Highlights of ATLAS top properties measurements

Richard Hawkings (CERN) on behalf of ATLAS

Lake Louise Winter Institute, Canada, 15/2/19

- Selected measurements:
  - Top mass: 8 TeV l+jets analysis and Run-1 combination: arXiv:1810.01772
  - Top spin correlations at 13 TeV: ATLAS-CONF-2018-027
  - Top-pair + W/Z and + photon: arXiv:1901.03584, arXiv:1812.01697
  - Rare decays: lepton flavour violation, and t→Hq: ATLAS-CONF-2018-044, arXiv:1812.11568
- Conclusions

- More details at ATLAS TopPublicResults

# Introduction – why is the top quark interesting?

- Fits into the 3-generations of quark doublets

- But it is very heavy – 40x bottom quark
  - Same mass scale as W, Z and Higgs bosons – connection to EW symmetry breaking?
  - Now we know m_H=125 GeV, top Yukawa coupling is almost exactly 1… coincidence?

  $$y_t = \sqrt{2}m_t/v \simeq 1$$

    - SM could be valid up to Plank scale, meta-stable?

- Top decays quickly, as a bare quark: t→Wb
  - Lifetime of ~10^{-25} s too short to form hadrons (10^{-24} s)

- Heaviest particle in SM, copiously produced
  - Cross-section 0.2-0.8 nb at LHC energies (7-13 TeV)
    - Laboratory for QCD studies at highest energies
  - Important background and/or decay mode for BSM searches involving new heavy states

- >100M top-pairs @ ATLAS at Run-2
  - Time for precision…
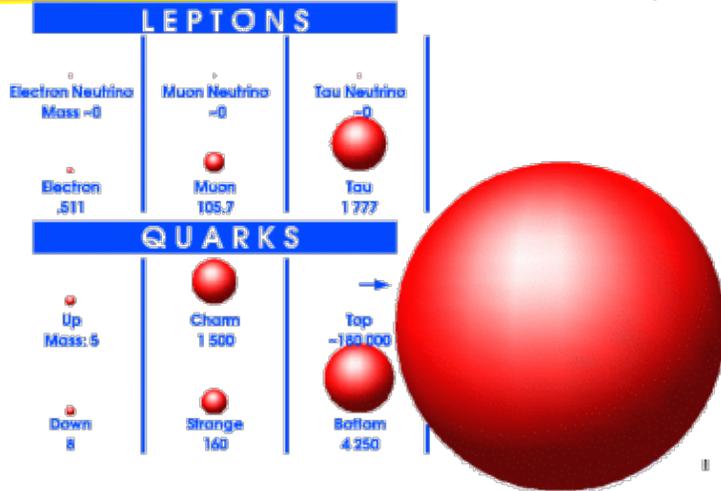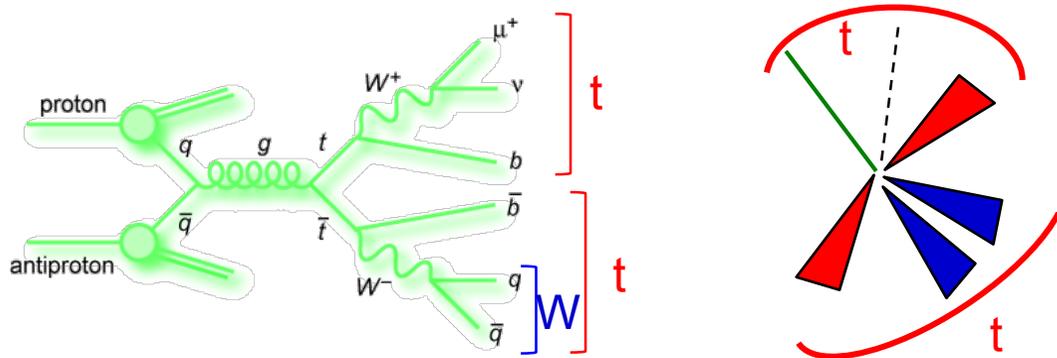
Degrassi, arXiv:1405.6852

8th June 2016

Richard Hawkings
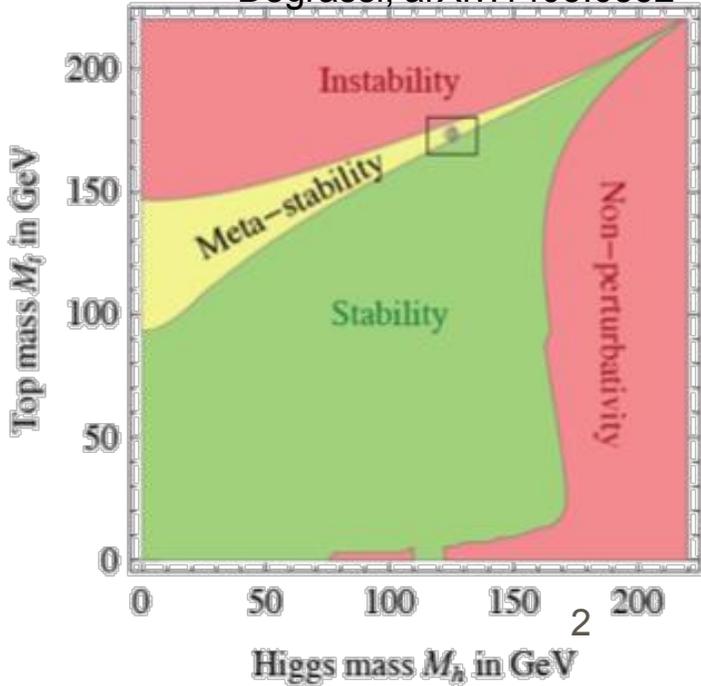
Top quark mass from l+jets events

- Measure m_t from inv. mass of decay products

- Kinematic fit to reconstruct m_t^{reco} event by event
  - Fit to 'templates' from simulation with different m_t
    - Assuming MC simulation adequately describes parton shower, hadronisation, jets…
- Precision limited by jet energy scale calibration
  - Known to ~2% at p_T~50 GeV (γ/Z+jet balance)
- Can improve with in-situ constraint on W→jj
  - m_W known to $2 \cdot 10^{-4}$ from LEP/Tevatron/ATLAS
  - Fit a 'jet-scale-factor' JSF along with m_t (2D fit)
  - 3D fit: add a b-JSF from $(p_T^{b1}+p_T^{b2}) / (p_T^{q1}+p_T^{q2})$
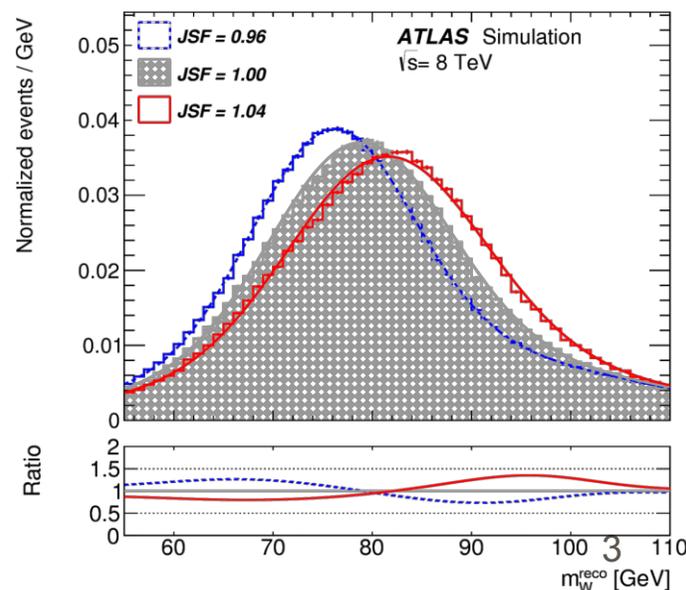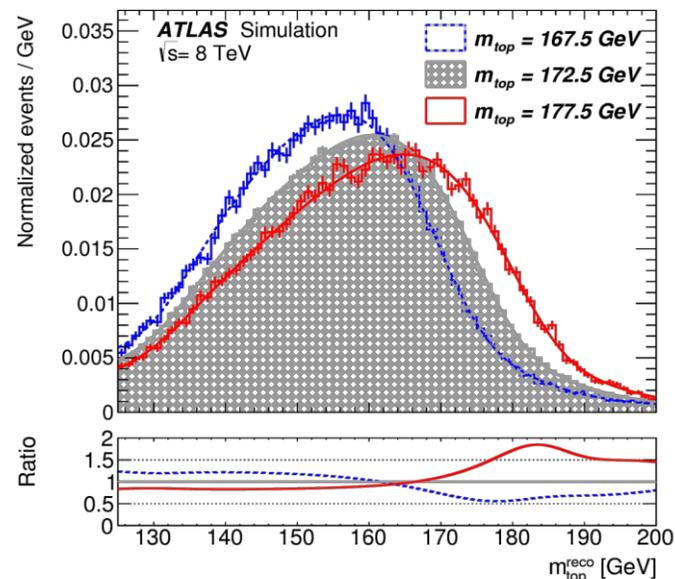
l+jet top mass result
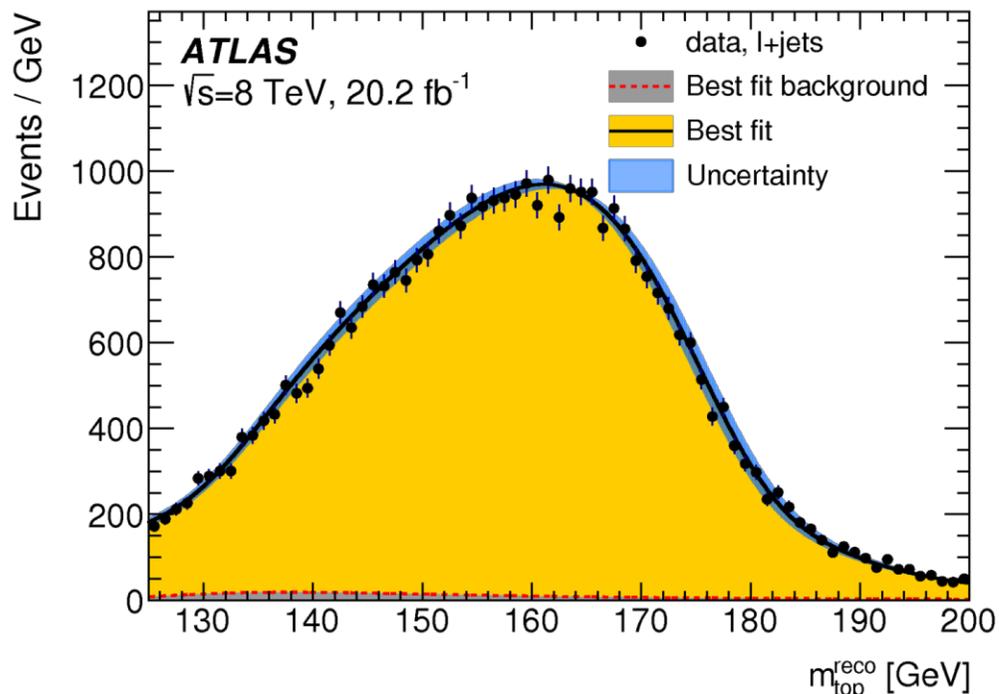
- ## Fit m_t, JSF, bJSF in 38k events at 8 TeV

- $m_t = 172.08 \pm 0.39(\text{stat}) \pm 0.82(\text{syst})$ GeV (0.53%)

- Largest uncertainties from

  - Jet energy scale and resolution

  - b-tagging efficiency (inc. jet p_T dependence)

  - Data statistics (due to floating b-JSF)

| Event selection	unc. (GeV)
m_{top} result [GeV]	172.08
Statistics	0.39
$\quad$ – *Stat. comp.* (m_{top})	0.11
$\quad$ – *Stat. comp.* (JSF)	0.11
$\quad$ – *Stat. comp.* (bJSF)	0.35
Method	0.13 ± 0.11
Signal Monte Carlo generator	0.16 ± 0.17
Hadronization	0.15 ± 0.10
Initial- and final-state QCD radiation	0.08 ± 0.11
Underlying event	0.08 ± 0.15
Colour reconnection	0.19 ± 0.15
Parton distribution function	0.09 ± 0.00
Background normalization	0.08 ± 0.00
W+jets shape	0.11 ± 0.00
Fake leptons shape	0
Jet energy scale	0.54 ± 0.02
Relative b-to-light-jet energy scale	0.03 ± 0.01
Jet energy resolution	0.20 ± 0.04
Jet reconstruction efficiency	0.02 ± 0.01
Jet vertex fraction	0.09 ± 0.01
b-tagging	0.38 ± 0.00
Leptons	0.16 ± 0.01
Missing transverse momentum	0.05 ± 0.01
Pile-up	0.15 ± 0.01
Total systematic uncertainty	0.82 ± 0.06
Total	0.91 ± 0.06

Combining top mass measurements

- **Combine with dilepton / all-jets at 8 TeV**
  - **And l+jets, dilepton, all-jets at 7 TeV**
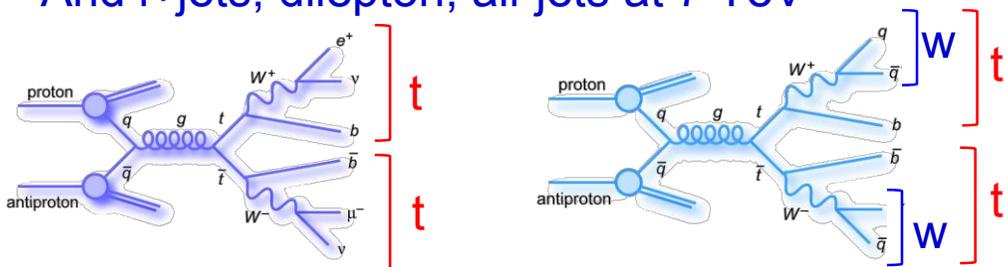
  - **Dilepton has no in-situ JES constraint**
    - **Effect of some jet energy scale uncertainties (blue) anticorrelated between l+jets and dilepton**
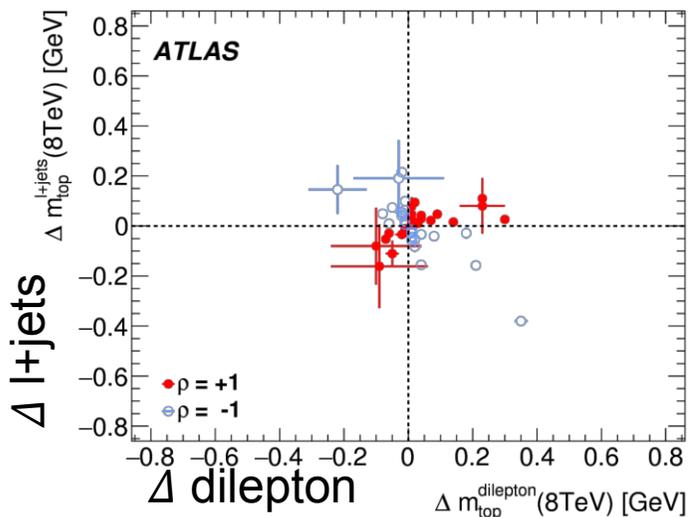
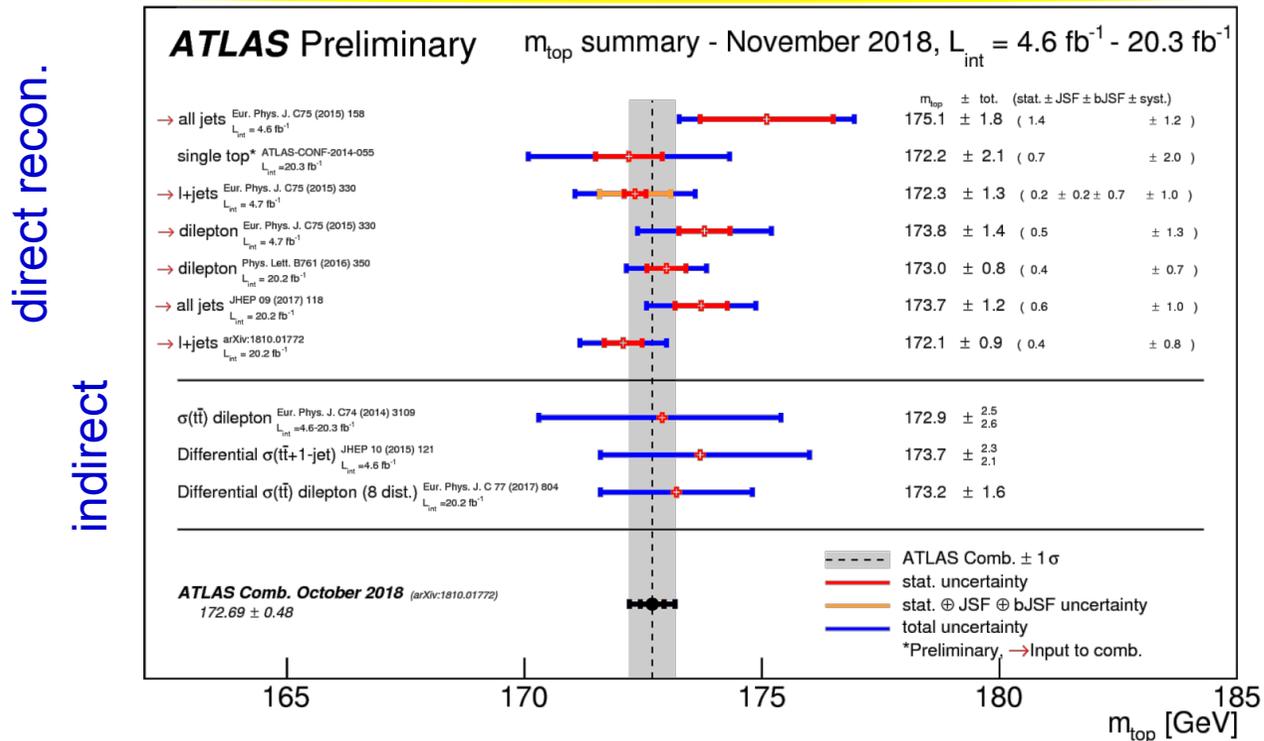Shifts for individual JES uncertainty components

  - **Analyses optimised to maximise combination gain**

Combination

	m_{top} [GeV]
Results	172.69
Statistics	0.25
Method	0.06
Signal Monte Carlo generator	0.12
Hadronization	0.00
Initial- and final-state QCD radiation	0.07
Underlying event	0.03
Colour reconnection	0.08
Parton distribution function	0.05
Background normalization	0.02
W/Z+jets shape	0.06
Fake leptons shape	0.03
Data-driven all-jets background	0.03
Jet energy scale	0.22
Relative b-to-light-jet energy scale	0.17
Jet energy resolution	0.09
Jet reconstruction efficiency	0.03
Jet vertex fraction	0.05
b-tagging	0.17
Leptons	0.08
Missing transverse momentum	0.04
Pile-up	0.06
Trigger	0.01
Fast vs. full simulation	0.01
Total systematic uncertainty	0.41 ± 0.03
Total	0.48 ± 0.03

Direct and indirect top mass measurements

ATLAS Preliminary — m_{top} summary - November 2018, L_{int} = 4.6 fb^{-1} - 20.3 fb^{-1}

direct recon.

indirect

	m_{top} ± tot.	(stat. ± JSF ± bJSF ± syst.)
→ all jets Eur. Phys. J. C75 (2015) 158, L_{int} =4.6 fb^{-1}	175.1 ± 1.8	(1.4 ± 1.2)
single top* ATLAS-CONF-2014-055, L_{int} =20.3 fb^{-1}	172.2 ± 2.1	(0.7 ± 2.0)
→ l+jets Eur. Phys. J. C75 (2015) 330, L_{int} =4.7 fb^{-1}	172.3 ± 1.3	(0.2 ± 0.2 ± 0.7 ± 1.0)
→ dilepton Eur. Phys. J. C75 (2015) 330, L_{int} =4.7 fb^{-1}	173.8 ± 1.4	(0.5 ± 1.3)
→ dilepton Phys. Lett. B761 (2016) 350, L_{int} = 20.2 fb^{-1}	173.0 ± 0.8	(0.4 ± 0.7)
→ all jets JHEP 09 (2017) 118, L_{int} =20.2 fb^{-1}	173.7 ± 1.2	(0.6 ± 1.0)
→ l+jets arXiv:1810.01772, L_{int} = 20.2 fb^{-1}	172.1 ± 0.9	(0.4 ± 0.8)
σ(t$\bar{t}$) dilepton Eur. Phys. J. C74 (2014) 3109, L_{int} =4.6-20.3 fb^{-1}	172.9 ± $^{2.5}_{2.6}$	
Differential σ(t$\bar{t}$+1-jet) JHEP 10 (2015) 121, L_{int} =4.6 fb^{-1}	173.7 ± $^{2.3}_{2.1}$	
Differential σ(t$\bar{t}$) dilepton (8 dist.) Eur. Phys. J. C 77 (2017) 804, L_{int} =20.2 fb^{-1}	173.2 ± 1.6	

ATLAS Comb. October 2018 (arXiv:1810.01772)
172.69 ± 0.48

- - - ATLAS Comb. ± 1σ
— stat. uncertainty
— stat. ⊕ JSF ⊕ bJSF uncertainty
— total uncertainty
*Preliminary, →Input to comb.

165   170   175   180   185 m_{top} [GeV]

- **Final run-1 combination 172.69 ± 0.48 GeV (±0.28%)**
  - Also various 'indirect' measurements with tighter relation to theory (not 'MC mass')
  - From total top-pair cross-section, top-pair + jet and lepton differential distributions
    - Typically fitted to dedicated theory predictions at NLO or NNLO (+) in QCD
    - Compatible results, but insufficient precision (1.5-2.5 GeV) to look for O(1 GeV) shifts
  - Active theoretical development, and 13 TeV analyses to come

Spin correlation measurement

- Top quark lifetime 3 10^{-25} sec – decays as a bare quark, does not hadronise
  - Top spin information transferred to decay products, not 'corrupted' by QCD
  - Expect negligible polarisation in SM, but correlation between top/anti-top spins
    - Charged leptons from W decays carry almost the full available information
- 'Classical' spin observable: azimuthal $\Delta\phi$(ll) in dileptonic top-pair events
  - Already used at Run-1 to establish spin correlations at ~ level predicted by SM
  - With Run-2 data sample, can start to look differentially in bins of m(tt) system
    - Implies reconstruction of the top-pair kinematics (neutrino weighting technique)
  - Significant change in $\Delta\phi$ shape from low to high m(tt) – generally well modelled
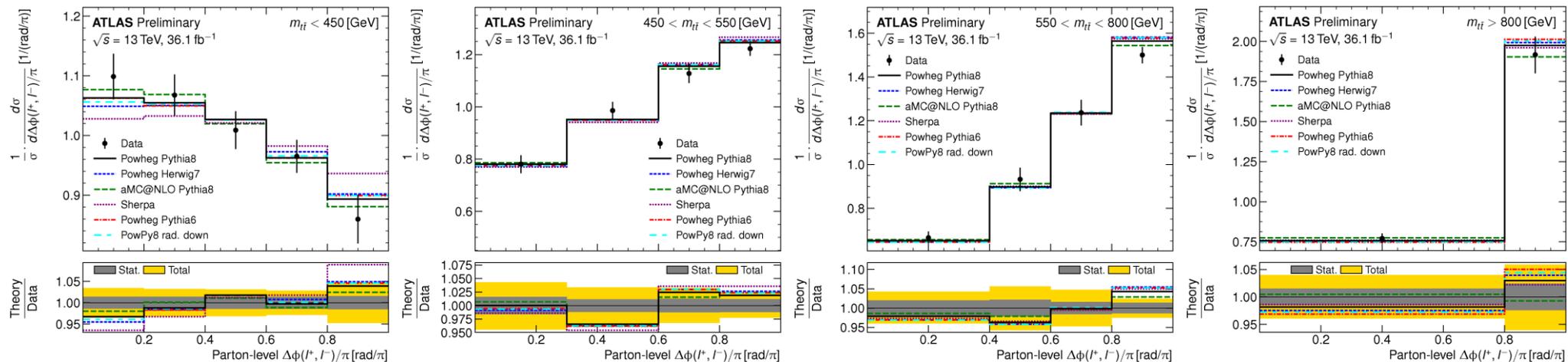
Quantifying the spin correlation

- Fit the inclusive $\Delta\phi$ distribution to templates
  - MC with SM-like spin correlation ON/ OFF
    - Steeper distribution with OFF (C=0)

$$n_i = f_{SM} \cdot n_{spin} + (1 - f_{SM}) \cdot n_{nospin}$$

  - f_{SM}=1 for 'SM-like' spin correlation, 0 for none
- Obtain f_{SM}=1.250 $\pm$0.026 (stat) $\pm$0.063 (syst)
  - f_{SM} is 3.2 std. dev. above 1, when including QCD scale and PDF uncertainties on templates
    - f_{SM} also above 1 in m(tt) bins, lower significance

Parton level $\Delta\phi(l^+, \bar{l}^-)/\pi$ [rad/π]
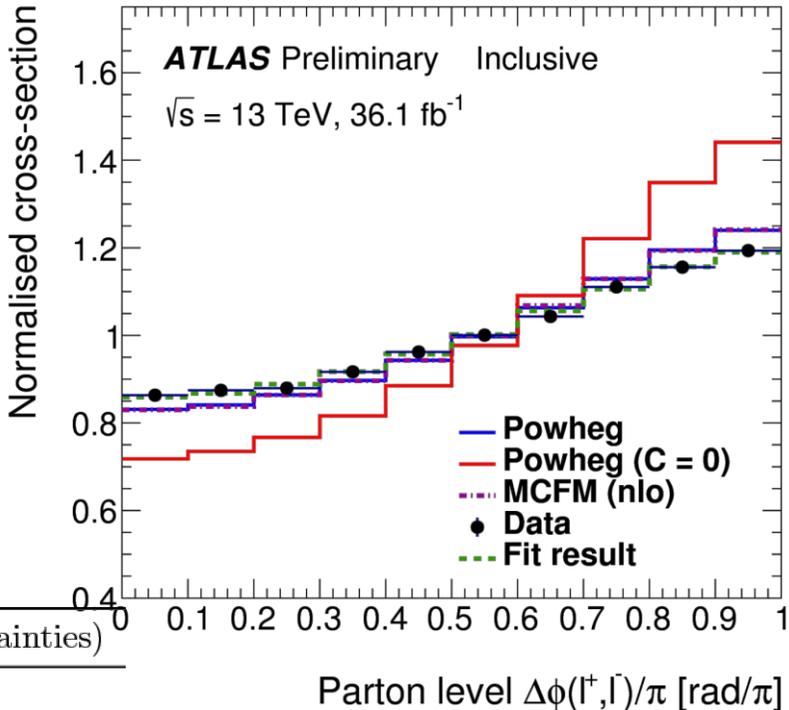
Region	f_{SM}	Significance (incl. theory uncertainties)
$m_{t\bar{t}} < 450$ GeV	$1.11 \pm 0.04 \pm 0.13$	0.85 (0.84)
$450 < m_{t\bar{t}} < 550$ GeV	$1.17 \pm 0.09 \pm 0.14$	1.00 (0.91)
$550 < m_{t\bar{t}} < 800$ GeV	$1.60 \pm 0.24 \pm 0.35$	1.43 (1.37)
$m_{t\bar{t}} > 800$ GeV	$2.2 \pm 1.8 \pm 2.3$	0.41 (0.40)
inclusive	$1.250 \pm 0.026 \pm 0.063$	3.70 (3.20)

- 'Too much' spin correlation wrt. prediction?
  - Robust against variation of generator for templates, or inclusion of NLO top decays
  - Recent work arXiv:1901.05407 (Behring et al) suggests NNLO corrections are important

Top-pair + vector boson production

- Production of top pair + W or Z provides direct probe of top-weak couplings

tZ coupling
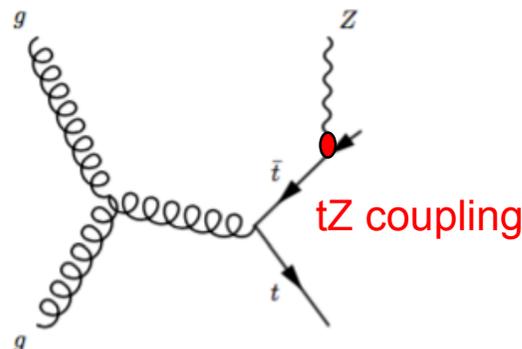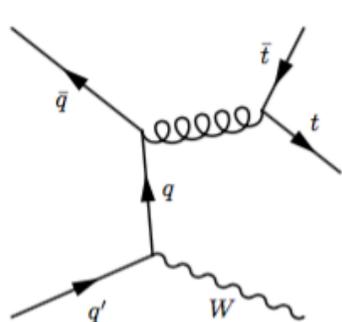
Process	$t\bar{t}$ decay	Boson decay	Channel
$t\bar{t}W$	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{\pm}\nu$	SS dilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{\pm}\nu$	Trilepton
$t\bar{t}Z$	$(q\bar{q}b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	OS dilepton
	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	Trilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{+}\ell^{-}$	Tetralepton

- Small (~1pb) cross-sections at 13 TeV (830 pb for tt), and BR(W→lv), Z→ll
- Final states with 2-4 leptons, jets and b-tagged jets
  - Many different combinations of SS, OS leptons, on and off Z-peak
    - Making use of dilepton, single-lepton and all-hadronic top-pair decays
    - SS dilepton particularly important for ttW, trilepton (with Z→ll) for ttZ
  - Backgrounds from top-pair, dibosons (WW/WZ/ZZ), fake/charge-flip leptons
    - Typically estimated using control regions from data where possible
- Extract signal strengths in simultaneous fit to many different samples
  - BDT discriminator used in high-statistics OS dilepton region

Top-pair + W/Z results

	Result (pb)	Prediction (pb)
σ(ttZ)	0.95 $\pm$0.08 $\pm$0.10	0.88 +0.09 -0.11
σ(ttW)	0.87 $\pm$0.13 $\pm$0.14	0.60 +0.08 -0.07

Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	2.9%	4.5%
Simulated sample statistics	2.0%	5.3%
Data-driven background statistics	2.5%	6.3%
JES/JER	1.9%	4.1%
Flavor tagging	4.2%	3.7%
Other object-related	3.7%	2.5%
Data-driven background normalization	3.2%	3.9%
Modeling of backgrounds from simulation	5.3%	2.6%
Background cross sections	2.3%	4.9%
Fake leptons and charge misID	1.8%	5.7%
$t\bar{t}Z$ modeling	4.9%	0.7%
$t\bar{t}W$ modeling	0.3%	8.5%
Total systematic	10%	16%
Statistical	8.4%	15%
Total	13%	22%

- ttZ ≫5σ observation, ttW 4.3σ (exp. 3.4σ)
  - Agreement with NLO QCD+EW predictions

- Similar statistical / systematic uncertainties
  - Systematics dominated by signal / background modelling, and statistics in control regions
- ttZ result used to constrain EFT operators

Top-pair + photon production

- ttγ production probes top EM coupling (top charge)
  - Photon can also be emitted from initial-state quark in qq→tt or from decay products (W, b, lepton)
    - Cannot separate, but isolation cuts reduce FSR contrib[n]
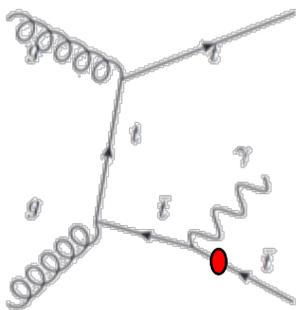
tγ coupling   ISR (qq→tt only)   FSR
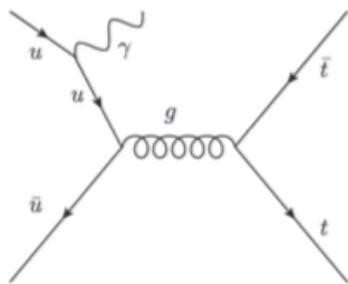
photon p_T
(single-lepton channel)
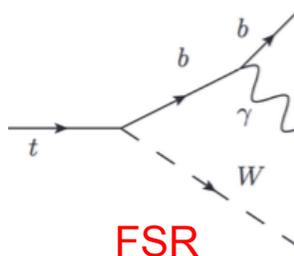
- Analysis in tt single-lepton and dilepton channels
  - Standard selection, plus isolated photon p_T>20 GeV
    - Dilepton channel cleaner, but single lepton can reach higher photon p_T due to higher statistics
  - Main backgrounds from hadronic jets or electrons mis-identified as photon, or real γ+W/Z events
  - Photon ID and event-level MVAs to suppress b/g
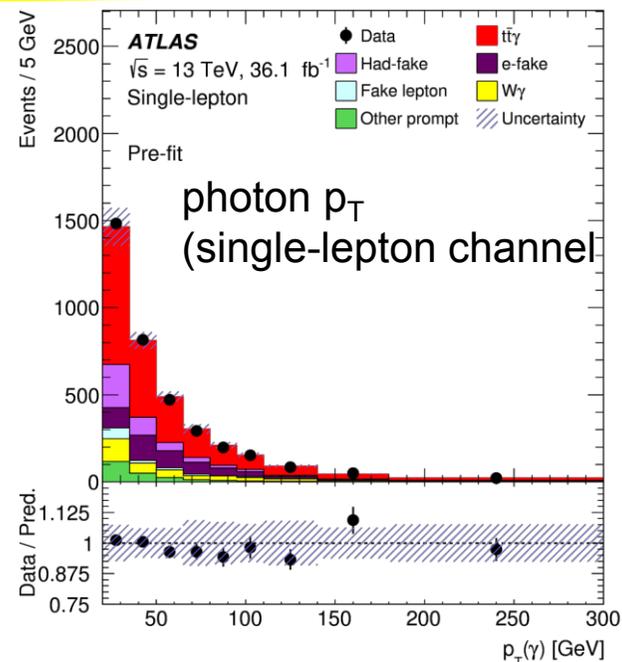
Channel	Single lepton	Dilepton
$t\bar{t}\gamma$	$6\,490 \pm 420$	720 ± 34
Hadronic-fake	$1\,440 \pm 290$	49 ± 27
Electron-fake	$1\,650 \pm 170$	2 ± 1
Fake lepton	360 ± 200	-
$W\gamma$	$1\,130$	
$Z\gamma$		75 ± 52
Other prompt	690 ± 260	18 ± 7
Total	$11\,750 \pm 710$	863 ± 78
Data	$11\,662$	902

Top-pair + photon results

- Inclusive cross-section in fiducial region agrees with NLO predictions for ttγ

  - Normalised photon p$_T$ spectrum agrees with LO ttγ ME calculations

    - Powheg+Pythia8 inclusive tt sample (photons from parton shower) is too soft

 - Dilepton $\Delta\phi$ is slightly less steep than prediction – modelling of spin-correlations?
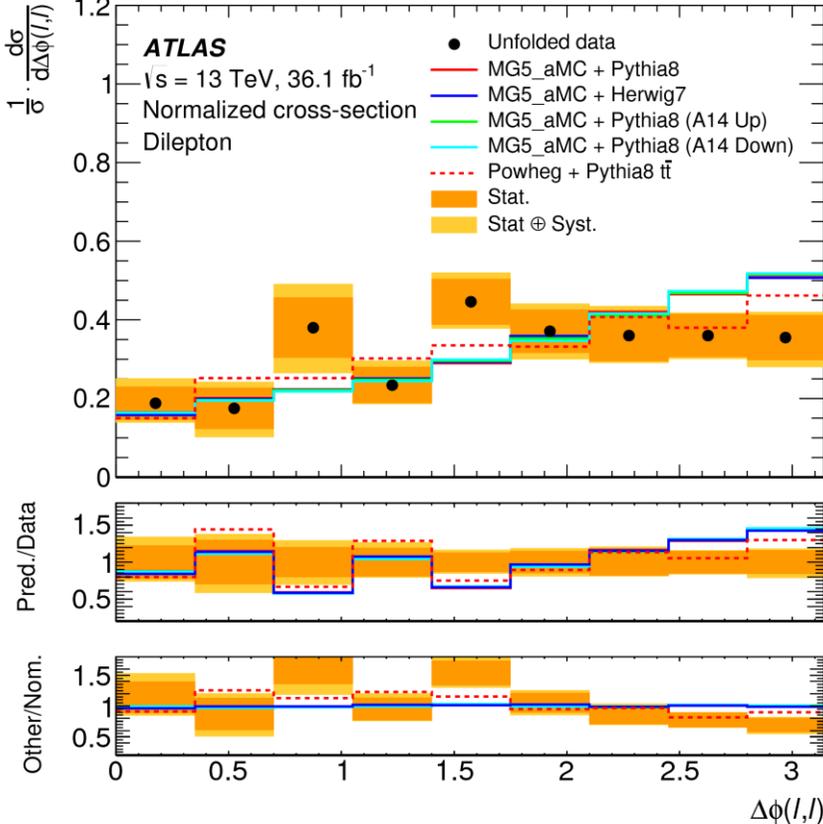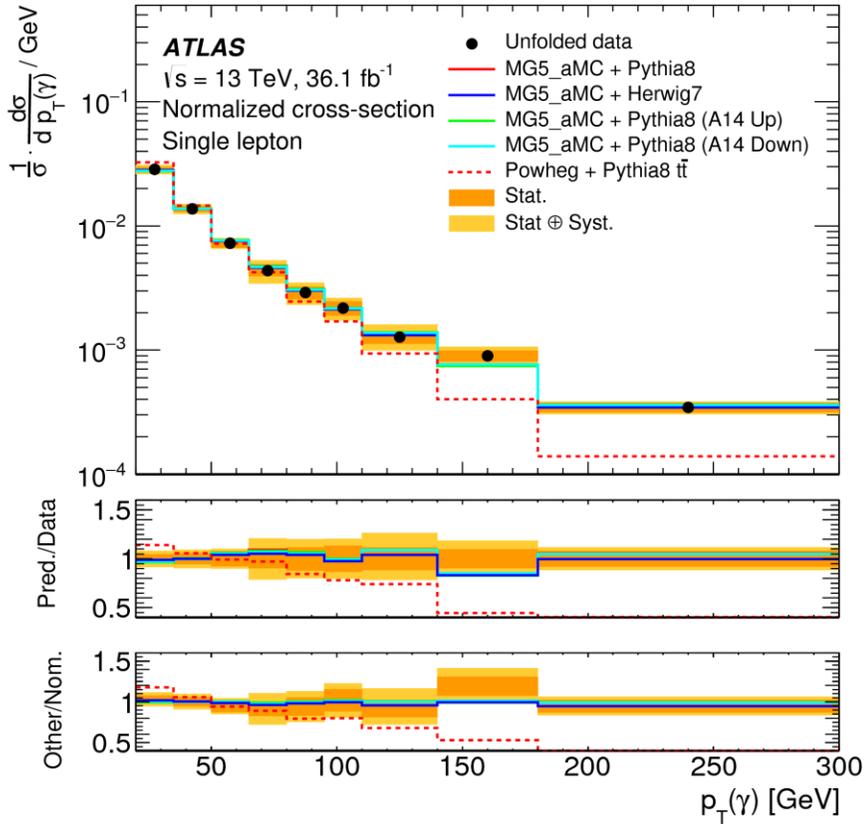
Search for lepton-flavour-violation decay t→eμq

- Charged lepton flavour violation t→l⁺l'⁻ q (l'≠l)
    - Clear BSM signal: LQ unification, SUSY, technicolour
    - Indirect limit of BR(t→eμq) <3.7 10^{-3}
- Search using 2015-2017 ATLAS data (80 fb^{-1})
    - Top-pair events, with one cLFV decay, one t→Wb→lνb
    - Select tri-lepton events with 1b+1 light jet
        - 2 real+1 fake lepton background from data (same-flavour)
   - Final BDT discriminant using kinematic variables

1st disc. var: m_{ll}(OSSF)

2nd disc. var: m_t(cLFV)
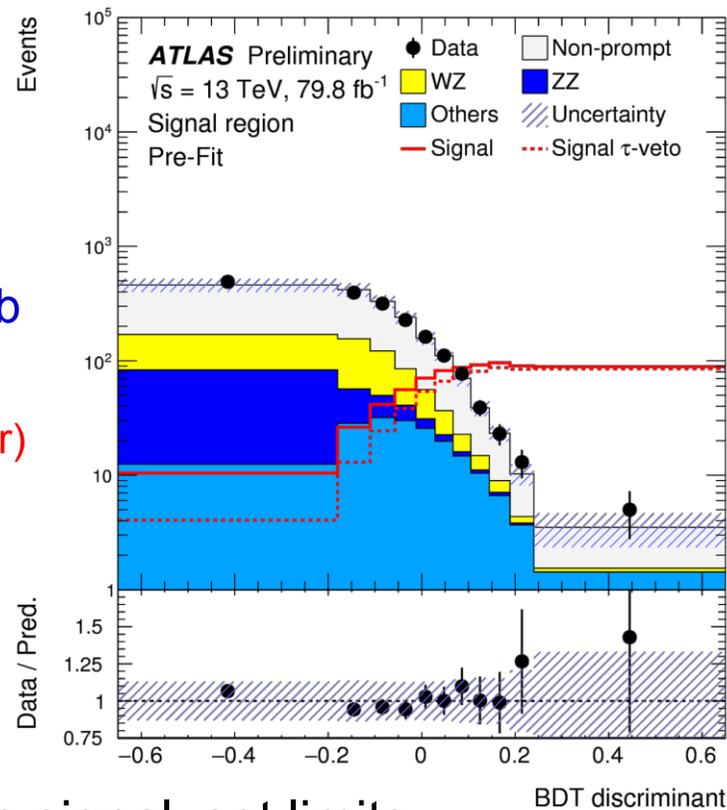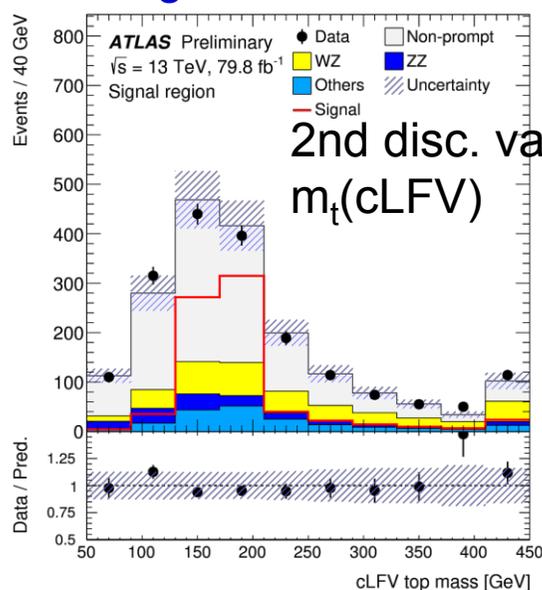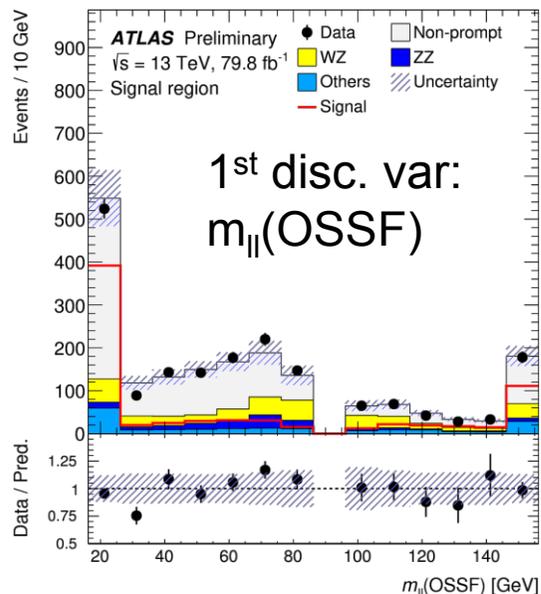
- No signal, set limits …

	BR(t→eμq)
Including τ in cLFV vertex	1.86 10^{-5}
Excluding τ in cLFV vertex	6.6 10^{-6}

Top FCNC decays to Hc, Hu

- **FCNC decays t→Hc / t→Hu @ $10^{-15}/10^{-17}$ in SM**
  - Could be 10^{-5} in type 1/2 2HDM or SUSY models
    - ~10^{-3} in type-3 2HDM without flavour conservation
- **Search in top-pair: t→bW + t→Hc/Hu**
  - Previous analyses with H→$\gamma\gamma$ and H→multileptons
    - Good S/B (in particular $\gamma\gamma$), low statistics
- **Now complemented with new analyses (36 fb^{-1})**
  - H→bb with other t→lνb
    - Final state with lepton + 4 jets, 3b
    - Likelihood discriminant in various jet/b multiplicities
  - H→$\tau\tau$ with ≥1 hadronic τ, t→qqb
    - Final state with 2 τ-candidates, 4 jets, 1b
    - Kinematic reconstruction and BDT discriminant
- **No signal, limits from comb^n of all H decay modes**
  - Limits 1.1 10^{-3} for Br(t→Hc) / 1.2 10^{-3} for Br(t→Hu)
  - Also set limits in 2D plane, and on tqH couplings
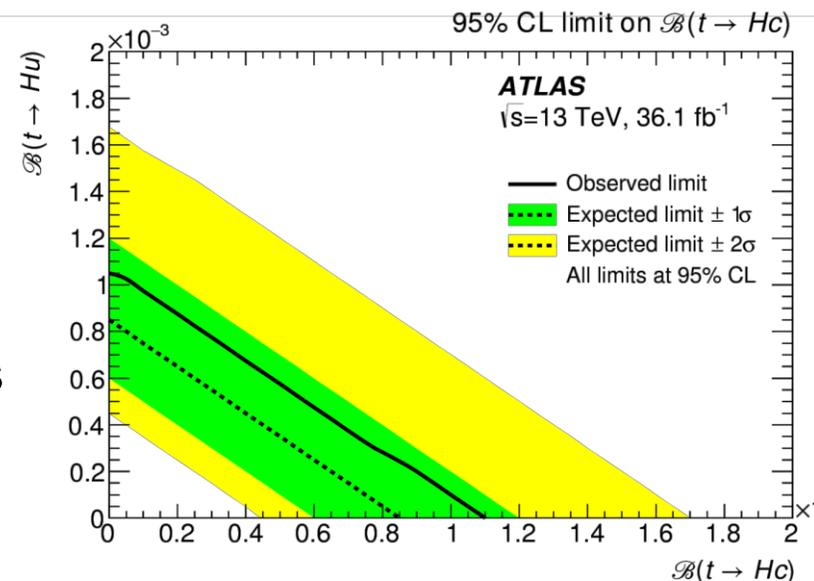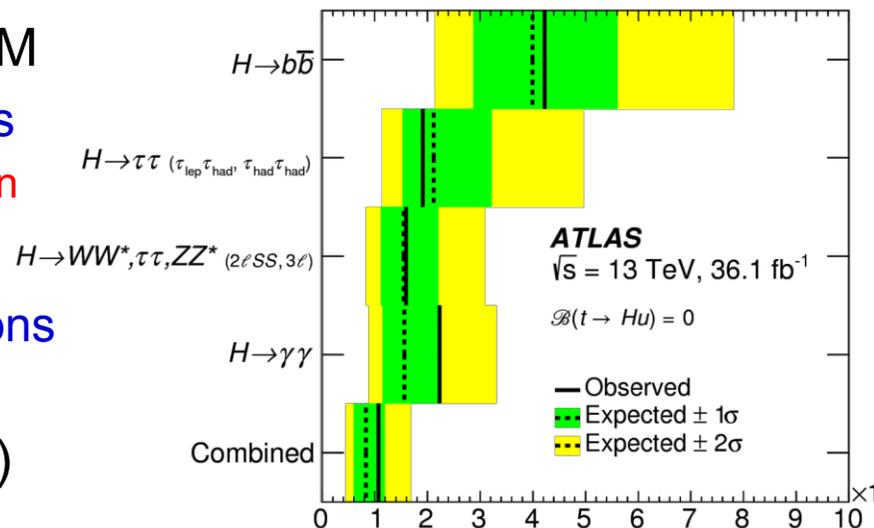
Conclusions

- Top quark property measurements entering the precision era …
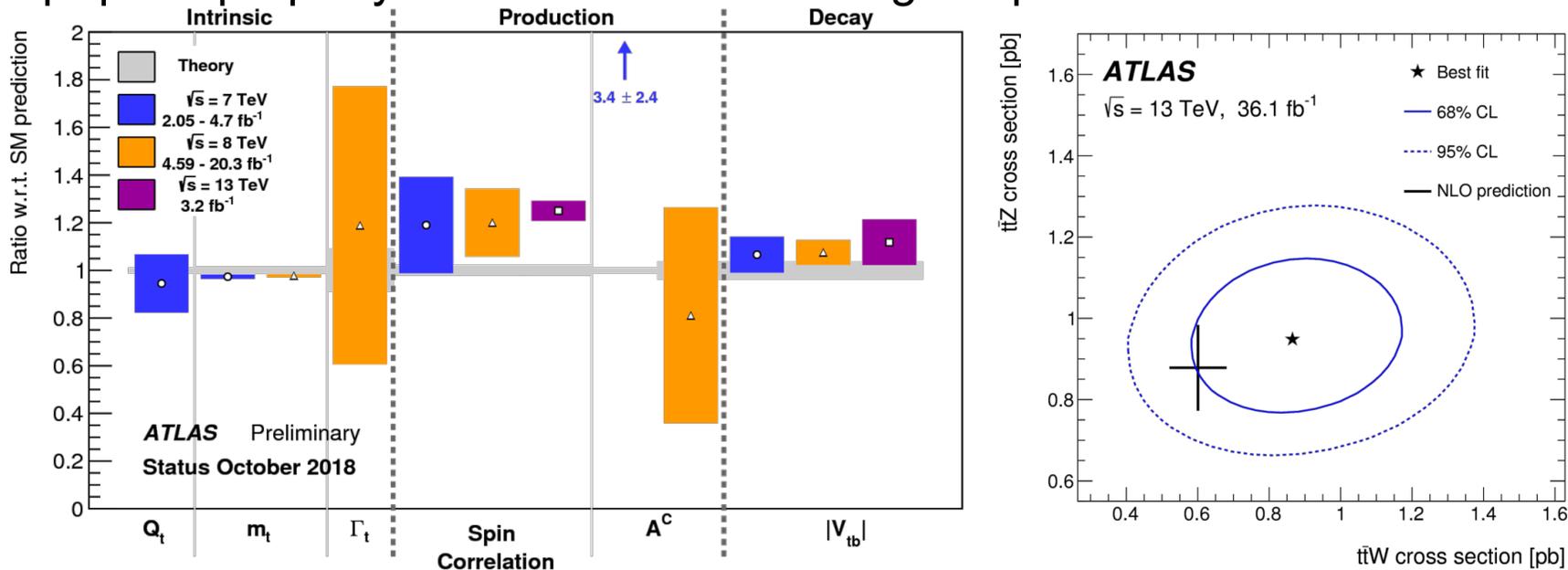
- Top mass now known to 0.3% (0.5 GeV)
  - More data to come, but 'straining' the theory – what are we actually measuring?
- Precise spin correlations measurements – a hint of a discrepancy?
- Top-pair + W, Z, γ (and H) well established – probing the top couplings
  - Move to differential measurements with full Run-2 and Run-3 datasets
- Rare decay limits at 10^{-3} to 10^{-5} level, but no sign of BSM physics so far
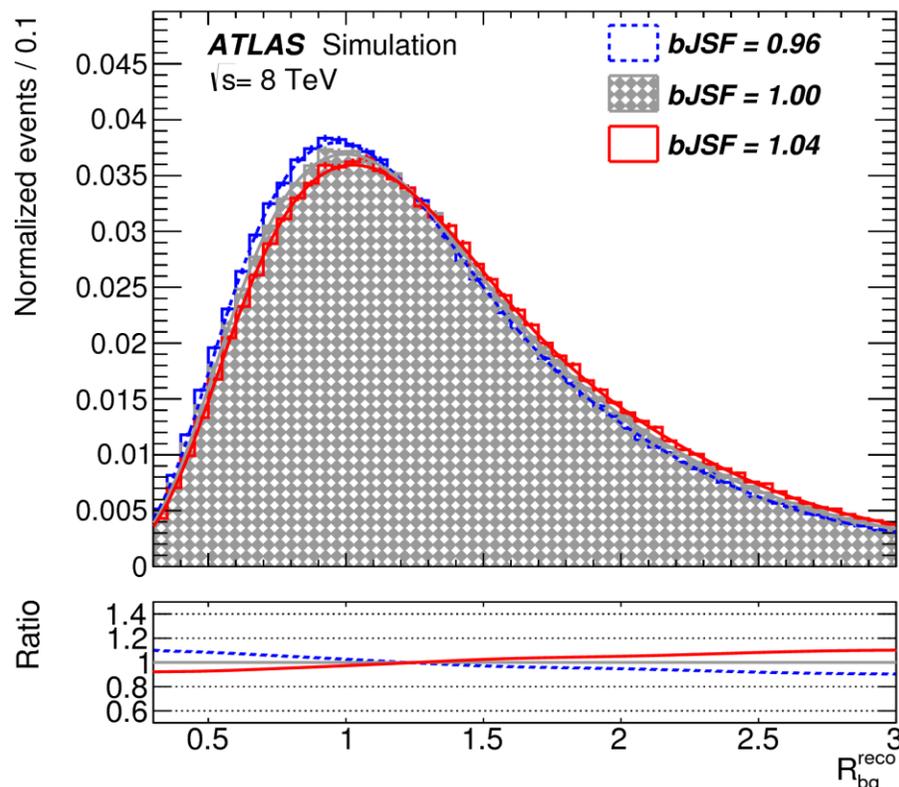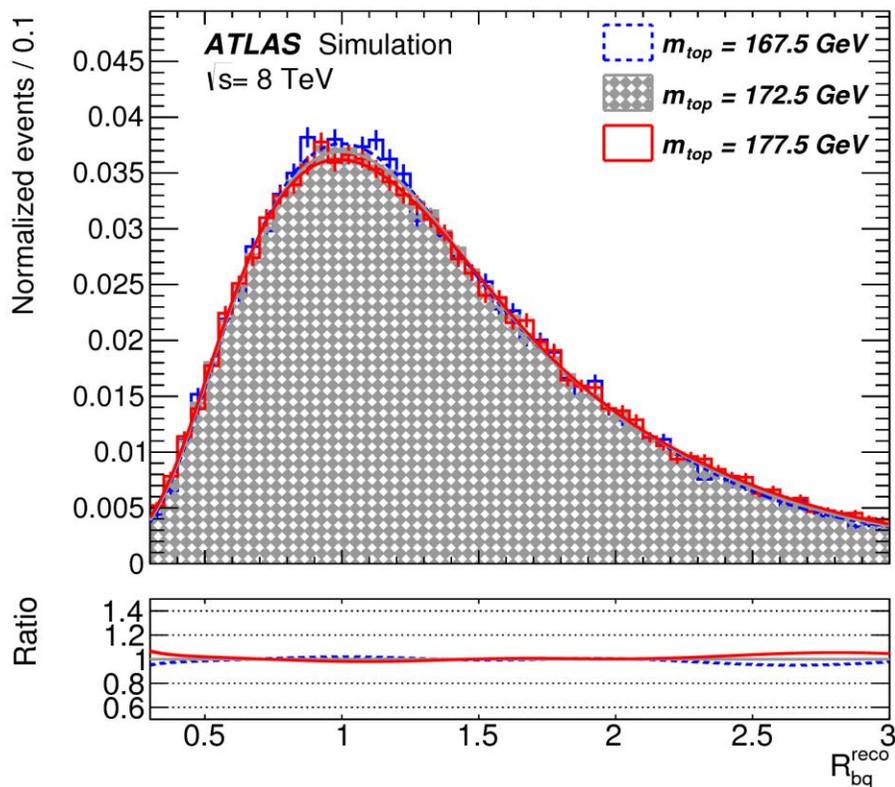
Backup

- Backup slides

Top mass l+jets: 3D fit

- Simultaneous fit to m_t^{reco}, JSF and bJSF

  - bJSF measured via variable R_{reco}^{bq}

  - Sensitive to relative b-to-light jet energy scale, but not to m_t or inclusive JSF

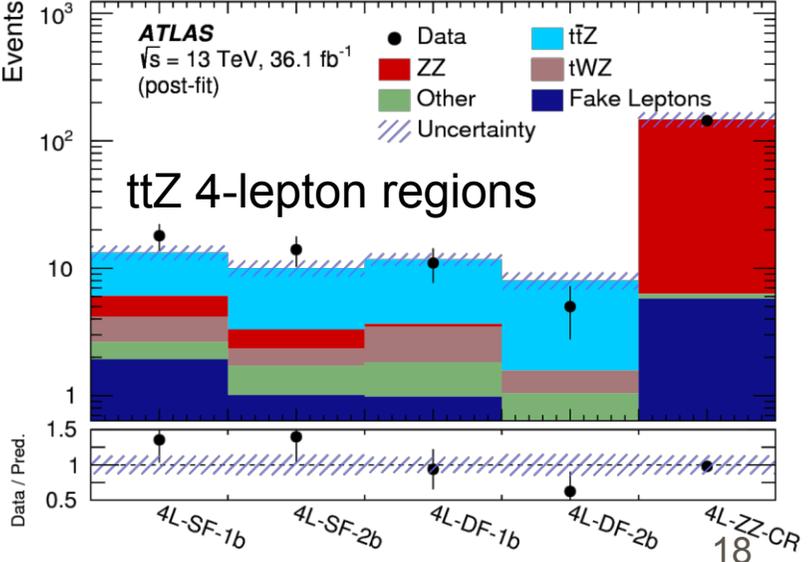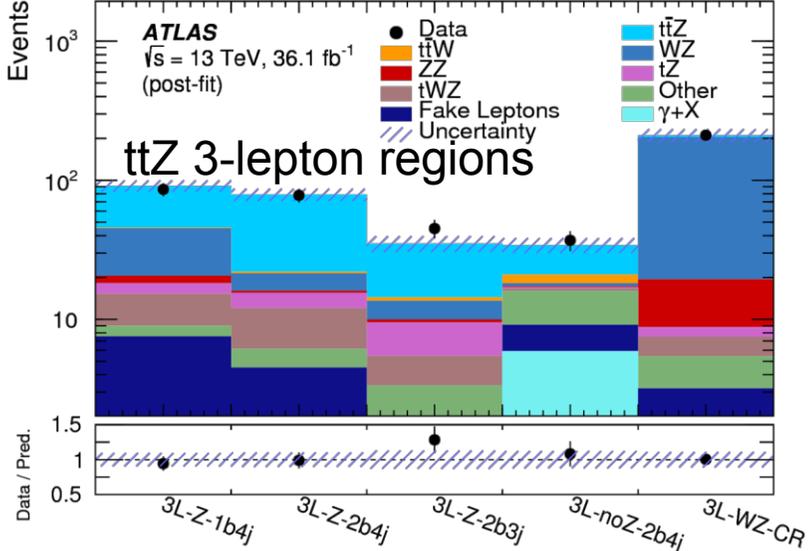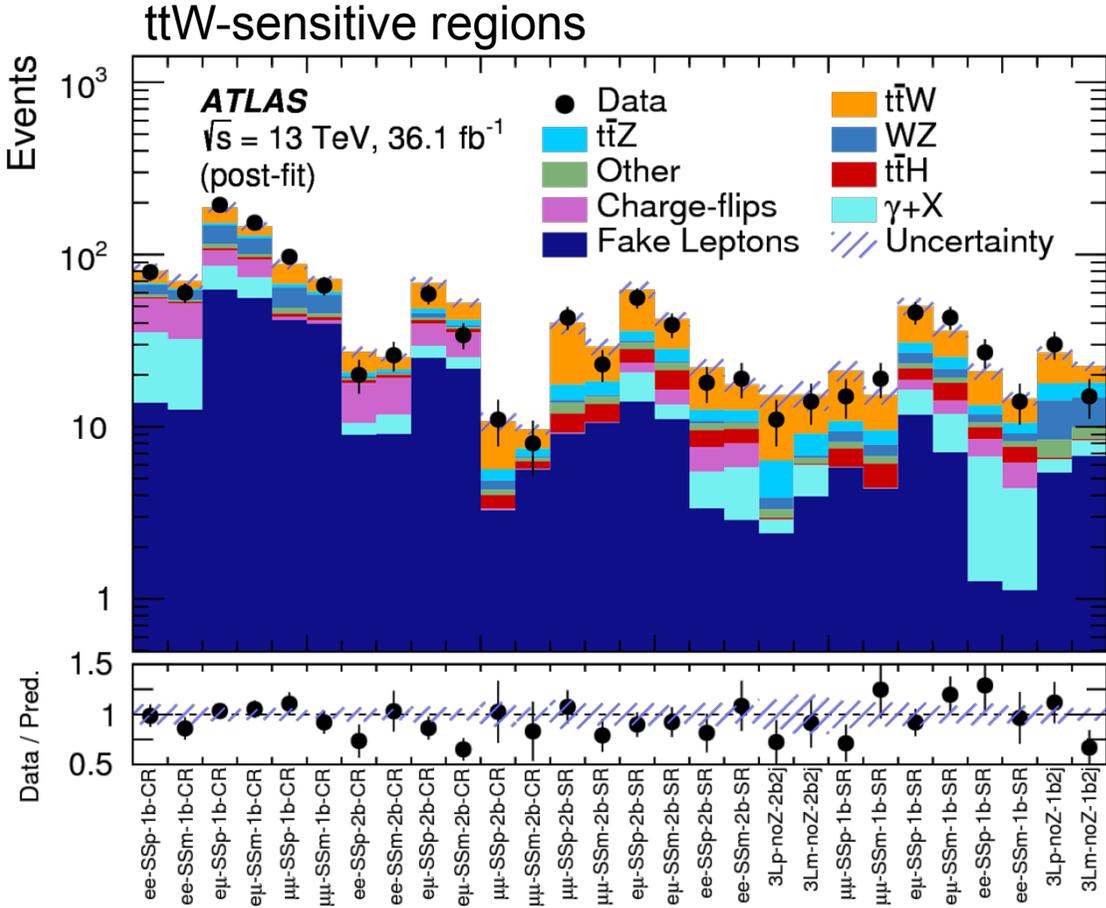$$R_{bq}^{reco} = \frac{p_T^{b_{had}} + p_T^{b_{lep}}}{p_T^{q_1} + p_T^{q_2}}$$

- **Results from simultaneous fit**
  - Event yields compared to fitted contributions

# EFT limits from top-pair +Z cross-section

- **ttZ vertex modified by various EFT operators**
  - Each associated with a Wilson coefficient C_i

$$\sigma_{\text{tot},i} = \sigma_{\text{SM}} + \frac{C_i}{(\Lambda/1\text{TeV})^2}\sigma_i^{(1)} + \frac{C_i^2}{(\Lambda/1\text{TeV})^4}\sigma_{ii}^{(2)}$$

  - Λ is the energy scale of the new physics
  - Constrain C/Λ^2 values using fit to 3 and 4 lepton regions
  - Some secondary minima excluded by indirect constraints
- **Results c.f. previous direct/indirect limits (in $1/\text{TeV}^2$)**

ATLAS $\sqrt{s} = 13$ TeV 36.1 fb^{-1}
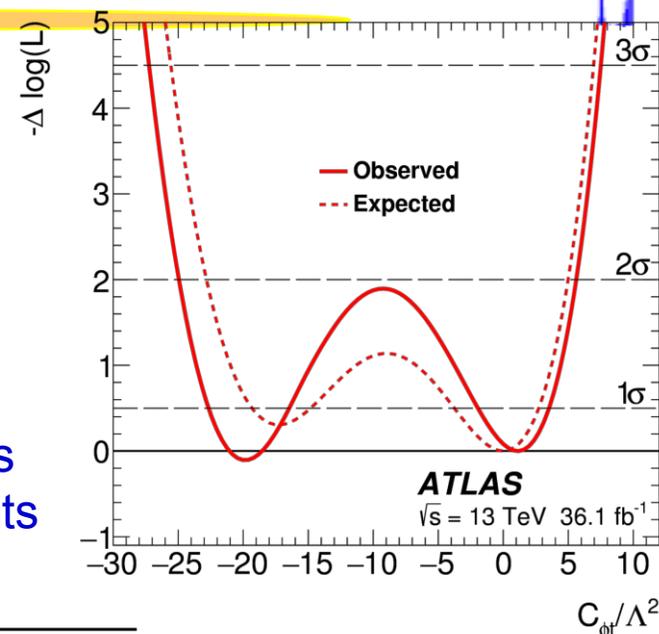
$-\Delta L$ curve for $O_{\phi t}$

Coefficients	$\mathcal{C}_{\phi Q}^{(3)}/\Lambda^2$	$\mathcal{C}_{\phi t}/\Lambda^2$	$\mathcal{C}_{tB}/\Lambda^2$	$\mathcal{C}_{tW}/\Lambda^2$
Previous indirect constraints at 68% CL	[−4.7, 0.7]	[−0.1, 3.7]	[−0.5, 10]	[−1.6, 0.8]
Previous direct constraints at 95% CL	[−1.3, 1.3]	[−9.7, 8.3]	[−0.2, 0.7]	[−4.0, 3.5]
Expected limit at 68% CL	[−2.1, 1.9]	[−3.8, 2.7]	[−2.9, 3.0]	[−1.8, 1.9]
Expected limit at 95% CL	[−4.5, 3.6]	[−23, 4.9]	[−4.2, 4.3]	[−2.6, 2.6]
Observed limit at 68% CL	[−1.0, 2.7]	[−2.0, 3.5]	[−3.7, 3.5]	[−2.2, 2.1]
Observed limit at 95% CL	[−3.3, 4.2]	[−25, 5.5]	[−5.0, 5.0]	[−2.9, 2.9]
Expected limit at 68% CL (linear)	[−1.9, 2.0]	[−3.0, 3.2]	−	−
Expected limit at 95% CL (linear)	[−3.7, 4.0]	[−5.8, 6.3]	−	−
Observed limit at 68% CL (linear)	[−1.0, 2.9]	[−1.8, 4.4]	−	−
Observed limit at 95% CL (linear)	[−2.9, 4.9]	[−4.8, 7.5]	−	−