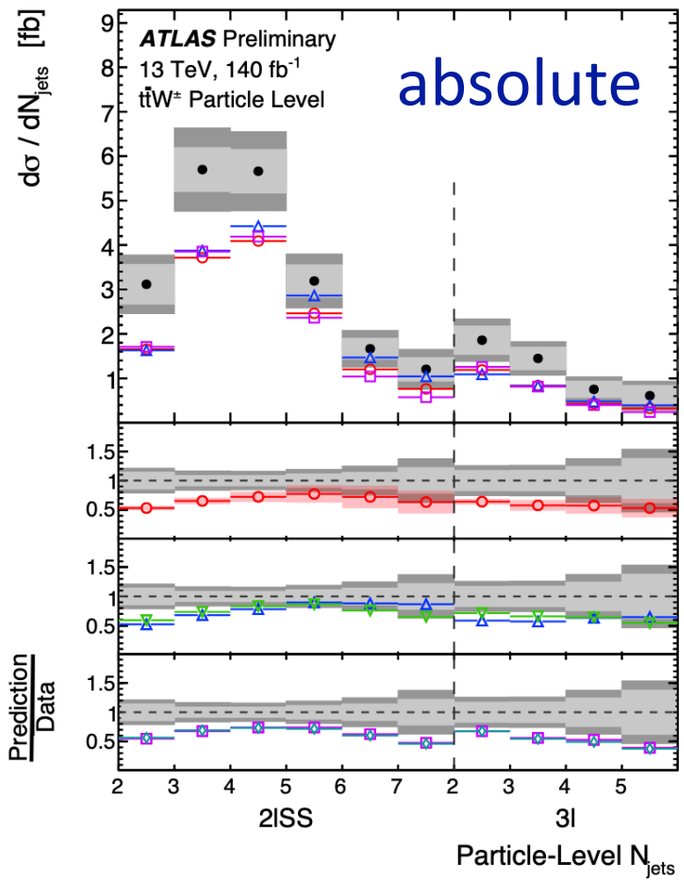
Good agreement with Sherpa prediction

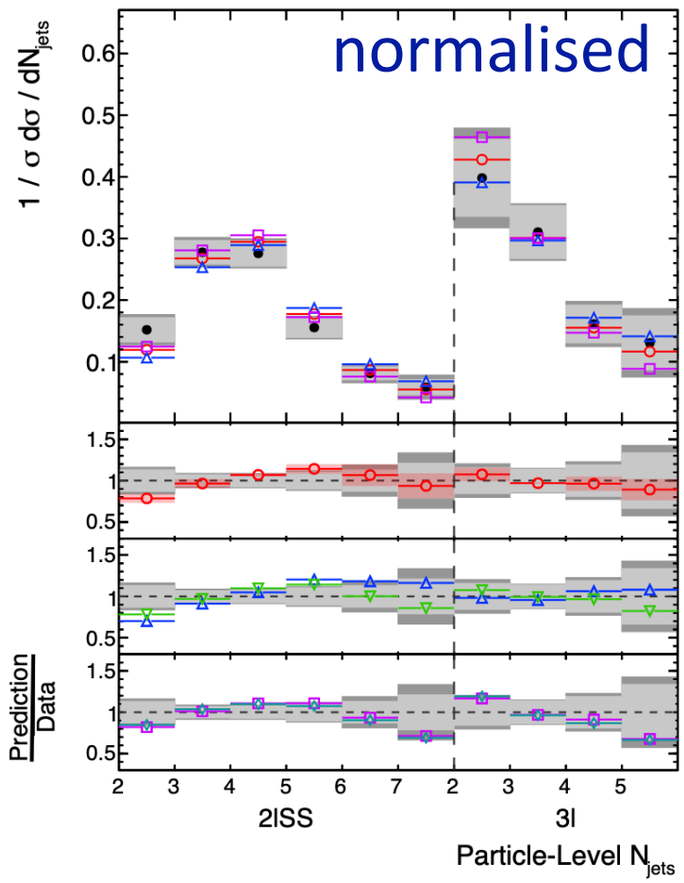
$$A_{C,t\bar{t}W} = 0.322 \pm 0.003\ (\text{scale}) \pm 0.007\ (\text{PDF})$$

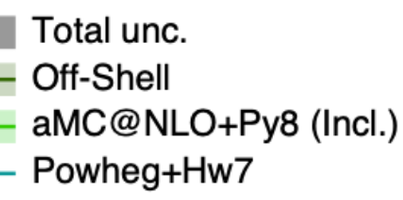


Differential results

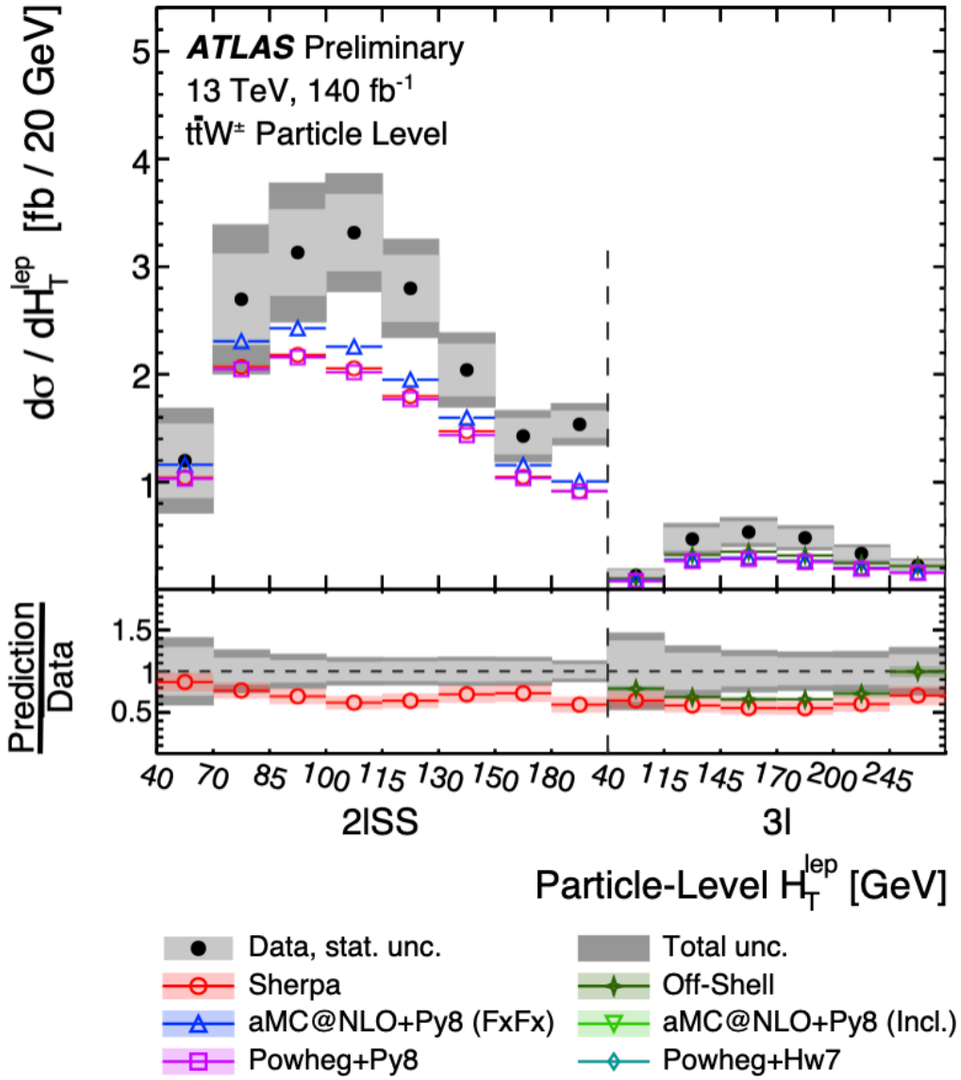
- Profile likelihood unfolding to particle level
- Same background model and CR included in the fit
- Tikhonov regularisation with optimised strength for each variable







Introduction to unfolding s4 in talk by Haider



- In 3L channel compare with calculation including off-shell effects
- Predicts slightly higher cross section

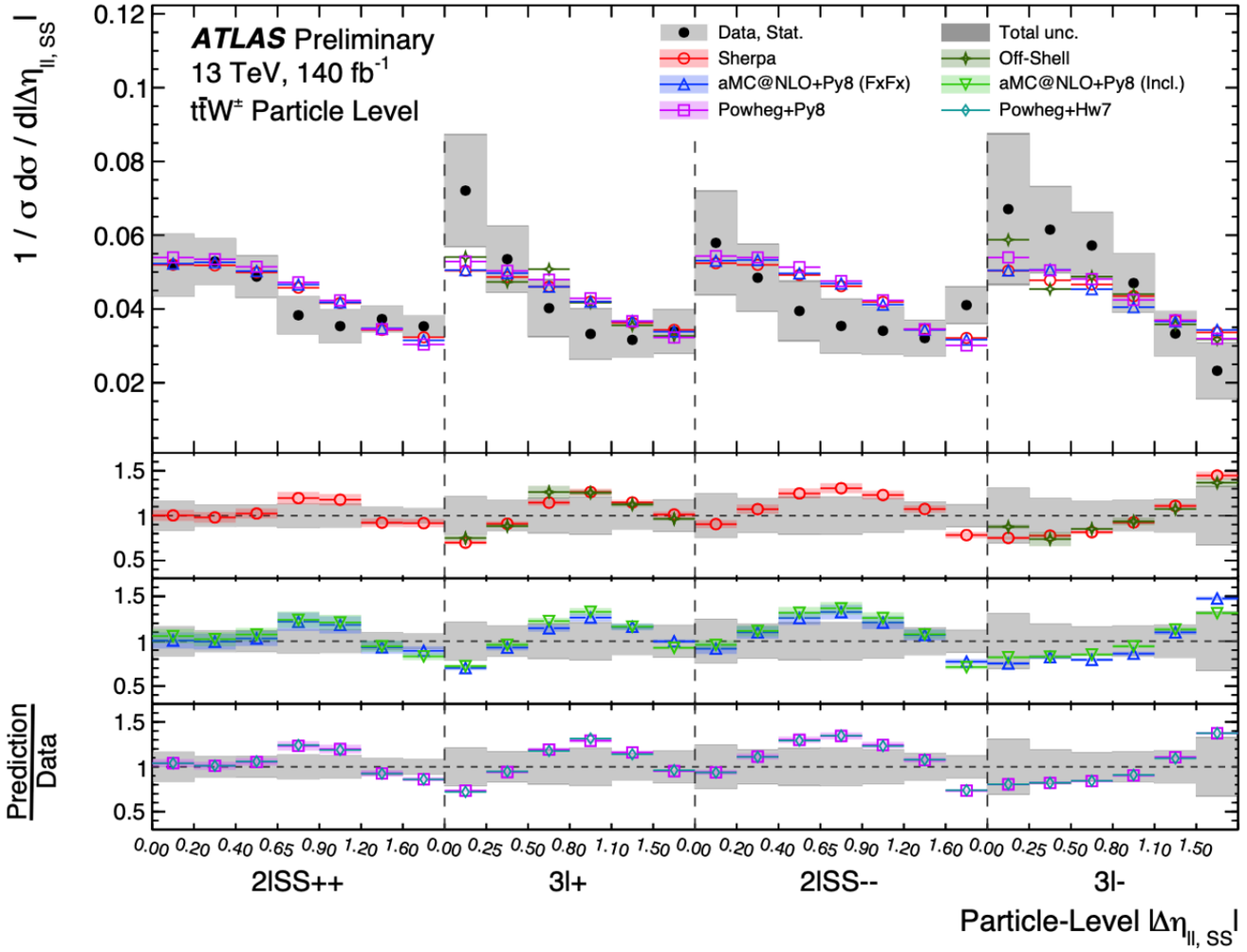
Eur. Phys. J. C **81** (2021) 675

Differential results summary

χ2 and *p*-values for unfolded normalised cross-section distributions in the 2lSS region

Observable	NDF	Sherpa 2.2.10		MG5aMC+Py8 FxFx		MG5aMC+Py8 Incl.		Powheg+Pythia8		Powheg+Herwig7	
		χ^2	*p*-value	χ^2	*p*-value	χ^2	*p*-value	χ^2	*p*-value	χ^2	*p*-value
N_{jets}	5	2.4	0.79	4.2	0.52	2.8	0.73	2.9	0.72	2.6	0.76
$H_{\text{T,jets}}$	5	0.7	0.98	1.1	0.95	0.8	0.98	1.5	0.91	2.0	0.85
$H_{\text{T,lep}}$	7	3.6	0.82	3.8	0.80	3.4	0.84	3.4	0.85	3.5	0.84
$\Delta R_{\text{lb, lead}}$	7	2.0	0.96	2.4	0.93	2.6	0.92	2.6	0.92	2.5	0.93
$\lvert\Delta\phi_{\text{ll, SS}}\rvert$	7	0.6	1.00	0.7	1.00	0.9	1.00	0.8	1.00	0.9	1.00
$\lvert\Delta\eta_{\text{ll, SS}}\rvert$	6	6.5	0.37	7.3	0.29	11.4	0.08	9.5	0.15	9.4	0.15
$M_{\text{jj, lead}}$	6	4.9	0.56	2.7	0.84	7.2	0.30	9.0	0.17	10.9	0.09

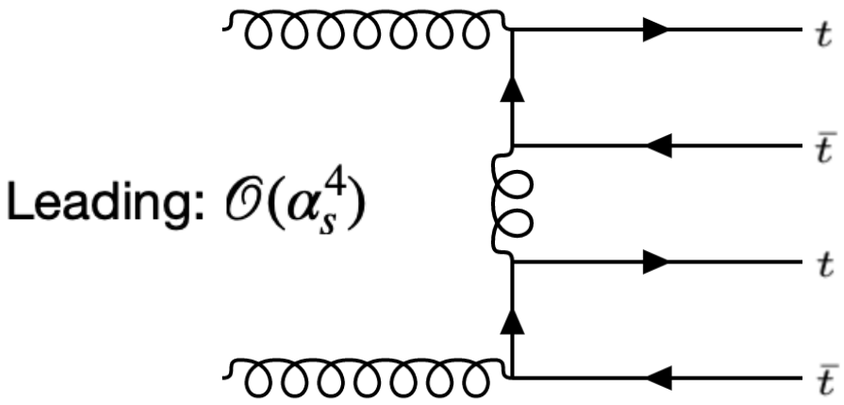
- Good agreement of unfolded data with all MC setups.
- Small tension of Δη between two leptons



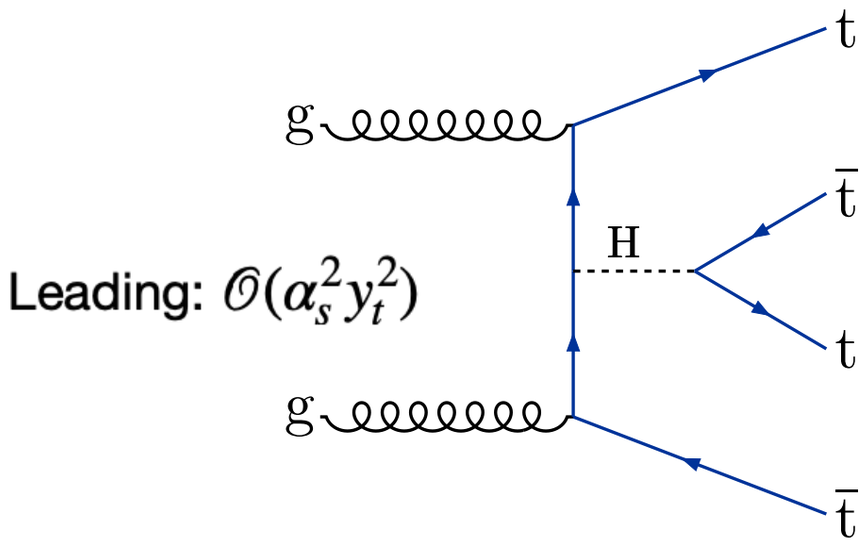
4-top quark production

4-top quark production

Heaviest particle final state

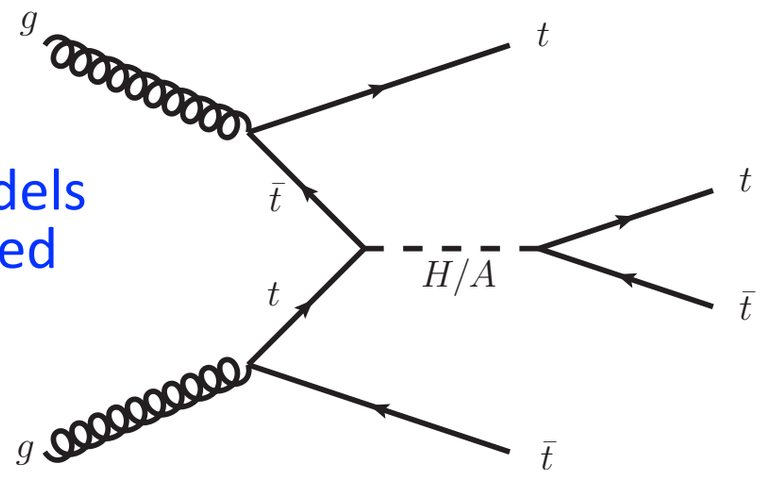


Sensitive to Higgs-Yukawa coupling strength and CP properties



Heavy scalar or pseudo-scalar Higgs boson in 2HDM

Many BSM models predict enhanced production



In EFT framework:

- sensitive to 4-fermion coupling
- Higgs oblique parameters

SM predictions

JHEP 02 (2018) 031 — NLO (QCD+EW)

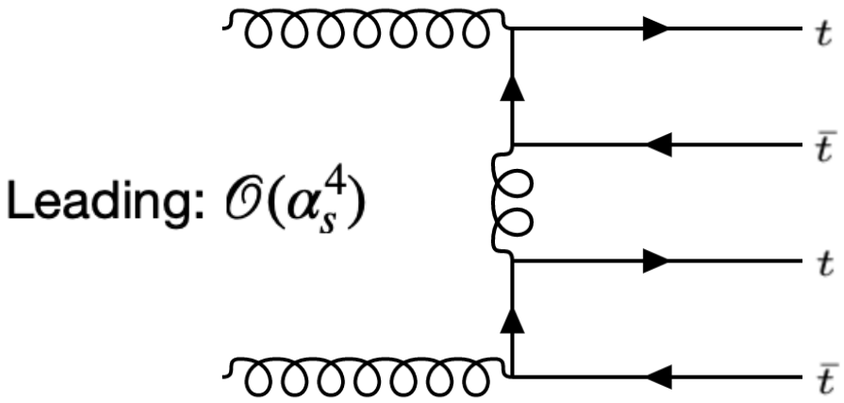
$$\sigma(t\bar{t}t\bar{t}) = 12.0 \pm 2.4 \text{ fb}$$

arXiv: 2212.03259 — including NLL'

$$\sigma(t\bar{t}t\bar{t}) = 13.4^{+1.0}_{-1.8} \text{ fb}$$

4-top quark production

Heaviest particle final state



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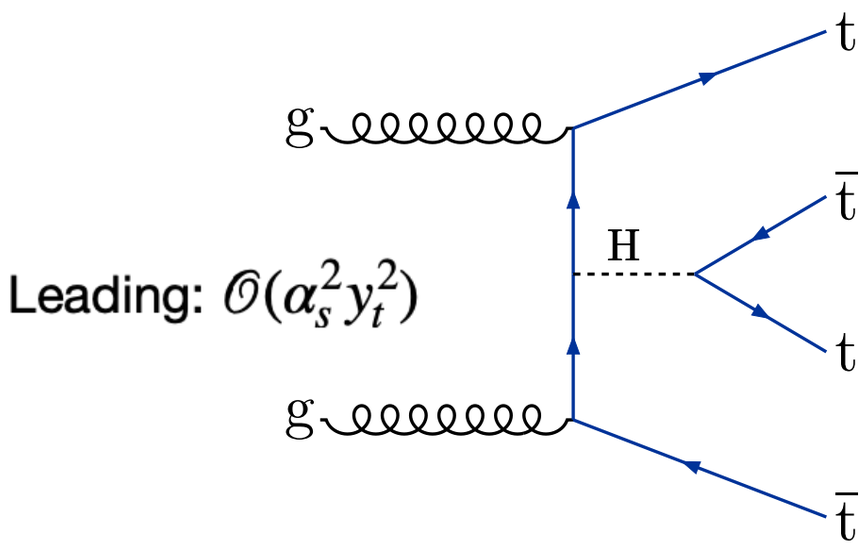
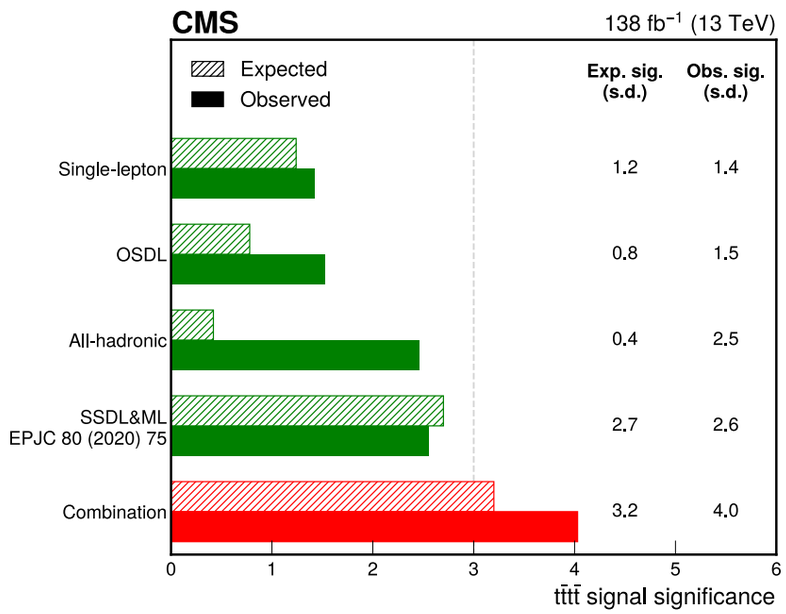
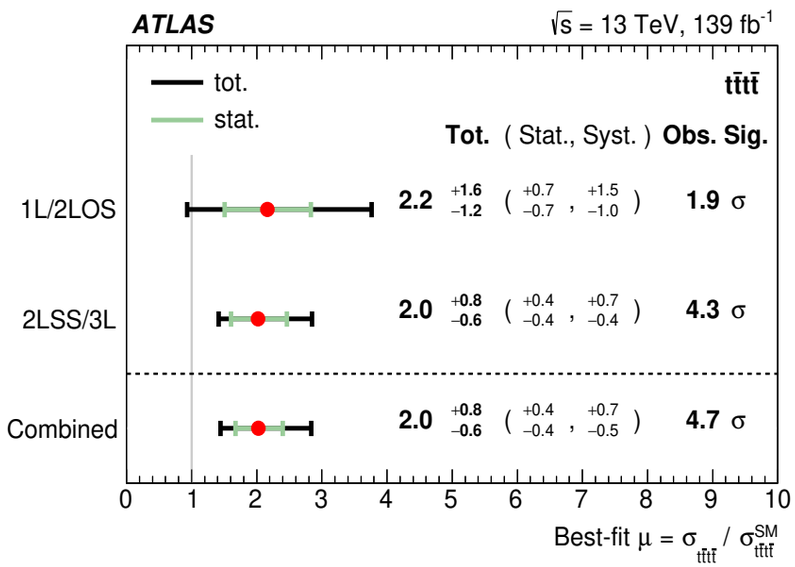


Evidence for 4-top quark production



$\sigma(t\bar{t}t\bar{t}) = 17 \pm 5$ fb

arXiv: 2303.03864



$\sigma(t\bar{t}t\bar{t}) = 24^{+7}_{-6}$ fb

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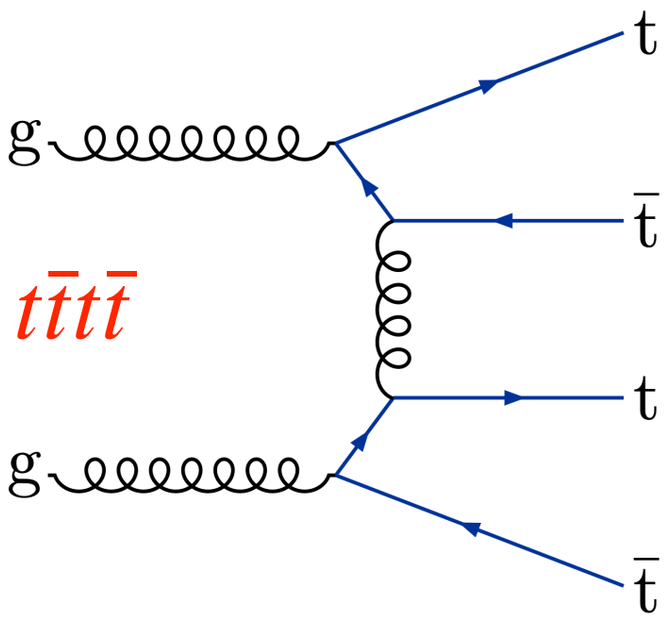
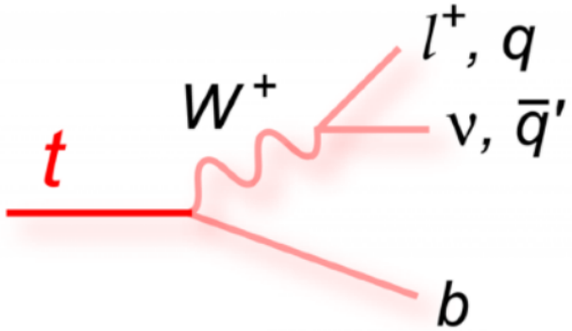
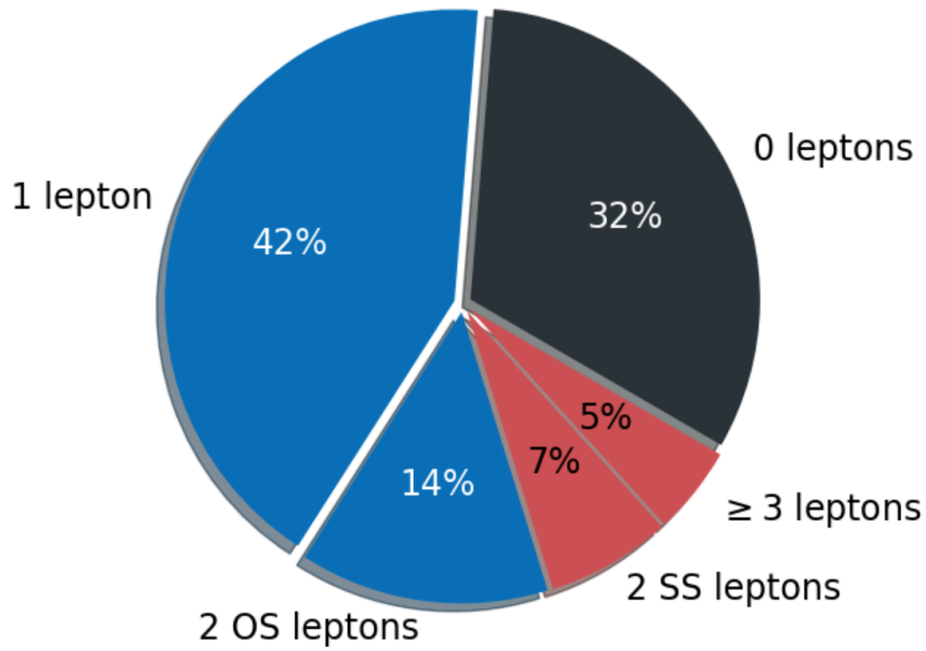
Measurements are consistent with theoretical calculations at 2σ level

Experimental signature

- Final state with high jet and b-jet multiplicity







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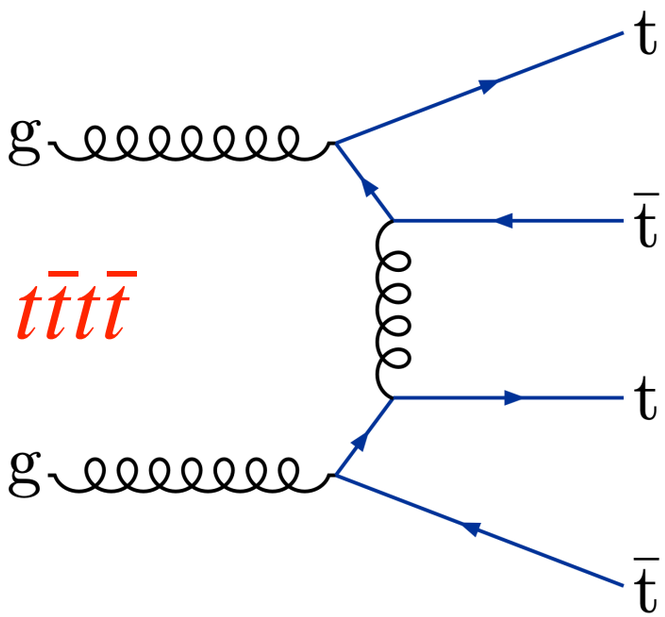
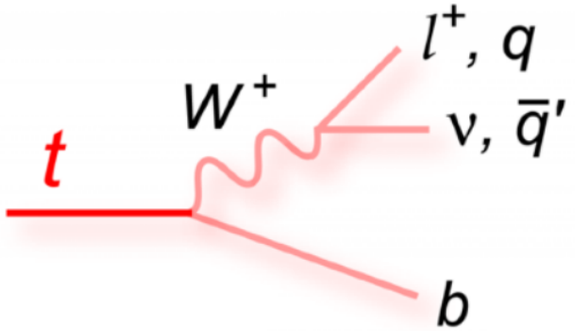
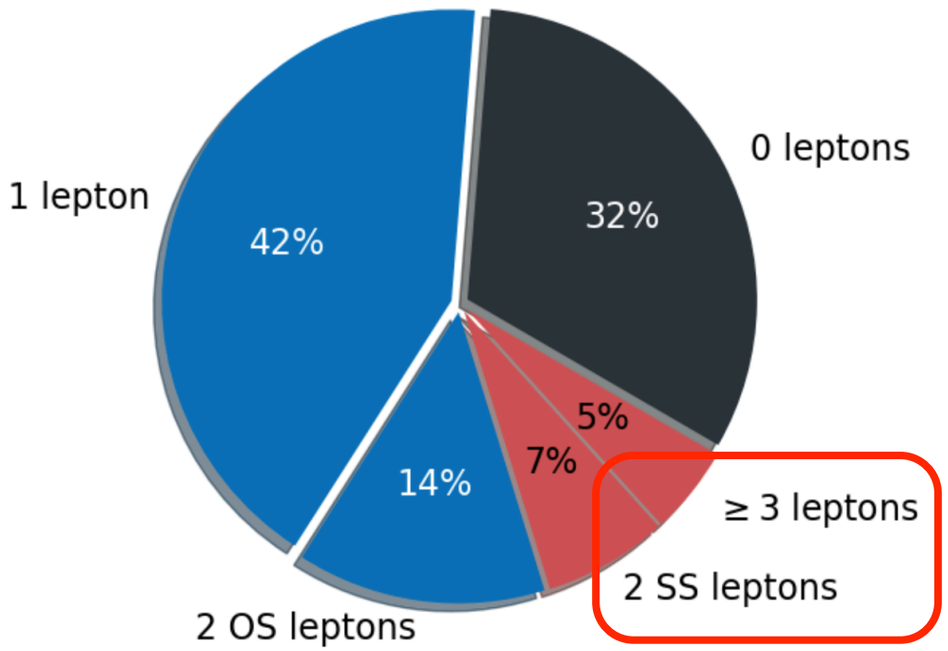
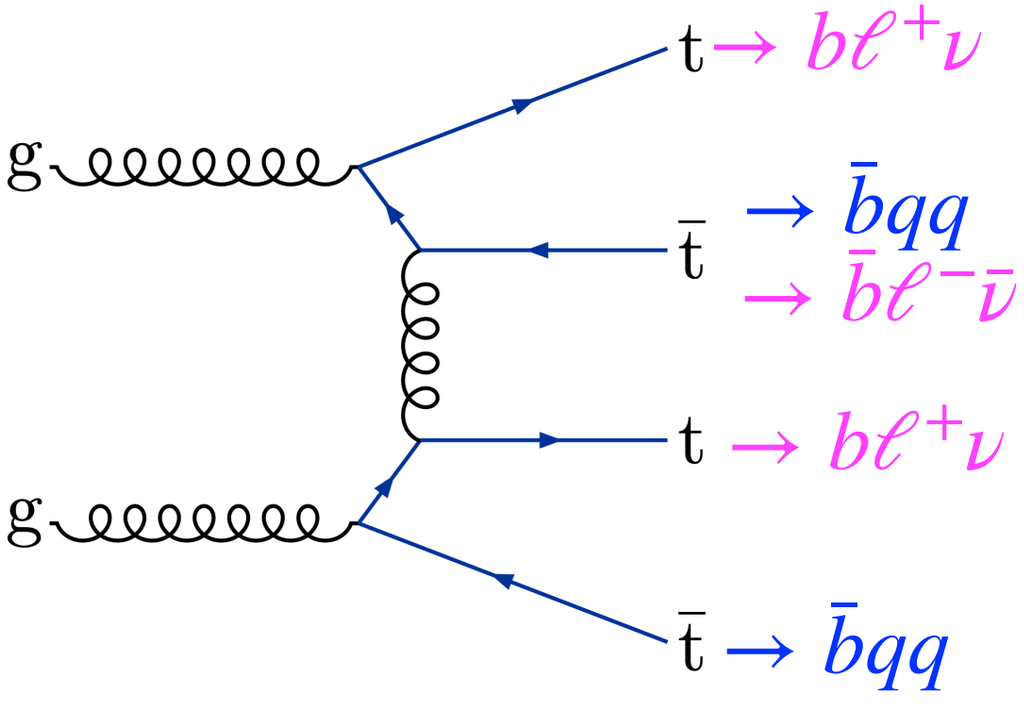








- small branching fraction (12%)
- small backgrounds

lepton	total jets	light/c jets	b-jets
SS	8	4	4
3L	6	2	

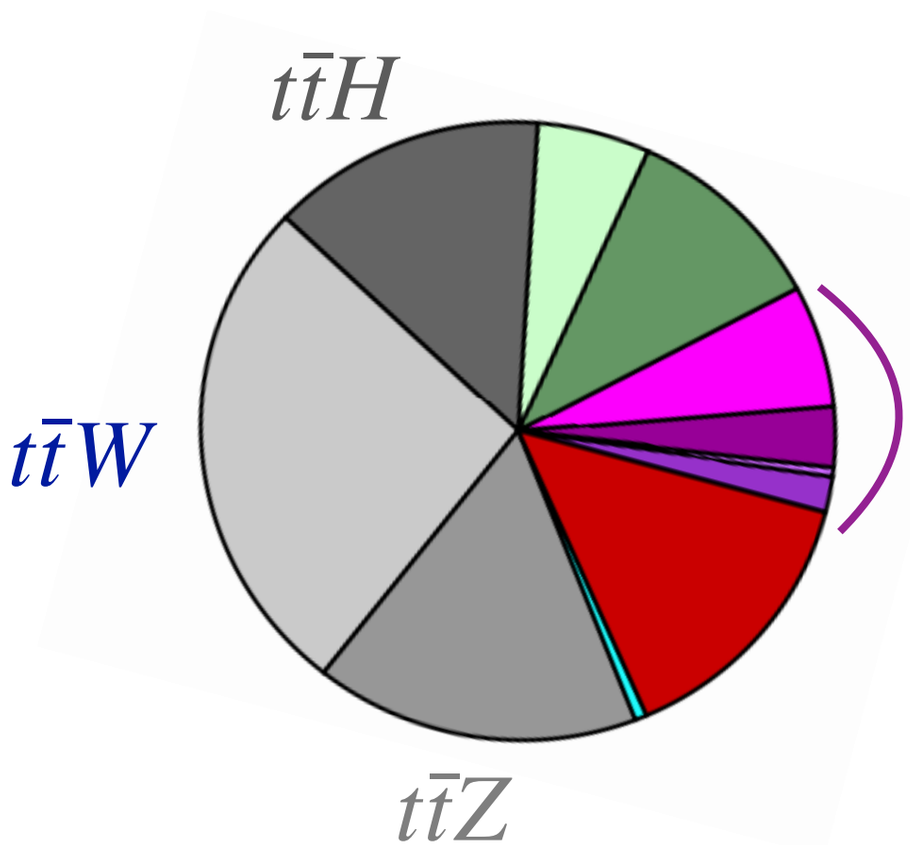
Most sensitive channel

Signal region selection

Signal region selection

- ≥6 jets, ≥2 b-jets
- HT > 500 GeV
- Graph Neural Network is trained to separate signal from background

Signal region composition



Fake and non-prompt leptons → Template method

Control regions are designed to evaluate ttW and fake/non-prompt background

Fake/non-prompt background

Template method

- Similar method as in ttW analysis
- 4 free parameters included in the signal extraction fit to determine normalisation
  - HF electron, HF muon
  - material conversions
  - virtual photon conversions

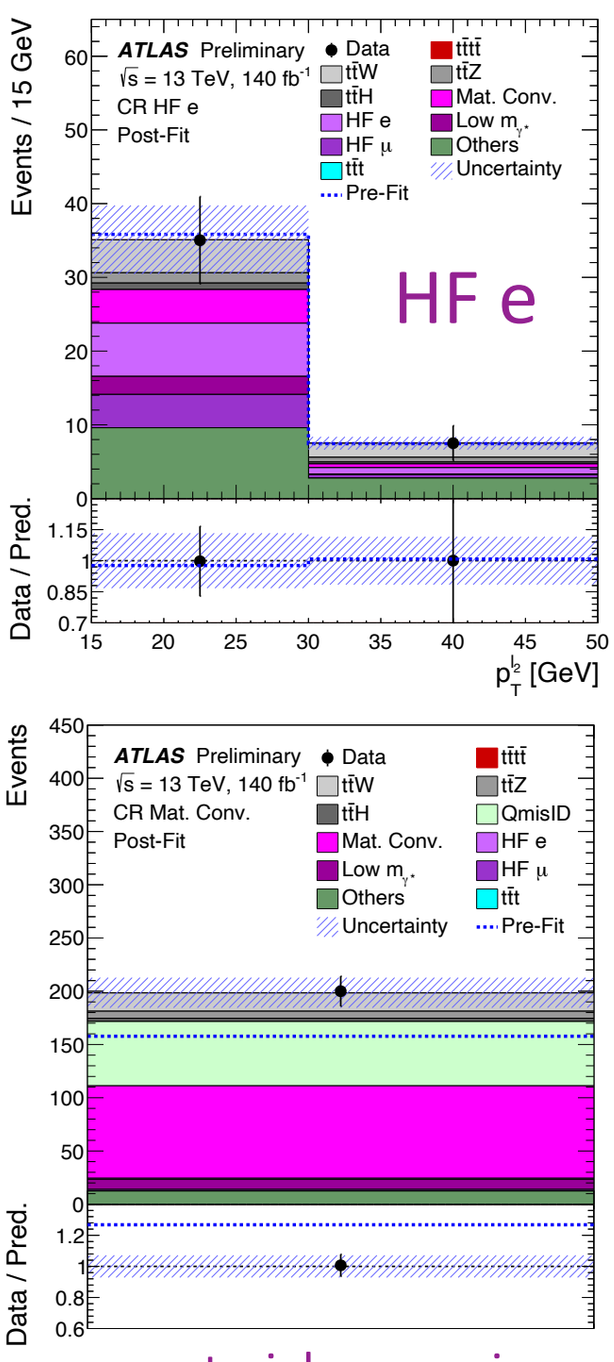
Fakes from HF decays

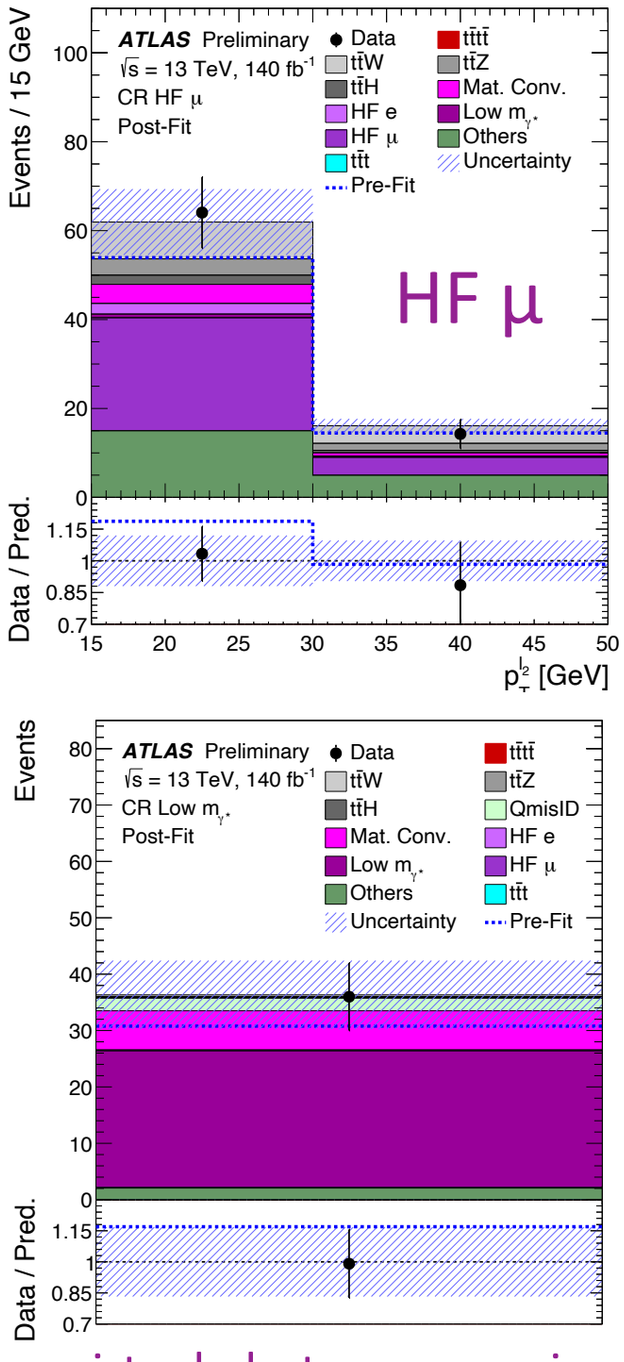
$NF_{HF\ e}$	$NF_{HF\ \mu}$
$0.66^{+0.75}_{-0.46}$	$1.27^{+0.53}_{-0.46}$

Fakes from conversions

$NF_{Mat.\ Conv.}$	$NF_{Low\ m_{\gamma^*}}$
$1.80^{+0.47}_{-0.41}$	$1.08^{+0.37}_{-0.31}$

Control regions





material conversions

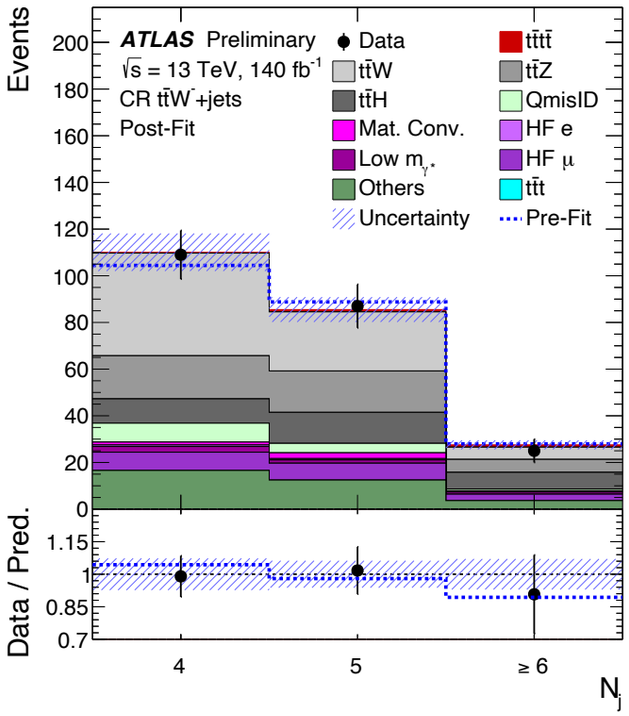
virtual photon conversions

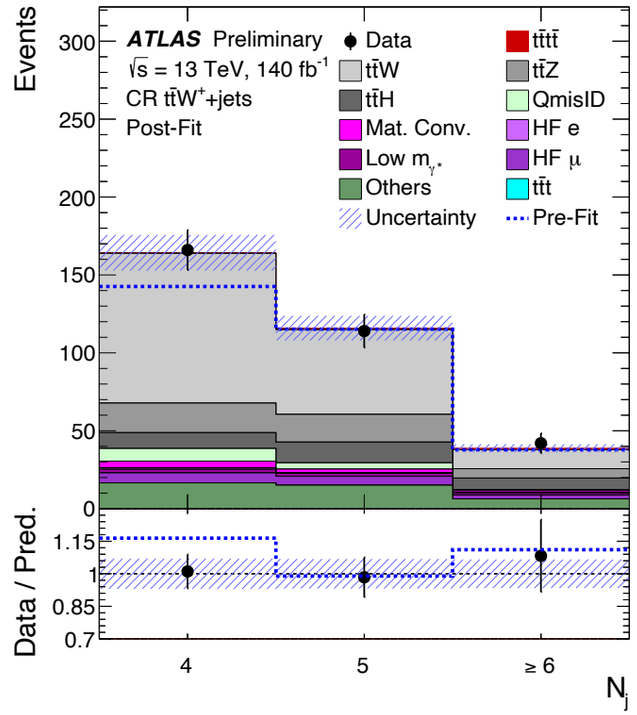
- Charge mis-ID for electrons fully data driven

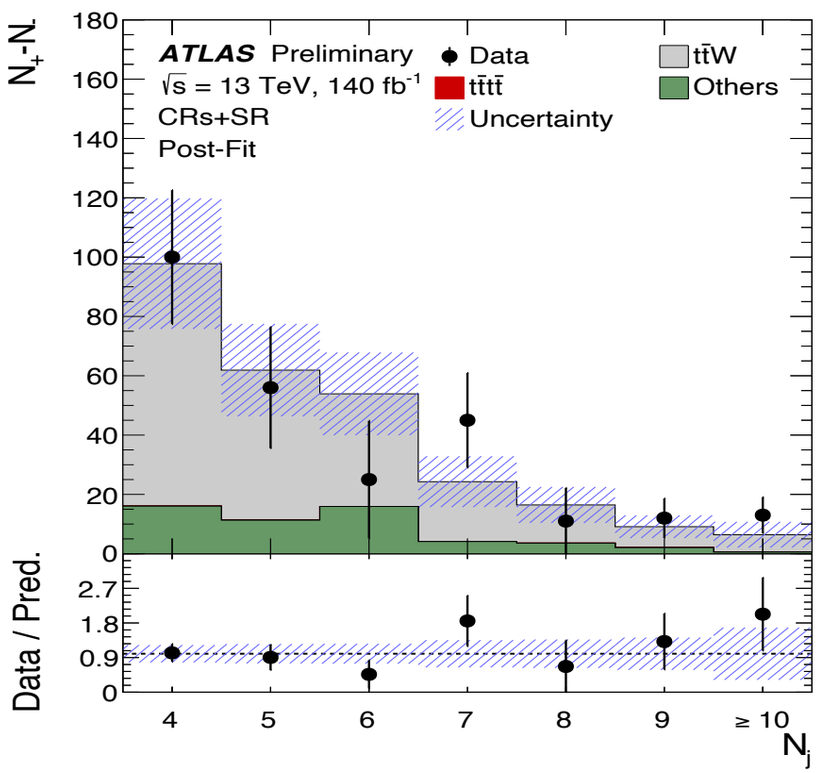
ttW background

- Estimate ttW background normalisation per jet bin from data based on the evolution R(j) = N(j+1)/N(j)
  - $R(j) = a_0$ for $j > j_{threshold}$
  - $R(n) = a_1/(n+1)$ for $n < j_{threshold}$, n=number of additional jets to hard process
- Shape from MC simulation

- 4 $t\bar{t}W$ control regions to determine
  - a0, a1
  - ttW^+ and ttW^- normalisation for j=4





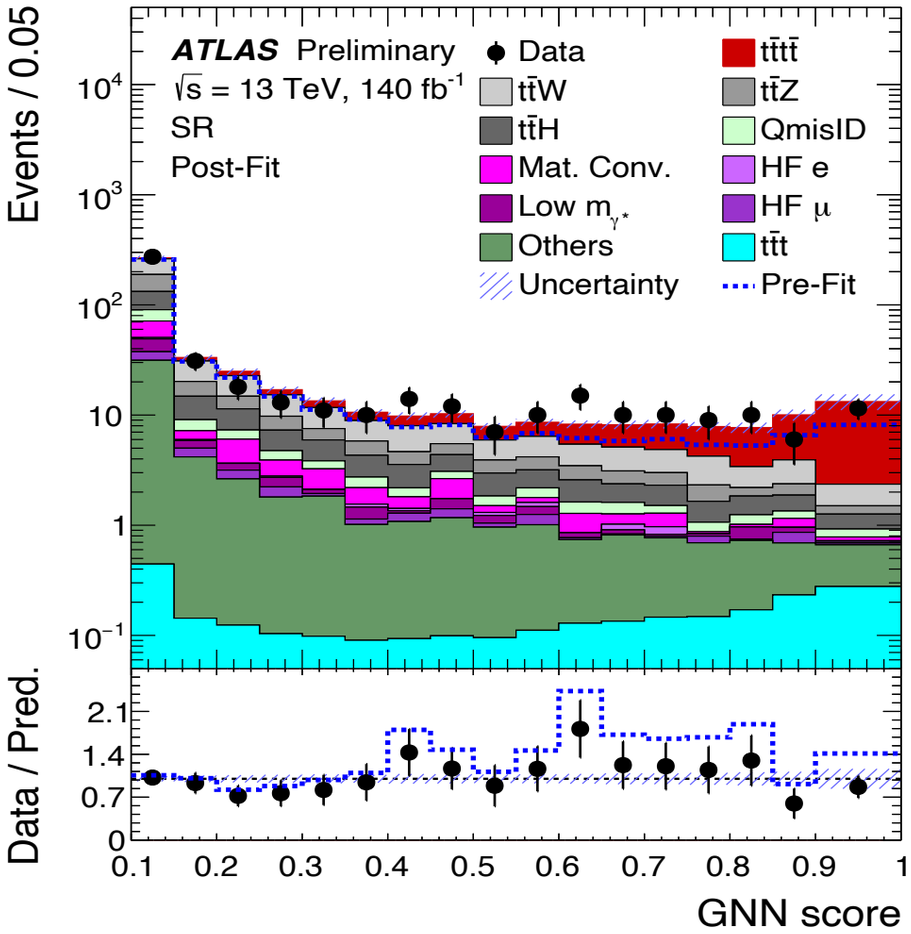


$t\bar{t}W$ background	a_0	a_1	$NF_{t\bar{t}W^+(4jet)}$	$NF_{t\bar{t}W^-(4jet)}$
Value	0.51 ± 0.10	$0.22^{+0.25}_{-0.22}$	$1.27^{+0.25}_{-0.22}$	$1.11^{+0.31}_{-0.28}$

Validation: plot $N_+ - N_-$ to suppress all charge symmetric backgrounds

4-top cross section result

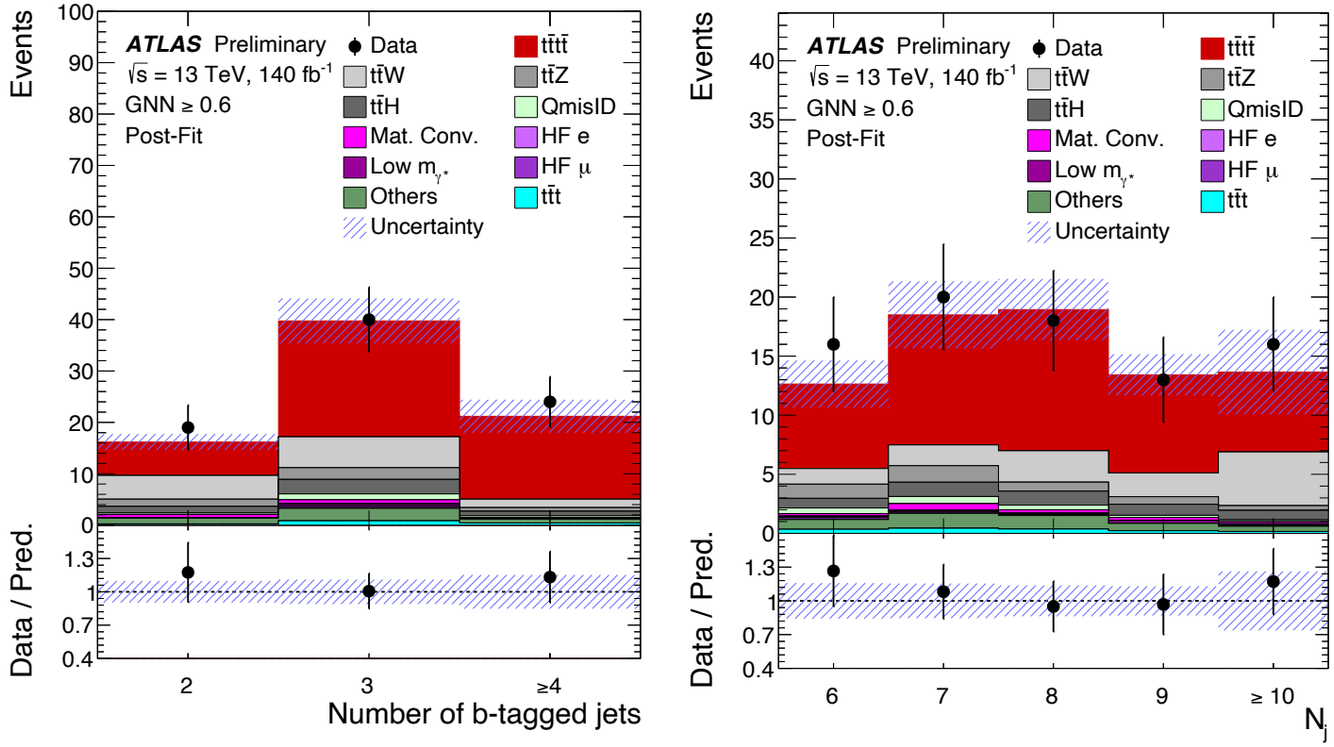
- Signal extraction
  - simultaneous fit to GNN in SR and distributions in 8 CRs



$\mu = 1.9 \pm 0.4\ (\text{stat})^{+0.7}_{-0.4}\ (\text{syst})$ fb

Largest systematic uncertainty from 4-top modelling, ttW DD parameters

Signal enriched region: GNN>0.6



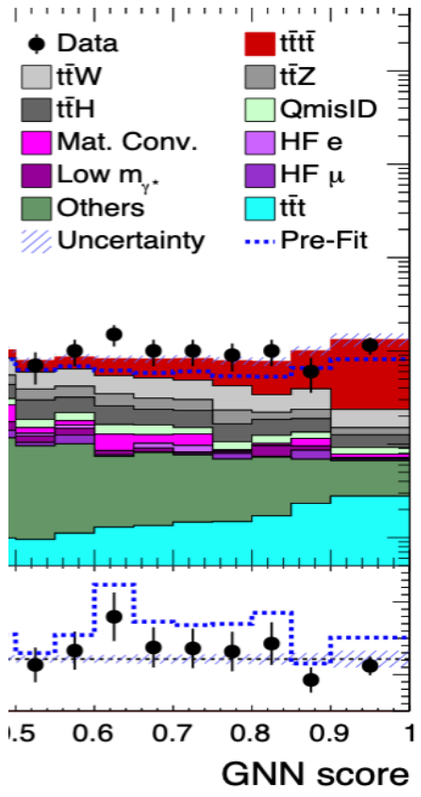
$\sigma(t\bar{t}t\bar{t}) = 22.5^{+6.6}_{-5.6}$ fb

6.1 (4.3) σ observed (expected) significance

Observation of the 4-top quark production

Consistent with SM prediction at 1.8/1.7 σ

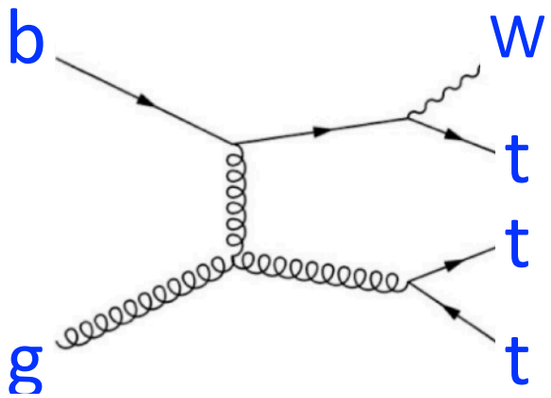
Three-top-quark production

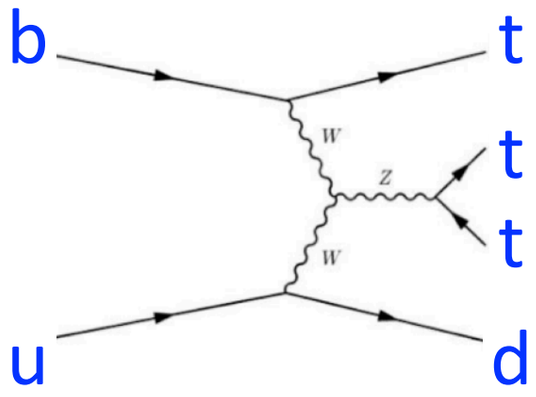


- Final state signature is similar to four top signal
- Populates region of high GNN score

$t\bar{t}t$

- In SM $t\bar{t}t$ produced always in association with other particles



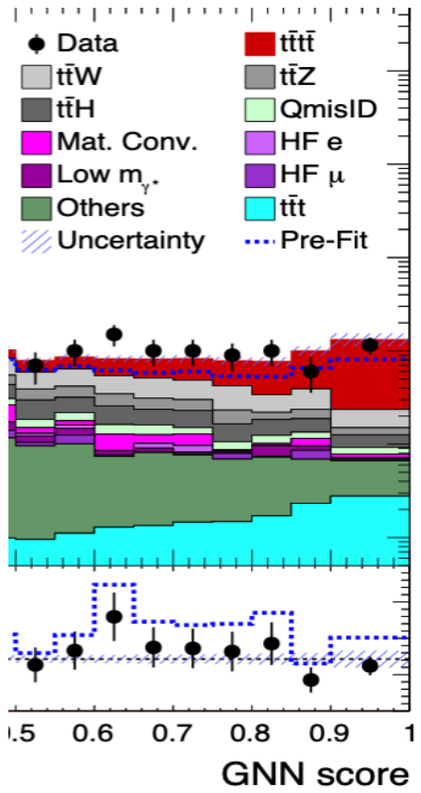


$\sigma(t\bar{t}tW) = 1.02$ fb $\quad \sigma(t\bar{t}tq) = 0.65$ fb

- 30% uncertainty on $t\bar{t}t$ cross section

We thank Gauthier Durieux for these predictions.

Three-top-quark production



- Final state signature is similar to four top signal
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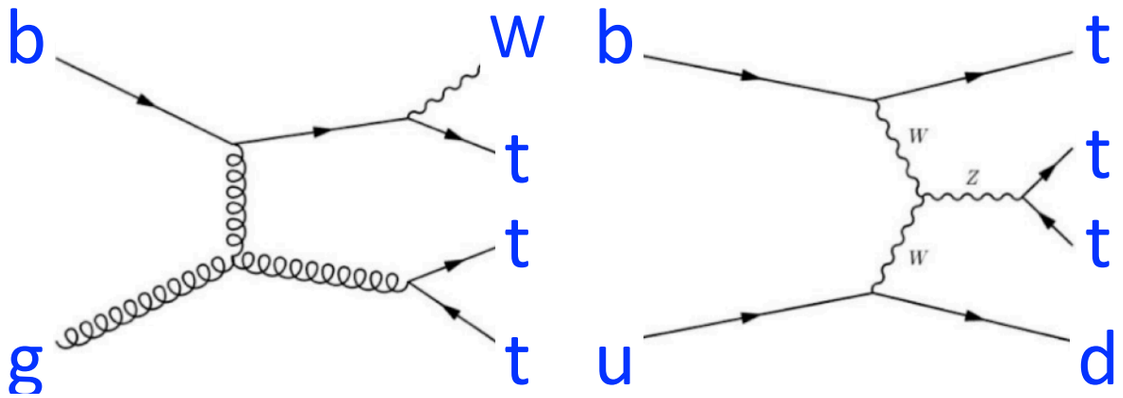
$t\bar{t}t$

- In SM $t\bar{t}t$ produced always in association with other particles

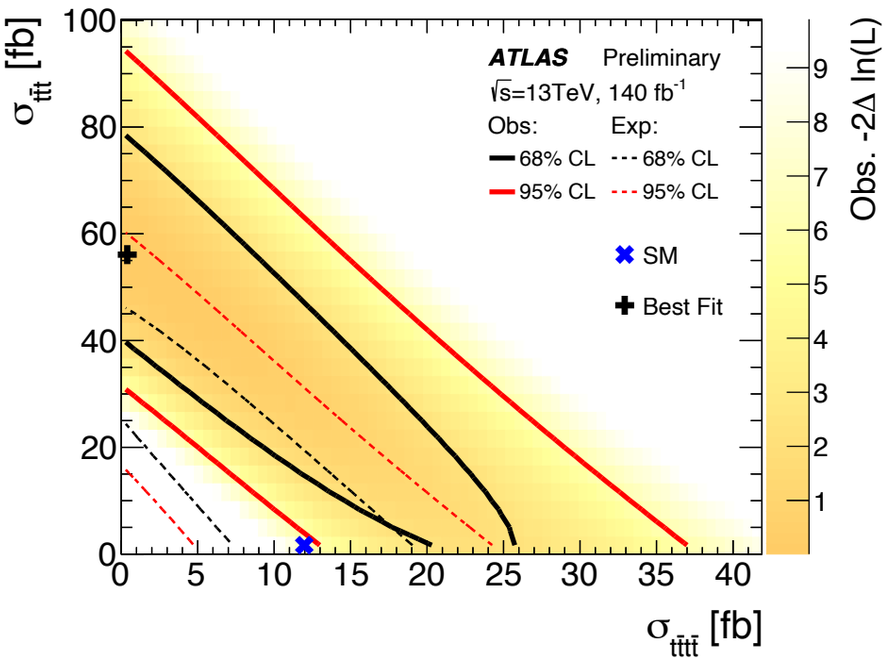


$\sigma(t\bar{t}tW) = 1.02$ fb $\quad \sigma(t\bar{t}tq) = 0.65$ fb

- 30% uncertainty on $t\bar{t}t$ cross section

We thank Gauthier Durieux for these predictions.

sum of $t\bar{t}tW$ and $t\bar{t}tq$



If both cross sections are free parameters of the fit anti-correlation is 93%

Limits on $t\bar{t}t$ production

Cross section [fb]	95% CL interval with $\mu_{t\bar{t}t\bar{t}} = 1$	95% CL interval with $\mu_{t\bar{t}t\bar{t}} = 1.9$
$t\bar{t}t$	[4.7, 60]	[0, 41]
$t\bar{t}tW$	[3.1, 43]	[0, 30]
$t\bar{t}tq$	[0, 144]	[0, 100]

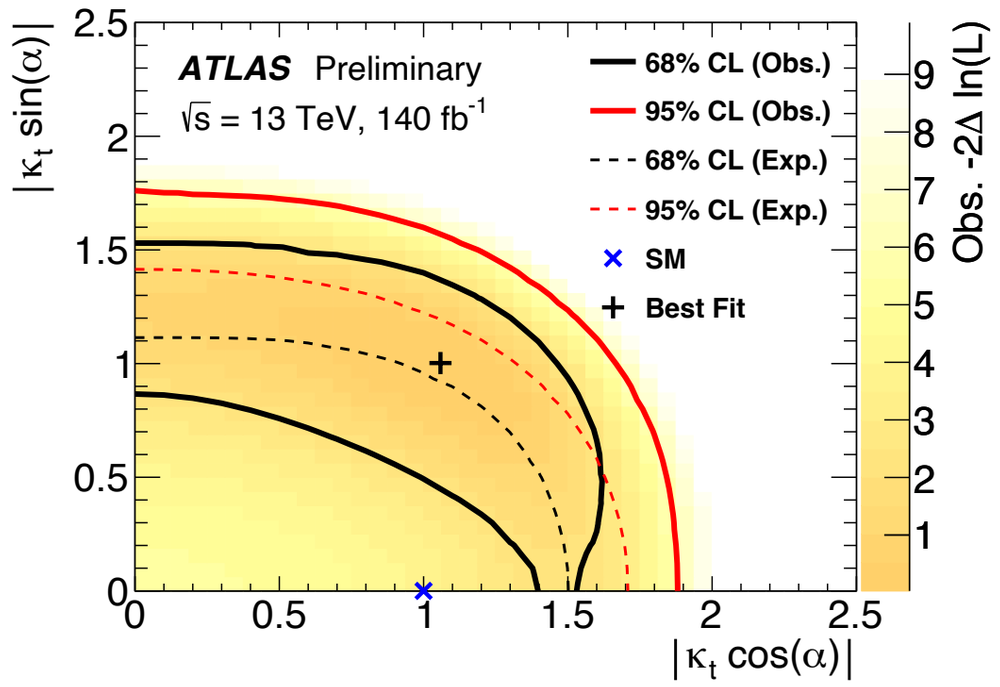
Interpretations

Top Yukawa coupling

$$\mathcal{L} = -\frac{1}{\sqrt{2}}\kappa_t y_t \bar{t}\,(\cos\alpha + i\sin\alpha\gamma_5)\,th$$

CP even CP odd

- CP even, obs (exp) $|k_t|<1.8$ (1.6) (ttH parameterised vs k_t)
- CP even, obs (exp) $|k_t|<2.2$ (1.8) (ttH free floating)



Limits on heavy flavour fermion operators in EFT (one parameter variation)

- Improved limits are highlighted

Operators	Expected C_i/Λ^2 [TeV^{-2}]	Observed C_i/Λ^2 [TeV^{-2}]
O^1_{QQ}	[-2.4,3.0]	[-3.5,4.1]
O^1_{Qt}	[-2.5,2.0]	[-3.5,3.0]
O^1_{tt}	[-1.1,1.3]	[-1.7,1.9]
O^8_{Qt}	[-4.2,4.8]	[-6.2,6.9]

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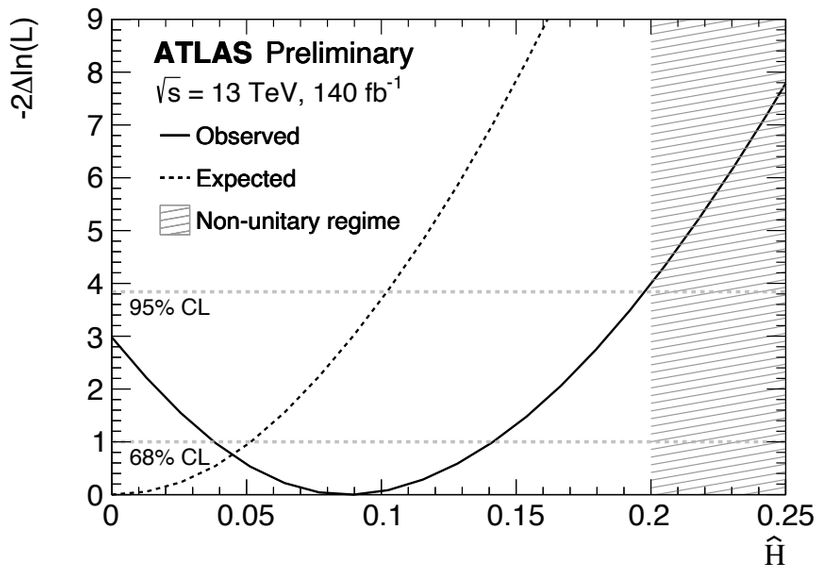
Higgs oblique parameter $\hat{H}$ modifies propagator of SM Higgs in dim-6 EFT

Upper limit: $\hat{H}<0.2$ ($\hat{H}=0$ in SM)



Summary

- Two new ATLAS results with full Run 2 data set and final calibrations in multilepton final state were presented

- Inclusive, fiducial and the first differential cross section measurement of $t\bar{t}W$
  - inclusive cross section is found to be higher than reference theory prediction and consistent with it at 1.5σ level
  - normalised differential distributions agree with data

- First 4-top quark observation was reported with 6.1σ significance
  - Measured cross section is consistent with SM prediction at 1.8σ level
  - The results are used to set limits on several BSM scenarios

Backup

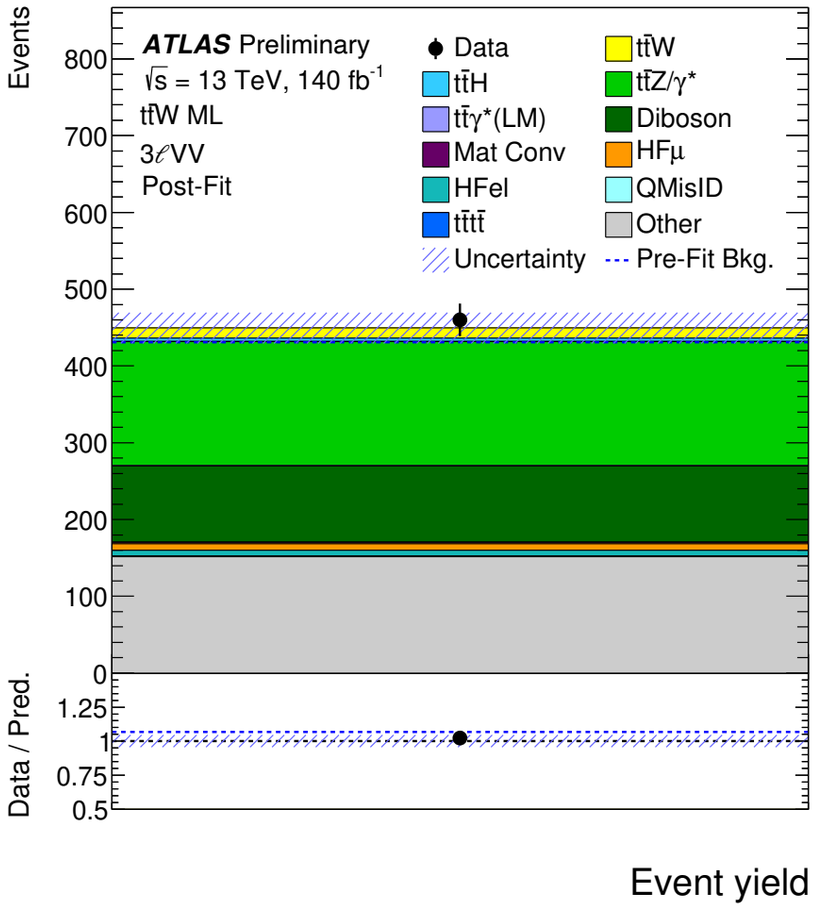
Irreducible background: ttW

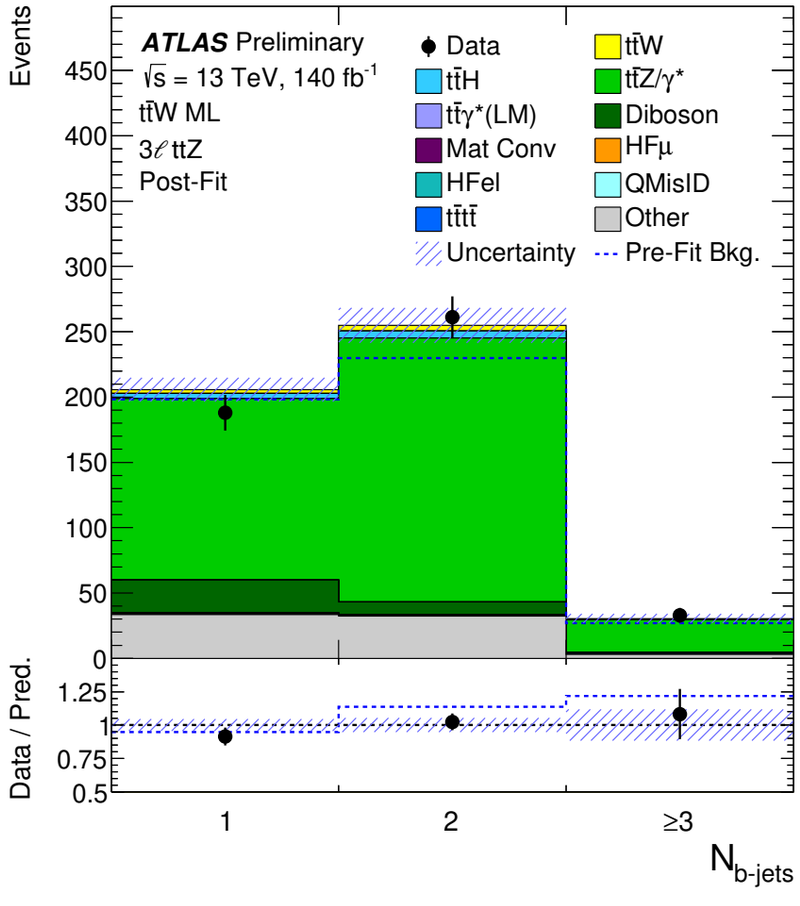
- ttZ and diboson from MC
- 2 CR to adjust VV, ttZ normalisation

VV/ttZ CRs [$L_{inc}M_{inc}M_{inc}$]

[2-3j, 1bj] [≥4j, ≥1bj]

WZ CR	ttZ CR
=1 Z cand.	=1 Z cand.
N_{bjets}	N_{bjets}





$NF_{VV} = 0.87 \pm 0.33$

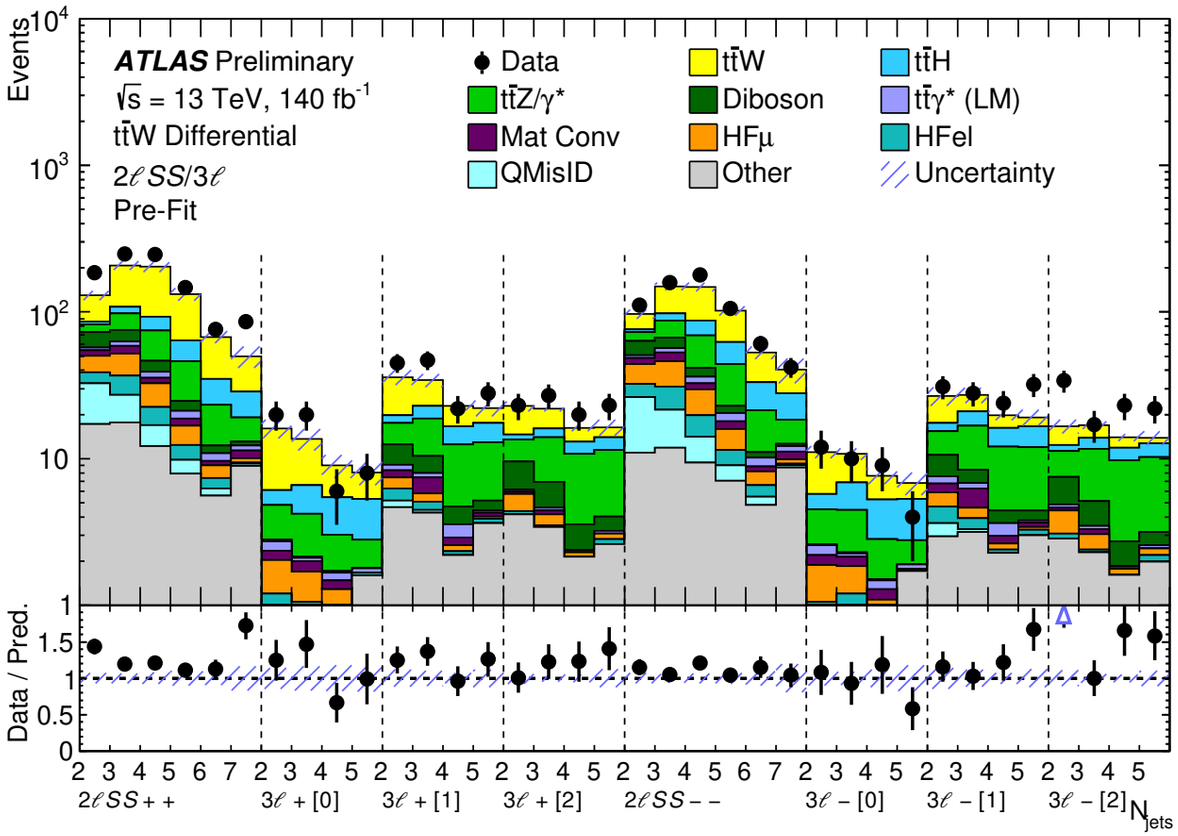
$NF_{ttZ} = 1.16 \pm 0.15$

Systematic inclusive

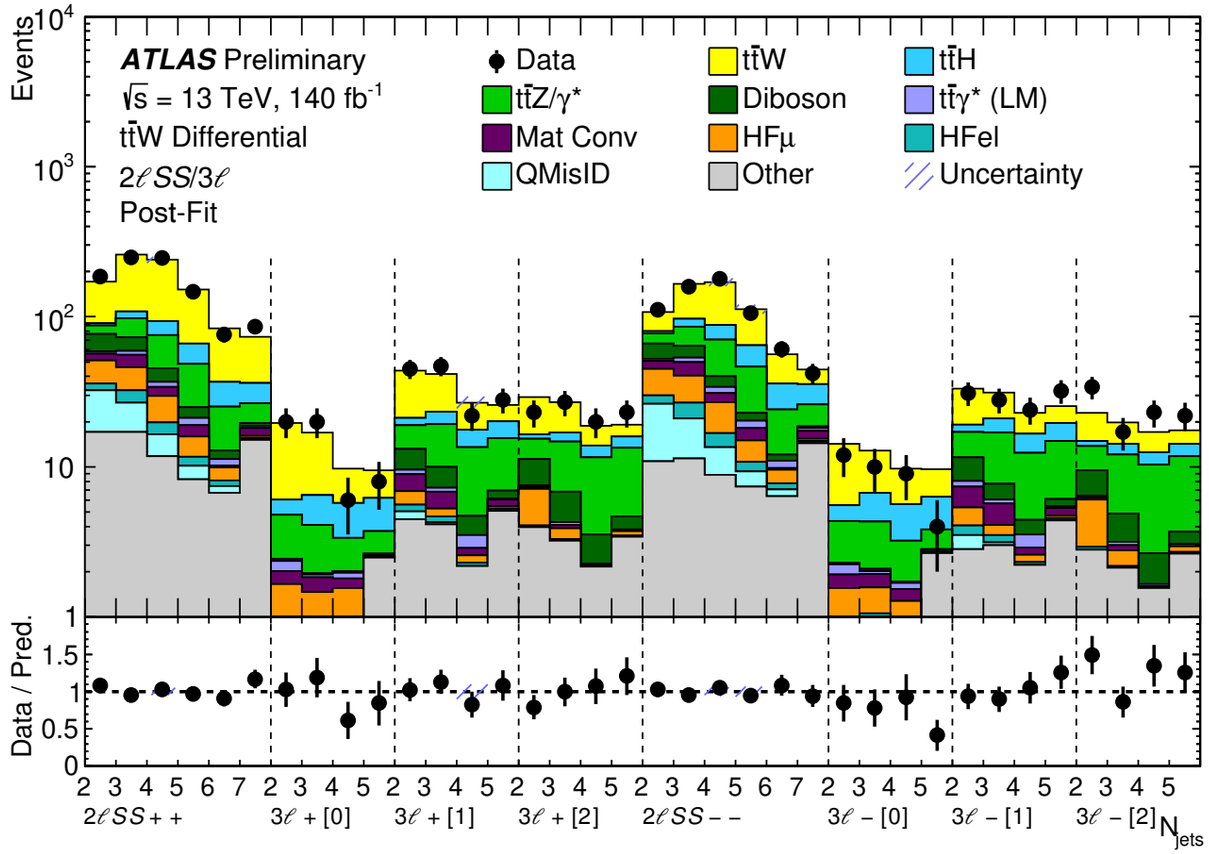
	$\frac{\Delta\sigma(t\bar{t}W)}{\sigma(t\bar{t}W)}$ [%]	$\frac{\Delta\sigma_{\text{fid}}(t\bar{t}W)}{\sigma_{\text{fid}}}$ [%]	$\frac{\Delta R(t\bar{t}W)}{R(t\bar{t}W)}$ [%]	$\frac{\Delta A_{\text{C}}^{\text{rel}}}{A_{\text{C}}^{\text{rel}}}$ [%]
$t\bar{t}W$ ME and PS modelling	6.0	7.0	6.0	8.0
Prompt lepton bkg. norm.	2.6	2.5	1.6	2.2
Lepton isolation BDT	2.3	2.3	1.0	1.2
Fakes/VV/$t\bar{t}Z$ norm. (free-floated)	2.3	2.7	1.8	2.5
Non-prompt lepton bkg. modelling	1.9	1.7	2.3	3.1
Trigger	1.9	1.8	0.5	0.7
MC statistics	1.5	1.6	1.9	2.5
$t\bar{t}W$ PDF	1.5	1.4	2.1	2.8
Jet energy scale	1.4	1.9	0.8	1.1
Prompt lepton bkg. modelling	1.3	1.3	1.3	1.9
Luminosity	1.0	1.0	0.08	0.13
Charge Mis-ID	0.7	0.7	0.4	0.5
Jet energy resolution	0.5	0.6	0.7	0.31
Flavour tagging	0.28	0.33	0.5	1.0
$t\bar{t}W$ Scale	0.21	0.9	1.4	1.9
Electron/photon reco.	0.15	0.2	0.12	0.3
MET	<0.10	<0.10	0.17	0.4
Muon	<0.10	<0.10	<0.10	0.4
Pile-up	<0.10	0.25	<0.10	0.3
Total syst.	8	10	8	10
Data statistics	5	5	10	16
Total	9	11	13	19

Differential results

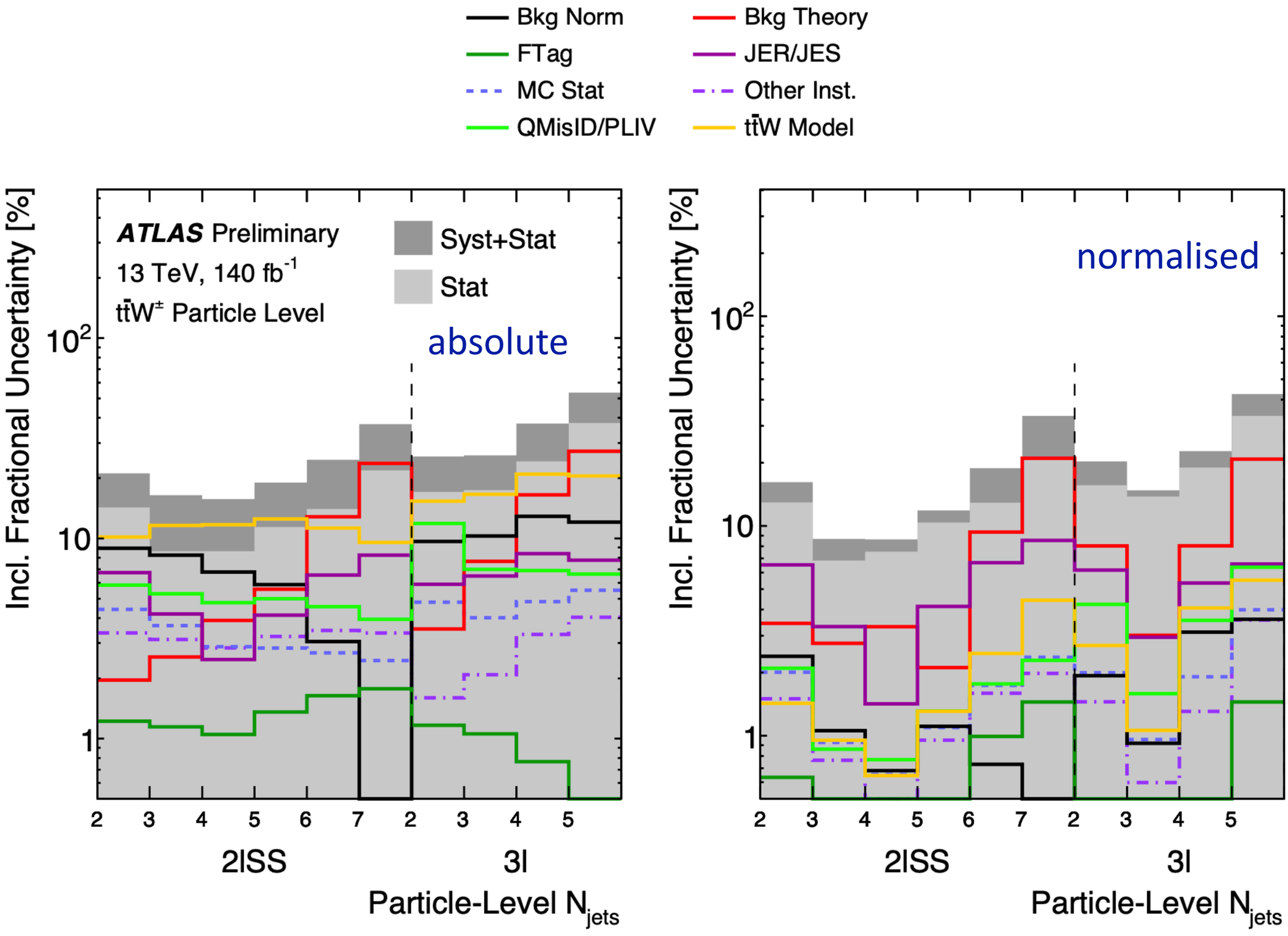
pre-fit



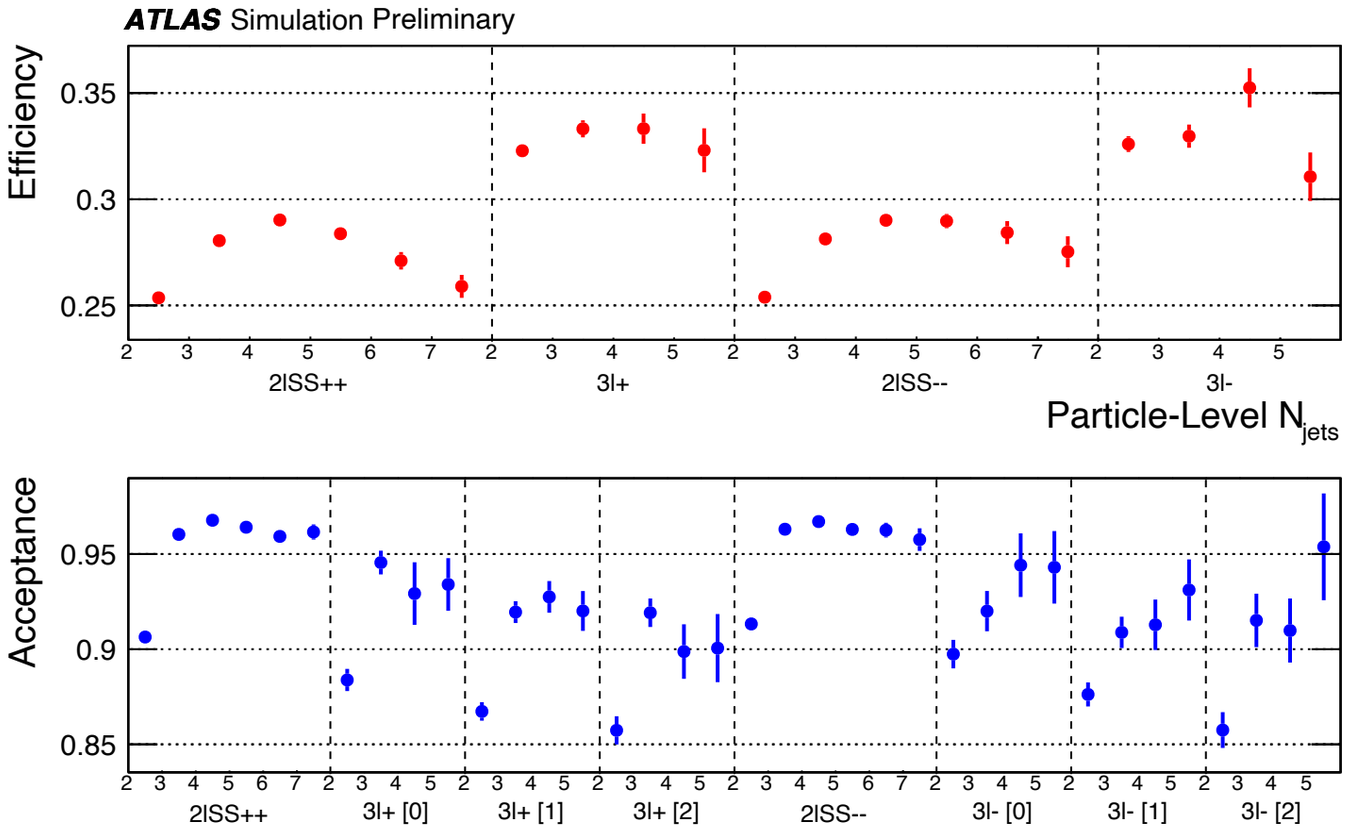
post-fit

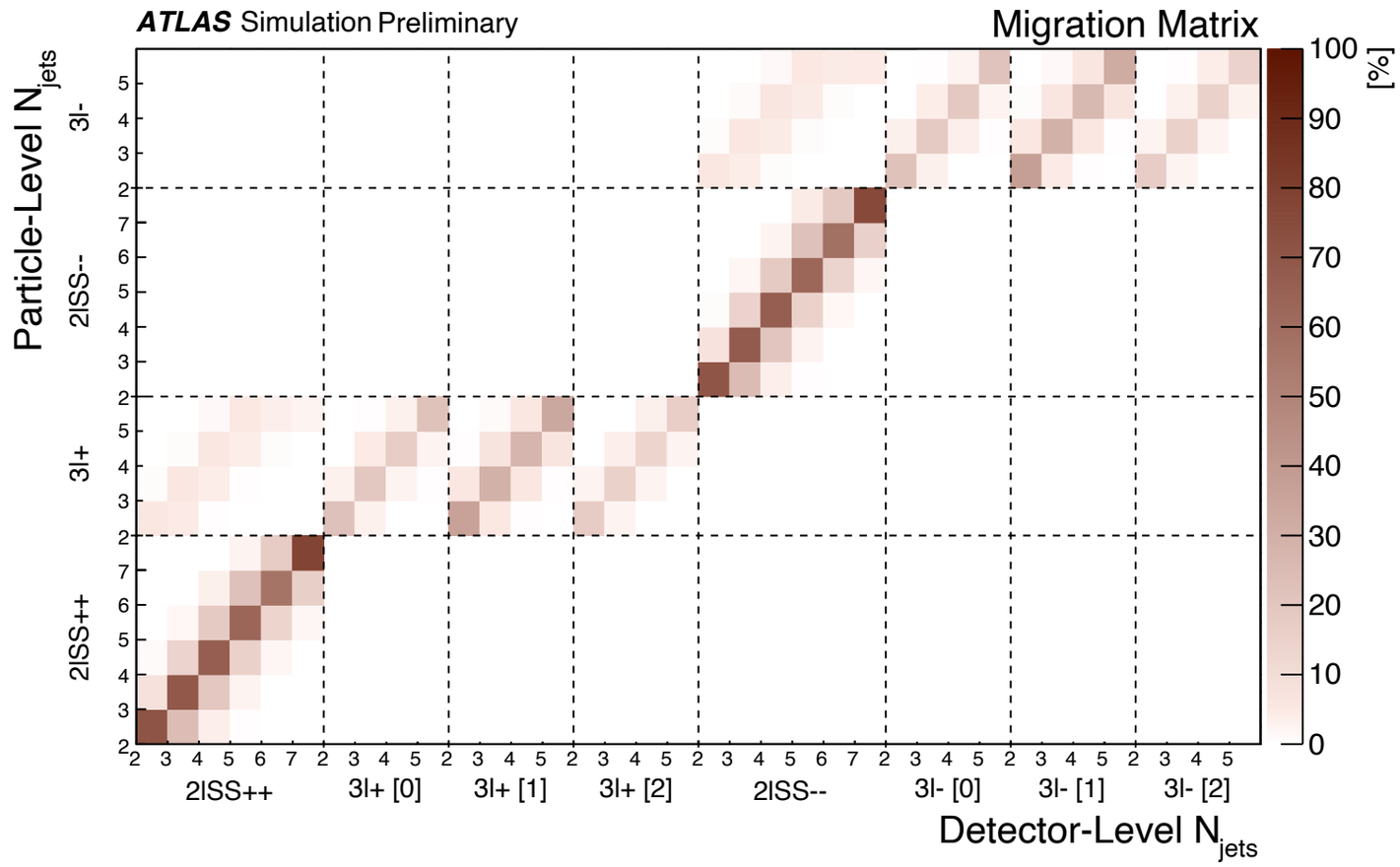


Systematics differential

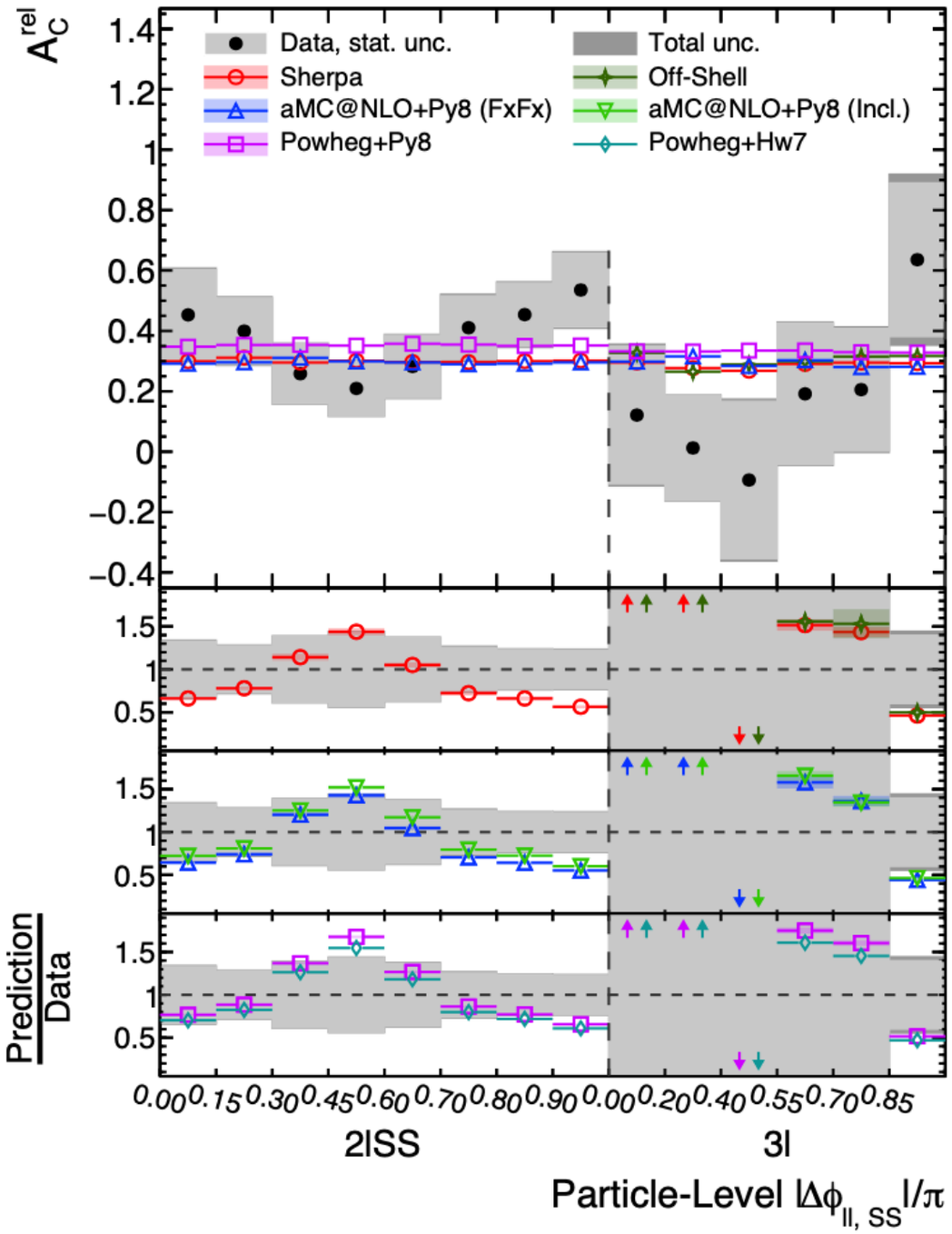


Unfolding

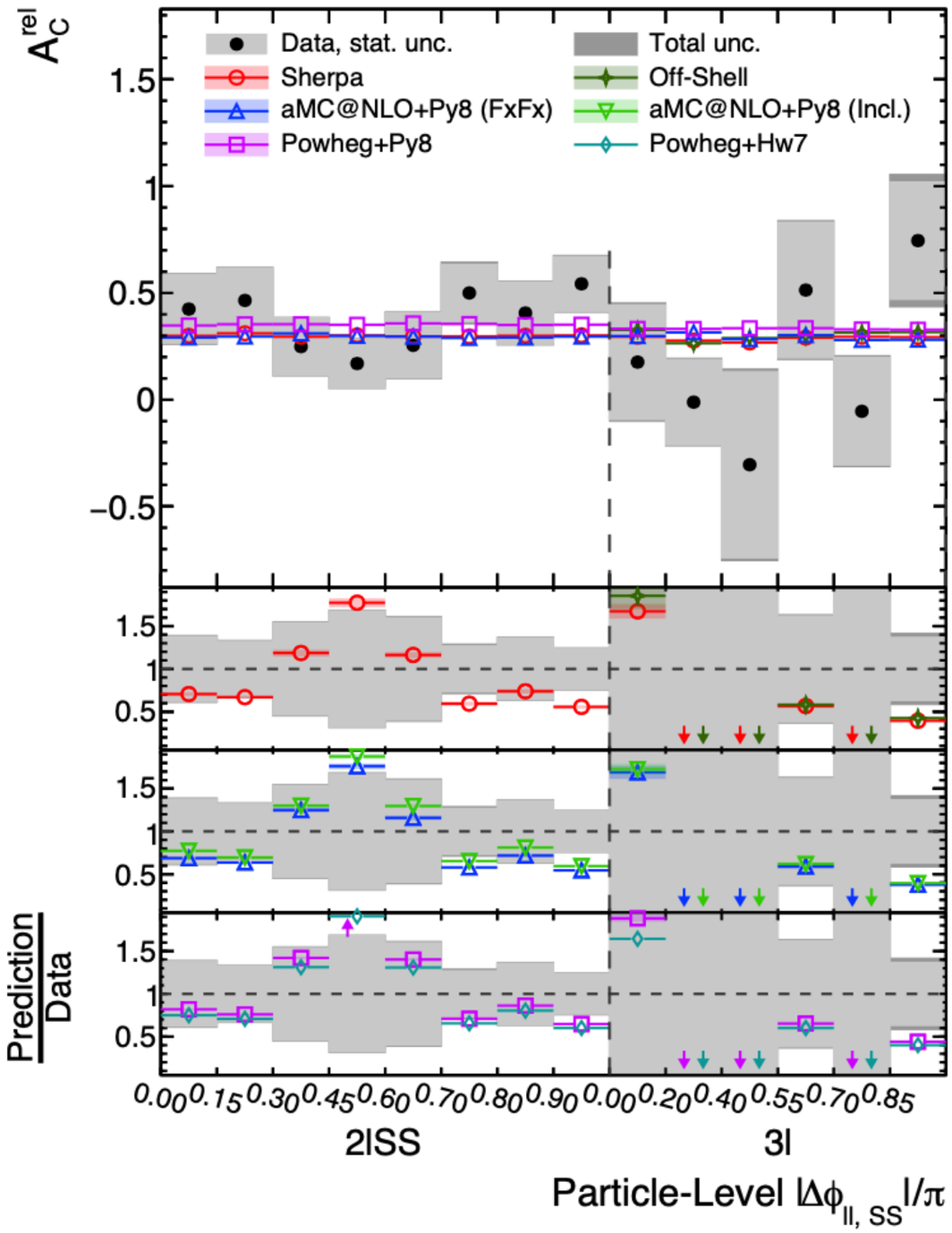

ATLAS Simulation Preliminary
Efficiency
0.35
0.3
0.25
2lSS++
3l+
2lSS--
3l-
Particle-Level N_jets
Acceptance
0.95
0.9
0.85
2lSS++
3l+ [0]
3l+ [1]
3l+ [2]
2lSS--
3l- [0]
3l- [1]
3l- [2]


ATLAS Simulation Preliminary
Migration Matrix
Particle-Level N_jets
3l-
2lSS--
3l+
2lSS++
Detector-Level N_jets
2lSS++
3l+ [0]
3l+ [1]
3l+ [2]
2lSS--
3l- [0]
3l- [1]
3l- [2]
[%]
100
90
80
70
60
50
40
30
20
10
0

Regularisation



regularised



no regularisation

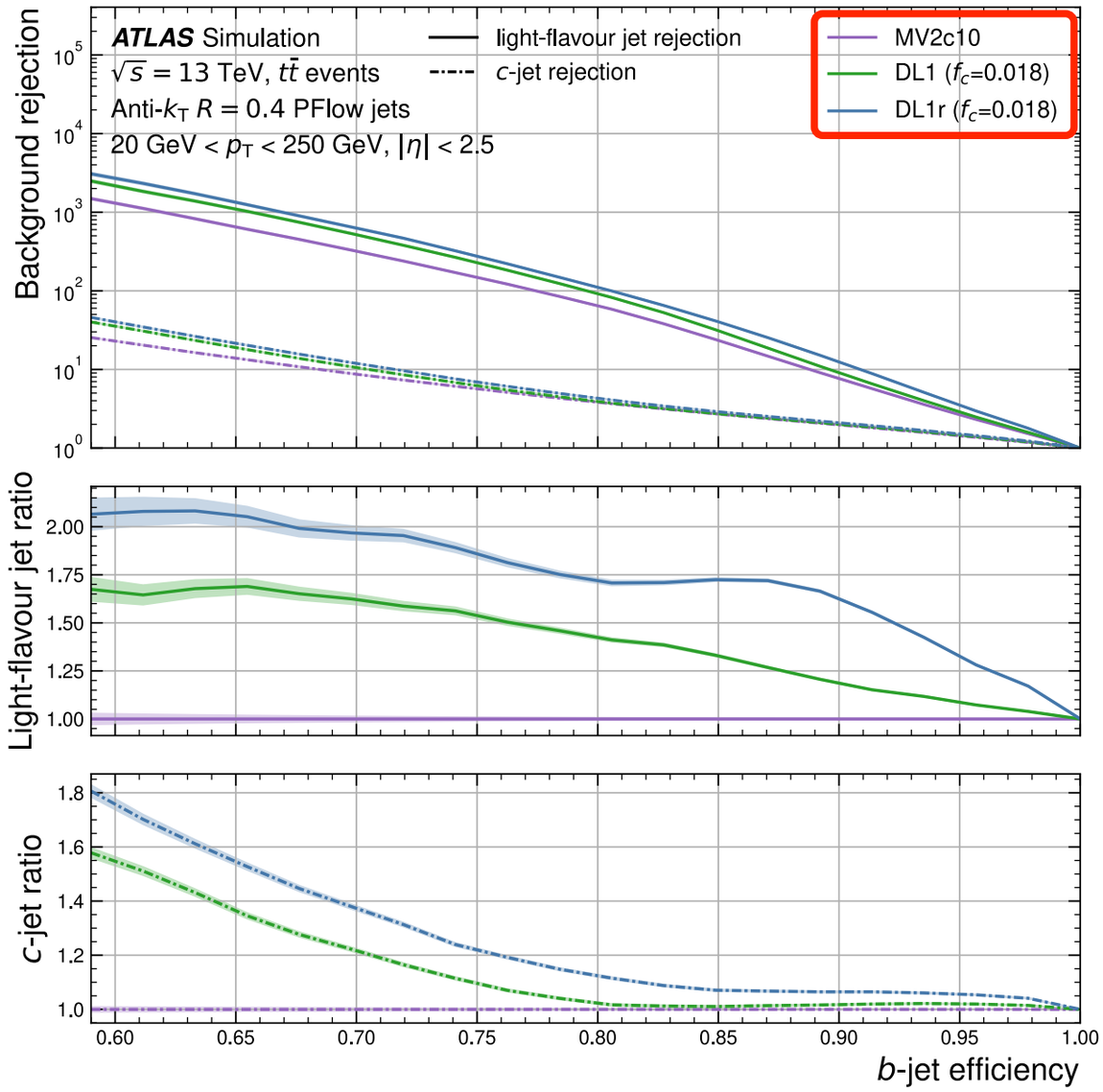
Regions 4-top

Region	Channel	N_j	N_b	Other selection	Fitted variable
CR Low m_{γ^*}	SS, ee or eμ	$4 \leq N_j < 6$	≥ 1	ℓ_0 or ℓ_1 is from virtual photon (γ^*) decay ℓ_0 and ℓ_1 are not from photon conversion	counting
CR Mat. Conv.	SS, ee or eμ	$4 \leq N_j < 6$	≥ 1	ℓ_0 or ℓ_1 is from photon conversion	counting
CR HF μ	e$\mu\mu$ or $\mu\mu\mu$	≥ 1	$= 1$	$100 < H_T < 300$ GeV $E_T^{miss} > 50$ GeV total charge is ± 1	$p_T^{\ell_2}$
CR HF e	eee or eeμ	≥ 1	$= 1$	$100 < H_T < 275$ GeV $E_T^{miss} > 35$ GeV total charge is ± 1	$p_T^{\ell_2}$
CR $t\bar{t}W^+$+jets	SS, eμ or $\mu\mu$	≥ 4	≥ 2	$\lvert\eta(e)\rvert < 1.5$ when $N_b = 2$: $H_T < 500$ GeV or $N_j < 6$ when $N_b \geq 3$: $H_T < 500$ GeV total charge > 0	N_j
CR $t\bar{t}W^-$+jets	SS, eμ or $\mu\mu$	≥ 4	≥ 2	$\lvert\eta(e)\rvert < 1.5$ when $N_b = 2$: $H_T < 500$ GeV or $N_j < 6$ when $N_b \geq 3$: $H_T < 500$ GeV total charge < 0	N_j
CR 1b(+)	2LSS+3L	≥ 4	$= 1$	ℓ_0 and ℓ_1 are not from photon conversion $H_T > 500$ GeV total charge > 0	N_j
CR 1b(-)	2LSS+3L	≥ 4	$= 1$	ℓ_0 and ℓ_1 are not from photon conversion $H_T > 500$ GeV total charge < 0	N_j
SR	2LSS+3L	≥ 6	≥ 2	$H_T > 500$	GNN score

Re-analysis of Run 2 data

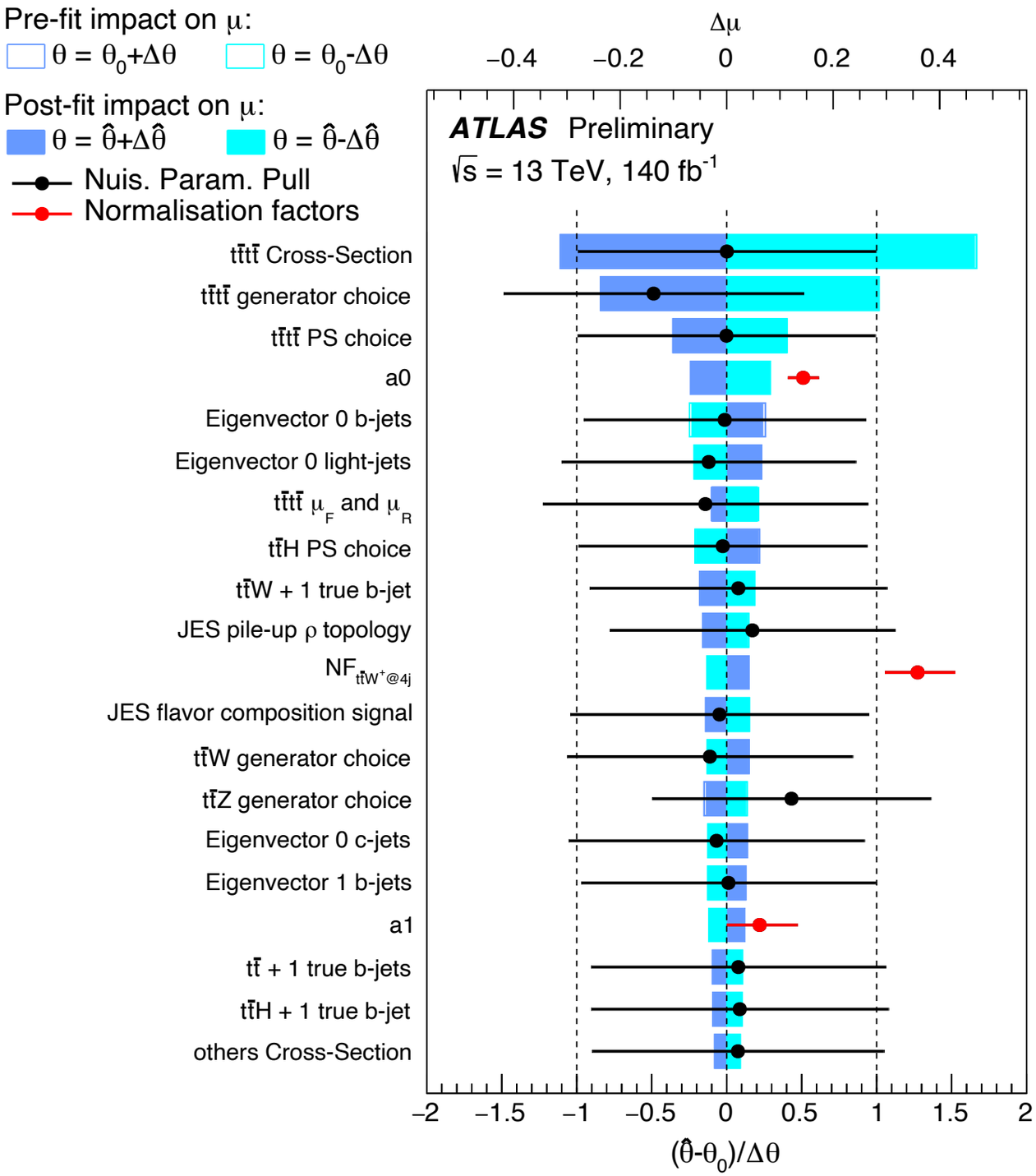
- What has changed?
- New jet reconstruction algorithm
  - lower jet pT cut (20 GeV)
- New optimised b-tagging algorithm DL1r
  - 77% b-tag efficiency, light/c-jet rejection 190/6
  - purest WP: 60% efficiency, light/c-jet rejection 2500/40
- Updated lepton calibration and new additional BDT-based isolation
  - lower lepton pT cuts: pT>15 GeV
- GNN (Graph Neural Network) and optimised BDT (cross check)
- Data-driven ttW estimate
- Updated MC simulation
- Updated luminosity calibration and uncertainty (140±0.83% fb^{-1})

flavour tagging algorithms performance



improved c/light-jet rejection for the same efficiency (MV2c10 used in previous analysis)

Uncertainties ranking



Uncertainties grouped

Uncertainty source	$\Delta\sigma$ [fb]		$\Delta\sigma/\sigma$ [%]	
Signal modelling				
$t\bar{t}t\bar{t}$ generator choice	+3.7	-2.7	+17	-12
$t\bar{t}t\bar{t}$ parton shower model	+1.6	-1.0	+7	-4
Other $t\bar{t}t\bar{t}$ modelling	+0.8	-0.5	+4	-2
Background modelling				
$t\bar{t}H$+jets modelling	+0.9	-0.7	+4	-3
$t\bar{t}W$+jets modelling	+0.8	-0.8	+4	-3
$t\bar{t}Z$+jets modelling	+0.5	-0.4	+2	-2
Other background modelling	+0.5	-0.4	+2	-2
Non-prompt leptons modelling	+0.4	-0.3	+2	-2
$t\bar{t}t$ modelling	+0.3	-0.2	+1	-1
Charge misassignment	+0.1	-0.1	+0	-0
Instrumental				
Jet flavour tagging (b-jets)	+1.1	-0.8	+5	-4
Jet uncertainties	+1.1	-0.7	+5	-3
Jet flavour tagging (light-flavour jets)	+0.9	-0.6	+4	-3
Jet flavour tagging (c-jets)	+0.5	-0.4	+2	-2
Simulation sample size	+0.4	-0.3	+2	-1
Other experimental uncertainties	+0.4	-0.3	+2	-1
Luminosity	+0.2	-0.2	+1	-1
Total systematic uncertainty	+5.1	-3.9	+22	-17
Statistical				
Intrinsic statistical uncertainty	+4.2	-3.9	+19	-17
$t\bar{t}W$+jets normalisation and scaling factors	+1.2	-1.1	+6	-5
Non-prompt leptons normalisation (HF, Mat. Conv., Low m_{γ^*})	+0.4	-0.3	+2	-1
Total statistical uncertainty	+4.7	-4.3	+21	-19
Total uncertainty	+6.6	-5.5	+29	-25

Graph neural network