Top quark properties and mass measurements with the ATLAS detector

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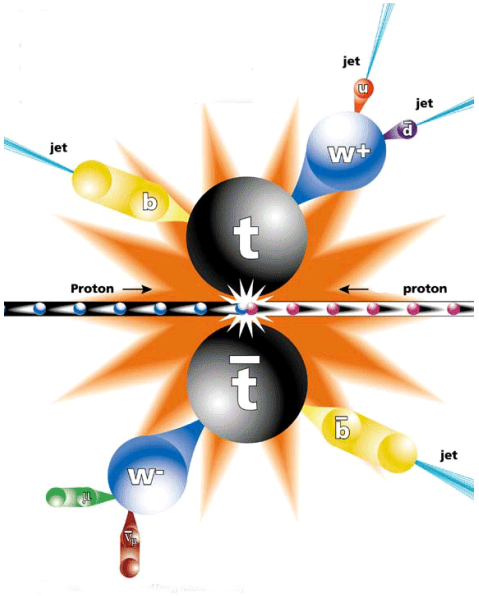
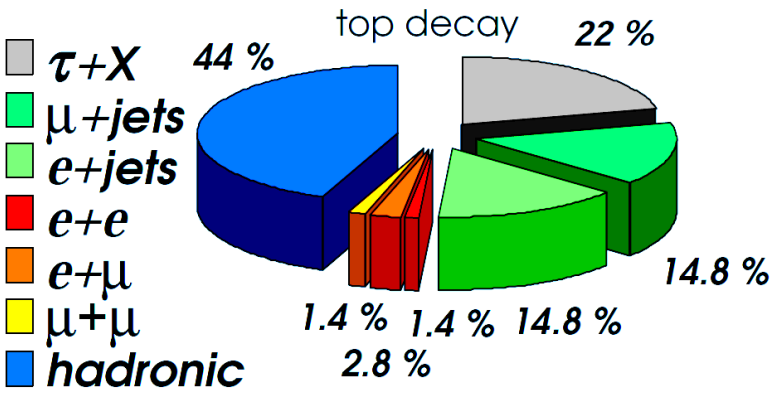
Top quark

Top quark

- Discovered in 1995 at the Tevatron
- Produced abundantly at LHC $\rightarrow$ precision measurements by ATLAS and CMS
- Heaviest known elementary particle ($m_t \approx 173$ GeV)
- Extremely short mean lifetime ($\approx 10^{-25}$ s)



Top quark decays

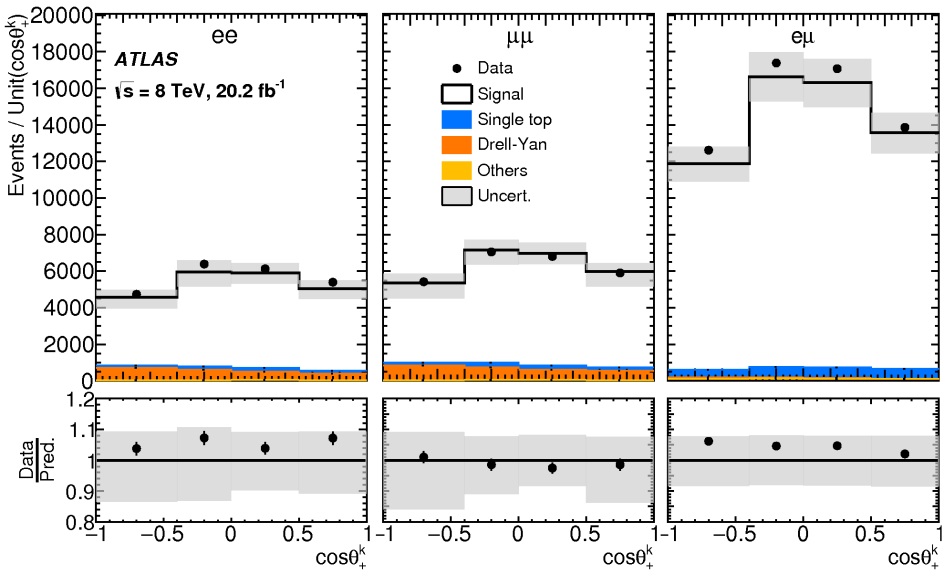


- Top quark decays before hadronization
- Access directly properties of a **bare quark**
- $t \rightarrow W + b$ almost 100%
- Study Wtb vertex in detail

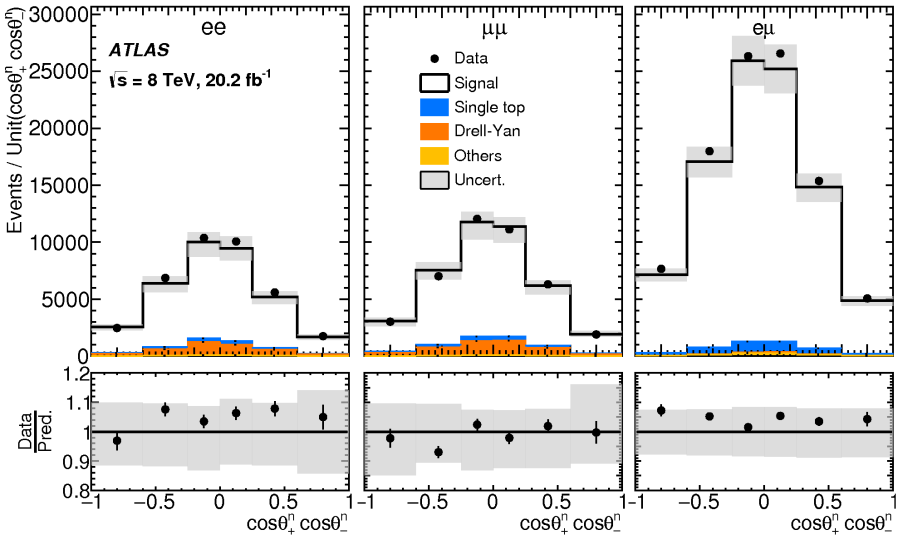
Measurement of top quark spin observables

JHEP 03 (2017) 113

- Top produced unpolarized but **spins are correlated**
- Top decays before any spin-flip can take place
- Angular distributions of decay products store all information
- Different particles have different analyzing power



$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta^a_+\, d\cos\theta^b} = \frac{1}{4}\left(1 + B^a_+\cos(\theta^a_+)B^b_-\cos\theta^b_- - C(a,b,)\cos(\theta^a_+)\cos\theta^b_-\right)$$



- $\sqrt{s} = 8$ TeV dataset: $20.2\,\mathrm{fb}^{-1}$, $t\bar{t}$ dilepton events: 2 leptons, Z-mass veto, $\geq$2 jets, $\geq$ 1b-jet
- Event reconstruction using **neutrino reweighting**

Measurement of top quark spin observables

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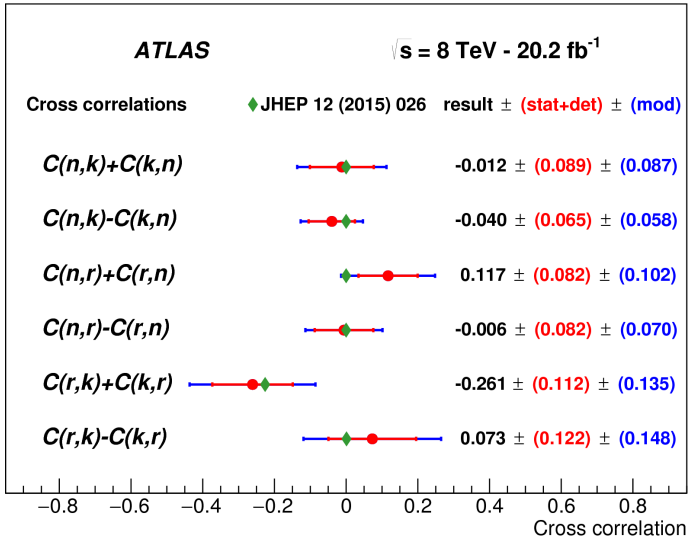
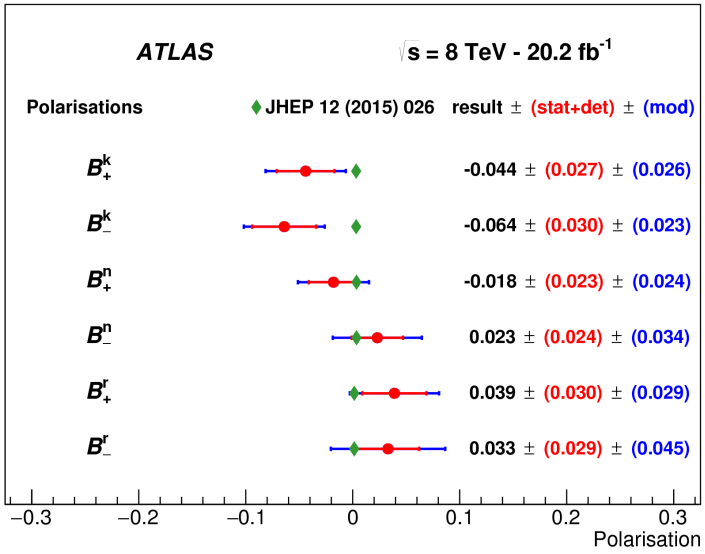
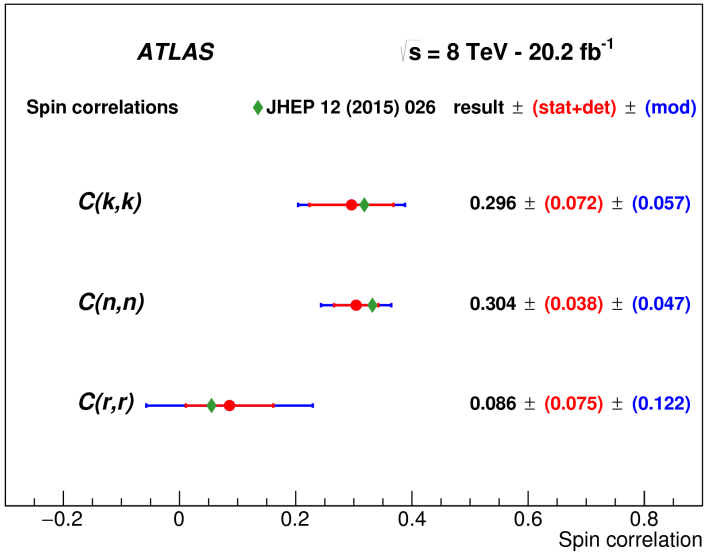
- Correlation depends on the **quantisation axis**
- Three quantization axes: helicity, transverse and *r*-axis
- **Six** observables for (anti-)top **spin polarization** + **nine** for **spin correlation**







Measurement of top quark spin observables - parton level

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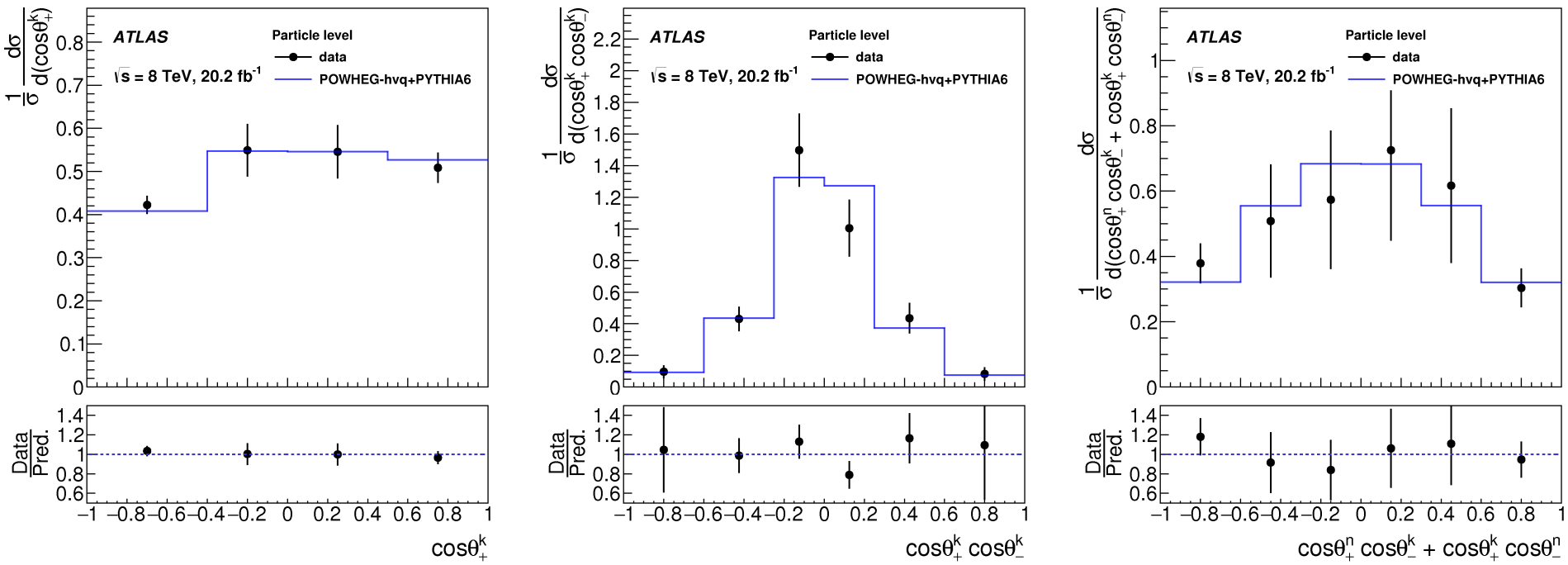
Unfolding to stable particle level



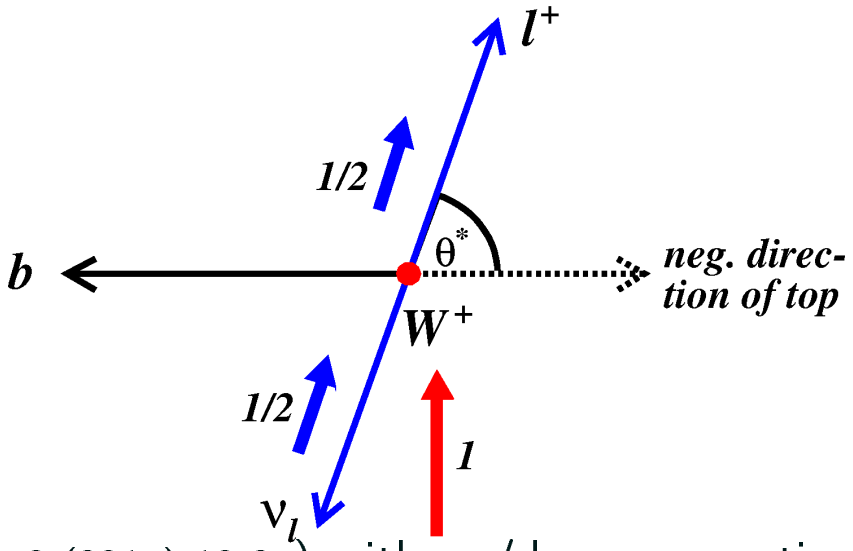
- 15 observables measured, 10 for the first time!
- $C(n,n)$ differs by $5.1\,\sigma$ from zero correlation

- Systematic uncert. dominated by signal modelling
- **All measurements are in agreement with the SM**

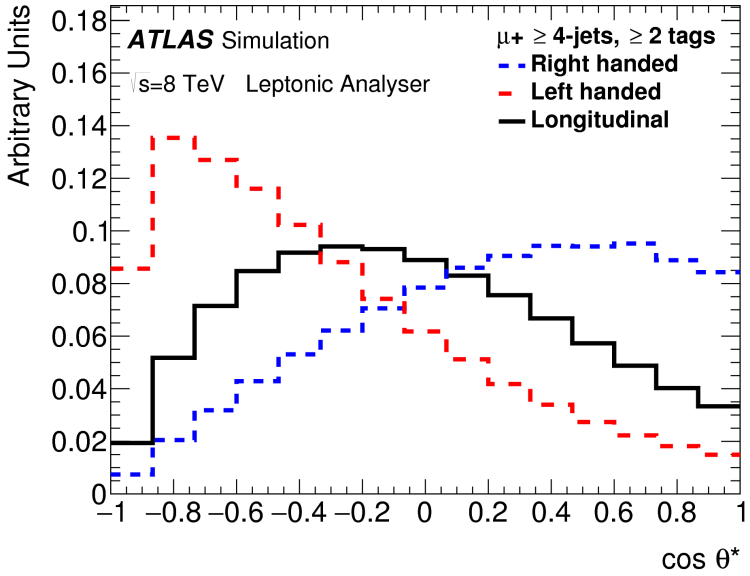
W helicity measurement in top quark events

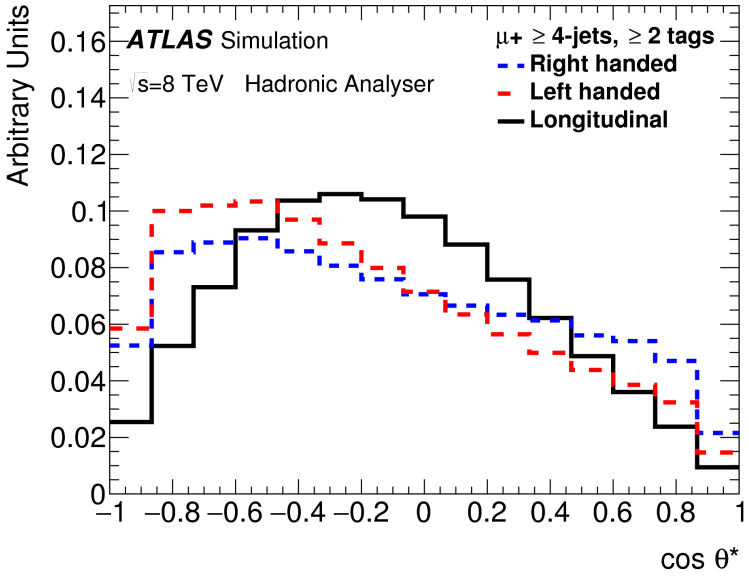
Eur. Phys. J. C 77 (2017) 264

- $m_t \gg m_b \rightarrow W$ from top is **polarized** due to V-A structure of the process
- Right-handed polarization **heavily suppressed** in SM
- $\sqrt{s} = 8$ TeV, 20.2 fb^{-1}, lepton+jets channel



- Event reconstruction: KLFitter (NIM A748 (2014) 18-25) with up/down separation





W helicity measurement in top quark events - Results

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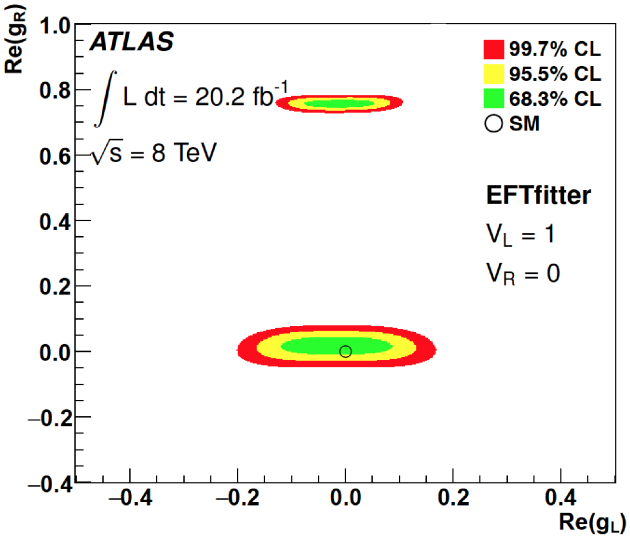
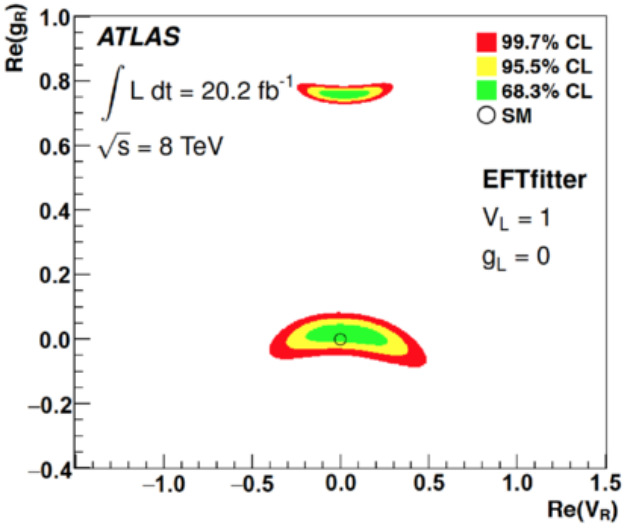
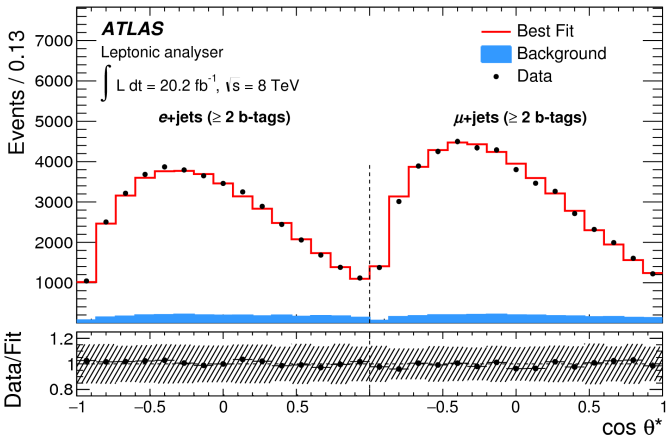
Helicity fractions extracted using template fit - set **limits on anomalous couplings**





Leptonic $\cos\theta^*$



Dominant syst. uncertainties: JES, JER, signal modelling

Theory (NNLO in QCD) -
Phys.Rev.D81:111503,2010

$F_0 = 0.687 \pm 0.005$
$F_L = 0.311 \pm 0.005$
$F_R = 0.0017 \pm 0.0001$

Measured - leptonic

$F_0 = 0.709 \pm 0.019$
$F_L = 0.299 \pm 0.015$
$F_R = -0.008 \pm 0.014$

Measured - hadronic

$F_0 = 0.659 \pm 0.053$
$F_L = 0.281 \pm 0.066$
$F_R = 0.061 \pm 0.103$

Most precise W-helicity measurement

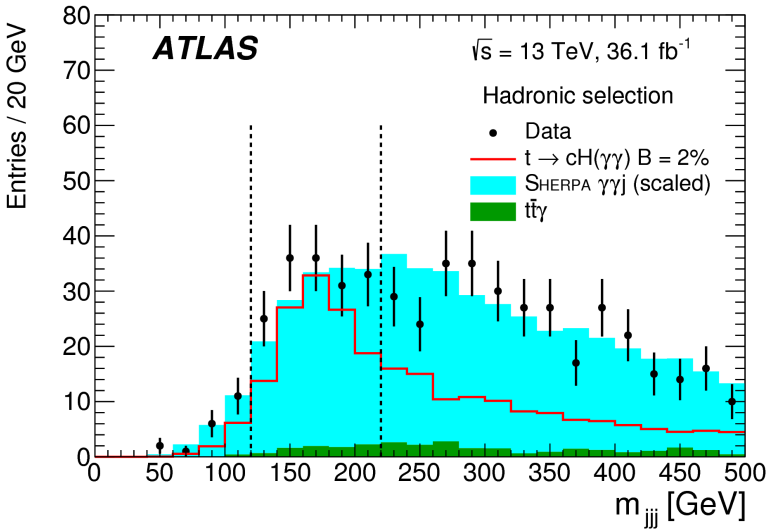
In **good agreement with SM** prediction

Searches for Flavour Changing Neutral Current with top

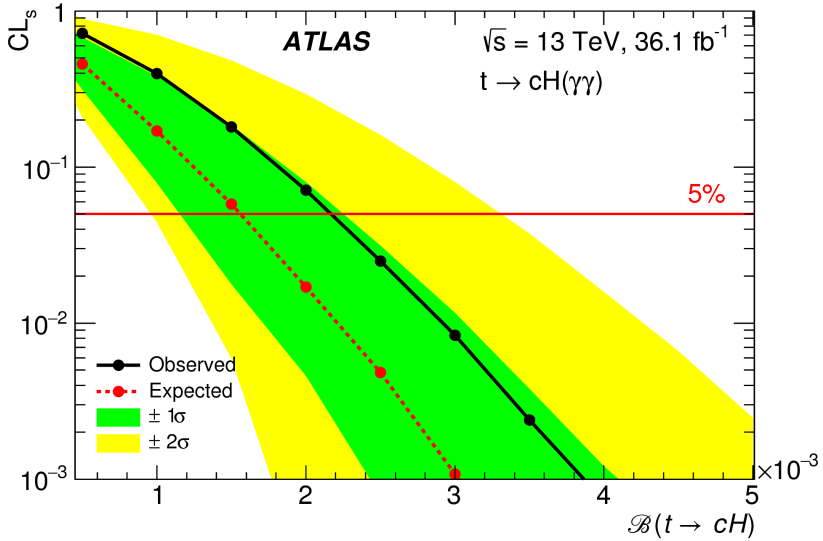
Eur. Phys. J. C76 (2016) 12, arXiv:1707.01404, Eur. Phys. J. C 76 (2016) 55

- FCNC are forbidden at tree level in SM and suppressed by GIM mechanism

- $t\bar{t}$, $t \to qH(\gamma\gamma)$, $q = c, u$
- SM branching ratio: $\approx 3 \times 10^{-15}$
- Leptonic/Hadronic selection - $t \to bW(jj)/t \to bW(\ell\nu)$
- Two categories - events passing full selection/events failing only mass criterion ($120 < m_{jjj} < 220$ GeV)



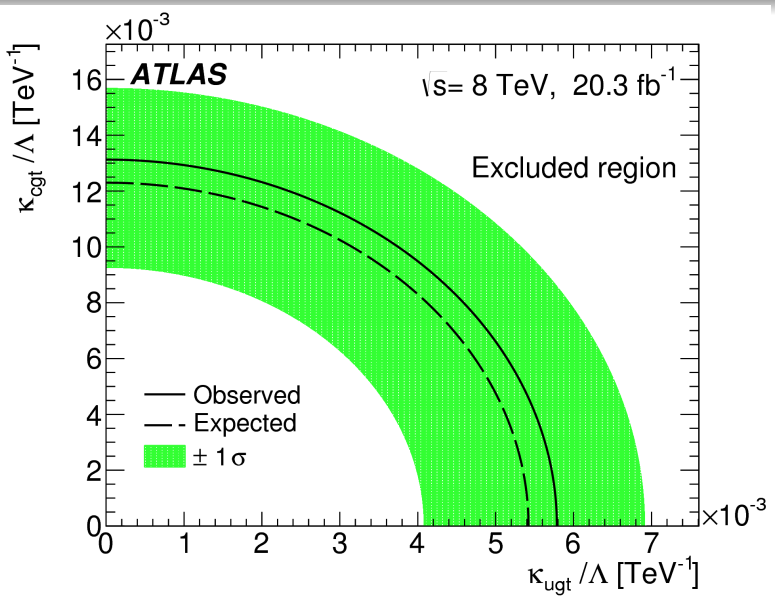
- Dominant systematic uncertainties: JES, ME generator and radiation modelling
- BR($t \to Hc$) $< 2.2 \times 10^{-3}$ @95% CL
- BR($t \to Hu$) $< 2.4 \times 10^{-3}$ @95% CL
- $\sqrt{\lambda_{tcH}^2 + \lambda_{tuH}^2} < 0.090$, $m_H = 125.09$ GeV
- Entering region sensitive to **flavour violating Yukawa coupling in 2HDM**

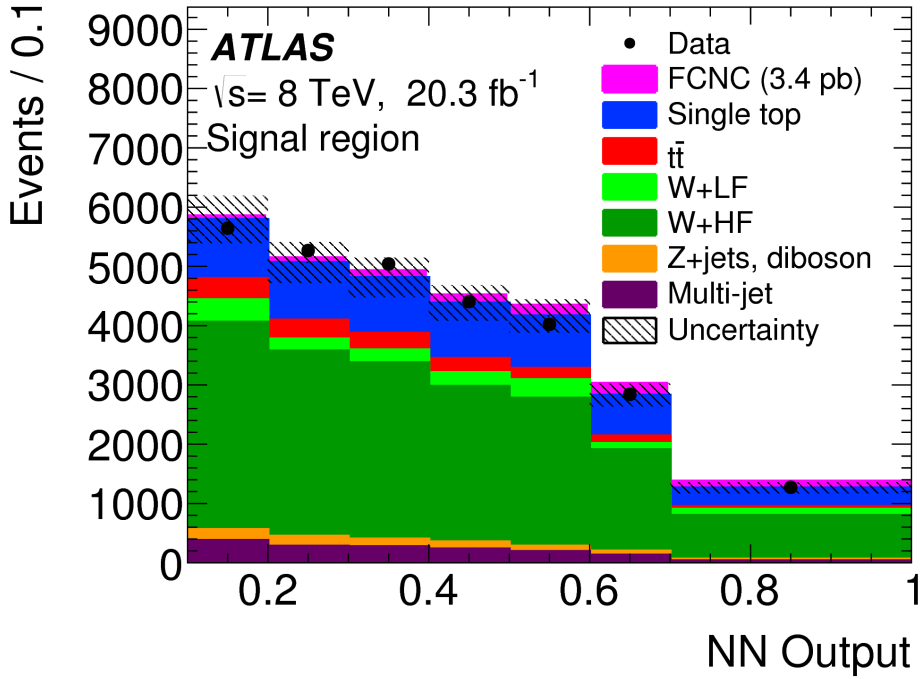


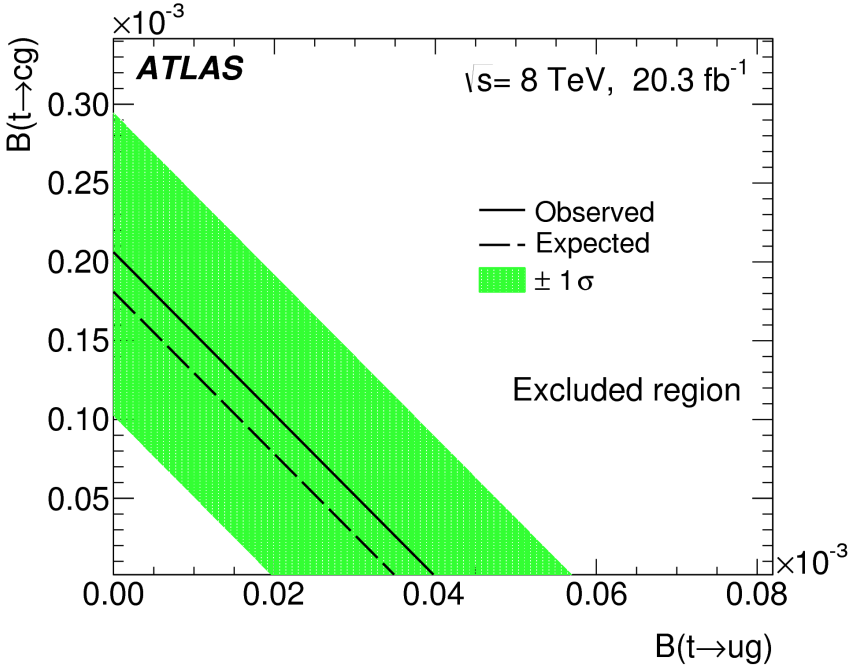
Searches for FCNC with top quarks

Eur. Phys. J. C76 (2016) 12, arXiv:1707.01404, Eur. Phys. J. C 76 (2016) 55

- Single top production, $qg \to t$
- **Using NN** to separate signal from background
- $\sigma_{qg\to t} \times \mathcal{B}(t \to Wb) < 3.4$ pb
- $K_{ugt}/\Lambda < 5.8 \times 10^{-3}$ TeV^{-1}, $K_{cgt}/\Lambda < 13 \times 10^{-3}$ TeV^{-1}
- $\mathcal{B}(t \to ug) < 4.0 \times 10^{-5}$ $\mathcal{B}(t \to cg) < 20 \times 10^{-5}$



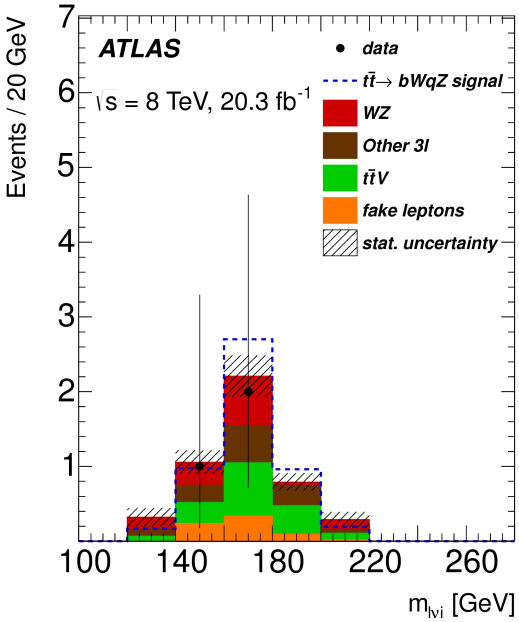




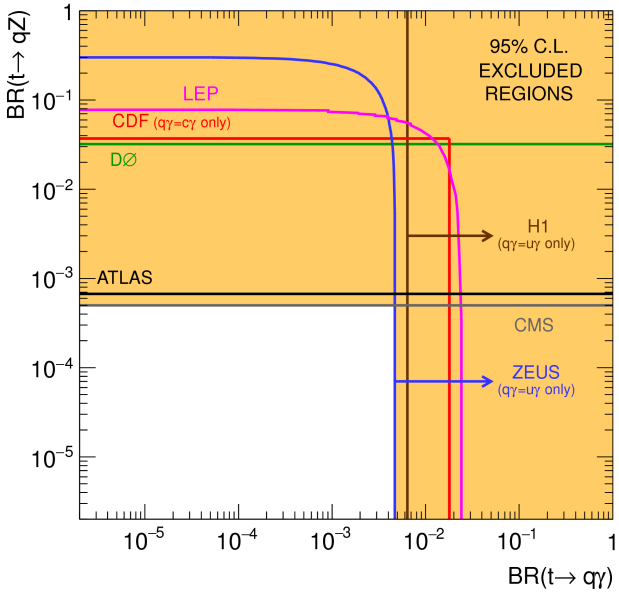
Searches for FCNC with top quarks

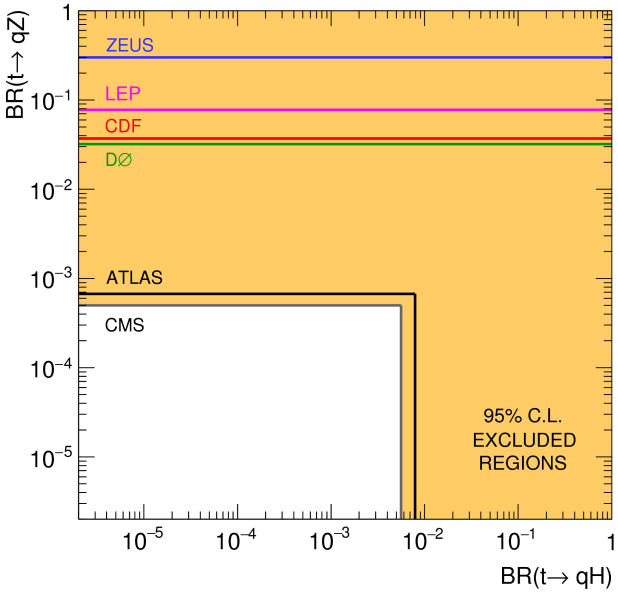
Eur. Phys. J. C76 (2016) 12, arXiv:1707.01404, Eur. Phys. J. C 76 (2016) 55

- Search for $t\bar{t}$ with $t \to qZ(Z \to \ell\ell)$
- 8 TeV, 20.3 fb^{-1}, leptonic decay of W
- Exactly 3 leptons ($p_T > 15$ GeV), 2 must be consistent with Z, ≥ 2 jets ($p_T > 35$ GeV), ≥ 1 b-tag
- χ^2 reconstruction of top kinematics
- Three control regions to constrain background

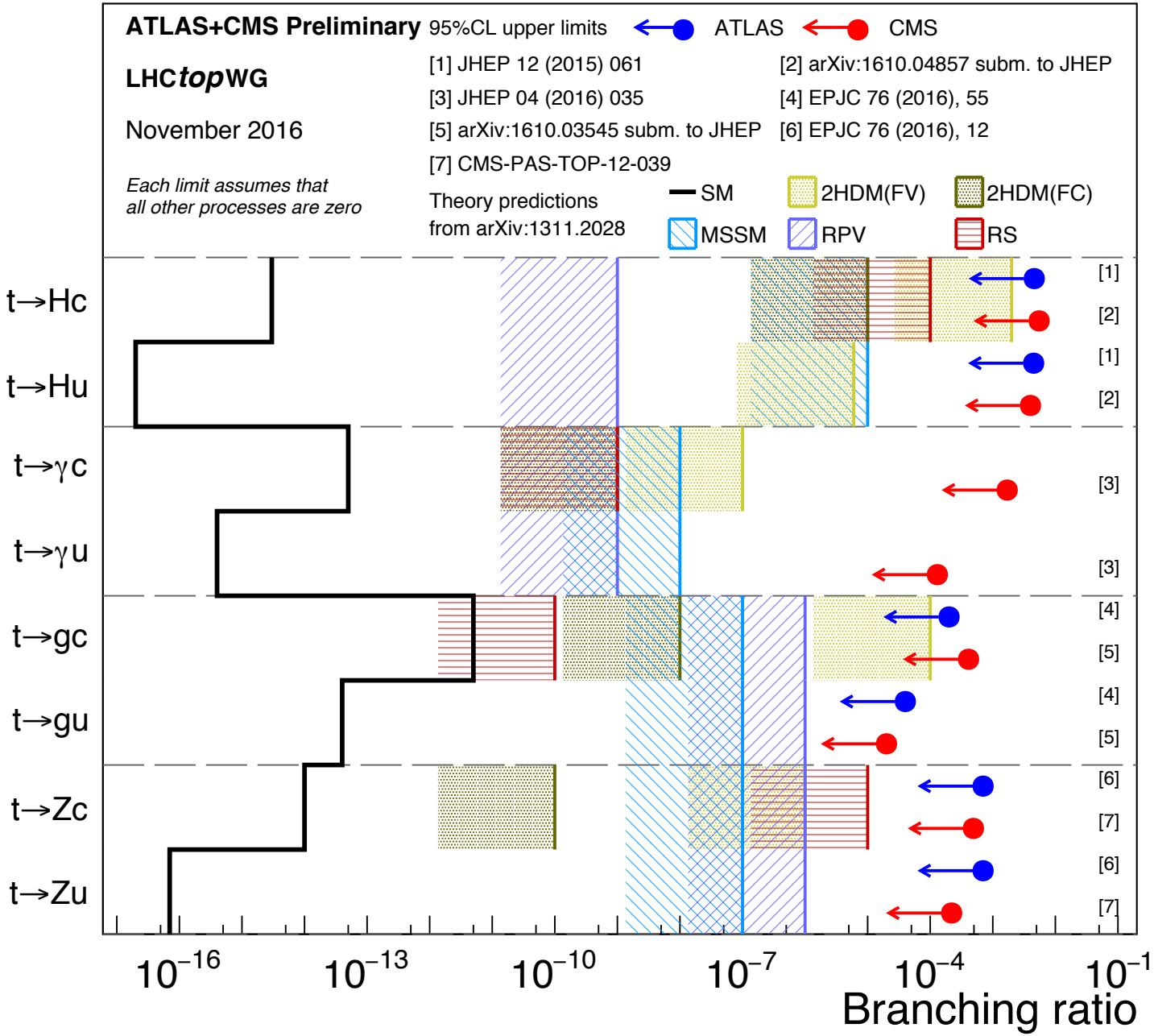


- Dominant systematic uncertainty: Background modelling
- Result: $\mathbf{BR}(t \to qZ) < 7 \times 10^{-4}$ (95% CL)





FCNC summary

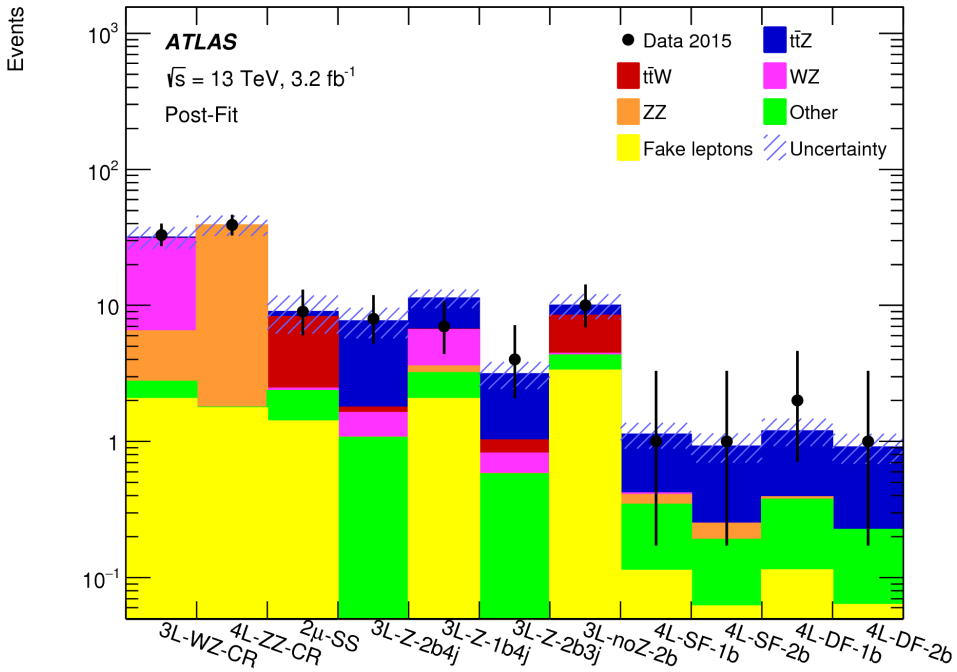


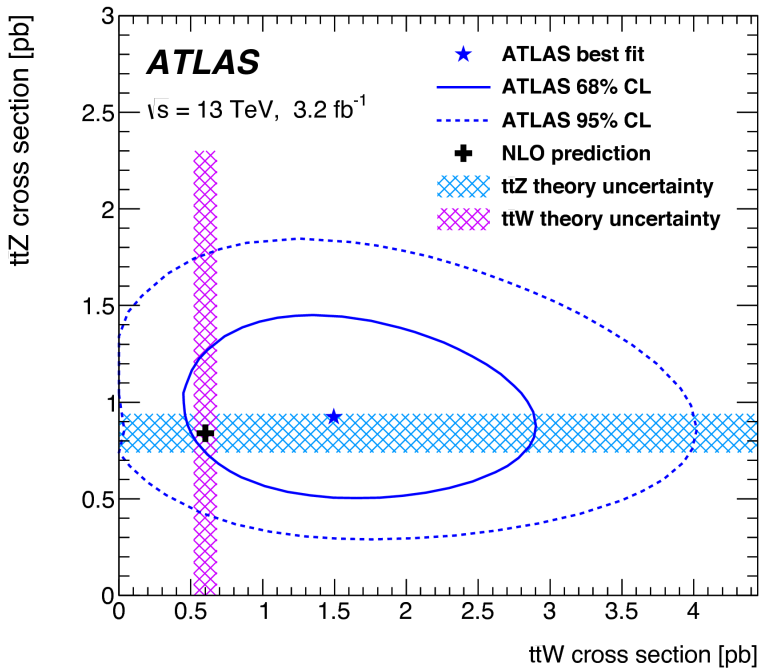
Measurements of $t\bar{t}W$ and $t\bar{t}Z$ production x-section

Eur. Phys. J. C 77 (2017) 40

- $t\bar{t}Z$ is sensitive to top neutral coupling
- $\sqrt{s} = 13$ TeV, 3.2 fb^{-1}, 2015 data
- Three decay modes: dilepton SS, trilepton, tetralepton
- Nine signal regions and two control regions - **profile likelihood**

- $\sigma_{t\bar{t}Z} = 0.92 \pm 0.29(\text{stat.}) \pm 0.10(\text{syst.})\text{pb}$
- $\sigma_{t\bar{t}W} = 1.50 \pm 0.72(\text{stat.}) \pm 0.3(\text{syst.})\text{pb}$
- Sig.: $3.9\sigma(2.2\sigma)$ for $t\bar{t}Z(t\bar{t}W)$
- Correlation: -0.13

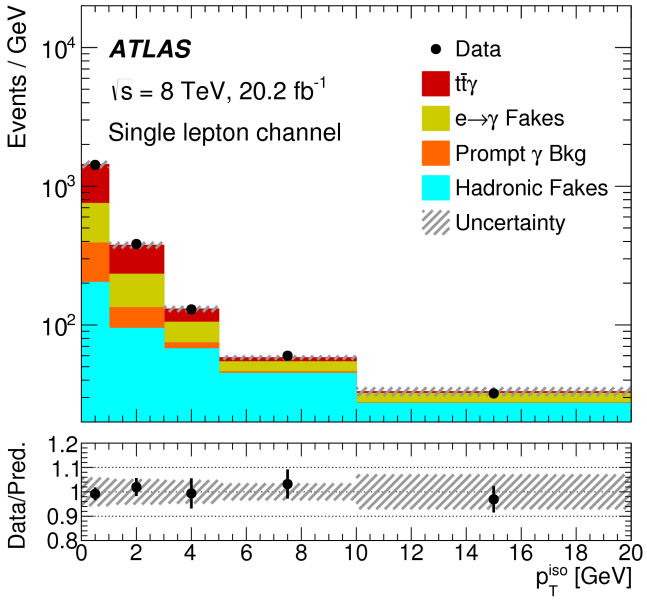


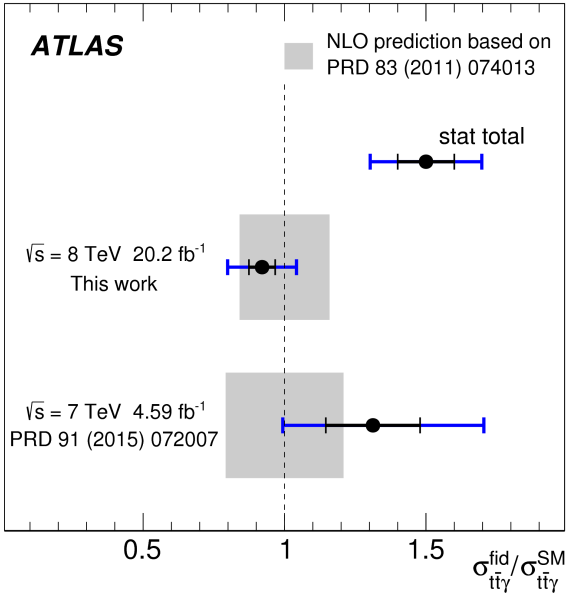


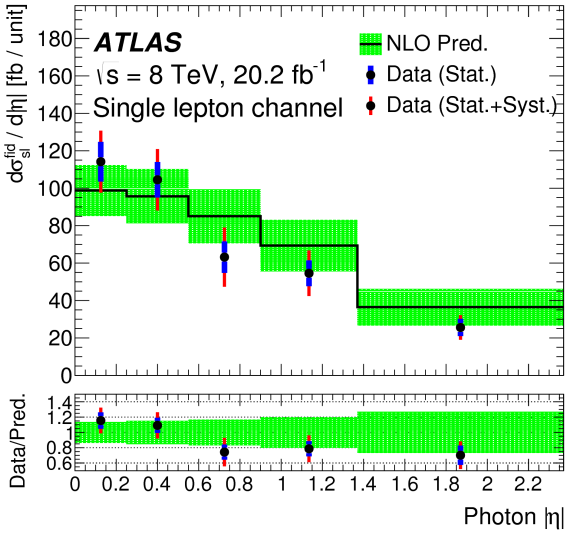
$t\bar{t}\gamma$ x-section measurement

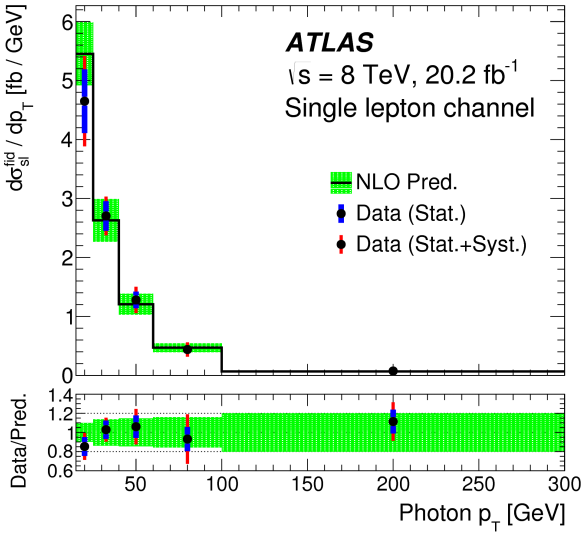
arXiv:1706.03046

- Probes neutral coupling of top quarks
- $\sqrt{s} = 8$ TeV, semileptonic decays
- **Three templates**: prompt γ, hadron fakes, mis-id electrons
- X-sec in fiducial region: $\sigma_{t\bar{t}\gamma} = 139 \pm 7(\text{stat.}) \pm 17(\text{syst.})\text{fb}$
- Limitation: Uncertainty in fakes templates



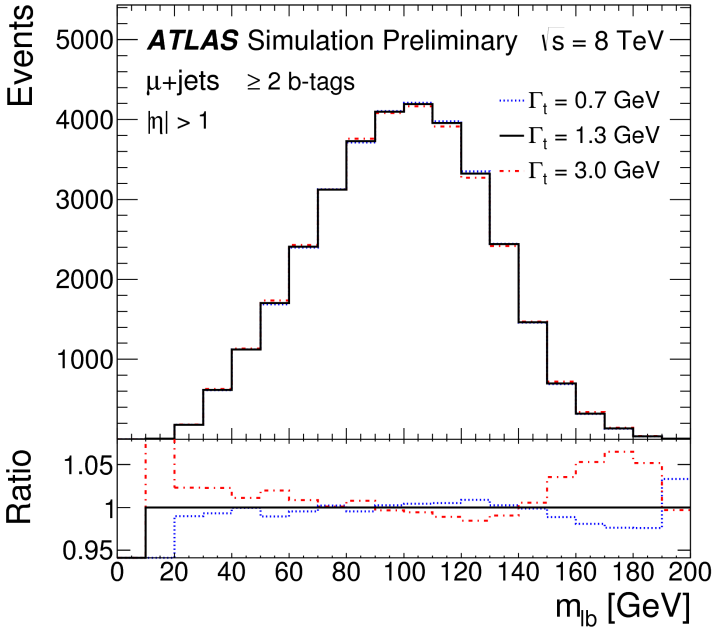


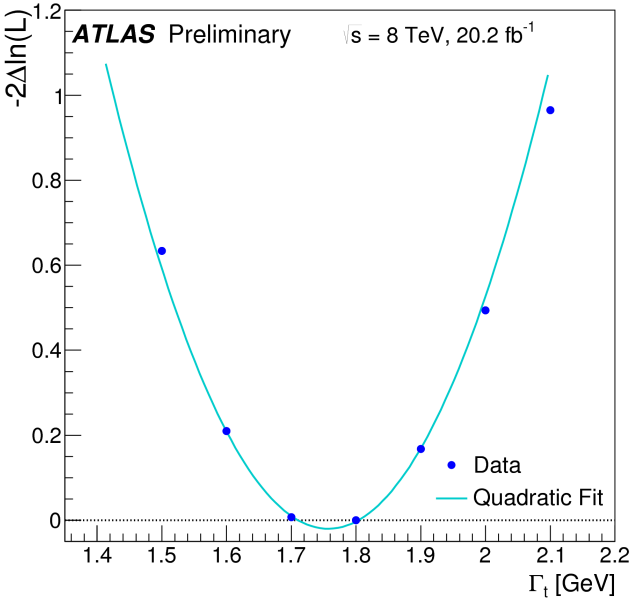




Top quark decay width measurement
ATLAS-CONF-2017-056

- **Direct measurement** - model independent
- 8 TeV, 20.2 fb^{-1}, ℓ+jets channel, ≥ 4 jets, ≥ 1 b-tagged
- $t\bar{t}$ reconstruction using KLFitter
- Events split by jet $|\eta| = 1$ - reduces dominant syst. uncert.
- Templates created by Breit-Wigner reweighting



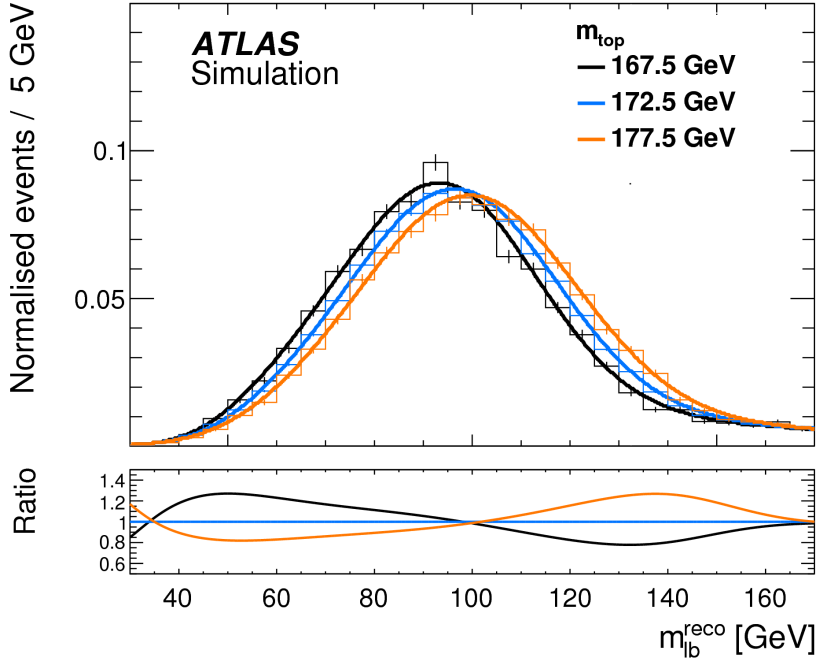


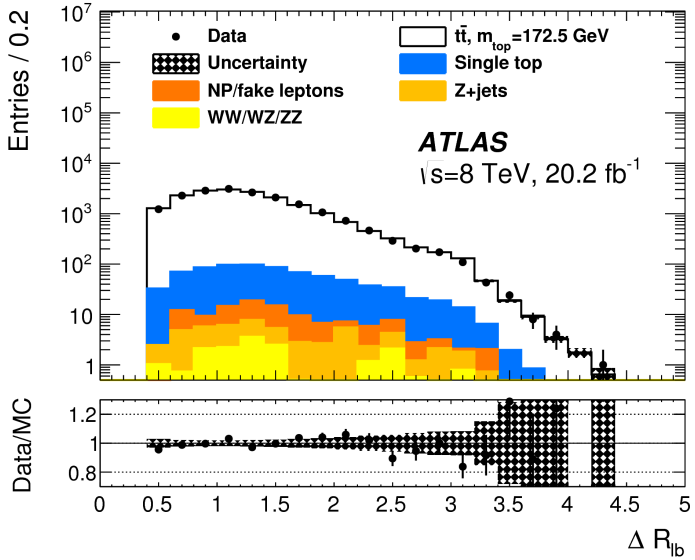
- Dominant uncertainties: JES, JER and signal modelling
- $\Gamma_{\text{top}} = 1.76 \pm 0.33(\text{stat.})^{+0.79}_{-0.68}(\text{syst.})$ GeV, assuming $m_{\text{top}} = 172.5$ GeV
- First direct top width measurement in ATLAS

Mass measurements - dilepton

Physics Letters B 761 (2016) 350 - 371

- **Template fit** using $m_{\ell b}$, $\sqrt{s} = 8$ TeV, $20.2\,\text{fb}^{-1}$
- Two OS leptons, Z-mass veto, ≥ 2 jets, ≥ 1 b-tagged jet
- Gauss + Landau function for signal, Landau for background





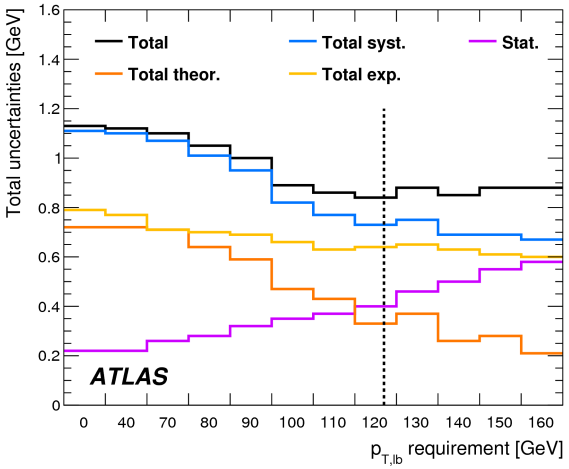
Reconstruction

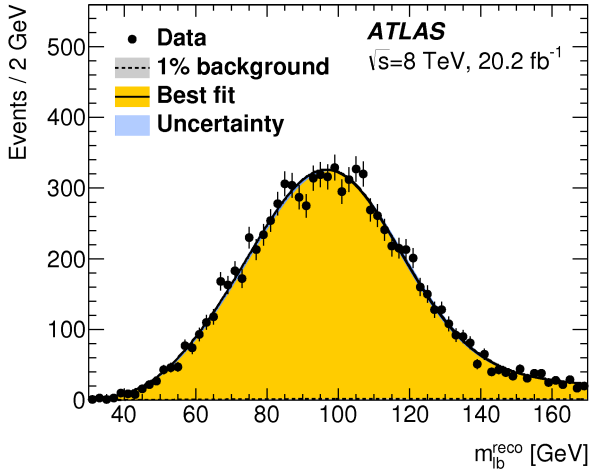
- 2 b-jets from top decay
- Assume: lowest average $m_{\ell b}$ = correct pairing
- Improved by cut on p_T of ℓb system

Mass measurements - dilepton

Physics Letters B 761 (2016) 350 - 371

- By optimization: $p_{T,\ell b} > 120$ GeV
- Uncertainty dominated by: **JES, bJES and MC modelling**

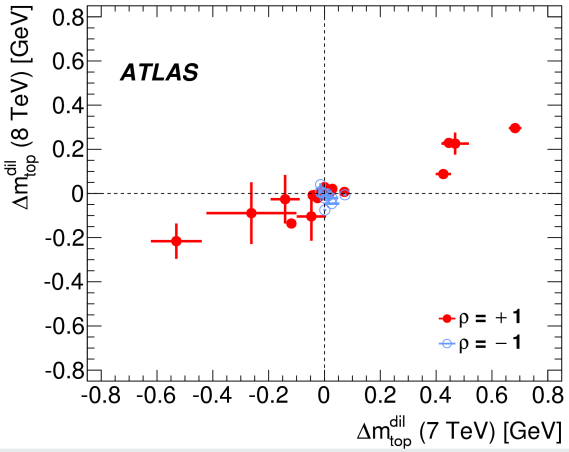


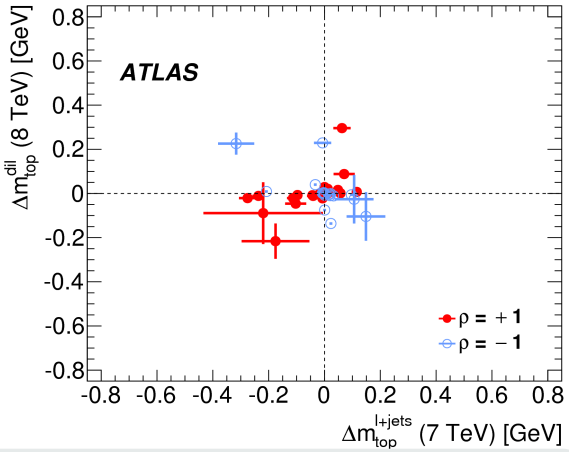


- $m_{top} = 172.99 \pm 0.41(\text{stat}) \pm 0.74(\text{syst})$ GeV, 0.5% relative uncertainty

Combination with 7 TeV

- **BLUE method**(Best Linear Unbiased Est.)
- Improvement by 17% w.r.t. most precise single measurement



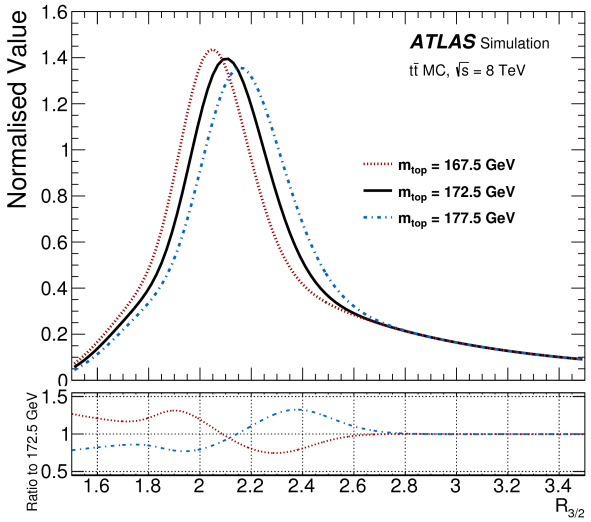


- $m_{top} = 172.84 \pm 0.34(\text{stat}) \pm 0.61(\text{syst})$ GeV, 0.4% relative uncertainty

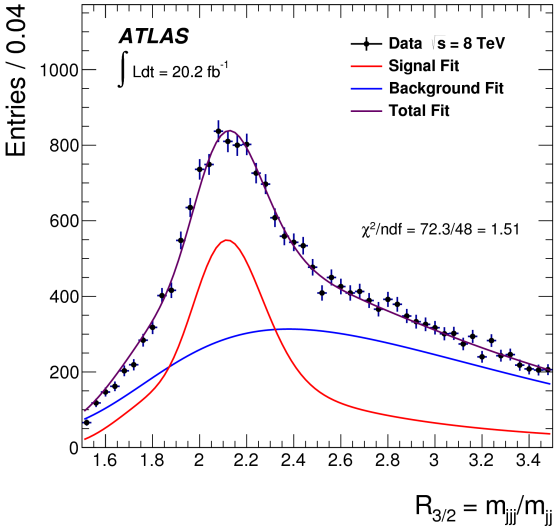
Mass measurements - all-hadronic

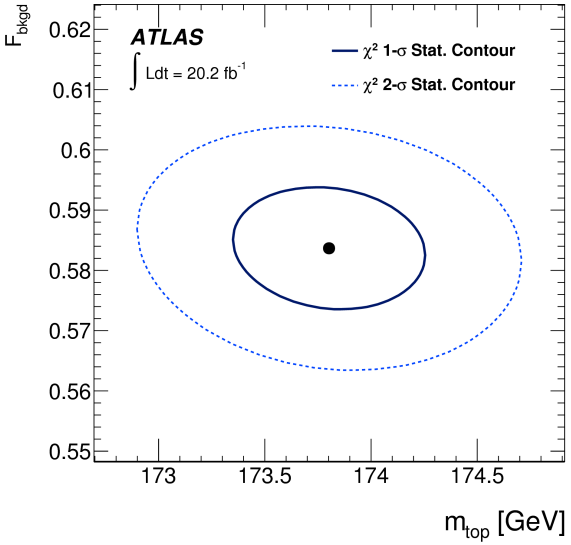
arXiv:1702.07546

- **Template fit** using 8 TeV data, 20.2 fb^{-1}
- ≥ 5 jets with $p_T > 55$ GeV, ≥ 2 b-tagged, $\Delta\phi(b_i, b_j) > 1.5$
- Observable: $R_{3/2} = m_{jjj}/m_{jj}$
- Multijet bkg. estimation: **ABCD** method



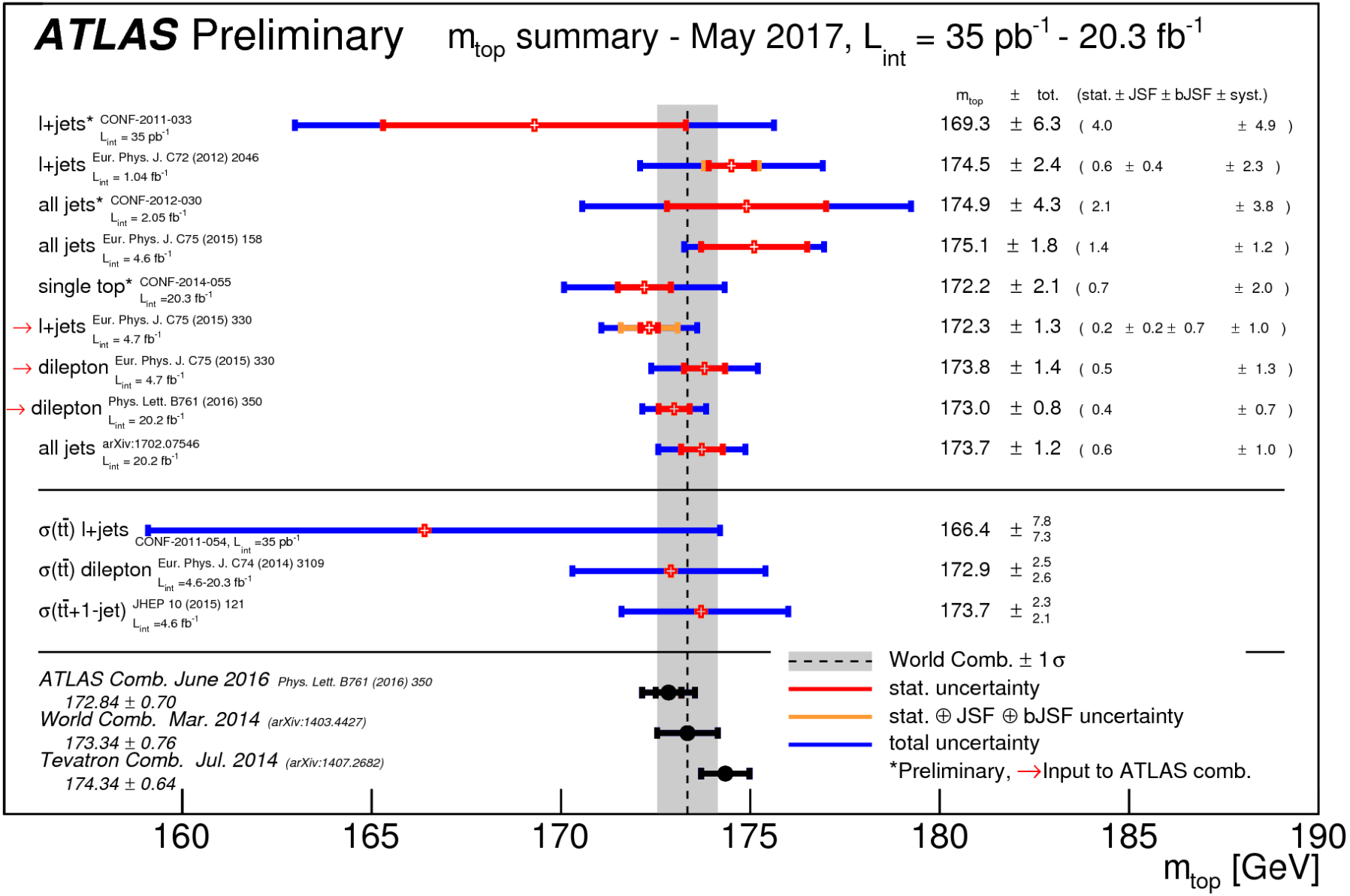
- Fit: Novosibirsk + Landau function
- Statistical uncertainty corrected by $\sqrt{1+\rho} = 1.26$
- Dominant uncertainties: JES and hadronization modelling





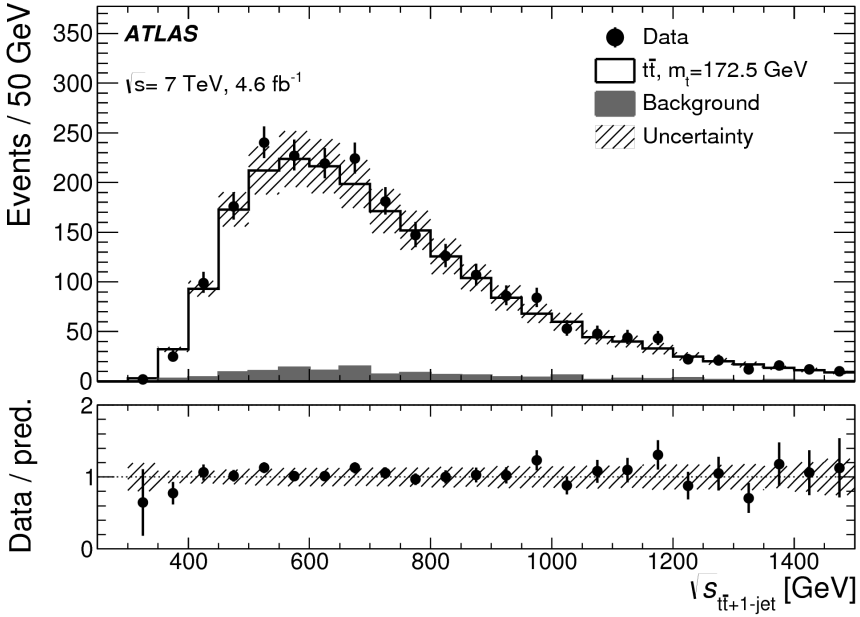
$$m_{top} = 173.72 \pm 0.55(\text{stat}) \pm 1.01(\text{syst}), \text{ rel. uncert. } 0.7\%$$

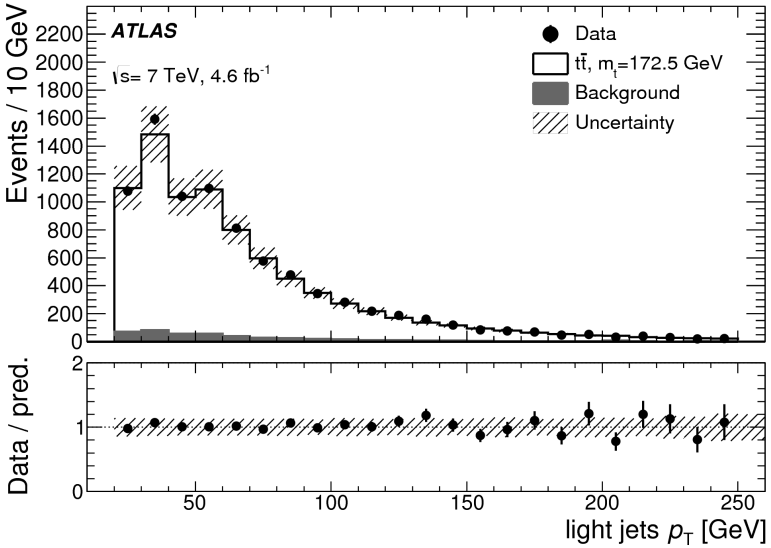
Mass measurements - ATLAS combination



Top-quark pole mass using $t\bar{t}+1$ ($t\bar{t} \to \ell$+jets) jet x-section @ 7 TeV

- **Gluon radiation is sensitive to top pole mass**
- Theoretically unambiguous - corresponds to $m_{\text{top}}^{\text{pole}}$ - unlike MC mass
- Higher precision than using $t\bar{t}$ inclusive x-sec which has low sensitivity, large PDF and scale uncertainty
- ≥ 5 jets, exactly 2 b-tagged





$t\bar{t}+1$ system reconstruction

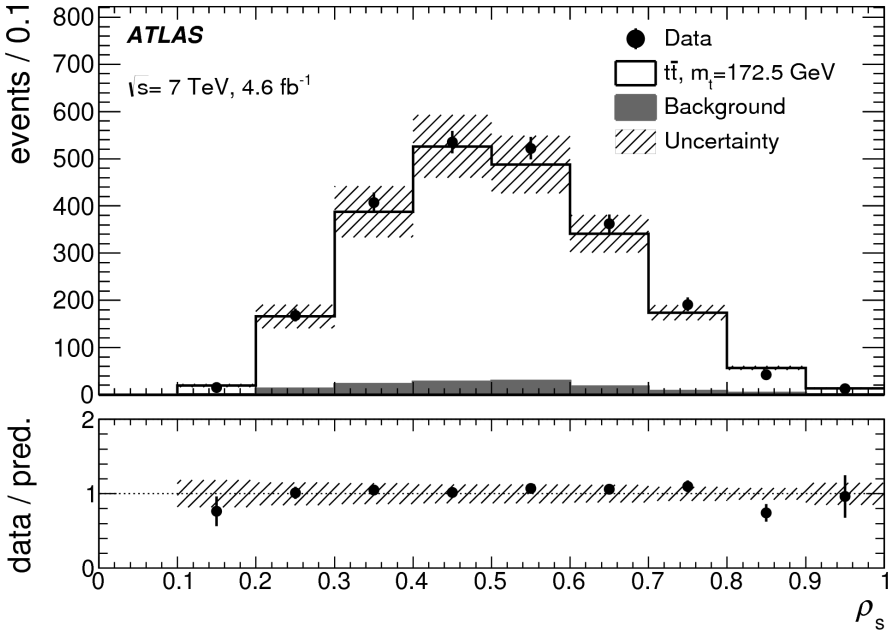
- $0.9 < m_W^{\text{ref}}/m_{ij} < 1.25$
- $\min(p_T^i, p_T^j).\Delta R(i,j) < 90$ GeV
- Minimize mass difference for had. and lep. top mass

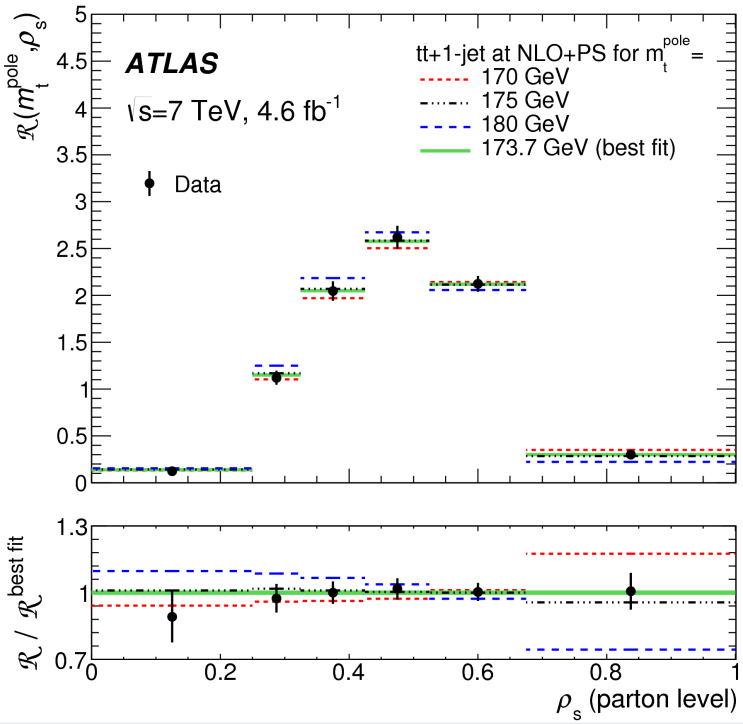
$$\rho_s = \frac{2m_0}{\sqrt{S_{t\bar{t}+1-\text{jet}}}}$$

Mass measurements - pole mass measurements

JHEP 10 (2015) 121

- **Fit parametrized NLO+PS prediction to normalized diff. x-section**
- Unfolding to **parton** level (Singular Value Decomposition)
- Parton level = after final state gluon radiation, before decay



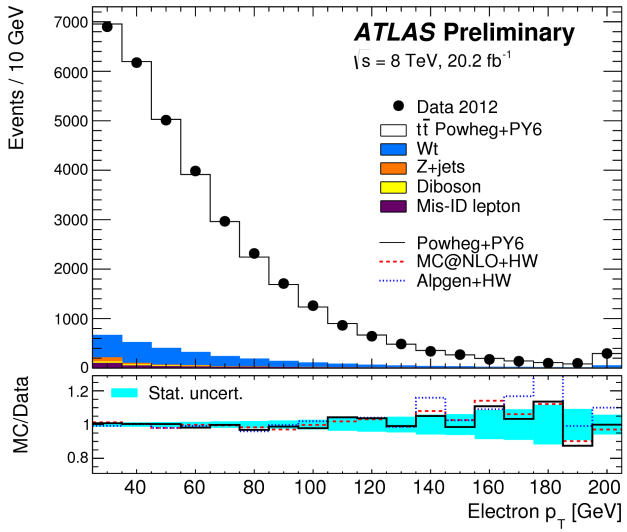


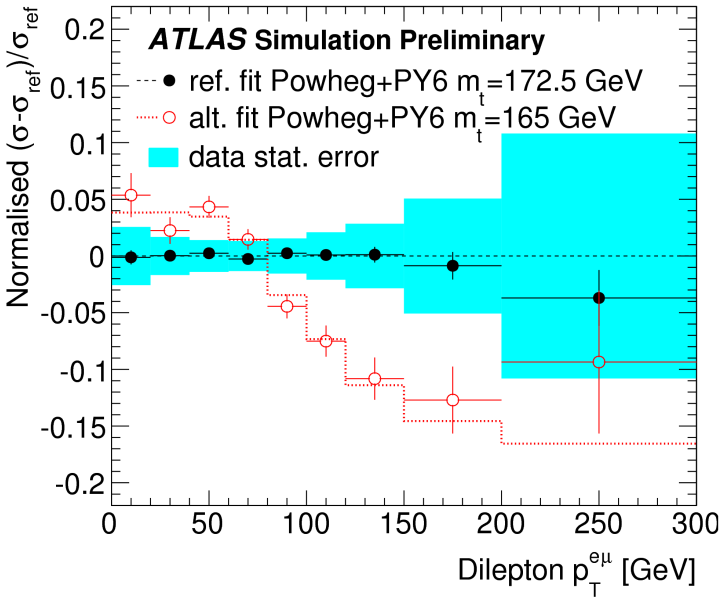
$$m_t^{\text{pole}} = 173.7 \pm 1.5(\text{stat}) \pm 1.4(\text{syst})^{+1.0}_{-0.5}(\text{theory})\text{GeV}$$

Relative uncertainty 1.3%

Lepton differential distributions @ 8 TeV

- Fixed-order measurements correspond more directly to m_t^{pole}
- $t\bar{t} \to b\bar{b}e\mu\nu\bar{\nu}$, $\sqrt{s} = 8$ TeV, 20.3 fb^{-1}
- One electron ($E_T > 25$ GeV), one muon $p_T > 25$ GeV



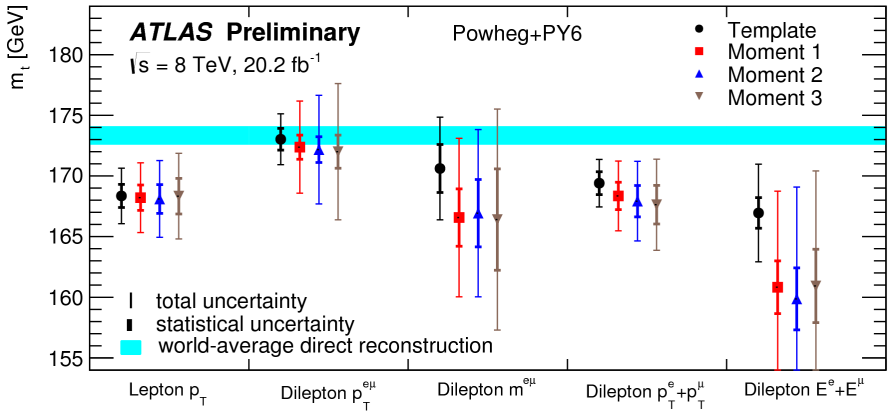


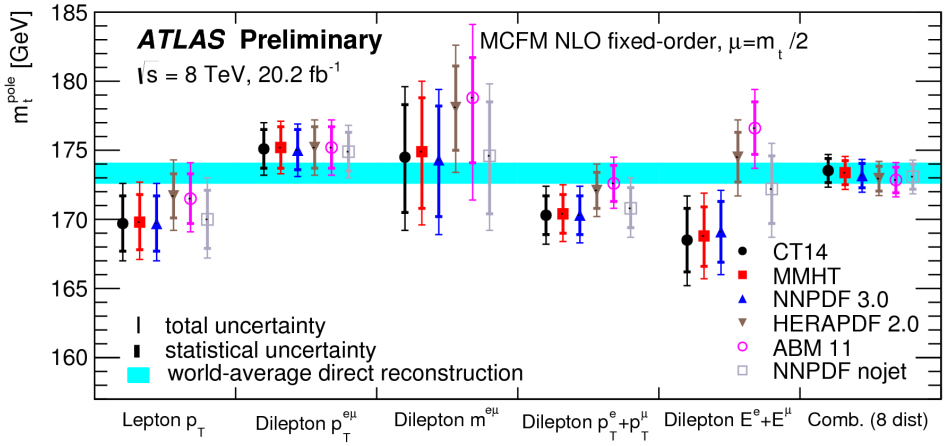
- **Template fit**
  - Similar to "traditional" measurements
- Extraction using **Mellin moments**
  - Compare to calib. curves from predictions
- **Fixed-order** predictions
  - MCFM generated samples with different PDFs compared to data (χ^2)

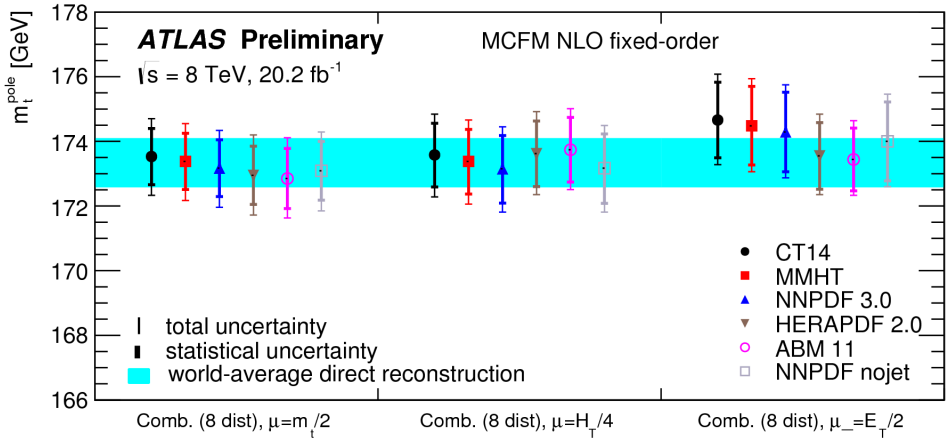
Mass measurements - pole mass measurements II

ATLAS-CONF-2017-044

- Template fit with **particle** level distributions
- Fixed-order (MCFM): templates from 161-180 GeV



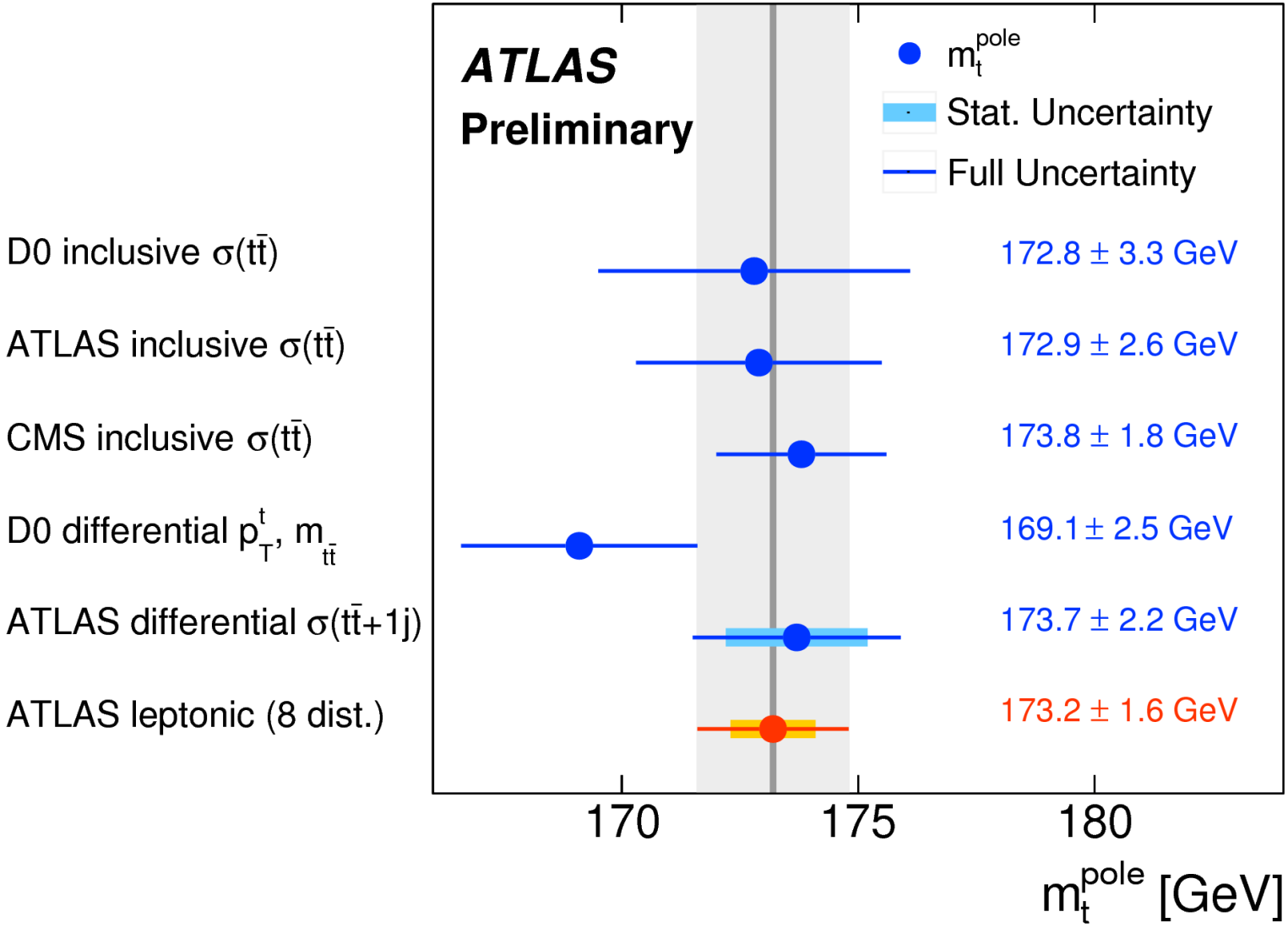




$$m_t^{\text{pole}} = 173.2 \pm 0.9(\text{stat}) \pm 0.8(\text{syst}) \pm 1.2(\text{theory})\ \text{GeV}$$

Most precise top pole mass measurement to date with 1.0% rel. uncertainty

Alternative mass measurements summary



Summary

SM tests

- Top quark spin observables measurement
- W-helicity measurement
- $t\bar{t}\gamma$ measurement
- $t\bar{t}W/Z$ measurement
- Top quark width measurement

10 new obs.

Most precise

New

Top mass

- **MC mass**
  - Dilepton - rel. unc. 0.4%
  - All-hadronic - rel. unc. 0.7%
- **Pole mass**
  - $t\bar{t} + 1$-jet cross-section
  - Lepton distributions

New combination

Most precise

Measurements are in good agreement with predictions

FCNC searches

- Decay: $t \to qH$, $t \to qZ$
- Production: $qg \to t$

Dominant systematic uncertainties

- Detector: JES, JER
- $t\bar{t}$ modelling

Not mentioned in this talk

- **Charge asym.** - Phys. Rev. D94 (2016) 032006, Phys. Lett. B756 (2016) 52
- **Cross-section** measurements - **See talk of Ye Chen**

Backup slides

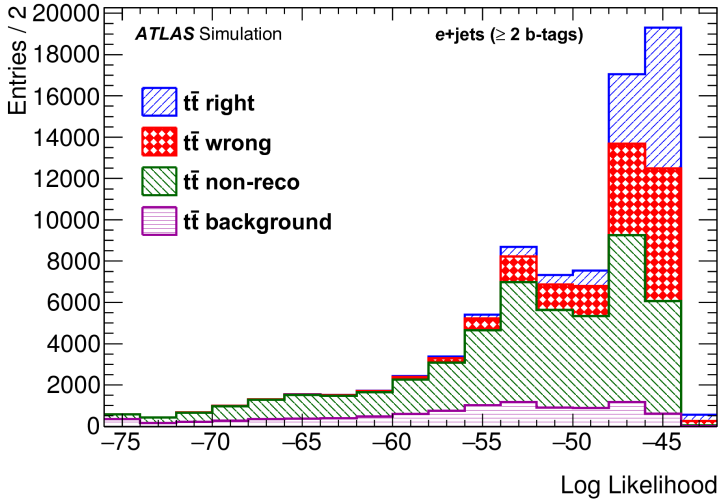
Measurement of top quark spin observables - Systematics

Measurements	Central	Total	Statistical	Detector	Modelling	Others	Mass
Full phase-space							
B_+^k	-0.044	±0.038	±0.018	±0.001	±0.026	±0.007	±0.027
B_-^k	-0.064	±0.040	±0.020	±0.001	±0.023	±0.014	±0.027
B_+^n	-0.018	±0.034	±0.020	±0.001	±0.024	±0.005	-
B_-^n	0.023	±0.042	±0.020	±0.001	±0.034	±0.005	-
B_+^r	0.039	±0.042	±0.026	±0.001	±0.029	±0.005	-
B_-^r	0.033	±0.054	±0.023	±0.002	±0.045	±0.006	±0.016
$C(k,k)$	0.296	±0.093	±0.052	±0.006	±0.057	±0.011	±0.037
$C(n,n)$	0.304	±0.060	±0.028	±0.001	±0.047	±0.001	±0.010
$C(r,r)$	0.086	±0.144	±0.055	±0.005	±0.122	±0.016	±0.038
$C(n,k)+C(k,n)$	-0.012	±0.128	±0.072	±0.005	±0.087	±0.029	-
$C(n,k)-C(k,n)$	-0.040	±0.087	±0.053	±0.004	±0.058	±0.003	-
$C(n,r)+C(r,n)$	0.117	±0.132	±0.070	±0.003	±0.102	±0.010	±0.010
$C(n,r)-C(r,n)$	-0.006	±0.108	±0.069	±0.005	±0.070	±0.004	±0.043
$C(r,k)+C(k,r)$	-0.261	±0.176	±0.083	±0.006	±0.135	±0.011	±0.065
$C(r,k)-C(k,r)$	0.073	±0.192	±0.087	±0.007	±0.148	±0.005	±0.025
Fiducial phase-space							
$3\langle\cos\theta_+^k\rangle$	0.125	±0.044	±0.018	±0.007	±0.025	±0.020	±0.027
$3\langle\cos\theta_-^k\rangle$	0.119	±0.040	±0.022	±0.008	±0.021	±0.014	±0.027
$3\langle\cos\theta_+^n\rangle$	-0.025	±0.042	±0.024	±0.001	±0.027	±0.005	-
$3\langle\cos\theta_-^n\rangle$	0.023	±0.046	±0.024	±0.001	±0.036	±0.006	-
$3\langle\cos\theta_+^r\rangle$	-0.104	±0.045	±0.027	±0.008	±0.030	±0.006	-
$3\langle\cos\theta_-^r\rangle$	-0.110	±0.060	±0.024	±0.008	±0.050	±0.010	±0.015
$-9\langle\cos\theta_+^k\cos\theta_-^k\rangle$	0.172	±0.078	±0.041	±0.016	±0.050	±0.017	±0.027
$-9\langle\cos\theta_+^n\cos\theta_-^n\rangle$	0.427	±0.079	±0.034	±0.011	±0.065	±0.004	±0.027
$-9\langle\cos\theta_+^r\cos\theta_-^r\rangle$	0.031	±0.144	±0.055	±0.005	±0.124	±0.020	±0.033
$-9\langle\cos\theta_+^n\cos\theta_-^k+\cos\theta_+^k\cos\theta_-^n\rangle$	0.024	±0.132	±0.078	±0.004	±0.085	±0.025	-
$-9\langle\cos\theta_+^n\cos\theta_-^k-\cos\theta_+^k\cos\theta_-^n\rangle$	-0.047	±0.096	±0.059	±0.004	±0.065	±0.002	-
$-9\langle\cos\theta_+^n\cos\theta_-^r+\cos\theta_+^r\cos\theta_-^n\rangle$	0.113	±0.143	±0.076	±0.005	±0.108	±0.023	±0.015
$-9\langle\cos\theta_+^n\cos\theta_-^r-\cos\theta_+^r\cos\theta_-^n\rangle$	-0.030	±0.118	±0.076	±0.005	±0.077	±0.007	±0.052
$-9\langle\cos\theta_+^r\cos\theta_-^k+\cos\theta_+^k\cos\theta_-^r\rangle$	-0.187	±0.151	±0.069	±0.023	±0.122	±0.006	±0.039
$-9\langle\cos\theta_+^r\cos\theta_-^k-\cos\theta_+^k\cos\theta_-^r\rangle$	0.047	±0.128	±0.070	±0.003	±0.082	±0.010	±0.023

W helicity measurement in top quark events - Systematics

Uncertainty	Leptonic, ≥2 b-tags			Hadronic, 1 + ≥2 b-tags		
	F_0	F_L	F_R	F_0	F_L	F_R
Reconstructed objects						
Electron	$^{+0.0028}_{-0.0030}$	$^{+0.0018}_{-0.0020}$	$^{+0.0011}_{-0.0011}$	$^{+0.0025}_{-0.0021}$	$^{+0.0028}_{-0.0038}$	$^{+0.0051}_{-0.0058}$
Muon	$^{+0.0024}_{-0.0029}$	$^{+0.0013}_{-0.0015}$	$^{+0.0010}_{-0.0015}$	$^{+0.0026}_{-0.0037}$	$^{+0.0046}_{-0.0035}$	$^{+0.0072}_{-0.0072}$
Jet energy scale	$^{+0.0063}_{-0.0033}$	$^{+0.0028}_{-0.0025}$	$^{+0.0037}_{-0.0014}$	$^{+0.0069}_{-0.0070}$	$^{+0.012}_{-0.008}$	$^{+0.014}_{-0.005}$
Jet energy resolution	$^{+0.0062}_{-0.0059}$	$^{+0.0048}_{-0.0018}$	$^{+0.0072}_{-0.0067}$	$^{+0.027}_{-0.031}$	$^{+0.033}_{-0.041}$	$^{+0.057}_{-0.071}$
Jet vertex fraction	$^{+0.0036}_{-0.0017}$	$^{+0.0019}_{-0.0013}$	$^{+0.0017}_{-0.0006}$	$^{+0.013}_{-0.009}$	$^{+0.0012}_{-0.0046}$	$^{+0.011}_{-0.005}$
Jet reconstruction ef ciency	$^{+0.0002}_{-0.0002}$	$^{<0.0001}_{<0.0001}$	$^{+0.0002}_{-0.0002}$	$^{+0.0008}_{-0.0008}$	$^{+0.0004}_{-0.0004}$	$^{+0.0011}_{-0.0011}$
b-tagging	$^{+0.0017}_{-0.0021}$	$^{+0.0012}_{-0.0013}$	$^{+0.0011}_{-0.0012}$	$^{+0.029}_{-0.031}$	$^{+0.013}_{-0.014}$	$^{+0.034}_{-0.035}$
Sum reconstructed objects	$^{+0.010}_{-0.008}$	$^{+0.0064}_{-0.0044}$	$^{+0.0085}_{-0.0072}$	$^{+0.043}_{-0.045}$	$^{+0.038}_{-0.044}$	$^{+0.069}_{-0.080}$
Signal modelling						
Showering and hadronisation	±0.0019	±0.0019	±0.0037	±0.015	±0.001	±0.014
ME event generator	±0.0025	±0.0032	±0.0057	±0.016	±0.024	±0.040
ISR/FSR	±0.0033	±0.0058	±0.0034	±0.018	±0.039	±0.057
PDF	±0.0033	±0.0042	±0.0009	±0.0010	±0.0020	±0.0020
Top quark mass	±0.0017	±0.0050	±0.0033	±0.0033	±0.0100	±0.0068
Sum signal modelling	±0.0058	±0.0094	±0.0082	±0.028	±0.047	±0.072
Method uncertainty						
Template statistics	±0.0091	±0.0056	±0.0044	±0.0076	±0.016	±0.016
Total uncertainty						
Total systematic	$^{+0.015}_{-0.014}$	$^{+0.013}_{-0.012}$	$^{+0.013}_{-0.012}$	$^{+0.052}_{-0.054}$	$^{+0.063}_{-0.067}$	$^{+0.100}_{-0.110}$
Stat. + bkg. norm	±0.012	±0.008	±0.006	±0.010	±0.021	±0.022

KLFitter logarithm of likelihood



Searches for FCNC with top quarks - Systematics

$t \to qH(\gamma\gamma)$

	Systematic uncertainty [%]			
Selection	Hadronic		Leptonic	
Category	1	2	1	2
$t\bar{t}$ production cross section	$^{+4.8}_{-5.5}$			
Branching ratio of the $H \to \gamma\gamma$ decay	5.0			
Luminosity	3.2			
Photon energy scale	0.3	0.5	1.9	0.6
Photon energy resolution	0.3	0.2	0.3	0.6
Photon identification	1.8	1.7	1.7	1.7
Jet energy scale	$^{+7.9}_{-6.5}$	$^{+6.2}_{-4.8}$	$^{+0.8}_{-2.1}$	$^{+4.3}_{-5.2}$
Jet energy resolution	-2.1	3.0	-2.2	3.5
Jet vertex tagging	0.7	0.4	0.3	0.2
b-tagging	3.3	3.6	3.2	6.5
Lepton identification and scale	–	–	0.6	1.2
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale	–	–	$^{+1.1}_{-0.6}$	$^{+1.8}_{-3.9}$
Pile-up reweighting	1.6	1.2	1.5	1.2
QCD scales	1.7	1.6	1.6	3.2
PDFs	0.7	0.5	0.7	0.5
Top quark mass	1.0	1.0	1.0	3.0
Generator	5.7	-5.8	11.7	6.3
ISR/FSR	$^{+0.4}_{-8.2}$	$^{-8.0}_{+3.8}$	$^{-4.4}_{+0.7}$	$^{-1.1}_{+4.3}$
Hadronisation/underlying event	-5.8	9.6	-4.9	23.2

Searches for FCNC with top quarks - Systematics

$gq \to t$

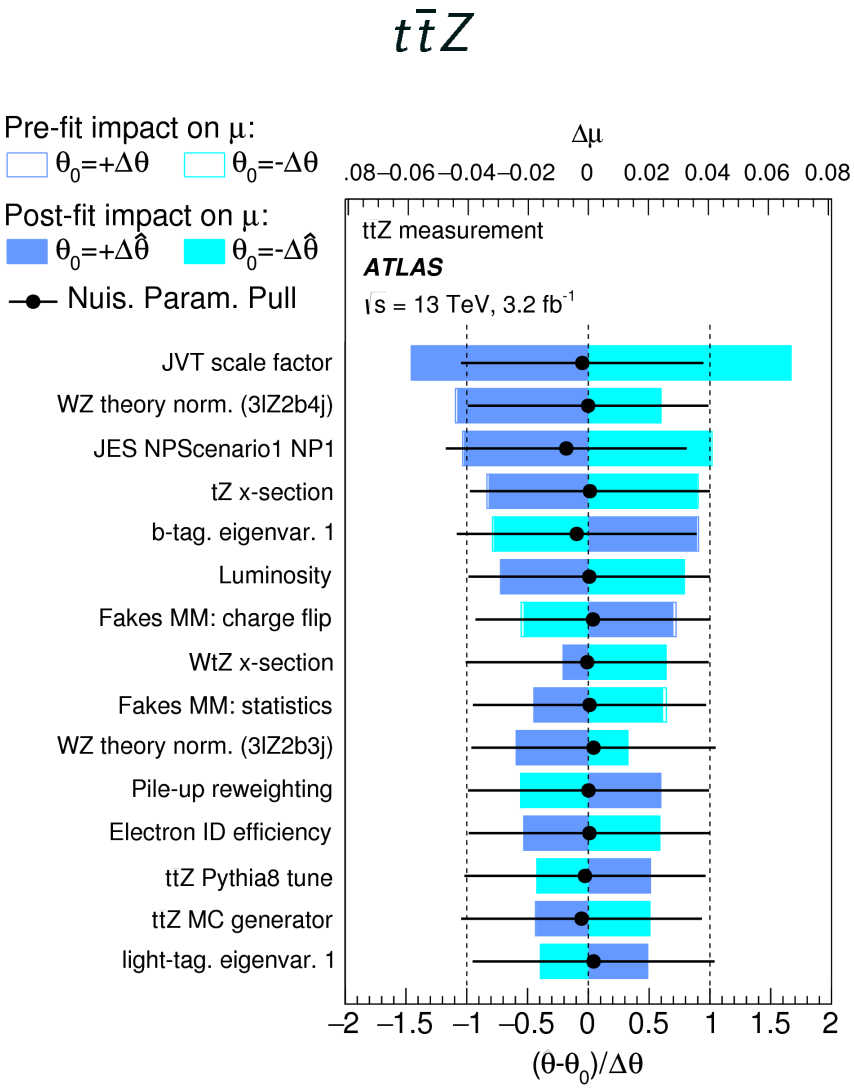
Source	Expected 95 % CL upper limit [pb]	Change in the upper limit [%]
Normalisation & MC statistics	1.5	-
Multi-jets normalisation and modelling	1.8	25
Luminosity	1.5	5
Lepton identification	1.5	3
Electron energy scale	1.6	8
Electron energy resolution	1.5	4
Muon momentum scale	1.5	1
Muon momentum resolution	1.5	5
Jet energy scale	1.6	8
Jet energy resolution	1.9	32
Jet reconstruction efficiency	1.5	4
Jet vertex fraction scale	1.5	3
b-tagging efficiency	1.5	3
c-tagging efficiency	1.5	4
Mistag acceptance	1.5	2
$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	1.9	34
PDF	1.5	5
Scale variations	1.5	2
MC generator (NLO subtraction method)	1.6	8
Parton shower modelling	1.5	5
All systematic uncertainties	2.9	-

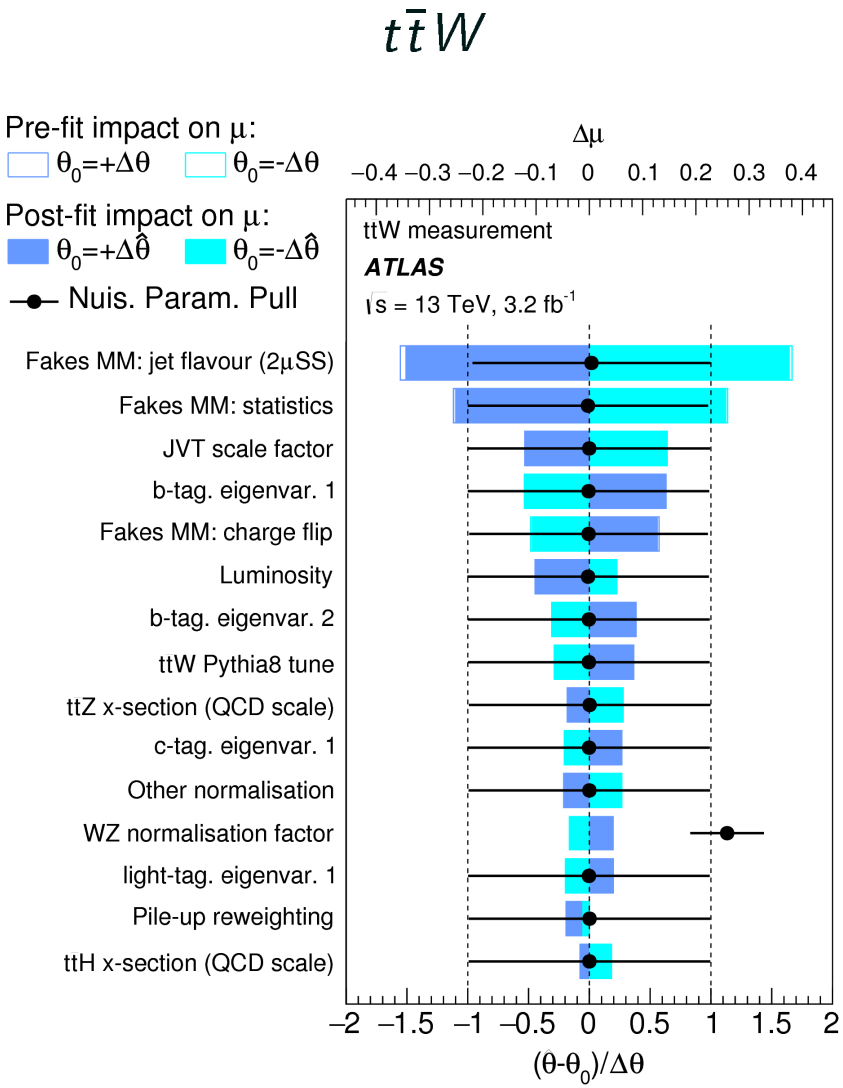
Searches for FCNC with top quarks - Systematics

$t \to qZ$

Source	Background [%]	Signal [%]
Background modelling	17	—
Signal modelling	—	5.5
Leptons	4.7	2.9
Jets	7.7	4.9
b-tagging	3.9	7.2
$E_{\mathrm{T}}^{\mathrm{miss}}$	3.2	1.5
Luminosity	2.4	2.8
Statistical	8.1	1.5

$t\bar{t}W$ and $t\bar{t}Z$ x-section - systematics





$t\bar{t}\gamma$ x-section - systematics

Source	Relative uncertainty [%]
Hadron-fake template	6.3
$e \to \gamma$ fake	6.3
Jet energy scale	4.9
$W\gamma$+jets	4.0
$Z\gamma$+jets	2.8
Initial- and final-state radiation	2.2
Luminosity	2.1
Photon	1.4
Single top+γ	1.2
Muon	1.2
Electron	1.0
Scale uncertainty	0.6
Parton shower	0.6
Statistical uncertainty	5.1
Total uncertainty	13

Top quark decay width- systematics

Source	Uncertainty [GeV]
Detector model	
Electron	$^{+0.14}_{-0.07}$
Muon	$^{+0.11}_{-0.06}$
Jet energy scale	$^{+0.42}_{-0.30}$
Jet resolution	± 0.27
Jet vertex fraction	$^{+0.13}_{-0.03}$
Jet reconstruction efficiency	± 0.03
Missing transverse momentum	± 0.01
b-Tagging	$^{+0.32}_{-0.24}$
Signal model	
ME generator	± 0.41
Color reconnection	± 0.19
Underlying event	± 0.11
Radiation	± 0.07
PDF	± 0.06
PS/fragmentation	± 0.05
Background model	
Multijet	$^{+0.04}_{-0.00}$
W+jets	± 0.02
Single top	< 0.01
Template statistics	± 0.07
Luminosity	$^{+0.03}_{-0.00}$
Total systematic uncertainty	$^{+0.79}_{-0.68}$

Top mass: dilepton - systematics

	$\sqrt{s}=7$ TeV		$\sqrt{s}=8$ TeV	Correlations			Combinations		
	$m_{\text{top}}^{\ell+\text{jets}}$ [GeV]	$m_{\text{top}}^{\text{dil}}$ [GeV]	$m_{\text{top}}^{\text{dil}}$ [GeV]	ρ_{01}	ρ_{02}	ρ_{12}	$m_{\text{top}}^{7\text{ TeV}}$ [GeV]	$m_{\text{top}}^{\text{dil}}$ [GeV]	$m_{\text{top}}^{\text{all}}$ [GeV]
Results	172.33	173.79	172.99				172.99	173.04	172.84
Statistics	0.75	0.54	0.41	0	0	0	0.48	0.38	0.34
Method	0.11 ± 0.10	0.09 ± 0.07	0.05 ± 0.07	0	0	0	0.07	0.05	0.05
Signal Monte Carlo generator	0.22 ± 0.21	0.26 ± 0.16	0.09 ± 0.15	+1.00	+1.00	+1.00	0.24	0.10	0.14
Hadronisation	0.18 ± 0.12	0.53 ± 0.09	0.22 ± 0.09	+1.00	+1.00	+1.00	0.34	0.24	0.23
Initial- and final-state QCD radiation	0.32 ± 0.06	0.47 ± 0.05	0.23 ± 0.07	−1.00	−1.00	+1.00	0.04	0.24	0.08
Underlying event	0.15 ± 0.07	0.05 ± 0.05	0.10 ± 0.14	−1.00	−1.00	+1.00	0.06	0.10	0.02
Colour reconnection	0.11 ± 0.07	0.14 ± 0.05	0.03 ± 0.14	−1.00	−1.00	+1.00	0.01	0.03	0.01
Parton distribution function	0.25 ± 0.00	0.11 ± 0.00	0.05 ± 0.00	+0.57	−0.29	+0.03	0.17	0.04	0.08
Background normalisation	0.10 ± 0.00	0.04 ± 0.00	0.03 ± 0.00	+1.00	+0.23	+0.23	0.07	0.03	0.04
W/Z+jets shape	0.29 ± 0.00	0.00 ± 0.00	0	0			0.16	0.00	0.09
Fake leptons shape	0.05 ± 0.00	0.01 ± 0.00	0.08 ± 0.00	+0.23	+0.20	−0.08	0.03	0.07	0.05
Jet energy scale	0.58 ± 0.11	0.75 ± 0.08	0.54 ± 0.04	−0.23	+0.06	+0.35	0.41	0.52	0.41
Relative b-to-light-jet energy scale	0.06 ± 0.03	0.68 ± 0.02	0.30 ± 0.01	+1.00	+1.00	+1.00	0.34	0.32	0.25
Jet energy resolution	0.22 ± 0.11	0.19 ± 0.04	0.09 ± 0.05	−1.00	0	0	0.03	0.08	0.08
Jet reconstruction efficiency	0.12 ± 0.00	0.07 ± 0.00	0.01 ± 0.00	+1.00	+1.00	+1.00	0.10	0.01	0.04
Jet vertex fraction	0.01 ± 0.00	0.00 ± 0.00	0.02 ± 0.00	−1.00	+1.00	−1.00	0.00	0.02	0.02
b-tagging	0.50 ± 0.00	0.07 ± 0.00	0.03 ± 0.02	−0.77	0	0	0.25	0.03	0.15
Leptons	0.04 ± 0.00	0.13 ± 0.00	0.14 ± 0.01	−0.34	−0.52	+0.96	0.05	0.14	0.09
$E_{\text{T}}^{\text{miss}}$	0.15 ± 0.04	0.04 ± 0.03	0.01 ± 0.01	−0.15	+0.25	−0.24	0.08	0.01	0.05
Pile-up	0.02 ± 0.01	0.01 ± 0.00	0.05 ± 0.01	0	0	0	0.01	0.05	0.03
Total systematic uncertainty	1.03 ± 0.31	1.31 ± 0.23	0.74 ± 0.29				0.77	0.74	0.61
Total	1.27 ± 0.33	1.41 ± 0.24	0.84 ± 0.29	−0.07	0.00	0.51	0.91	0.84	0.70

Top mass: all-hadronic - systematics

Source of uncertainty	Δm_{top} [GeV]
Monte Carlo generator	0.18 ± 0.21
Hadronisation modelling	0.64 ± 0.15
Parton distribution functions	0.04 ± 0.00
Initial/final-state radiation	0.10 ± 0.28
Underlying event	0.13 ± 0.16
Colour reconnection	0.12 ± 0.16
Bias in template method	0.06
Signal and bkgd parameterisation	0.09
Non all-hadronic $t\bar{t}$ contribution	0.06
ABCD method *vs.* ABCDEF method	0.16
Trigger efficiency	0.08 ± 0.01
Lepton/$E_{\text{T}}^{\text{miss}}$ calibration	0.02 ± 0.01
Overall flavour-tagging	0.10 ± 0.00
Jet energy scale (JES)	0.60 ± 0.05
b-jet energy scale (bJES)	0.34 ± 0.02
Jet energy resolution	0.10 ± 0.04
Jet vertex fraction	0.03 ± 0.01
Total systematic uncertainty	1.01
Total statistical uncertainty	0.55
Total uncertainty	1.15

Top mass: $t\bar{t} + 1$ jet - systematics

Description	Value [GeV]	%
$m_t^{\mathbf{pole}}$	**173.71**	
Statistical uncertainty	**1.50**	**0.9**
Scale variations	(+0.93, −0.44)	(+0.5, −0.3)
Proton PDF (theory) and α_s	0.21	0.1
Total theory systematic uncertainty	**(+0.95, −0.49)**	**(+0.5, −0.3)**
Jet energy scale (including b-jet energy scale)	0.94	0.5
Jet energy resolution	0.02	¡ 0.1
Jet reconstruction efficiency	0.05	¡ 0.1
b-tagging efficiency and mistag rate	0.17	0.1
Lepton uncertainties	0.07	¡ 0.1
Missing transverse momentum	0.02	0.1
MC statistics	0.13	¡ 0.1
Signal MC generator	0.28	0.2
Hadronization	0.33	0.2
ISR/FSR	0.72	0.4
Colour reconnection	0.14	¡ 0.1
Underlying event	0.25	0.1
Proton PDF (experimental)	0.54	0.3
Background	0.20	0.1
Total experimental systematic uncertainty	**1.44**	**0.8**
Total uncertainty	**(+2.29, −2.14)**	**(+1.3, −1.2)**

Top mass: lepton kinematics - systematics

Template	p_T^{ℓ}	$p_T^{e\mu}$	$m^{e\mu}$	$p_T^{e}+p_T^{\mu}$	$E^{e}+E^{\mu}$
χ^2/N_{dof}	8.1/8	7.5/7	13.9/10	8.0/6	12.5/8
m_t [GeV]	168.4 ± 2.3	173.0 ± 2.1	170.6 ± 4.2	169.4 ± 2.0	166.9 ± 4.0
Data statistics	± 1.0	± 0.9	± 2.0	± 0.9	± 1.3
Expt. systematic	± 1.6	± 1.0	± 3.1	± 1.6	± 1.5
PDF uncertainty	± 1.0	± 0.2	± 1.6	± 0.6	± 3.4
$t\bar{t}$ generator	± 0.4	± 1.4	± 1.4	± 0.4	± 1.1
QCD radiation	± 0.7	± 0.8	± 0.5	± 0.2	± 0.2
Moment 1	p_T^{ℓ}	$p_T^{e\mu}$	$m^{e\mu}$	$p_T^{e}+p_T^{\mu}$	$E^{e}+E^{\mu}$
m_t [GeV]	168.2 ± 2.9	172.4 ± 3.8	166.6 ± 6.5	168.4 ± 2.9	160.8 ± 7.9
Data statistics	± 1.0	± 1.0	± 2.4	± 1.1	± 2.2
Expt. systematic	± 2.1	± 1.6	± 3.8	± 2.1	± 3.1
PDF uncertainty	± 1.2	± 0.3	± 2.9	± 1.1	± 6.7
$t\bar{t}$ generator	± 0.2	± 1.3	± 3.4	± 0.2	± 2.0
QCD radiation	± 1.2	± 3.0	± 1.4	± 1.1	± 0.2
Moment 2	p_T^{ℓ}	$p_T^{e\mu}$	$m^{e\mu}$	$p_T^{e}+p_T^{\mu}$	$E^{e}+E^{\mu}$
m_t [GeV]	168.1 ± 3.2	172.2 ± 4.5	166.9 ± 6.9	167.9 ± 3.3	159.9 ± 9.2
Data statistics	± 1.2	± 1.1	± 2.8	± 1.3	± 2.6
Expt. systematic	± 2.3	± 2.0	± 4.3	± 2.4	± 3.4
PDF uncertainty	± 1.3	± 0.4	± 3.3	± 1.3	± 7.8
$t\bar{t}$ generator	± 0.4	± 1.2	± 3.2	± 0.4	± 2.4
QCD radiation	± 1.2	± 3.7	± 0.7	± 1.3	± 0.2
Moment 3	p_T^{ℓ}	$p_T^{e\mu}$	$m^{e\mu}$	$p_T^{e}+p_T^{\mu}$	$E^{e}+E^{\mu}$
m_t [GeV]	168.3 ± 3.5	172.0 ± 5.6	166.4 ± 9.1	167.6 ± 3.8	160.9 ± 9.5
Data statistics	± 1.5	± 1.4	± 4.2	± 1.6	± 3.0
Expt. systematic	± 2.5	± 2.6	± 6.0	± 2.7	± 3.7
PDF uncertainty	± 1.5	± 0.6	± 4.1	± 1.4	± 7.8
$t\bar{t}$ generator	± 0.6	± 1.1	± 3.5	± 0.7	± 2.4
QCD radiation	± 1.1	± 4.6	± 0.2	± 1.4	± 0.2

Top mass: lepton kinematics - systematics II

	p_T^{ℓ}	$p_T^{e\mu}$	$m^{e\mu}$	$p_T^{e}+p_T^{\mu}$	$E^{e}+E^{\mu}$
χ^2/N_{dof}	9/8	5/7	11/10	11/6	8/8
m_t^{pole} [GeV]	$169.7^{+2.9}_{-2.7}$	175.1 ± 1.9	$174.5^{+5.1}_{-5.3}$	170.3 ± 2.1	$168.5^{+3.2}_{-3.3}$
Data statistics	± 2.0	± 1.4	$^{+3.8}_{-4.0}$	± 1.4	± 2.3
Expt. systematic	$^{+2.5}_{-2.3}$	± 0.9	$^{+2.9}_{-3.3}$	$^{+1.5}_{-1.6}$	± 2.0
PDF uncertainty	± 0.5	± 0.1	± 1.1	± 0.5	± 1.4
QCD scales	± 1.1	$^{+0.7}_{-0.8}$	± 2.6	$^{+0.4}_{-0.5}$	± 0.7

	CT14	MMHT	NNPDF 3.0	HERAPDF 2.0	ABM 11	NNPDF nojet
$\mu_F = \mu_R = m_t/2$						
χ^2/N_{dof}	71/68	70/68	67/68	67/68	71/68	64/68
m_t^{pole} [GeV]	173.5 ± 1.2	173.4 ± 1.2	173.2 ± 1.2	172.9 ± 1.2	$172.8^{+1.3}_{-1.2}$	173.1 ± 1.2
Data statistics	± 0.9	± 0.9	± 0.9	± 0.9	± 0.9	± 0.9
Expt. systematic	$^{+0.7}_{-0.8}$	± 0.8	± 0.8	± 0.9	$^{+0.9}_{-0.8}$	± 0.8
PDF uncertainty	± 0.1	± 0.1	$^{+0.1}_{-0.2}$	± 0.1	± 0.1	± 0.4
QCD scales	± 0.1	± 0.1	$^{+0.1}_{-0.0}$	± 0.1	± 0.1	± 0.0
$\mu_F = \mu_R = H_T/4$						
χ^2/N_{dof}	69/68	67/68	64/68	61/68	66/68	60/68
m_t^{pole} [GeV]	173.6 ± 1.3	173.4 ± 1.3	173.2 ± 1.3	173.6 ± 1.3	$173.7^{+1.3}_{-1.2}$	$173.2^{+1.3}_{-1.4}$
$\mu_F = \mu_R = E_T/2$						
χ^2/N_{dof}	71/68	70/68	66/68	64/68	68/68	64/68
m_t^{pole} [GeV]	174.7 ± 1.4	$174.5^{+1.5}_{-1.4}$	$174.3^{+1.5}_{-1.4}$	$173.6^{+1.3}_{-1.2}$	$173.4^{+1.2}_{-1.1}$	$174.0^{+1.5}_{-1.4}$