Top quark mass and properties measurements with the ATLAS detector

Beijing, China, September 2017

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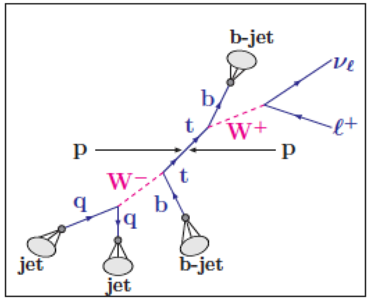
Contents

All ATLAS results on top quark physics can be found in:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
Only a selection of latest measurements is presented.
Charge asymmetry and CP violation in top quark decays are not shown due to time constraints.

Top mass measurement: template method – single lepton

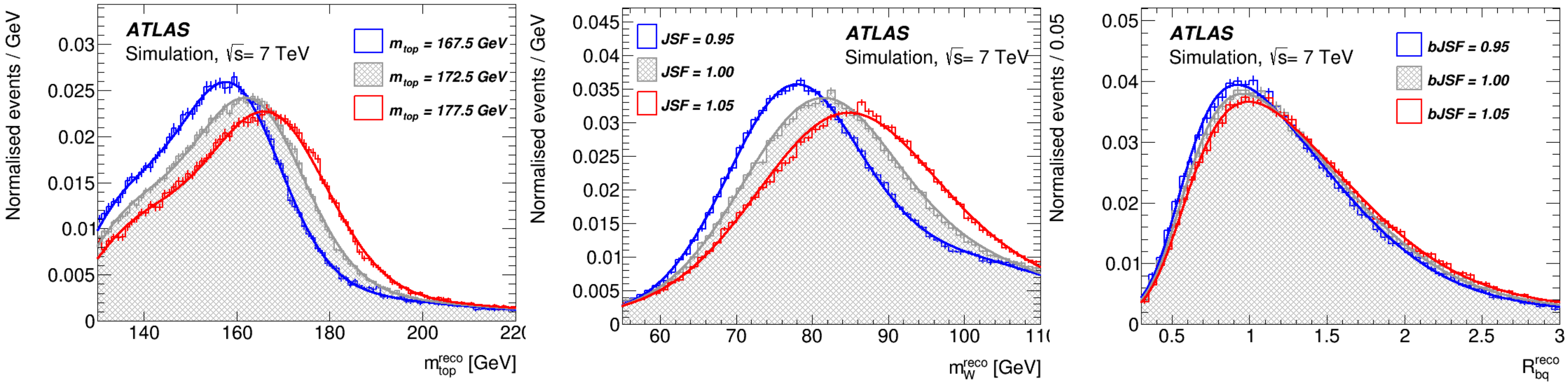
Eur. Phys. J. C75 (2015) 330



Single lepton channel, $\sqrt{s}$ = 7 TeV, 4.7 fb^{-1}
Selection: one lepton (e/μ), $E_{T,miss}$, ≥4 jets, ≥1 *b*-tagged jet (75% eff.)
Reconstruction: kinematic likelihood fit (using *b*-tagging info.)

Template fit (3D) using $\mathbf{m^{reco}_{top}}$ = f($\mathbf{m_{top}}$, **JSF, bJSF),**
$\mathbf{m^{reco}_{W}}$ = f(JSF), and
$\mathbf{R^{reco}_{bq}}$ = f(bJSF) = $\Sigma p_T(b)/\Sigma p_T(q)$ with a weak m_{top} dependence

essential to reduce systematic uncertainties, especially from jet energy scale (JES)



$\mathbf{m^{reco}_{top} \in (130,220)}$ **GeV** $\mathbf{m^{reco}_{W} \in (50,110)}$ **GeV** $\mathbf{R^{reco}_{bq} \in (0.3,3.0)}$

Top mass measurement: template method – single lepton

Single lepton channel, $\sqrt{s}$ = 7 TeV, 4.7 fb^{-1}

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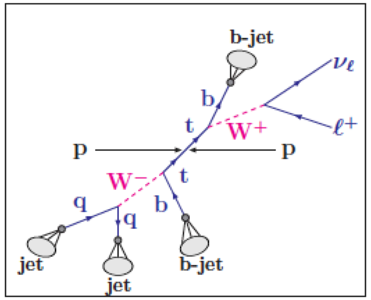

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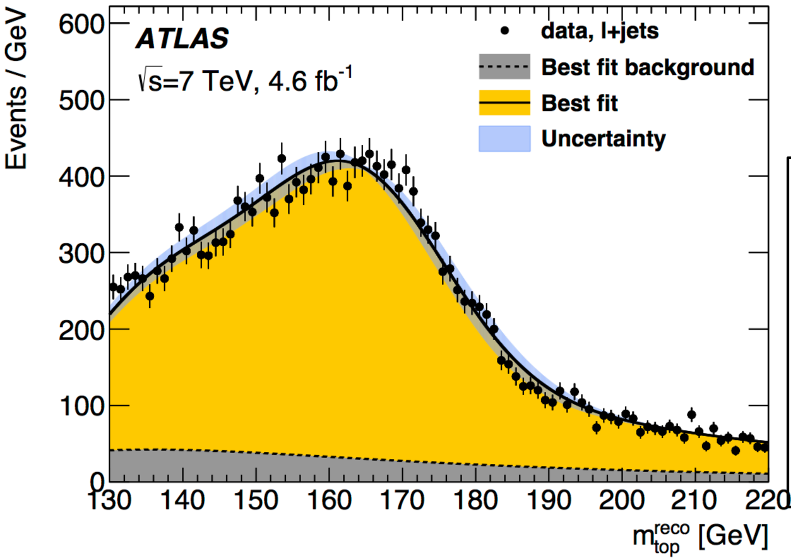
$\mathbf{m^{reco}_{W}}$ = f(JSF), and
$\mathbf{R^{reco}_{bq}}$ = f(bJSF) = $\Sigma p_T(b)/\Sigma p_T(q)$ with a weak m_{top} dependence

Gauss+Landau function for signal, Landau for background

Fit funtion	Signal	Bkg.
$\mathbf{m^{reco}_{top}}$	G+L	L
$\mathbf{m^{reco}_{W}}$	2G	2G
$\mathbf{R^{reco}_{bq}}$	G+L	2G



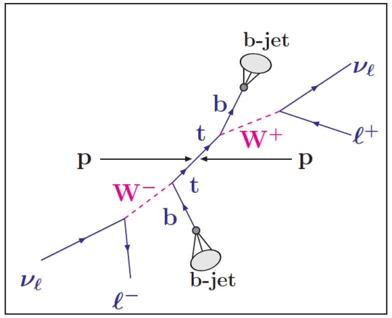
Single lepton 7 TeV:
$\mathbf{m_{top}}$ **= 172.33 ±0.75 (stat+JSF+bJSF) ±1.02 (syst) GeV**
= 172.33 ±1.27 GeV
0.7% rel. unc.
JSF = 1.019 ±0.003 (stat) ±0.027 (syst)
bJSF = 1.003 ±0.008 (stat) ±0.023 (syst)

- Main uncertainties: JES, *tt* modeling.
- Improvements wrt. 2D-fit: bJES 0.88 GeV (2D) → 0.06 GeV (3D)

Top mass measurement: template method – dilepton ch.

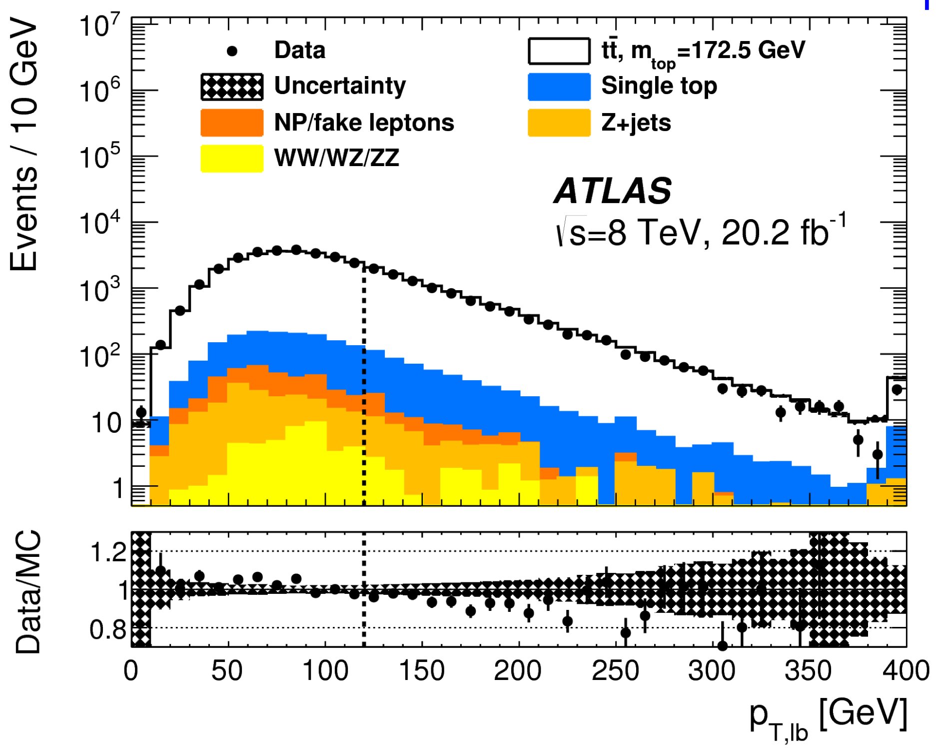
Phys. Lett. B761 (2016) 350

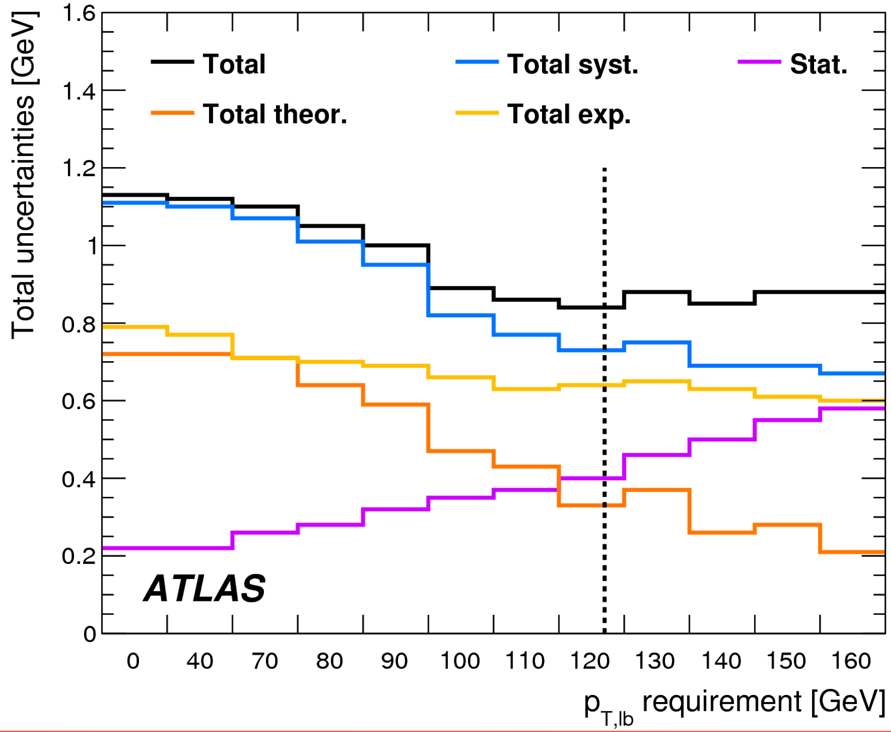
Dilepton channel, $\sqrt{s}$ = 8 TeV, 20.2 fb^{-1}
Selection: two OS leptons, *Z*-mass veto, ≥2 jets, ≥1 *b*-jet (70% eff.)
take 2 b-jets with highest b-tag weight,
assume lowest average m_{lb} = correct pairing
enough statistics → further quaility cuts: p_T of lb system > 120 GeV



Uncertainty vs. $p_{T,lb}$

The optimisation significantly reduces the total uncertainty.



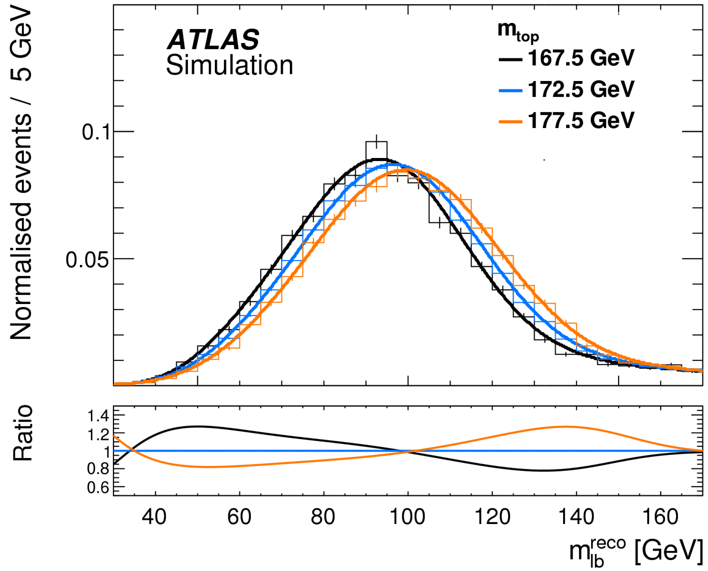


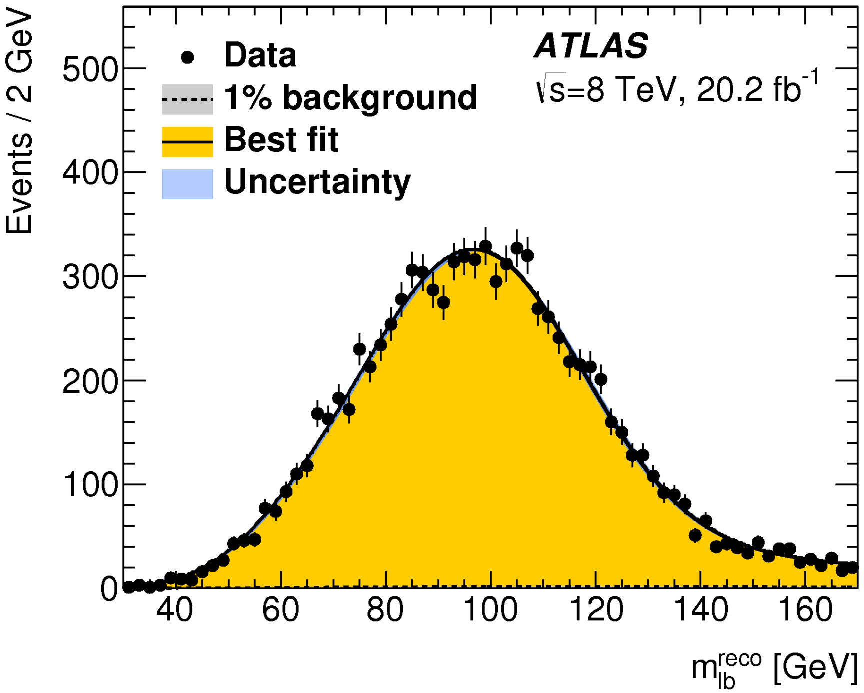
Top mass measurement: template method – dilepton ch.

Phys. Lett. B761 (2016) 350

Dilepton channel, $\sqrt{s}$ = 8 TeV, 20.2 fb^{-1}
Selection: two OS leptons, *Z*-mass veto, ≥2 jets, ≥1 *b*-jet (70% eff.)
lowest average m_{lb} = correct pairing
p_T of lb system > 120 GeV
Template fit using $\mathbf{m_{lb}}$
Gauss+Landau function for signal, Landau for background

$m^{reco}_{lb} \in$ (30,170) GeV





Uncertainty dominated by: JES, bJES and MC modelling (hadronisation and ISR/FSR)

Dilepton 8 TeV:
m_{top} = 172.99 ± 0.41 (stat) ± 0.74 (syst) GeV
0.5% rel. unc. (**most precise single meas.**)

Comb. dilepton 7+8 TeV & single lepton 7 TeV:
m_{top} = 172.84 +- 0.34 (stat) +- 0.61 (syst) GeV
0.4% rel. unc. (improvement by 17%)
<u>correlations of estimators for all syst. unc. evaluated</u>

Top mass measurement: template method – all hadronic

All hadronic channel, $\sqrt{s}$ = 8 TeV, 20.2 fb^{-1} arXiv:1702.07546

Selection: 0 leptons, $E_{T,miss}$<60 GeV, ≥6 jets (≥5 with p_T>55 GeV), ≥2 *b*-jets

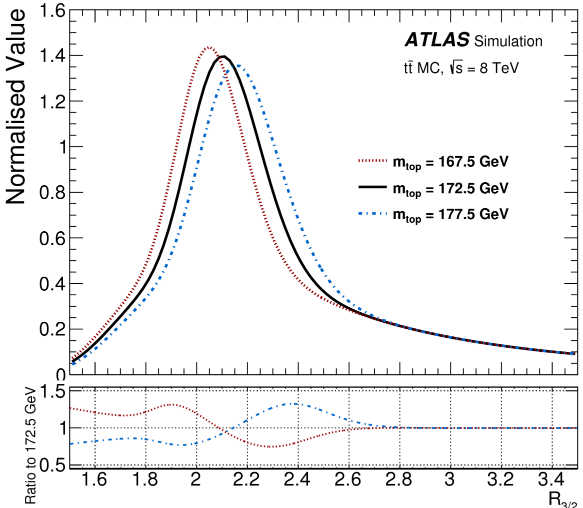
dPhi(b_i,b_j) > 1.5, <dPhi(b,W)> > 2.0

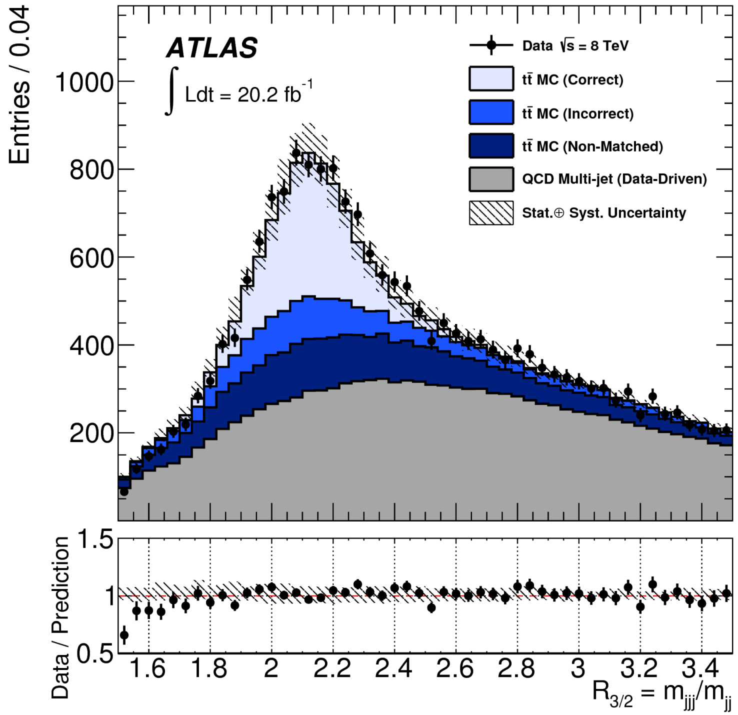
Reconstruction: χ^2 to select best permutation & cut χ^2<11

Multijet bkg. estimation: data-driven method

Template fit using **$R_{3/2} = m_{jjj}/m_{jj} = m_{bqq}/m_{qq}$**

Novosibirsk + Landau function





Two $R_{3/2}$ measurements per event (ρ=0.59) taken into account in final m_{top} stat. unc.

Dominant uncertainties:

JES (0.60 GeV), bJES (0.34 GeV) and hadronisation (0.64 GeV).

All hadronic 8 TeV:

m_{top} = 173.72 ± 0.55 (stat) ± 1.01(syst)

0.7% rel. unc.

40% improvement compared to 7 TeV result

m_{top}^{pole} from lepton and dilepton differential cross-sections

ATLAS-CONF-2017-044

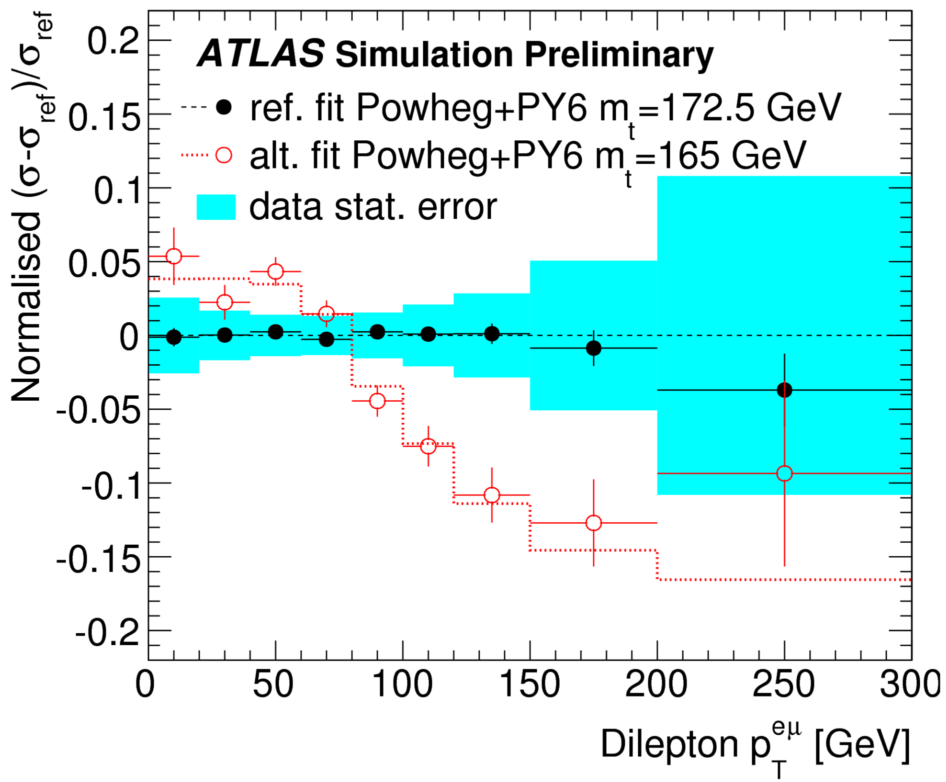
NEW

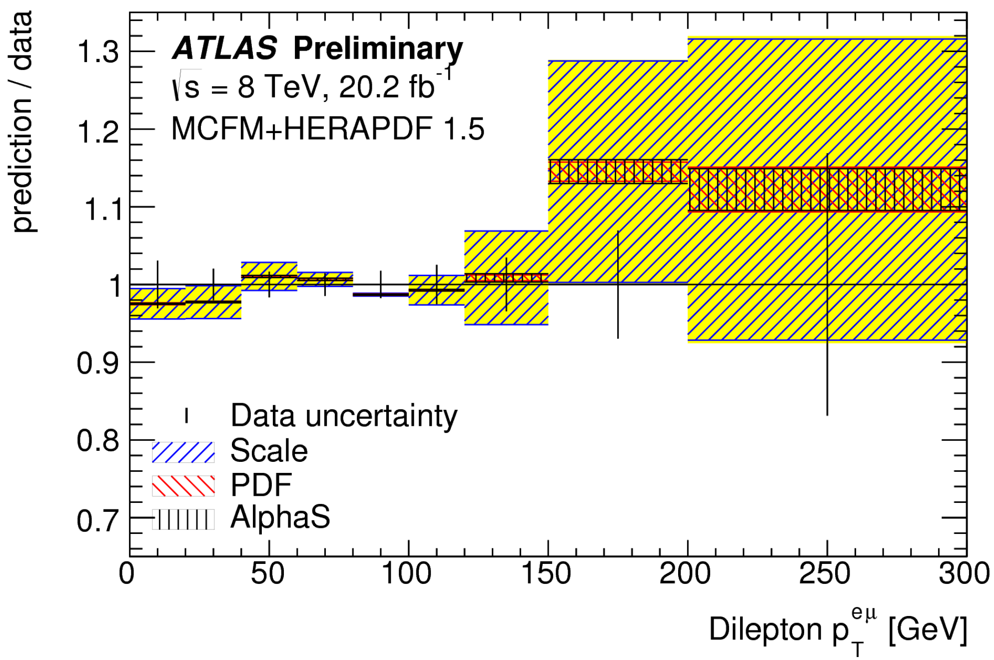
Dilepton channel, $\sqrt{s}$ = 8 TeV, 20.2 fb^{-1}
Selection: e+μ OS, *Z*-mass veto, ≥2 jets, ≥1 *b*-tagged jet

Observables: lepton ($p_{T,l}$, $|\eta_l|$, $p_{T,e}+ p_{T,m}$, $E_{,e}+ E_{,m}$) & dilepton ($p_{T,em}$, m_{em} , $|y_{em}|$, $\Delta\phi_{em}$) diff. dist.

→ Insensitive to detail of modelling the hadronic part of the decay

Pole mass extraction from templafe fits (NLO+PS samples), and
from fixed-order predictions (MCFM samples with diff. PDF)





Dominant uncertainties: limited data statistics, experimental systematics and theoretical unc.

m_{top}^{pole} from lepton and dilepton differential cross-sections

Dilepton channel, $\sqrt{s}$ = 8 TeV, 20.2 fb^{-1}

Selection: e+μ OS, *Z*-mass veto, ≥2 jets, ≥1 *b*-tagged jet

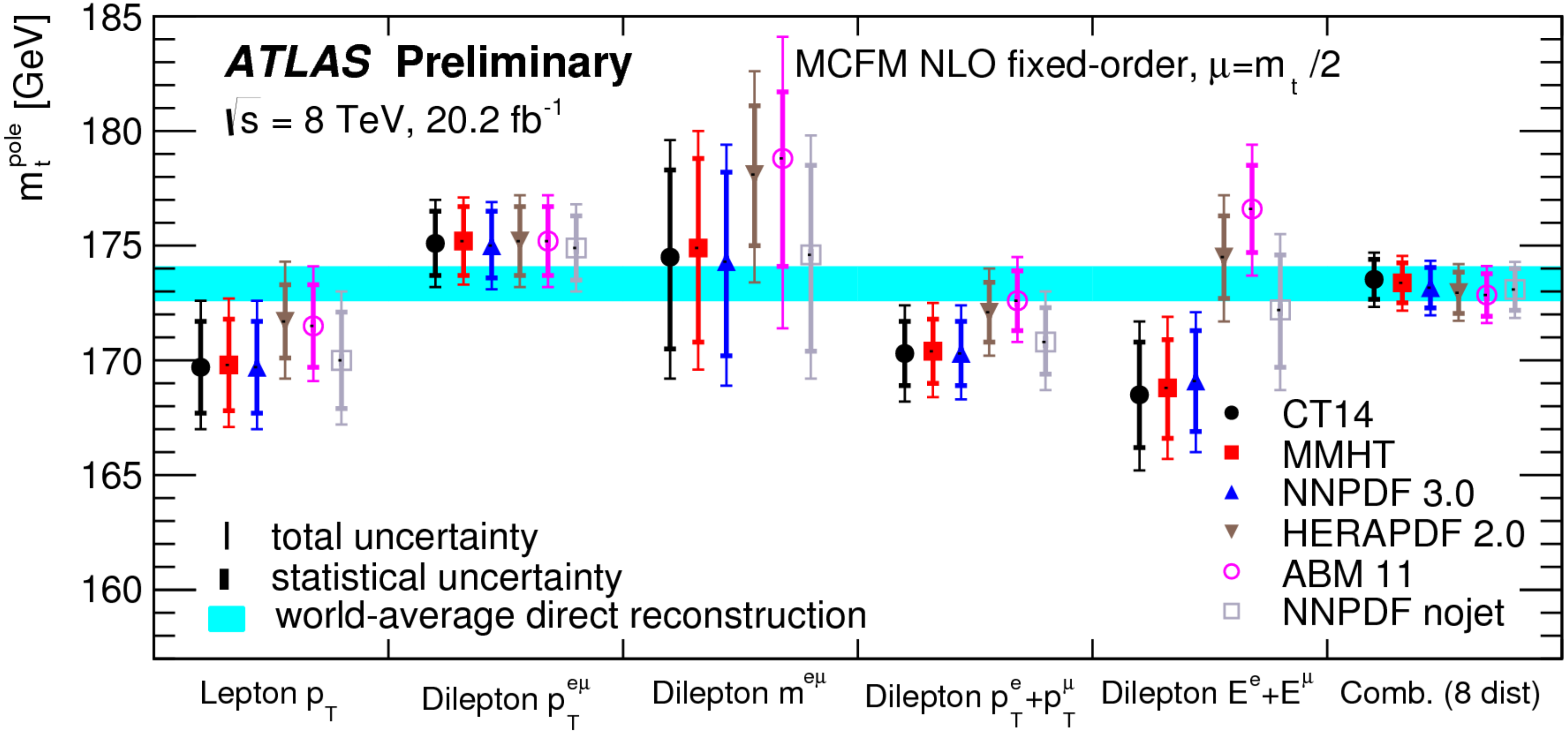
ATLAS-CONF-2017-044

NEW

Observables: lepton ($p_{T,l}$, $|\eta_l|$, $p_{T,e}+p_{T,m}$, $E_{,e}+E_{,m}$) & dilepton ($p_{T,em}$, m_{em} , $|y_{em}|$, $\Delta\phi_{em}$) diff. dist.

The combined result is: m_{top} = 173.2 ± 0.9(stat) ± 0.8(syst) ± 1.2(theory)

The spread in the individual results is about 6 GeV.



Summary top mass: road to < 0.3 GeV precision

Summary of latest "direct MC mass measurements"

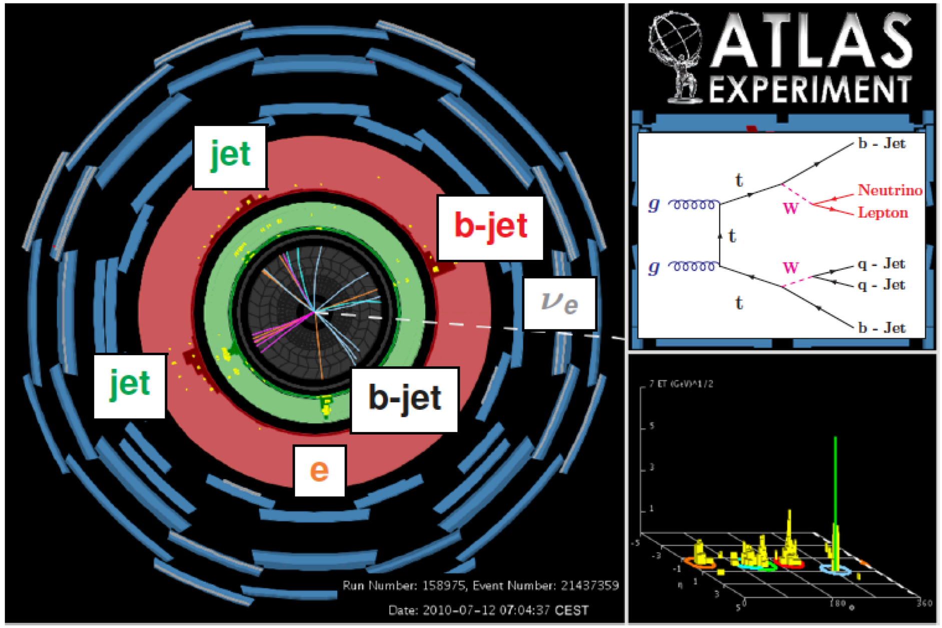
Channel ($\sqrt{s}$)	Value	Stat	Model	Background	Experimental	Total
All-jets (8)	173.72	0.55	0.70 ± 0.16	0.19	0.71 ± 0.04	1.15 (0.66 %)
Lepton + jets (7)	172.33	0.75	0.53 ± 0.11	0.31 ± 0.00	0.82 ± 0.08	1.27 (0.74 %)
Dilepton (8)	172.99	0.41	0.35 ± 0.09	0.08 ± 0.01	0.64 ± 0.04	0.85 (0.49 %)

(Experimental uncertainties) ~ (modelling uncertainties)

- Worthwhile trying **other mass reconstruction methods** than direct mass
- New approaches in standard and alternative channels in template method:
  single top, *J/ψ* in final state, soft muon tagger, secondary vertices with leptons, MVAs, etc.
- Other approaches to measure pole mass:
  tt+jets or 2D differential distributions

- Need **more control of event generators**
  e.g. parton shower, hadronisation, ISR/FSR
- **Precise** (and **in-situ) calibrations** of the energy scale of inclusive jets (**JES**) and the relative *b*-to-light-jet energy scale (**bJES**) are vital for precise measurements of m_{top}

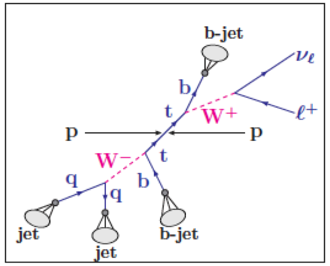
$$t\bar{t} \to (b\, e\, \nu)\,(b\, q\, q),\quad M(qq) = m_W,\quad M(bqq) = m_{top}$$



Top width direct measurement (model independent)

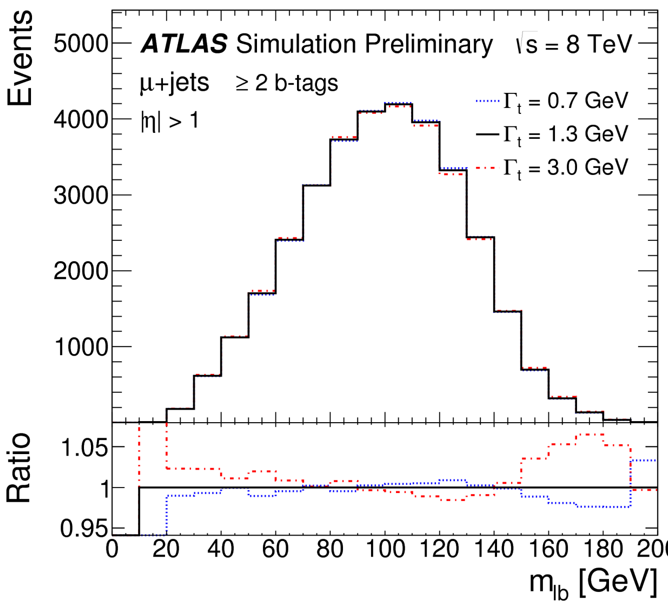
ATLAS-CONF-2017-056

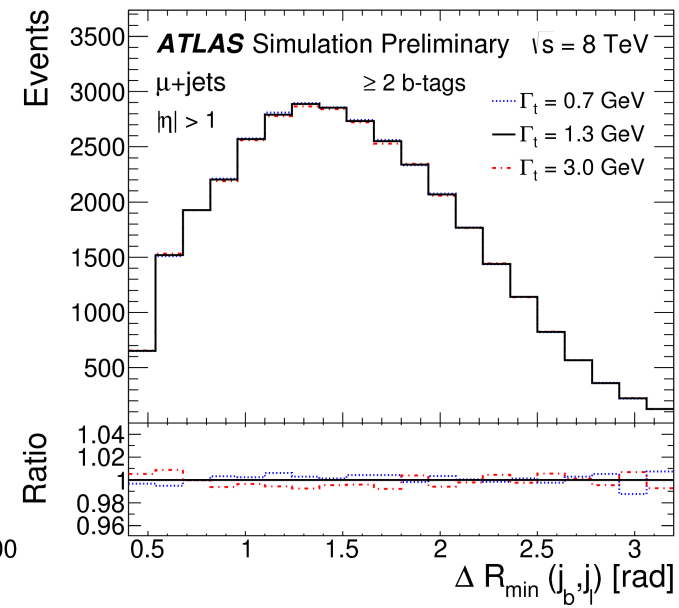
Single lepton channel, $\sqrt{s}$ =8 TeV, 20.2 fb^{-1}
Selection: one lepton, ≥4 jets, ≥1 *b*-tagged jet
Reconstruction: kinematic likelihood fit (using *b*-tagging info.)
Events split into 8 regions: (e/μ) x (=1b, ≥2b) and ($|\eta_{jet}|\leq 1$,$|\eta_{jet}|>1$)

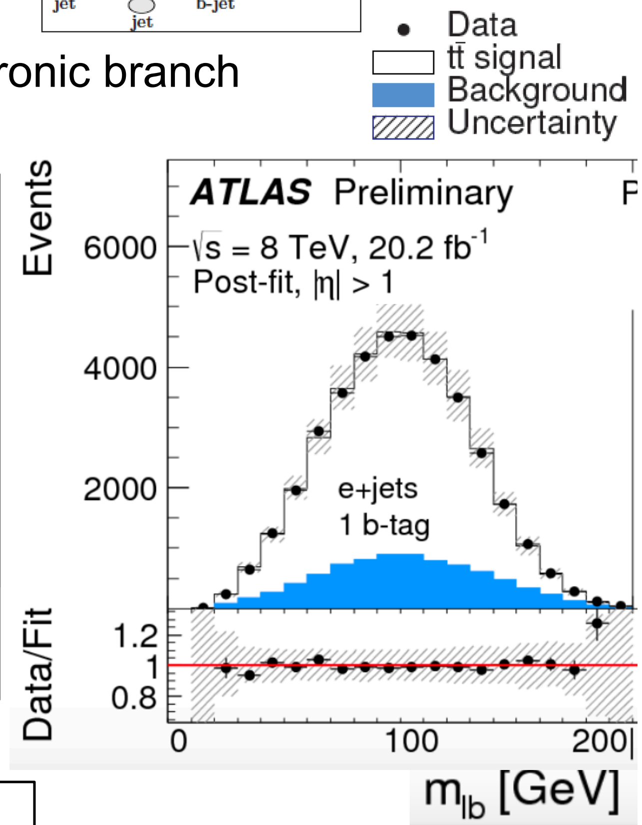


NEW

Template fit using $\mathbf{m_{lb}}$ for the leptonic branch and
$\mathbf{\Delta R_{min(b,q)}}$ (*b*-jet and closest light jet) for the hadronic branch
- templates created by Breit-Wigner reweighting







Γ_{top} = 1.76 ±0.33(stat) $^{+0.79}_{-0.68}$ (syst) GeV for m_{top}=172.5 GeV
→ Consistent with SM Γ_{top} (SM) ~1.32 GeV
→ **First direct top width measurement in ATLAS** (rel.prec. 50%)

Dominant systematics: JES, JER and signal modelling

Top quark couplings

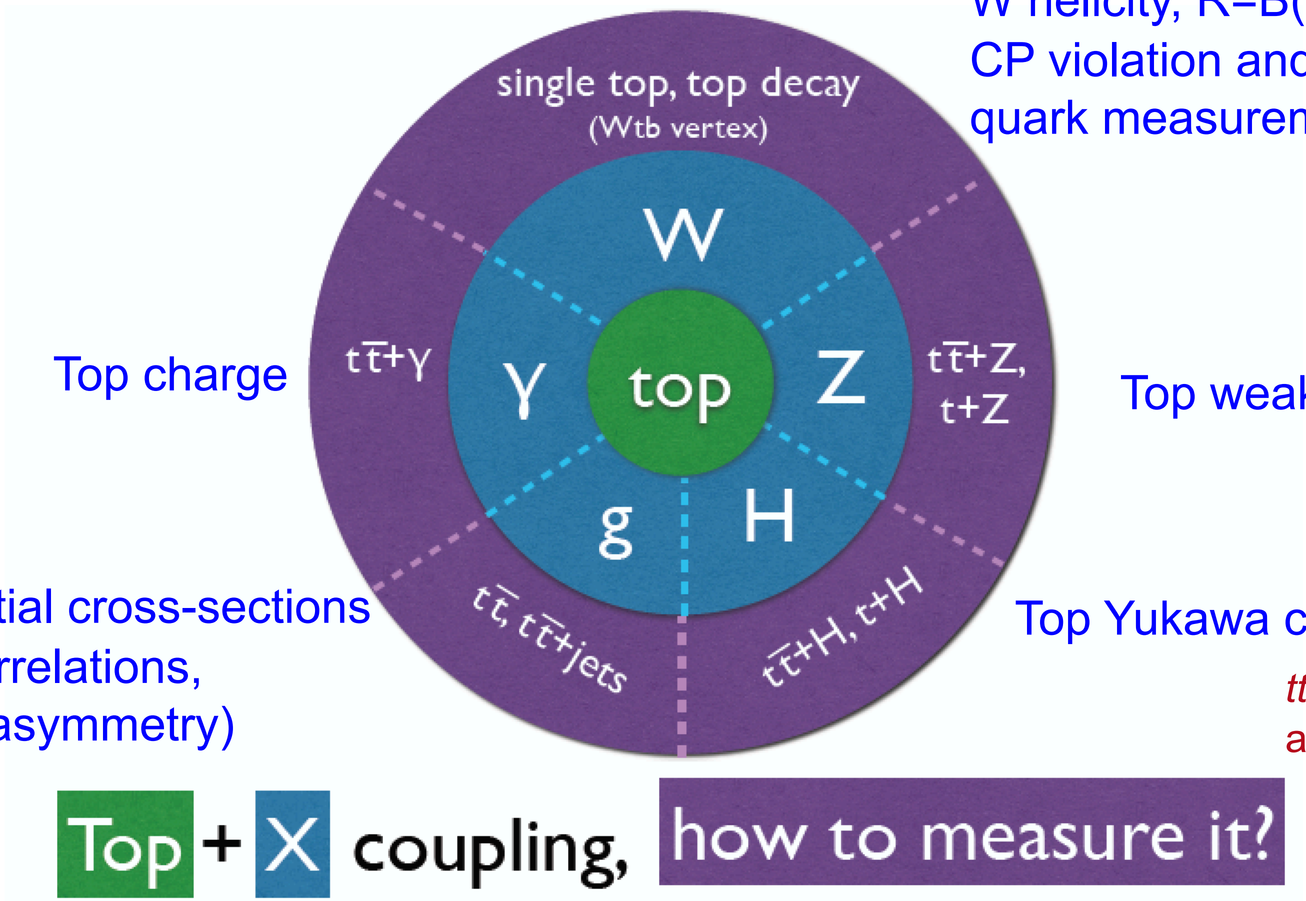
Top quark couples to other SM fields through its **gauge and Yukawa interactions.**
t→*Wb* coupling measured already at the Tevatron.
High statistics at the LHC: *tt*+bosons (γ, *Z*, *W* and *H*) becomes available!!

* Observation of *tt*+γ/*Z*/*W* processes by both ATLAS and CMS with LHC Run1 data.
* Not yet for *tt*+*H* process but getting close… (Run1 LHC Higgs combination: 4.4 σ)

W helicity, R=B(*t*→*Wb*)/B(*t*→*Wq*), CP violation and different single top quark measurements

More details in talk from Markus Cristinziani

Top charge



Top weak isospin

Differential cross-sections (spin correlations, charge asymmetry)

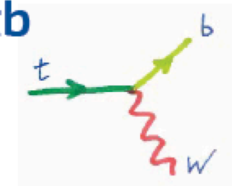
Top Yukawa coupling

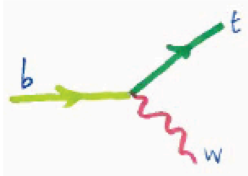
tt+*H* covered in Higgs talks and Shuyang Hu's poster

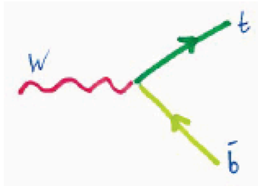
Top coupling to *W* boson (*Wtb* vertex)

Flavour changing charged current

- **Wtb**

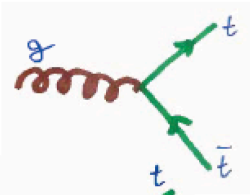


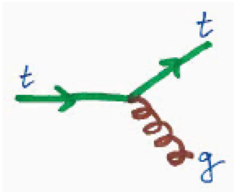




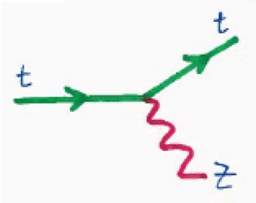
Flavour conserving neutral current

- **tgt**

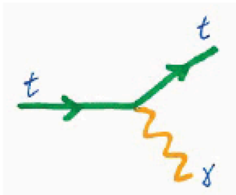




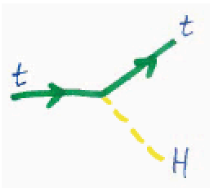
- **tZt**



- **tγt**

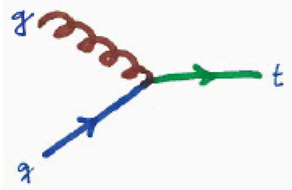


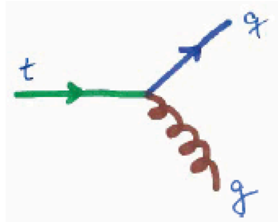
- **tHt**

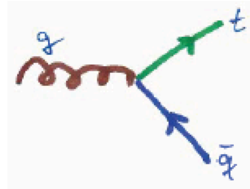


… and neutral current

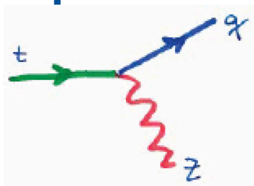
- **tgq**

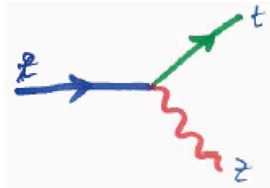




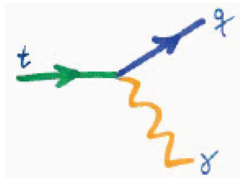


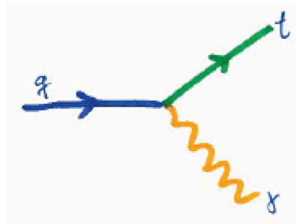
- **tZq**



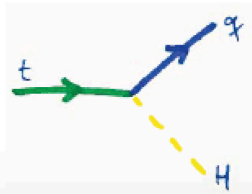


- **tγq**





- **tHq**



Top coupling to *W* boson: *W* helicity fractions in *tt* events

Test V-A structure via angular observables → *W* helicity fractions

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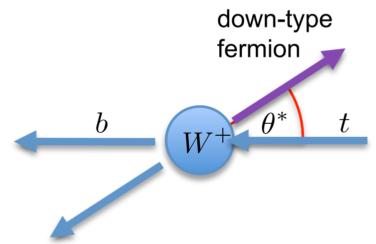
W bosons from top quark decays → 3 possible polarizations: longitudinal, left and right handed

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right) F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R$$

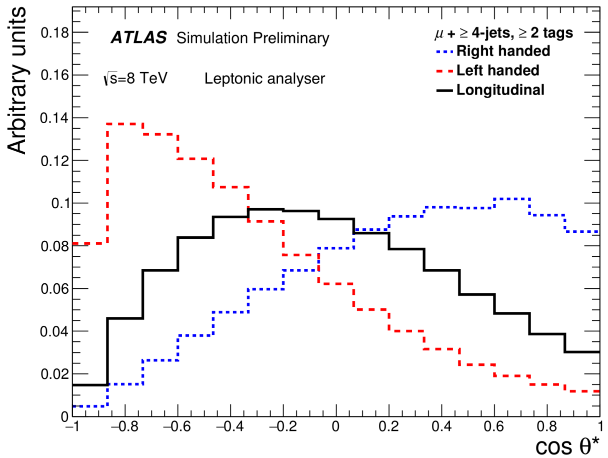


θ_l^* angle between down-type fermion (charged lepton or down-type quark) from W and reversed direction of top quark, both in the W boson rest frame.

Single lepton ch., √s = 8 TeV, 20.2 fb^{-1}
Event reconstruction with KLfitter
Helicity fractions extracted using template fit
Two analyzers: leptonic and hadronic

- Leptonic: [e+μ] x [≥ 2b] → most sensitive
- Hadronic: [e+μ] x [1b + ≥ 2b]

Overall combination: similar to leptonic



NNLO QCD calculation
Phys.Rev.D81:111503,2010

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

Leptonic analyser (most precise)

$F_0 = 0.709 \pm 0.012$ (stat.+bkg.norm.) ± 0.015 (syst.)
$F_L = 0.299 \pm 0.008$ (stat.+bkg.norm.) ± 0.013 (syst.)
$F_R = -0.008 \pm 0.006$ (stat.+bkg.norm.) ± 0.012 (syst.)

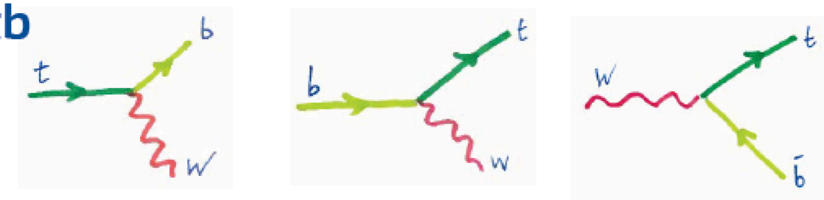
$\rho_{0,L} = -0.55,\ \rho_{0,R} = -0.75,\ \rho_{L,R} = +0.16$

Main uncertainties: JES, JER, signal modelling

Anomalus coupling	95% CL limit
$\mathrm{Re}(V_R)$	[-0.24, 0.31]
$\mathrm{Re}(g_L)$	[-0.14, 0.11]
$\mathrm{Re}(g_R)$	[-0.02, 0.06], [0.74, 0.78]

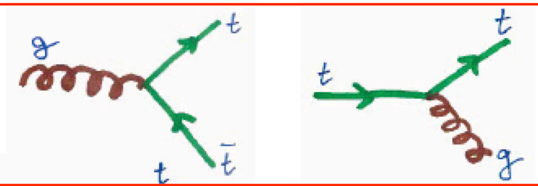
Flavour changing charged current

- Wtb

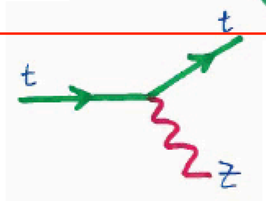


Flavour conserving neutral current

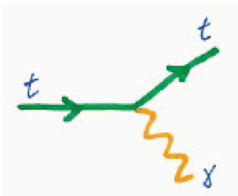
- tgt



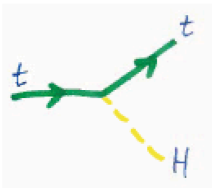
- tZt



- tγt

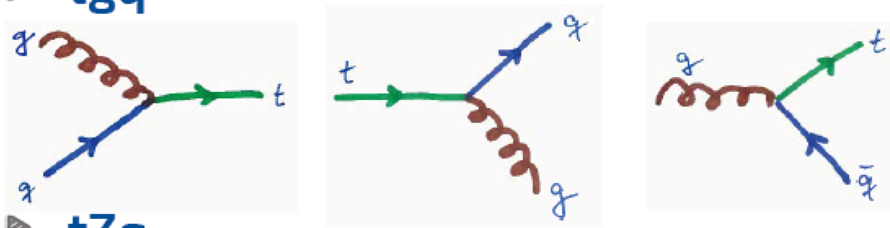


- tHt

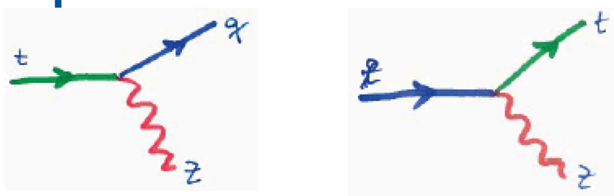


… and neutral current

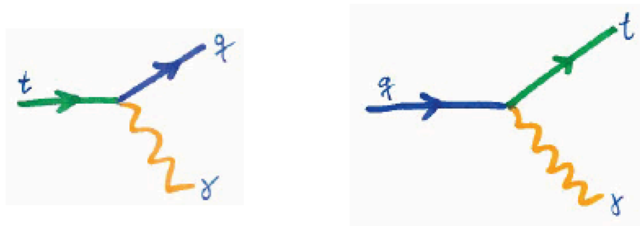
- tgq



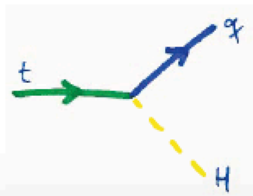
- tZq



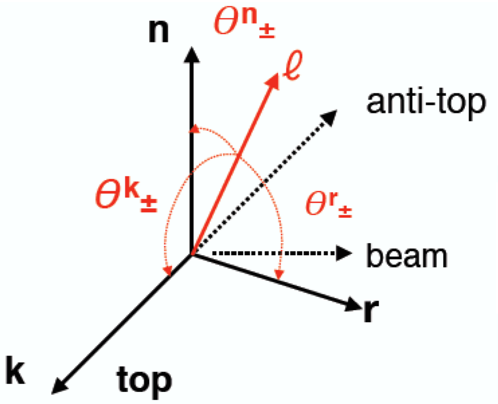
- tγq



- tHq



Top quark coupling to gluon: probe spin correlations



- Top quarks produced via strong interaction are unpolarised, but top and antitop spins are correlated (sensitive to new physics).
- Double angular distribution for decay products stores all information:

t & anti-t polarisation *$t\bar{t}$ spin corr*

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

a,b={k,n,r} +=top decay -=anti-top decay

$\cos\theta^{a,b}_\pm$: **6 angles:**
2 lepton directions in top/anti-top parent rest frame w.r.t **3 spin quantization axes** (a or b)

- **k**: top quark direction **in $t\bar{t}$ rest frame**
- **n**: ⊥ to **k** & **laboratory beam direction**
- **r** : ⊥ to **k** and **n**

15 spin density matrix elements

Dilepton channel, √s = 8 TeV, 20.2 fb^{-1}
Selection: Two OS leptons,
Z-mass veto, ≥2 jets, ≥1 *b*-jet
Event reconstruction using neutrino weighting.

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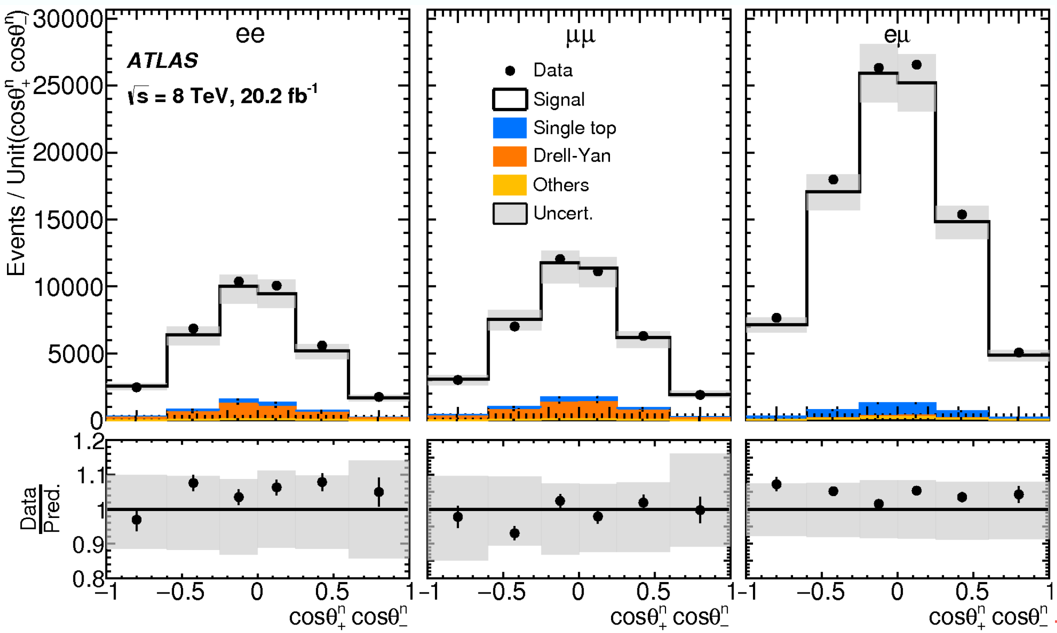
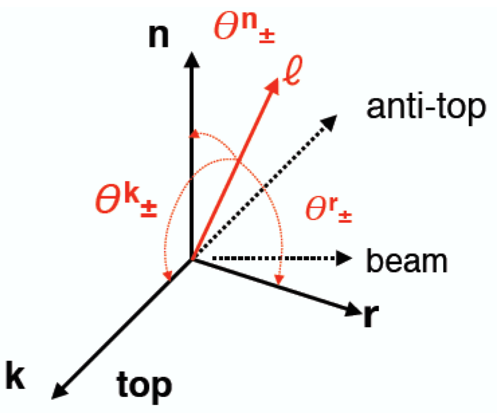


Top quark coupling to gluon: probe spin correlations



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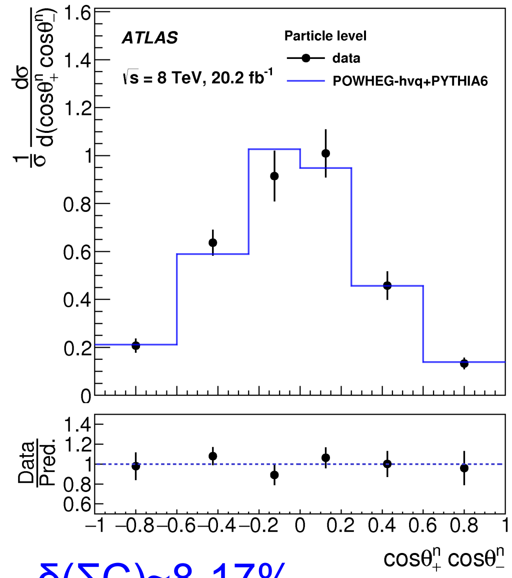
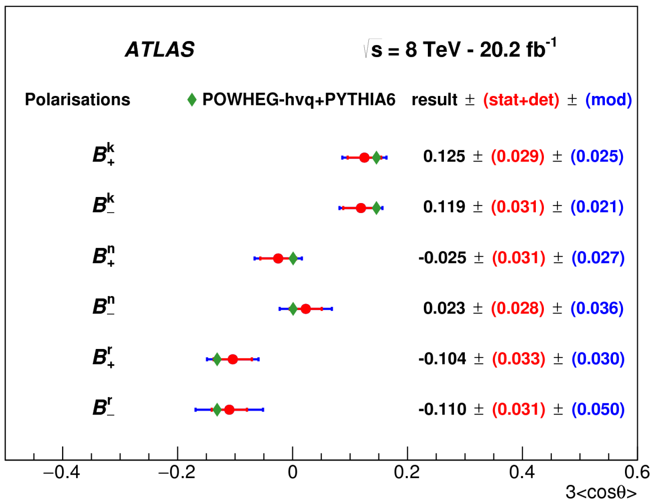
Unfold $\cos\theta^{a,b}_{\pm}$ **&** $\cos\theta^{a}_{+}\cos\theta^{b}_{-}$ with Bayesian scheme, *marginalize sys*

$$C(a,b) = -9\langle \cos\theta^a_+ \cos\theta^b_- \rangle$$

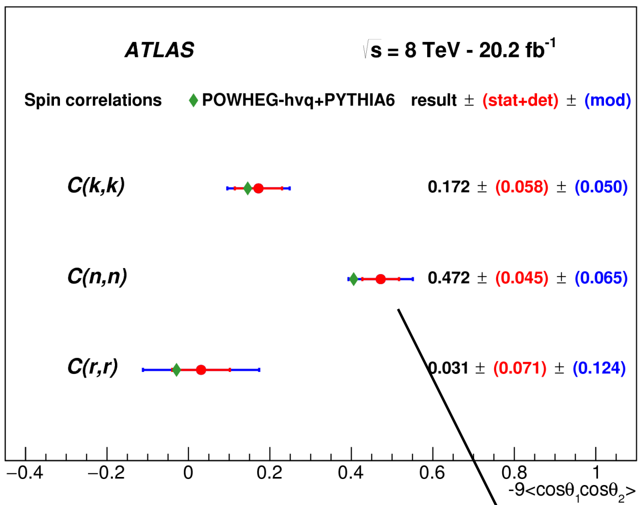
$$B^a = 3\langle \cos\theta^a \rangle$$



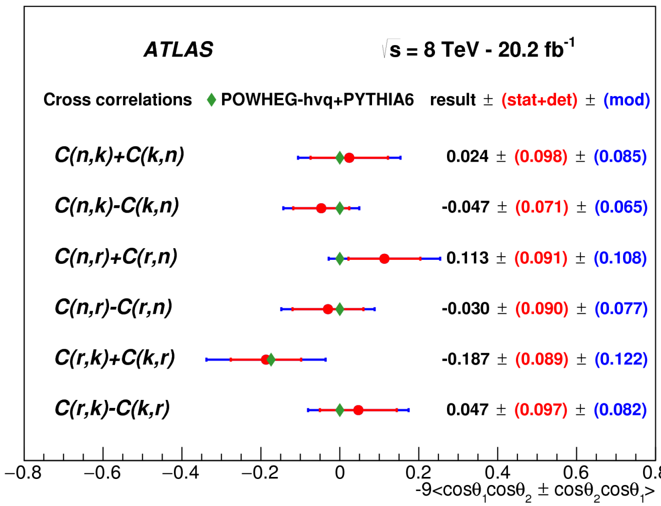
Top polarisation~0 δB~3-4%



δC/C~20-30%



δ(ΣC)~8-17%

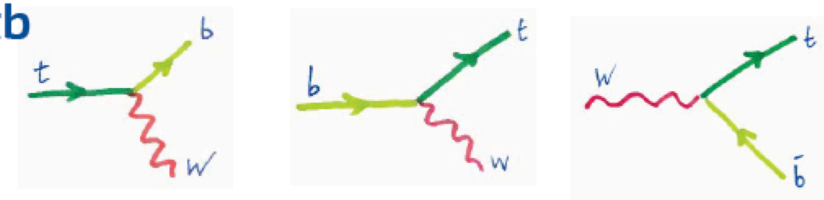


All measurements are in agreement with the SM.
Systematic uncert. dominated by signal modelling.

C(n,n) differs by 5σ from zero correlation

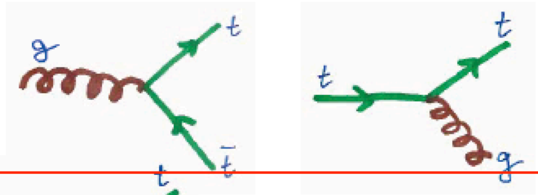
Flavour changing charged current

- Wtb

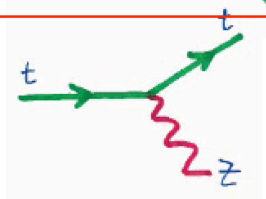


Flavour conserving neutral current

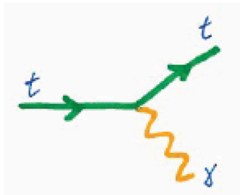
- tgt



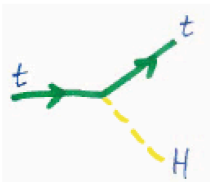
- tZt



- tγt

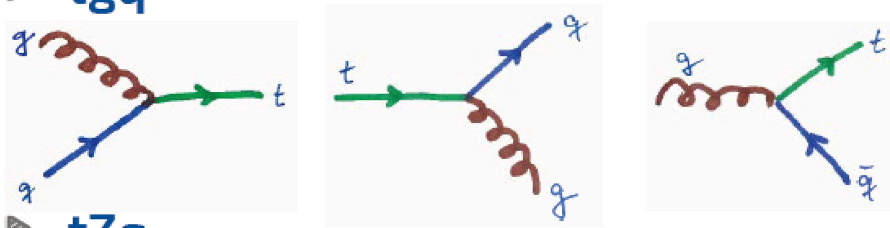


- tHt

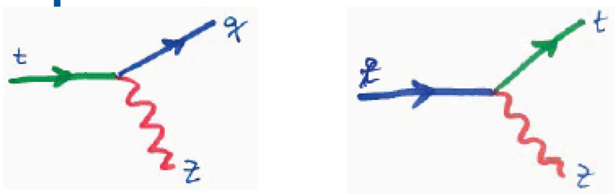


… and neutral current

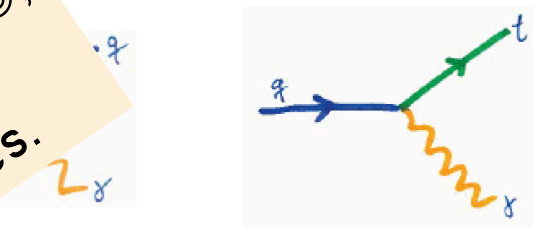
- tgq



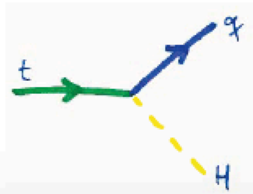
- tZq



- tγq



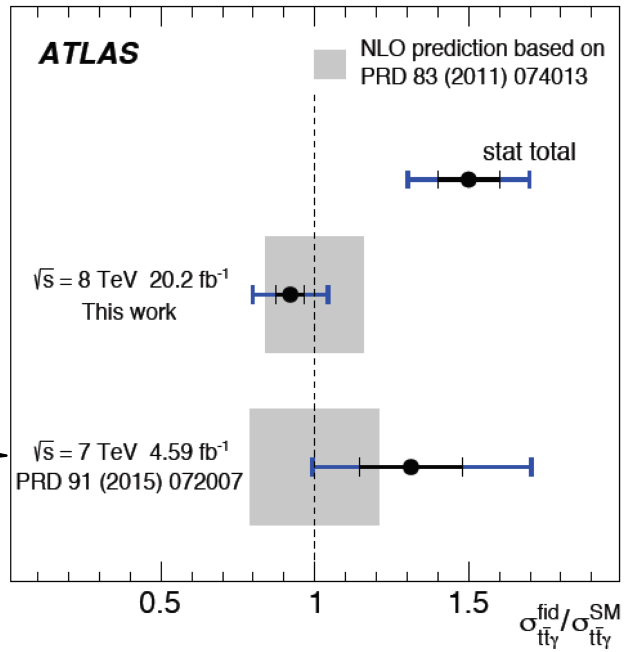
- tHq



One of the highlights of LHC Run II ☺, but very challenging for both experimental and theoretical sides.

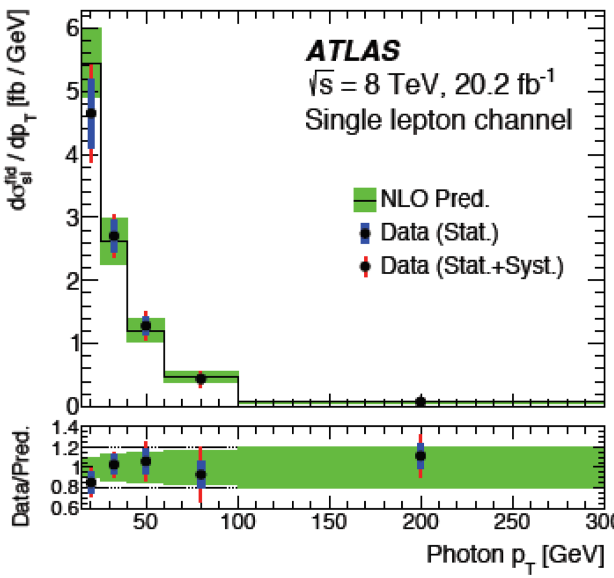
Top coupling to photon: *tt+γ*

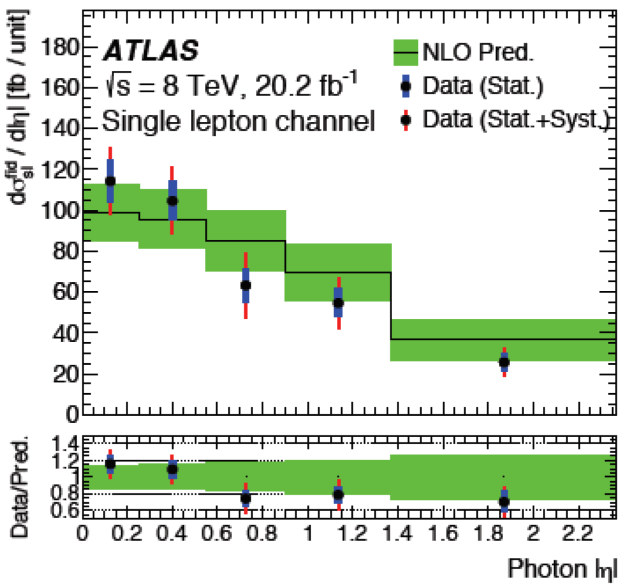
- **First observation (5.3 σ) with 7 TeV data**
  - measurement performed in a fiducial region within the ATLAS acceptance (as p_T^{γ} > 20 GeV)
  - non-prompt photon contributions data-driven
  - template fit to track isolation distribution of photons
  - systematics limited, dominant sources: jet energy scale, photon, signal modelling, *b*-tagging

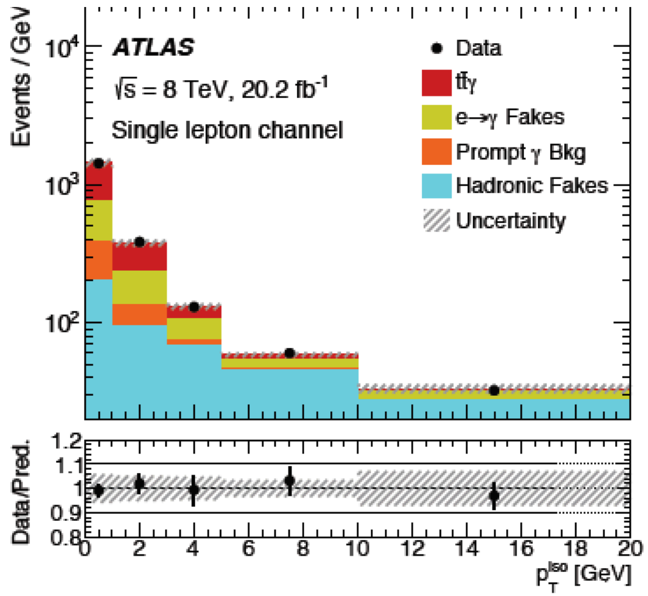


NEW

- **First differential measurements with 8 TeV data** in photon p_T and |η| arXiv:1706.0304
  - fiducial cross-section: rel. unc. 13% (~ theoretical pred.)







Top coupling to vector bosons: *tt+Z/W*

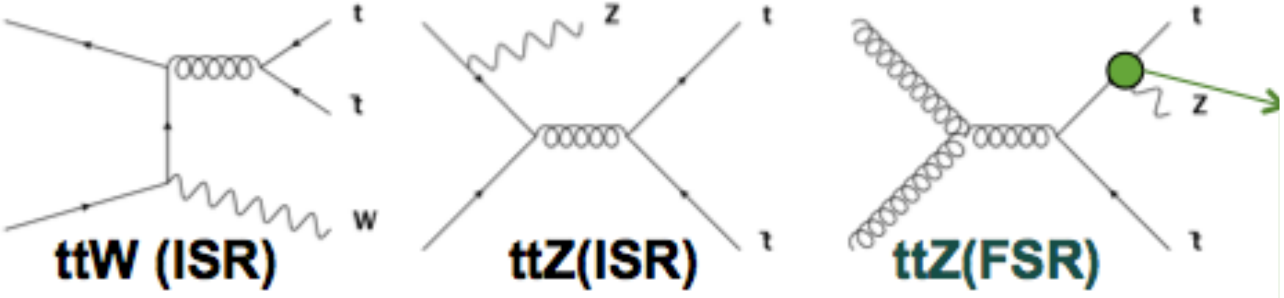
tt+W and *tt+Z* are rare processes - could be modified by new physics
→ Important irreducible background for *tt+H*(multilep), new physics (VLQ, SUSY, etc)

(predicted cross section NLO QCD ~ 600-800 fb each @ 13 TeV).

$$\gamma^\mu(C_V^{SM} - \gamma_5 C_A^{SM})$$

$$C_V^{SM} = T^3 - 2Q_t sin^2(\theta_W)$$

$$C_A^{SM} = T^3$$



Direct measurement of top coupling to *Z* gauge boson in *tt+Z* production via FSR.

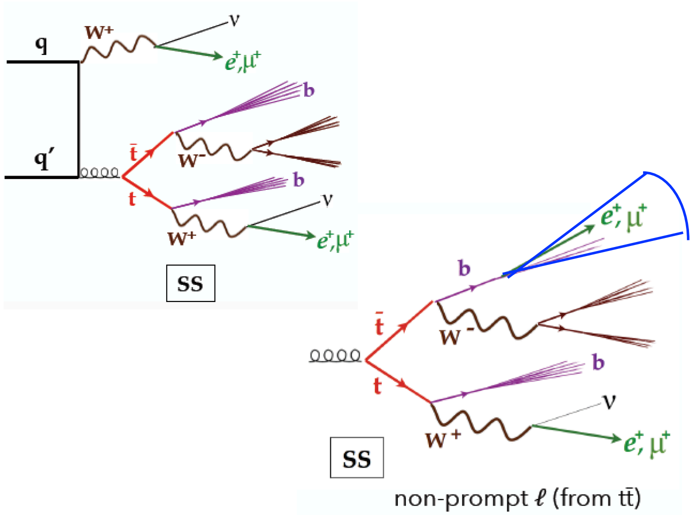
Many experimental signatures.
Most sensitive channels explored in latest ATLAS results ($3.2 fb^{-1}$, 2015 data):
EPJC 77 (2017) 40

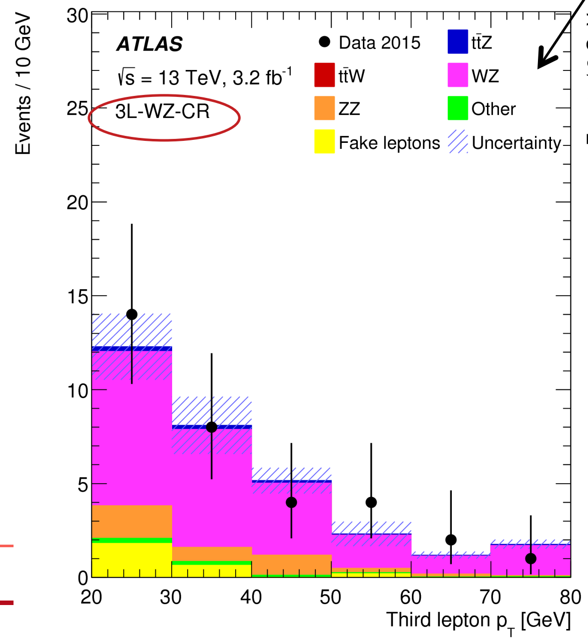
Process	$t\bar{t}$ decay	Boson decay	Channel
$t\bar{t}W^\pm$	$(\mu^\pm\nu b)(q\bar{q}b)$ $(\ell^\pm\nu b)(\ell^\mp\nu b)$	$\mu^\pm\nu$ $\ell^\pm\nu$	SS dimuon Trilepton
$t\bar{t}Z$	$(\ell^\pm\nu b)(q\bar{q}b)$ $(\ell^\pm\nu b)(\ell^\mp\nu b)$	$\ell^+\ell^-$ $\ell^+\ell^-$	Trilepton Tetralepton

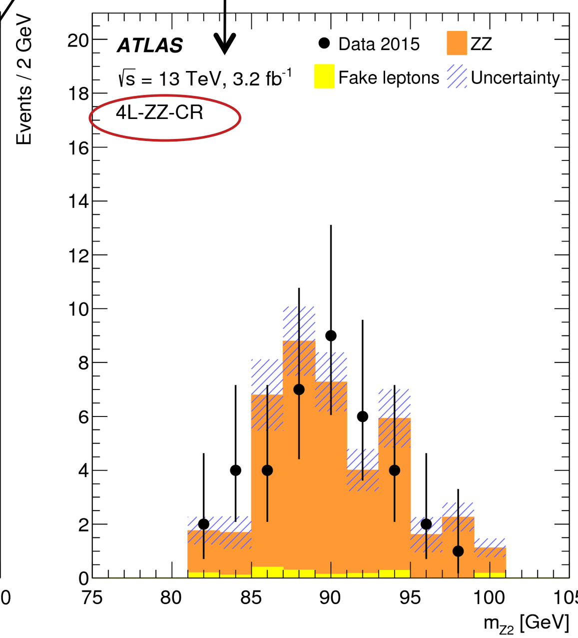
Top coupling to vector bosons: *tt+Z/W*

Sample statistics, S/B ratio and dominant backgrounds vary across different channels
for each of them, several SRs (lepton flavour/charge, nJets, nBjets) and CRs (*WZ*, *ZZ*)

Channel	Sub-channels	Characteristics	Main cuts	Main background
SS dilepton	μμ	targets *tt+W*	≥2 *b*-tags, $E_{T,miss}$	fake leptons (from *tt* events) derived from matrix method (DD) in control sample with 2l OS+SS and looser lepton requirements
Trilepton	*tt*+Z (*W*) enriched	small sample size, good S/B	≥1 *b*-tag Z mass (veto)	leptonic decay *WZ* (fake leptons) One *WZ* CR is included in the fit; another is defined for validation
Tetralepton	*tt*→ same (diff.) flavour	very small sample size, excellent S/B	1-2 OSSF pairs	leptonic decay *ZZ* (rare SM) One *ZZ* CR is included in the fit

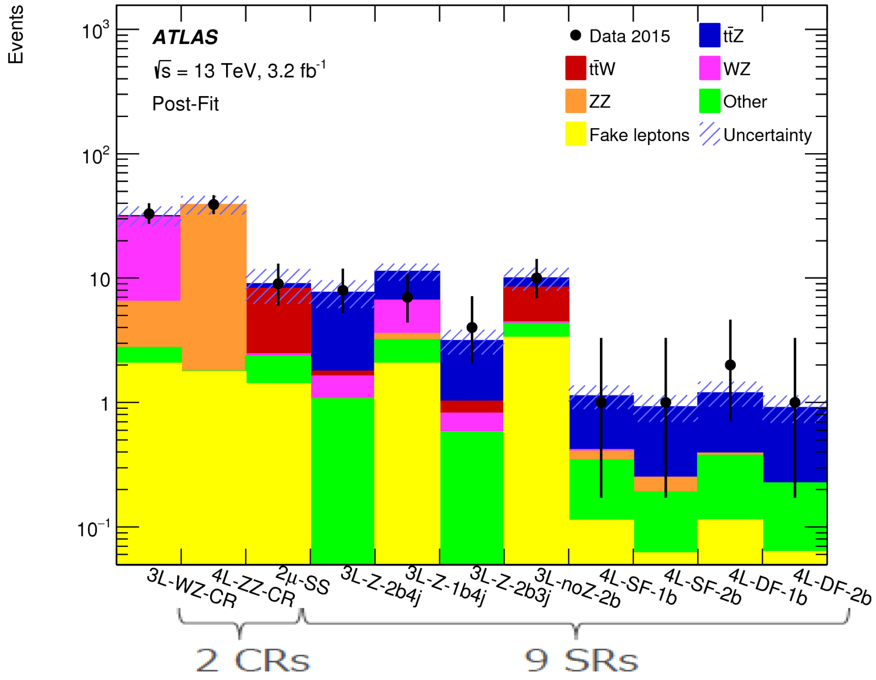


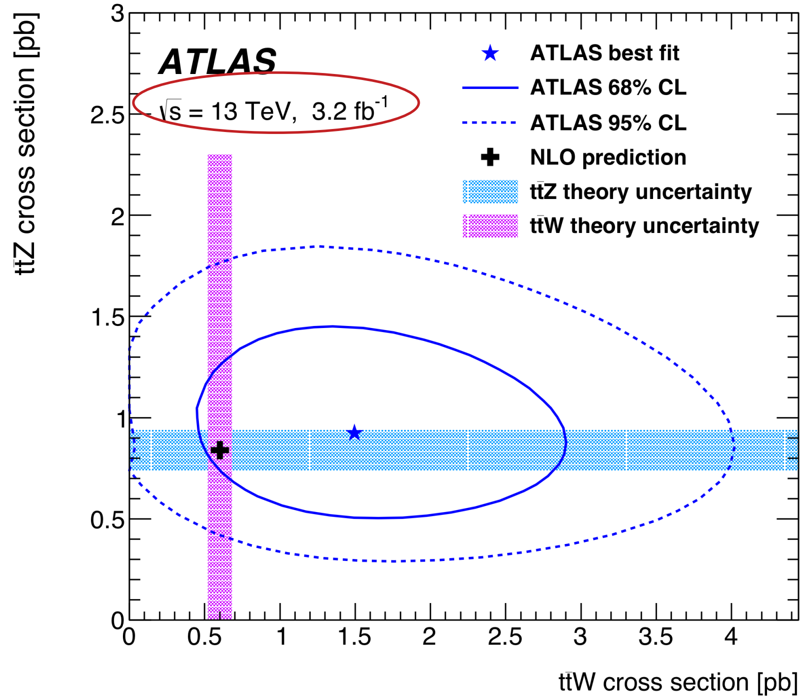




Top coupling to vector bosons: *tt+Z/W*

→ Cross-sections obtained from combined profile likelihood fit to signal and control regions





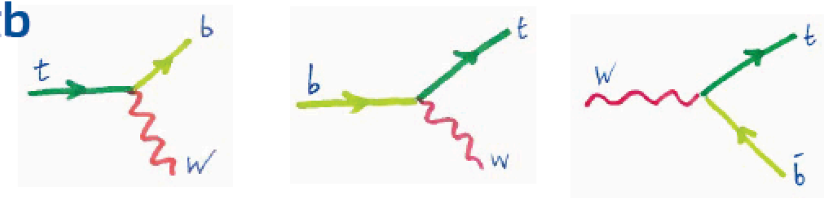
Δσ/σ (%), Significance	*tt+Z*	*tt+W*
ATLAS 2012	32%, 4.2σ	26%, 5.0σ
CMS 2012	27%, 6.4σ	31%, 4.8σ
ATLAS 2015	32%, 3.9σ (31% stat.)	only μμ 53%, 2.2σ (48% stat.)
CMS 2015+2016	14%, 9.9σ (stat ~syst. unc.)	15%, 5.5σ (stat ~syst. unc.)

Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	2.6%	3.1%
Reconstructed objects	8.3%	9.3%
Backgrounds from simulation	5.3%	3.1%
Fake leptons and charge misID	3.0%	18.7%
Signal modelling	2.3%	4.2%
Total systematic	11%	22%
Statistical	31%	48%
Total	32%	53%

Flavour changing neutral currents

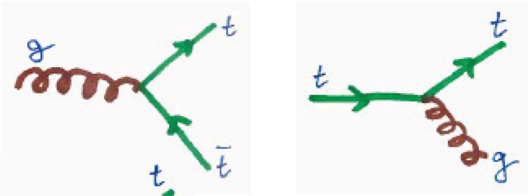
Flavour changing charged current

- Wtb

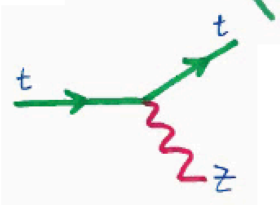


Flavour conserving neutral current

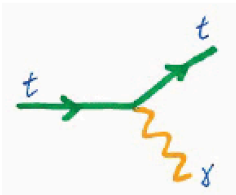
- tgt



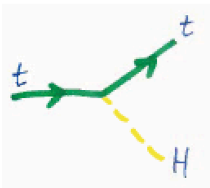
- tZt



- tγt

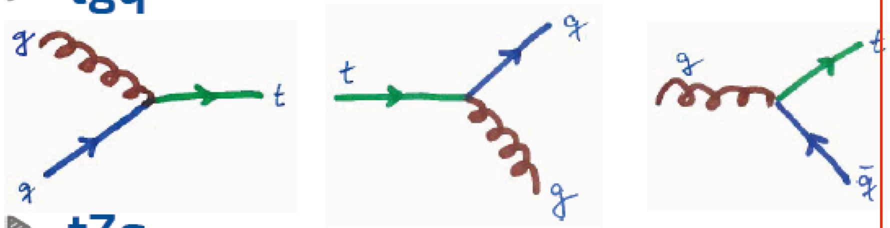


- tHt

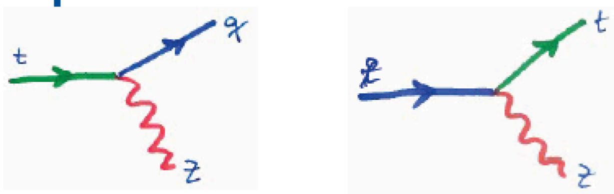


… and neutral current

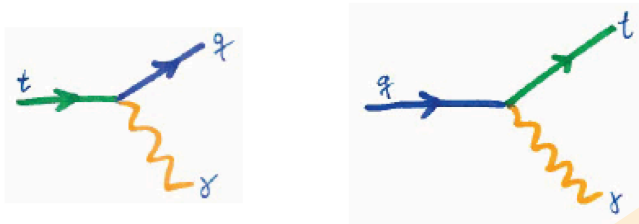
- tgq



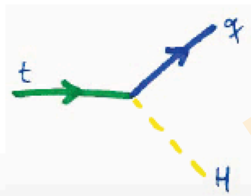
- tZq



- tγq



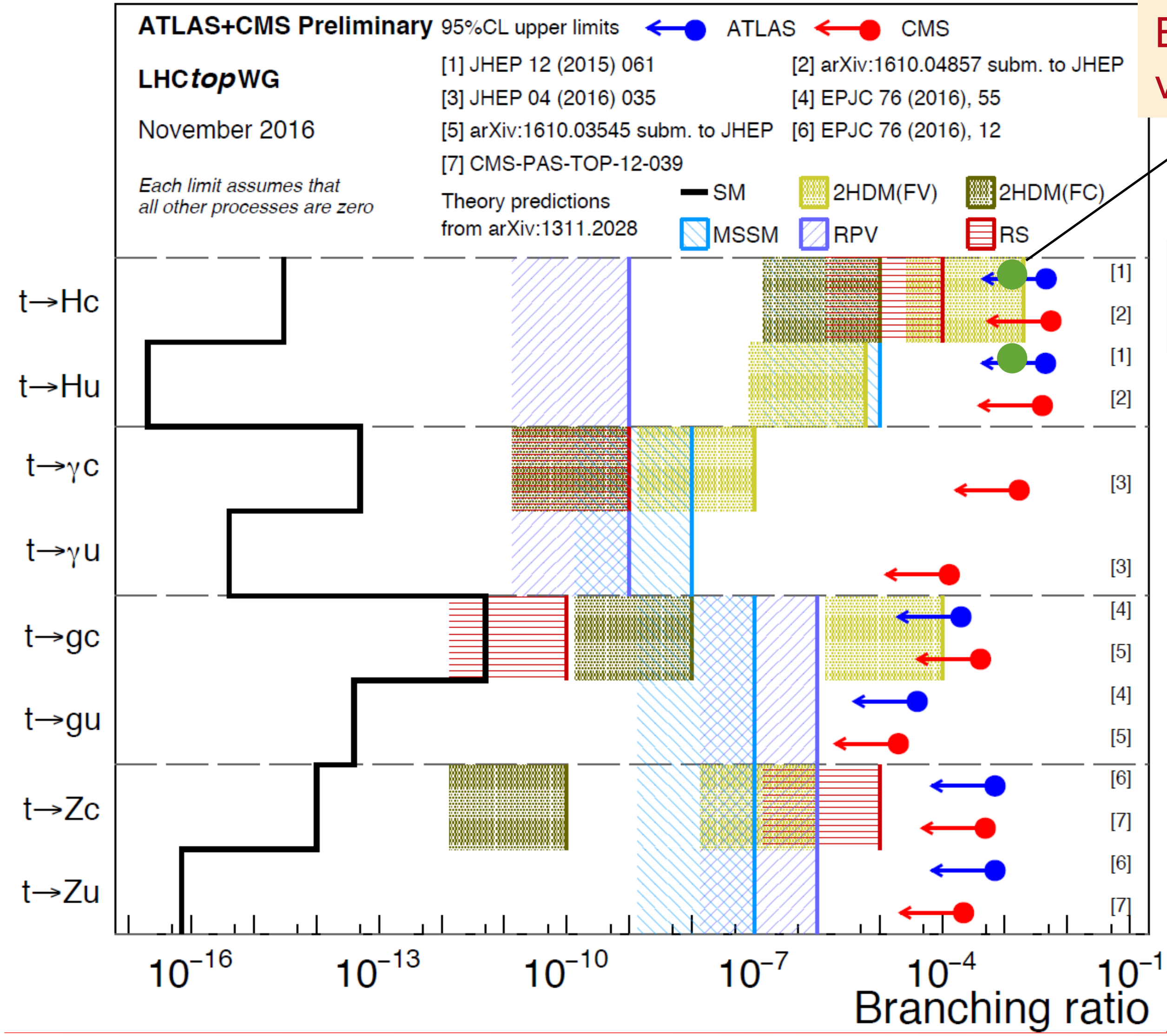
- tHq



→ Searches in decay ($t \to Xq$) and production ($pp \to tX$)

Run I LHC top FCNC searches

FCNC are forbidden in SM at tree level, strongly suppressed by GIM mechanism at higher orders
➔ Powerful probe for new physics BSM can enhance FCNC production.



Entering region sensitive to flavour violating Yukawa coupling in 2HDM

BR(10^{-4})	ATLAS 8 / 13 TeV	CMS (7+)8 TeV
$t \to Hc$	46 / 22(γγ)	40
$t \to Hu$	45 / 24(γγ)	55
$t \to \gamma c$	-	17
$t \to \gamma u$	-	1.3
$t \to gc$	2	4.1
$t \to gu$	0.4	0.2
$t \to Zc$	7	4.9
$t \to Zu$	7	2.2

FCNC $t \rightarrow H(\text{all})q$, $t_{SM} \rightarrow bW$
JHEP12(2015)061
($\sqrt{s}$ = 8 TeV, 20.3 fb^{-1})

$H \rightarrow WW, \tau\tau, ZZ$
- multilepton final states
- reinterpretation of tH search

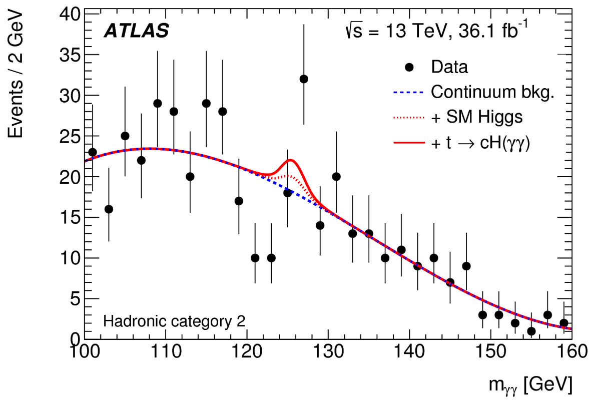
$H \rightarrow bb$
- dedicated analysis
- split events into several regions (nJets, nBjets)
- sophisticated MVA techniques

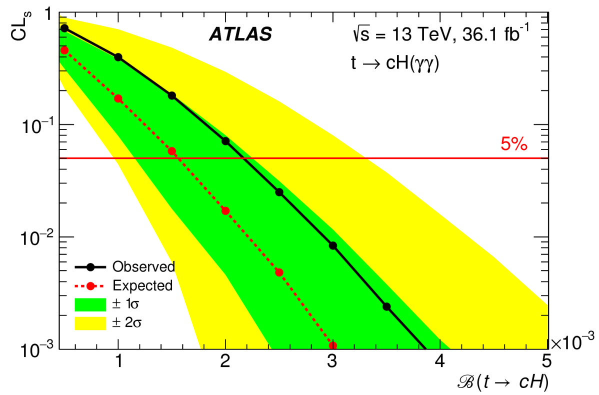
$H \rightarrow \gamma\gamma$
- limited by data statistcs

BR $t \rightarrow Hc < 4.6 \times 10^{-3}$ @95% CL
BR $t \rightarrow Hu < 4.5 \times 10^{-3}$ @95% CL

FCNC $t \rightarrow H(\gamma\gamma)$ q, $t_{SM} \rightarrow bW$ NEW
arXiv:1707.01404
($\sqrt{s}$ = 13 TeV, 36.1 fb^{-1})

- Two modes for t_{SM}:
  - Hadronic: 2 photons, ≥4 jets, ≥1 b-jets
  - Leptonic: 2 photons, 1e or 1μ, ≥ 2 jets
- Cuts on m(t_{FCNC}) and m(t_{SM})
- For each of mode, two categories:
  passing full selection / failing only t_{SM} mass criterion
- 4-channels combined: **BR $t \rightarrow H(\gamma\gamma)c < 2.2 \times 10^{-3}$ @95% CL**
  BR $t \rightarrow H(\gamma\gamma)u < 2.4 \times 10^{-3}$ @95% CL





- Compatibility of channels: 2.3σ
- Statistics limited. Dominant systematic uncertainties: JES, ME generator and radiation modelling

Outlook

The top quark is the **heaviest fundamental particle**, leading to unique properties from both the theoretical and experimental sides → **sensitive to new physics in production and decay**

→ Precise measurements of the top quark mass and couplings may provide insights on the underlying mechanism for EWSB and whether or not the top quark plays a role in it.

All measurements are in good agreement with SM predictions

* most of the measurements: systematically limited (experimental unc. ~ modelling unc.)
* largest experimental unc. stem from the calibration of the jet and b-jet energy scales
* largest modelling unc. are due to hadronisation and ISR/FSR radiation.

SM measurements (rel. precisions achieved in ATLAS)

- ✓ Top quark mass: MC mass (0.4%) and pole mass (1%)
- ✓ Top quark width (first direct measurement: 50%)
- ✓ Spin observables (full spin matrix, 15 observables, 3-30%)
- ✓ Most precise *W*-helicity measurement (2-5%)
- ✓ $tt+\gamma$ cross-section (13%)
- ✓ *tt+Z/W* cross-sections (30%, 50%)

FCNC searches

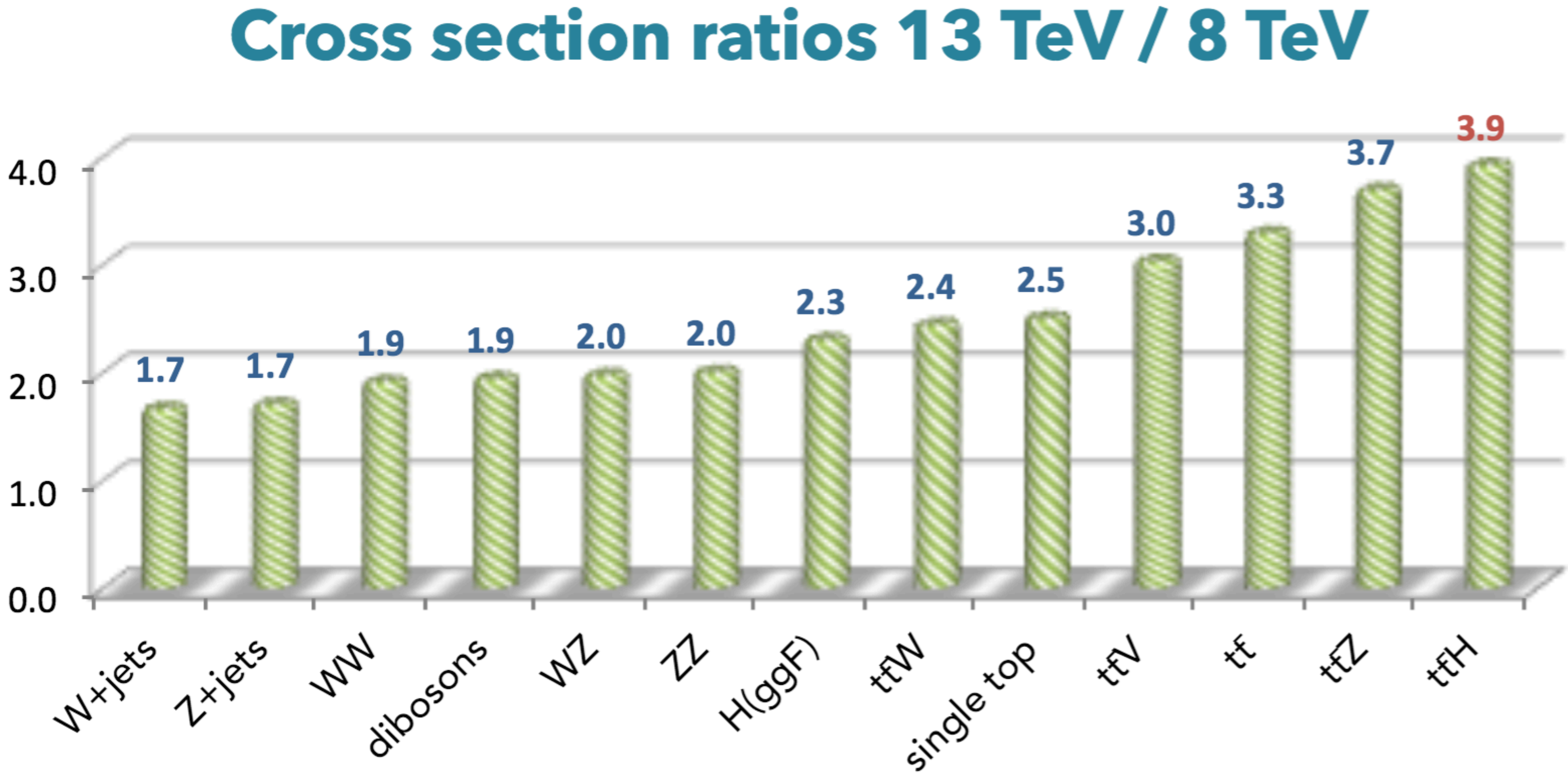
Decay: $t \rightarrow qH$, $t \rightarrow qZ$
Production: $qg \rightarrow t$

Entering region sensitive to flavour violating Yukawa coupling in 2HDM

THANKS FOR YOUR ATTENTION

BACK-UP

Increase of expected cross section in Run 2 → more tt+X events in Run2 !!!!!



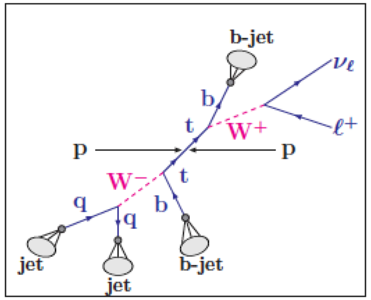
Top mass measurement: template method – single lepton

Single lepton channel, $\sqrt{s}$ = 7 TeV, 4.7 fb^{-1}

Eur. Phys. J. C75 (2015) 330

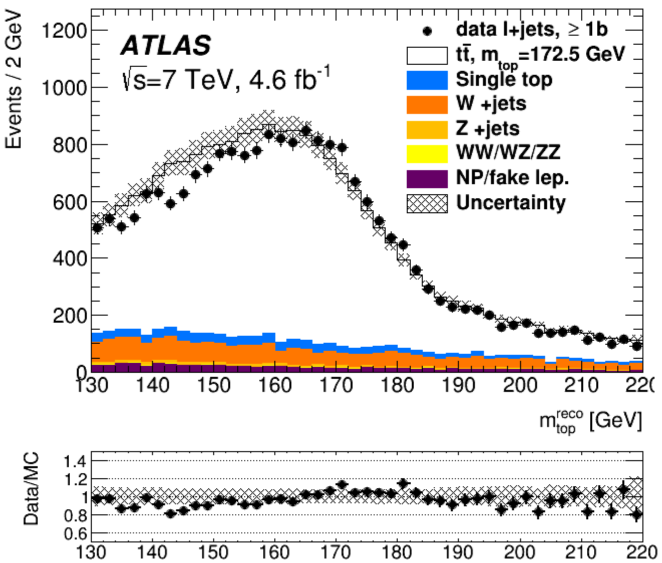
Selection: one lepton (e/μ), MET, ≥4 jets, ≥1 b-tagged jet (75% eff.)

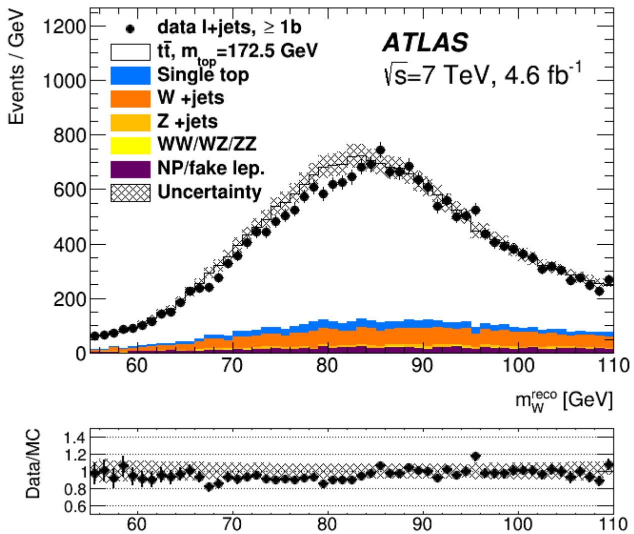
Reconstruction: kinematic likelihood fit (using b-tag info.)

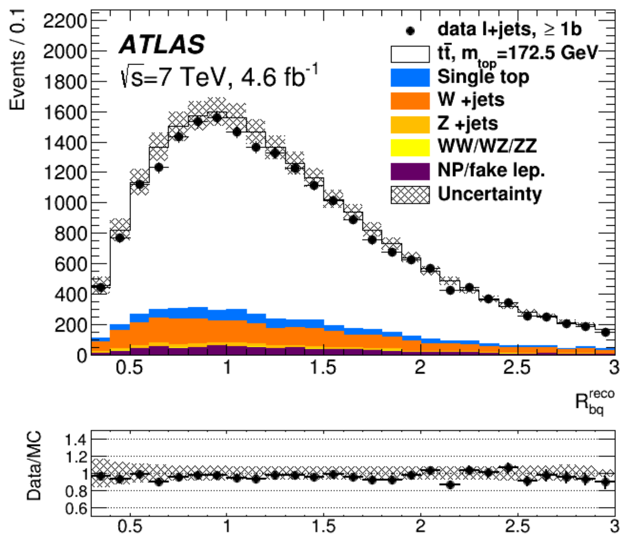


Template fit (3D) using $\mathbf{m^{reco}_{top}}$ = f(**mtop, JSF, bJSF),**
$\mathbf{m^{reco}_{W}}$ = f(JSF), and
$\mathbf{R^{reco}_{bq}}$ = f(bJSF) = $\Sigma p_T(b)/\Sigma p_T(q)$ with a weak m_{top} dependence

essential to reduce the systematic uncertainty, especially from JES

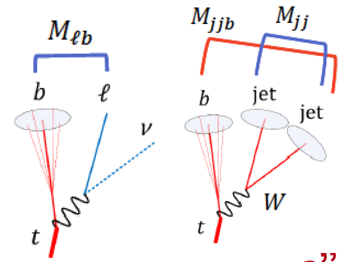






$\mathbf{m^{reco}_{top}}$ ε **(130,220) GeV** $\mathbf{m^{reco}_{W}}$ ε **(50,110) GeV** $\mathbf{R^{reco}_{bq}}$ ε **(0.3,3.0)**

Summary of latest ATLAS top mass measurements

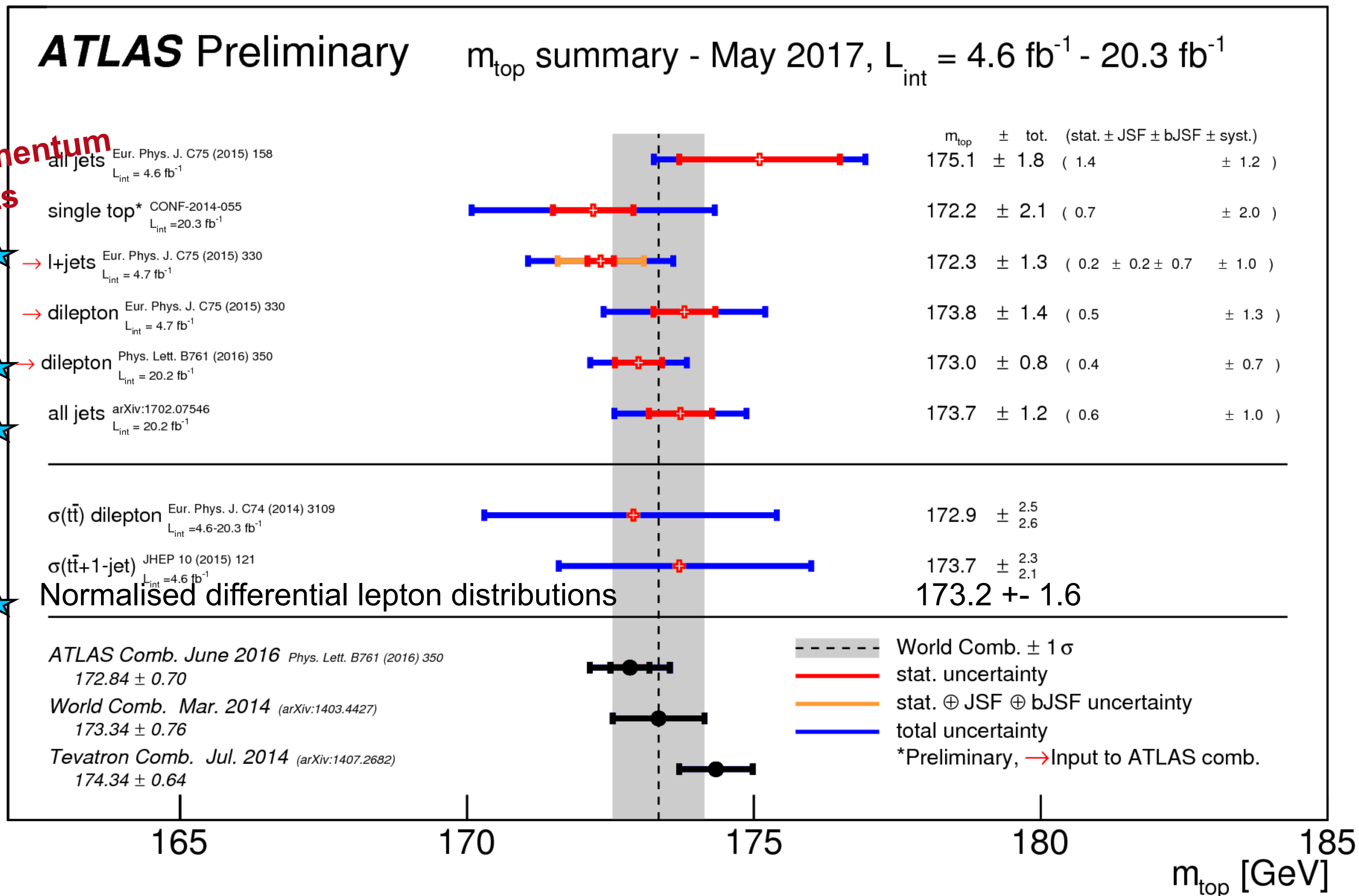


✓Relative precisions: MC mass (0.4%) and pole mass (1%)

"Direct MC mass" measuring 4-momentum of decay products

"Pole mass" from normalised differential dist. (shapes)

"MC mass" combinations



★ covered in this talk

m_{top}^{pole} from lepton and dilepton differential cross-sections

ATLAS-CONF-2017-044

	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

Table 15: Measurements of the top quark mass from individual fits to the lepton p_T^ℓ and dilepton $p_T^{e\mu}$, $m^{e\mu}$, $p_T^e + p_T^\mu$ and $E^e + E^\mu$ distributions, using fixed-order predictions from MCFM with the CT14 PDF set. The χ^2 value at the best-fit mass for each distribution, the fitted mass with its total uncertainty, and the individual uncertainty contributions from data statistics, experimental systematics, and uncertainties on the predictions from PDF and QCD scale effects are shown.

m_{top}^{pole} from lepton and dilepton differential cross-sections

ATLAS-CONF-2017-044

	CT14	MMHT	NNPDF 3.0	HERAPDF 2.0	ABM 11	NNPDF nojet
$\mu_F = \mu_R = m_t/2$						
$\chi^2/N_{\rm dof}$	71/68	70/68	67/68	67/68	71/68	64/68
$m_t^{\rm pole}$ [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
$\mu_F = \mu_R = H_T/4$						
$\chi^2/N_{\rm dof}$	69/68	67/68	64/68	61/68	66/68	60/68
$m_t^{\rm pole}$ [GeV]	173.6 ± 1.3	173.4 ± 1.3	173.2 ± 1.3	173.6 ± 1.3	$173.7\,^{+1.3}_{-1.2}$	$173.2\,^{+1.3}_{-1.4}$
$\mu_F = \mu_R = E_T/2$						
$\chi^2/N_{\rm dof}$	71/68	70/68	66/68	64/68	68/68	64/68
$m_t^{\rm pole}$ [GeV]	174.7 ± 1.4	$174.5\,^{+1.5}_{-1.4}$	$174.3\,^{+1.5}_{-1.4}$	$173.6\,^{+1.3}_{-1.2}$	$173.4\,^{+1.2}_{-1.1}$	$174.0\,^{+1.5}_{-1.4}$

Table 16: Measurements of the top quark mass from combined fits to all eight lepton and dilepton distributions, using fixed-order predictions from MCFM with the CT14, MMHT, NNPDF 3.0, HERAPDF 2.0, ABM 11 and NNPDF 3.0_nojet PDF sets, and various choices for the central QCD factorisation and renormalisation scales μ_F and μ_R. The upper section of the table gives the results for $\mu_F = \mu_R = m_t/2$, showing the χ^2 values at the best-fit mass for each PDF set, the fitted mass with its total uncertainty, and the breakdown of individual uncertainty contributions from data statistics, experimental systematics, and uncertainties on the predictions from PDF and QCD scale effects. Uncertainties given as '0.0' are smaller than 0.05 GeV. The lower parts of the table give the χ^2 values, fitted mass and total uncertainty for alternative scale choices of $\mu_F = \mu_R = H_T/4$ and $E_T/2$.

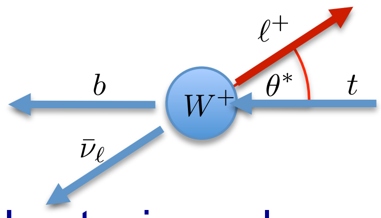
Top coupling to W boson: W helicity fractions in tt events

Test V-A structure via angular observables → W helicity fractions

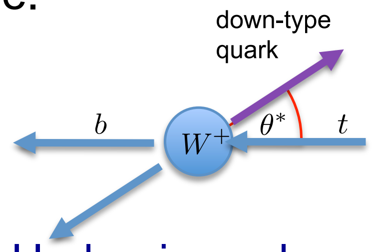
W bosons from top quark decays → 3 possible polarizations (helicity fractions): longitudinal F_0, left-handed F_L, right-handed F_R

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right) F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R$$

θ_l^* angle between down-type fermion (charged lepton or down-type quark) from W and reversed direction of top quark, both in the W boson rest frame.



Leptonic analyser



Hadronic analyser

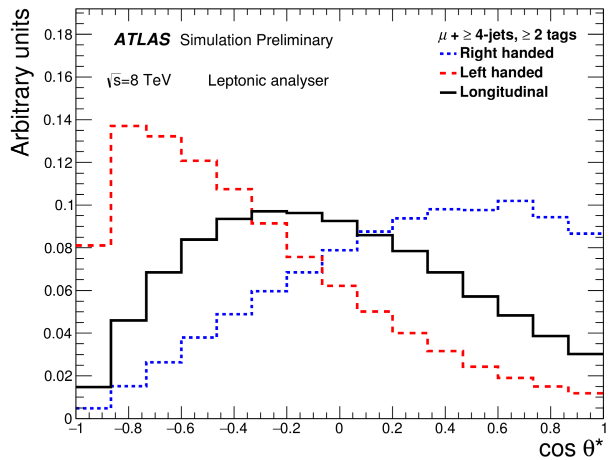
Single lepton ch., √s = 8 TeV, 20.2 fb^{-1}
Event reconstruction with KLfitter
Helicity fractions extracted using template fit
Two analyzers: <u>leptonic and hadronic</u>

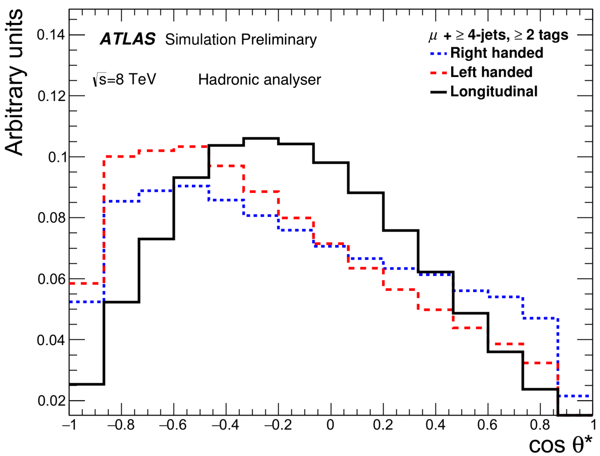
→ two measurements per event

- Leptonic: [e+μ] x [≥ 2b] → most sensitive
- Hadronic: [e+μ] x [1b + ≥ 2b]

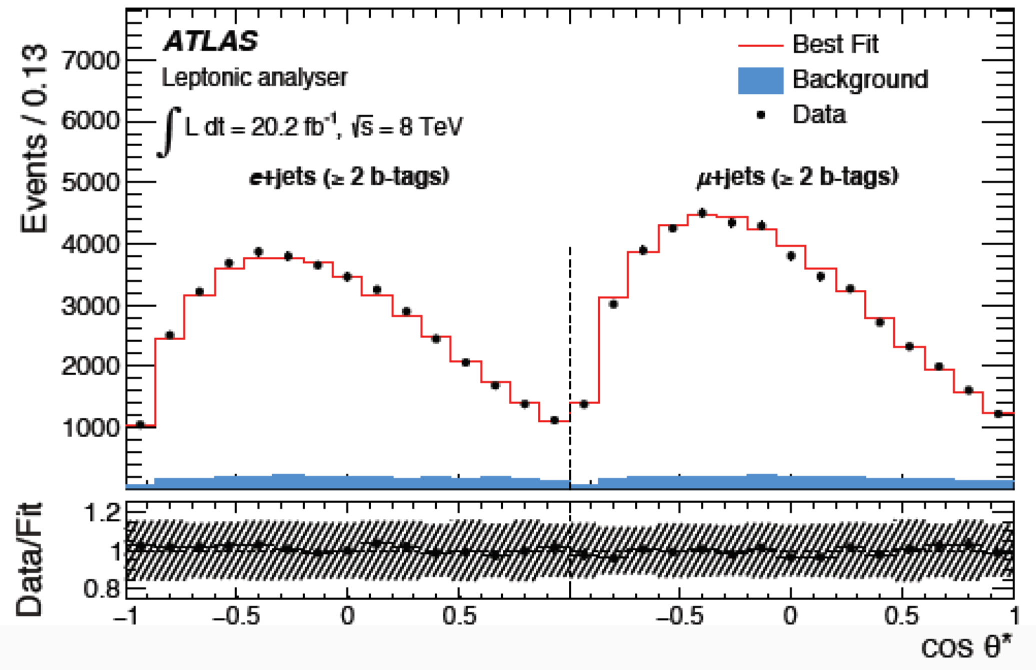
Overall best combination:
same as leptonic

EPJC 77 (2017) 264





Top coupling to W boson: W helicity fractions in tt events



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NNLO QCD calculation
Phys.Rev.D81:111503,2010

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

Leptonic analyser (most precise)

$F_0 = 0.709 \pm 0.012$ (stat.+bkg.norm.) ± 0.015 (syst.)
$F_L = 0.299 \pm 0.008$ (stat.+bkg.norm.) ± 0.013 (syst.)
$F_R = -0.008 \pm 0.006$ (stat.+bkg.norm.) ± 0.012 (syst.)

$\rho_{0,L} = -0.55,\ \rho_{0,R} = -0.75,\ \rho_{L,R} = +0.16$

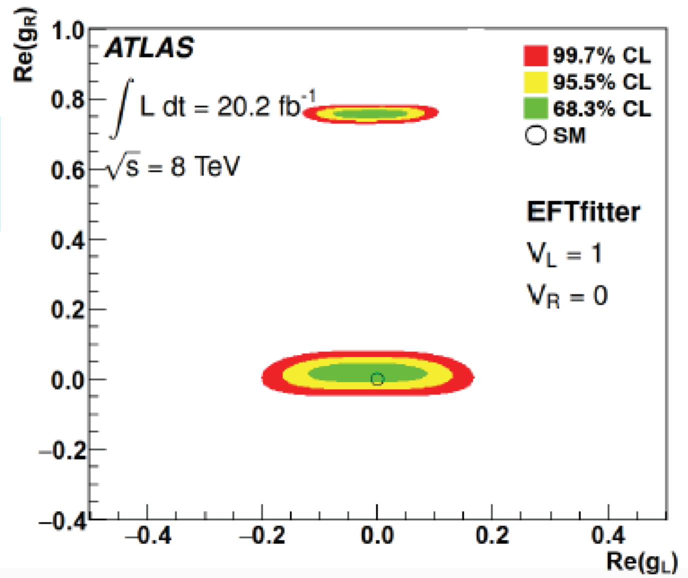
Main uncertainties: JES, JER, signal modelling

A general extension of the SM Lagrangian for Wtb vertex:

$$L_{Wtb} = -\frac{g}{\sqrt{2}}\bar{u}_b\gamma^{\mu}\left(V_L P_L + V_R P_R\right)u_t W_{\mu}^{+} - \frac{g}{\sqrt{2}}\bar{u}_b\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_L P_L + g_R P_R\right)u_t W_{\mu}^{+} + \text{h.c.}$$

$SM \Rightarrow V_L = V_{tb} \sim 1$ $\quad V_R = g_L = g_R = 0$

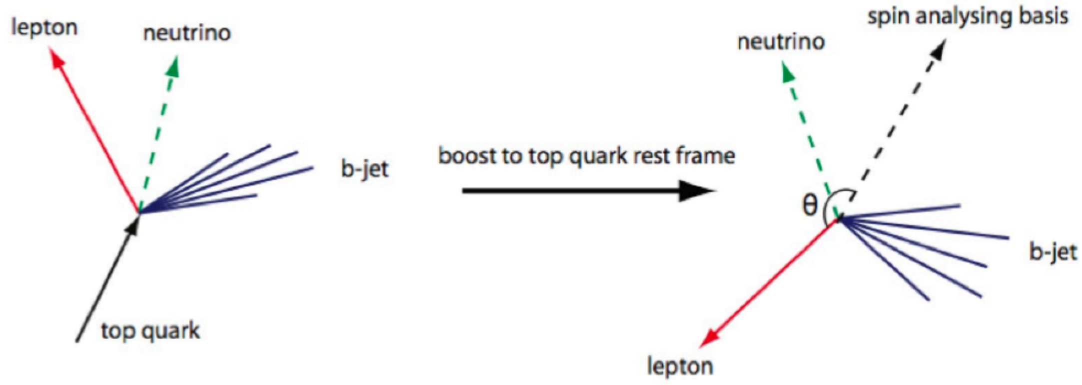
Coupling	95% CL limit
$Re(V_R)$	[-0.24, 0.31]
$Re(g_L)$	[-0.14, 0.11]
$Re(g_R)$	[-0.02, 0.06], [0.74, 0.78]



Doubly differential cross section:

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1\, d\cos\theta_2}=\frac{1}{4}(1\pm(\alpha P)_1\cos\theta_1\pm(\alpha P)_2\cos\theta_2 - C\cos\theta_1\cos\theta_2)$$

- α_i: spin analyzing power of decay product i; θ_i: direction of daughter wrt. chosen axis
- P: polarization
- C spin correlation; C= $A\alpha_1\alpha_2$

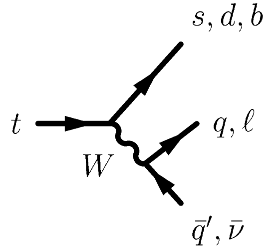


	b	lepton	d	u
$\alpha_{i/j}$ (LO)	-0.41	1.00	1.00	-0.31
$\alpha_{i/j}$ (NLO)	-0.39	0.998	0.93	-0.31

$$A=\frac{N(\uparrow\uparrow)+N(\downarrow\downarrow)-N(\uparrow\downarrow)-N(\downarrow\uparrow)}{N(\uparrow\uparrow)+N(\downarrow\downarrow)+N(\uparrow\downarrow)+N(\downarrow\uparrow)}$$

Flavour changing neutral currents

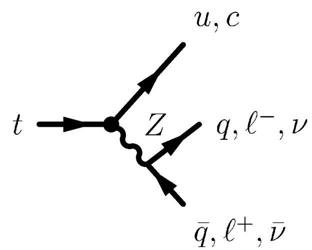
Top quark decays → **Charged current decays**:
BR(t→bW,sW,dW) ~100%, ~0.2% 0.01%

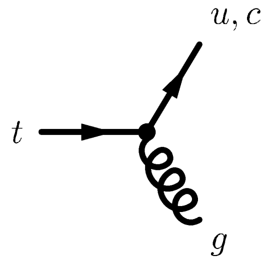


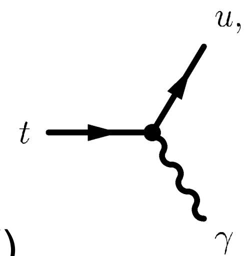
Flavour changing neutral currents (FCNC)
are forbidden in SM at tree level, strongly suppressed by GIM mechanism at higher orders
➔ Powerful probe for new physics BSM can enhance FCNC production.

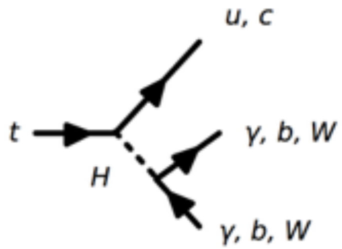
K.Agashe et al., arXiv:1311.2028

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$









➔ Latest ATLAS searches in decay (t→Xq) and production (pp→tX)

FCNC top decay: **t→Hq**
t→H(γγ)q arXiv:1707.01404
(√s = 13 TeV, 36.1 fb^{-1})
t→H(all)q JHEP12(2015)061
(√s = 8 TeV, 20.3 fb^{-1})

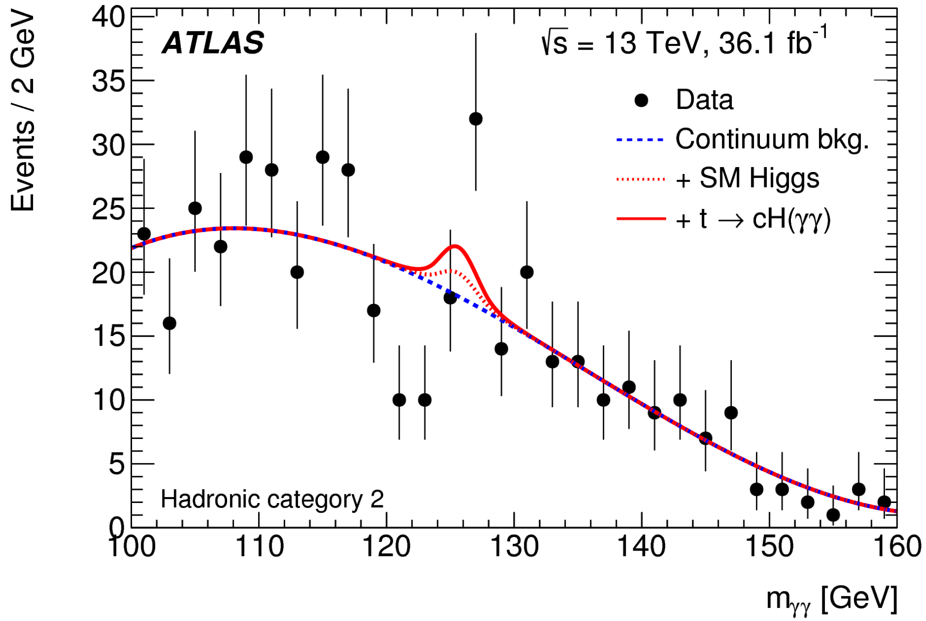
FCNC top decay: **t→Zq**
Eur. Phys. J. C76 (2016) 55
(√s = 8 TeV, 20.3 fb^{-1})

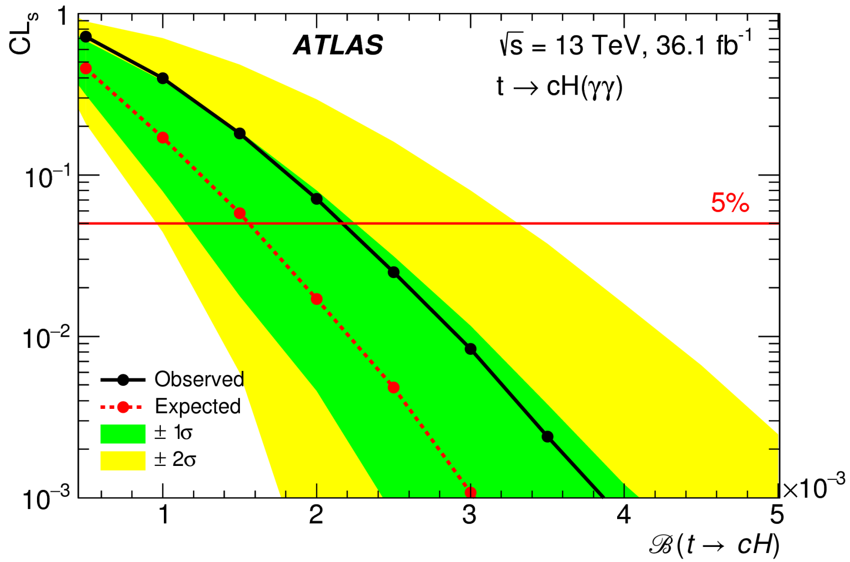
FCNC single top production: **qg→t**
Eur. Phys. J. C76 (2016) 55
(√s = 8 TeV, 20.3 fb^{-1})

New FCNC t→qH(γγ) results

t_{FCNC}→qH(γγ) with q = c,u, t_{SM}→bW with W=jj,lν, $\sqrt{s}$ =13 TeV, 36.1 fb^{-1} arXiv:1707.01404

- Two modes for t_{SM}:
  - Hadronic: 2 photons, ≥4 jets, ≥1 b-tagged.
  - Leptonic: 2 photons, 1e or 1μ, ≥ 2 jets.
- Invariant mass combinations with kinematic compatibility with two top quark decays.
- For each of the modes, two categories: events passing full selection
  events failing only t_{SM} mass criterion
- Main backgrounds: γγj, Xγ and Xγγ (X: W,Z,ttbar) and ttH(→γγ).
- Fit S and B to data: $m_{\gamma\gamma}$ distributions [γγj bkg. shape from SHERPA, signal from MG5_aMC@NLO]
- Dominant systematic uncertainties: JES, ME generator and radiation modelling





BR(t→Hc) < 2.2x10^{-3} @95% CL
BR(t→Hu) < 2.4x10^{-3} @95% CL

Top quark couplings: towards a global fit (EFT)

The effects of new physics at a scale Λ can be described by an effective Lagrangian

* These operators can induce corrections to SM couplings (e.g. may originate anomalous couplings of the top quark to the gauge bosons).
* Effective vertices, V=W, Z, H, γ, g:

$$\mathcal{L}^{\mathrm{eff}} = \sum \frac{C_x}{\Lambda^2} O_x + \ldots$$

O_x = dim 6 gauge invariant operators

C_X=complex constants

→ need to identify which operators contribute to each process

Process	O_{tG}	O_{tB}	O_{tW}	$O^{(3)}_{\varphi Q}$	$O^{(1)}_{\varphi Q}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	O_G	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	N		L	L				L		
$pp \to t\bar{q}$	N		L	L				L		
$pp \to tW$	L		L	L				N	N	N
$pp \to t\bar{t}$	L						N	L	L	L
$pp \to t\bar{t}\gamma$	L	L	L				N	L	L	L
$pp \to t\bar{t}Z$	L	L	L	L	L	L	N	L	L	L
$pp \to t\bar{t}h$	L						L	L	L	L
$gg \to H, H \to \gamma\gamma$	N						N			L

- $\mathcal{O}_{\phi t}, \mathcal{O}_{\phi Q^3}, \mathcal{O}_{\phi Q^1}$ - $t\bar{t}Z$ vertex
- $\mathcal{O}_{tW}, \mathcal{O}_{tB}$ - $t\bar{t}Z$ and $t\bar{t}\gamma$ vertices
- $\mathcal{O}_{tG}$ - $t\bar{t}g$ vertex

Standard model deviations are described by higher dimensional operators:

$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \dots$$

Interference SM-BSM — Pure BSM term

$$\sigma = \sigma_{SM} + \sum_i \frac{C_i}{(\Lambda/1\mathrm{TeV})^2}\sigma_i^{(1)} + \sum_{i\leq j} \frac{C_i C_j}{(\Lambda/1\mathrm{TeV})^4}\sigma_{ij}^{(2)}$$

Dimension 6 operators relevant for top quark physics.

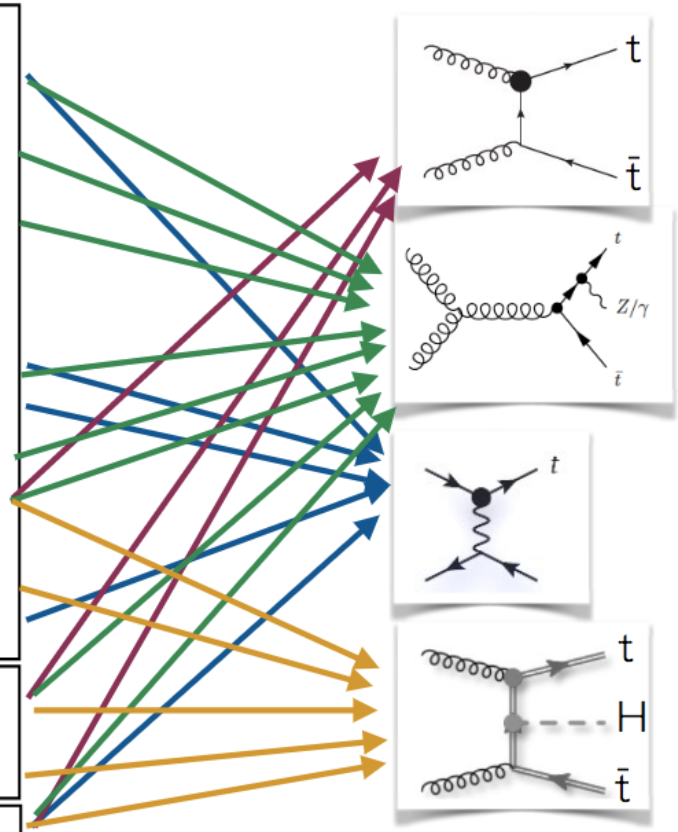
modify vector and axial coupling of top to EW gauge bosons

O_{tB}, O_{tW}: EW dipole operator
O_{tG}: chromomagnetic dipole operator

$$O_{\varphi Q}^{(3)} = i\tfrac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q)$$
$$O_{\varphi Q}^{(1)} = i\tfrac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$
$$O_{\varphi t} = i\tfrac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$
$$O_{\varphi b} = i\tfrac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{b}\gamma^\mu b)$$
$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$
$$O_{bW} = y_b g_w (\bar{Q}\sigma^{\mu\nu}\tau^I b)\varphi W^I_{\mu\nu}$$
$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}$$
$$O_{t\varphi} = (\varphi^\dagger\varphi)(\bar{Q}t\tilde{\varphi})$$
$$O_{\varphi tb} = i(\varphi^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu b)$$

$$O_G = g_s f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$$
$$O_{\varphi G} = g_s^2 \left(\varphi^\dagger\varphi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

4-fermion ops



Searching for the tiniest signals: very challenging

Virtues:

Many possible final states to consider!

Challenges:

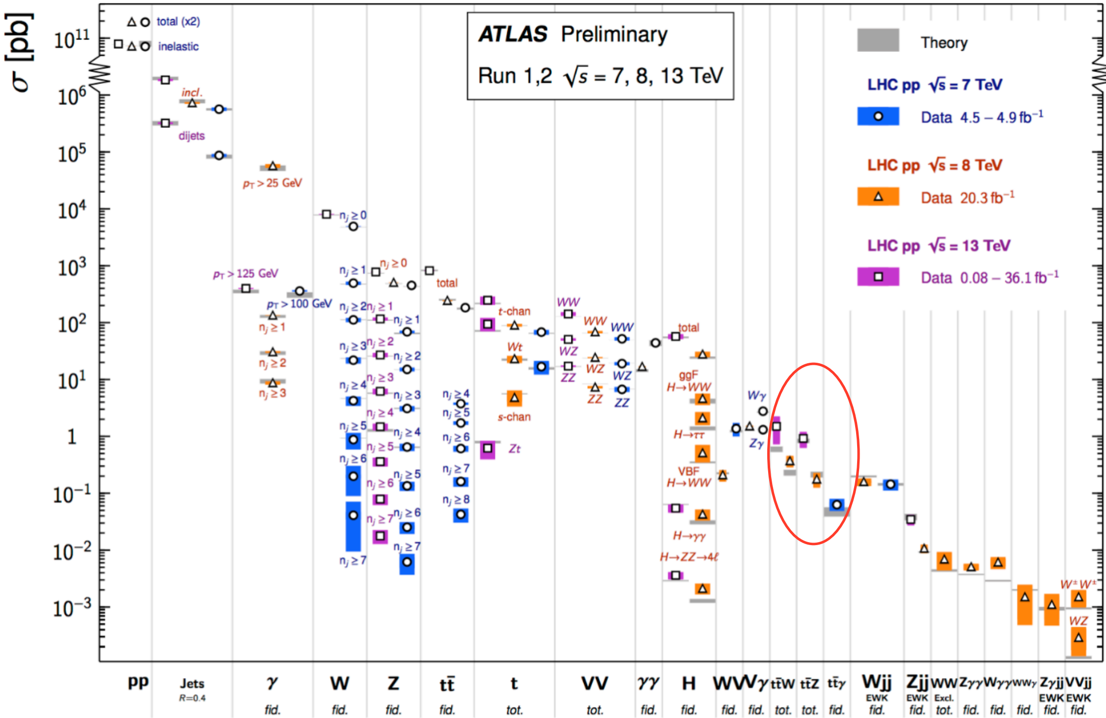
- low production cross section
- a priori many handles against backgrounds with large theoretical uncertainties!

→ Most of these analyses entering regime of results being systematically limited !!

→ Recent developments in theory community:

- NLO QCD+EW corrections to *tt+H/Z/W*
- NLO QCD corrections to *t+H*
- off-shell effects in *tt+H* production
- beyond NLO QCD: soft resummation

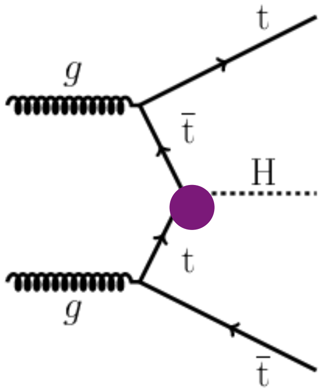
→ Implementation of latest theoretical developments is crucial to reduce uncertainties.



σ (pb)	8 TeV	13 TeV	13 / 8
tt+Z	0.206	0.839 (±12%)	3.7
tt+W	0.232	0.601 (±13%)	2.4
tt+H	0.129	0.5085 (±13%)	3.9
tt	~250	~830	3.3

Top coupling to Higgs bosons: tt+H

• **Indirect constraints** on the top-Higgs Yukawa coupling can be extracted from channels involving the ggH and Hγγ vertices (assumes no new particles in loops).

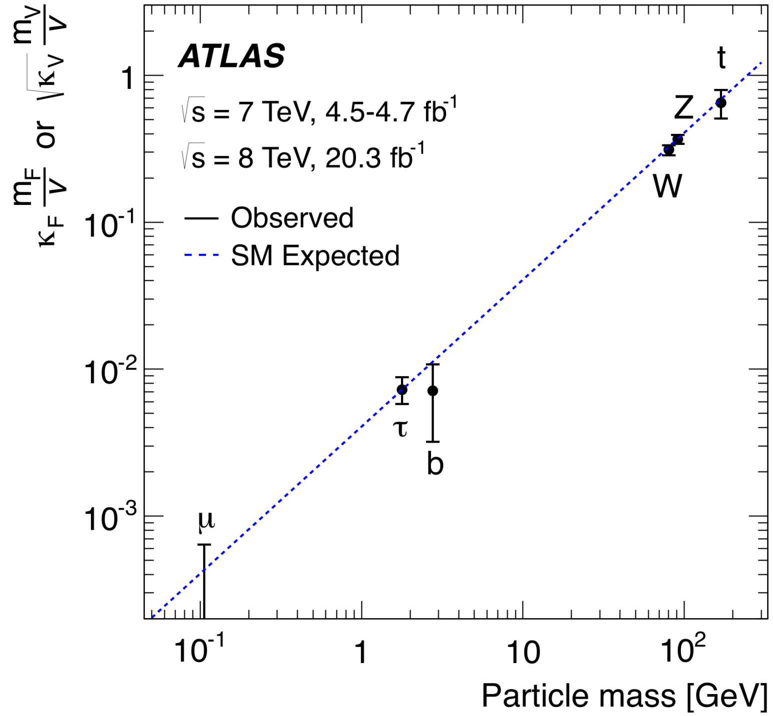


• ***tt+H* process allows for direct measurement of top Yukawa coupling**
→ allows probing for New Physics contributions in the ggH and Hγγ vertices.

Many possible final states to consider!
Need to find the best combinations of top and Higgs decay modes to isolate the signal.

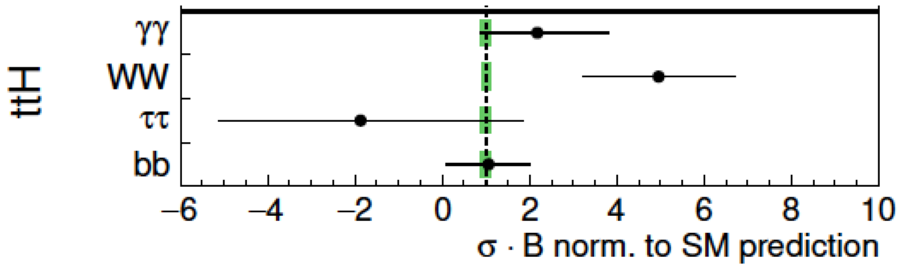
Several channels depending on the final signature
→ distinctive final states with high jet/b-tag multiplicity
→ different analysis regions with very different strategy

H→bb (BR=58%)	dominant mode but large background
H→WW, ZZ, ττ (BR=30%)	multilepton final state
H→γγ (BR<0.23%)	tiny but clean signature

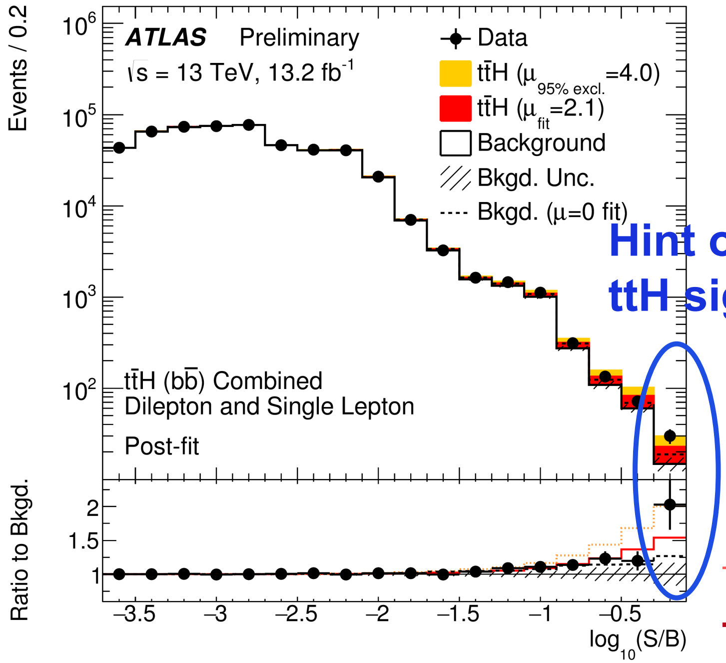


- Run 1 ATLAS+CMS Higgs combination:
  ttH significance of 4.4 σ (2.0 σ expected)

- Excess in both ATLAS and CMS $\mu_{ttH} = \sigma/\sigma_{SM}$
  - coming from ttH multilepton analyses

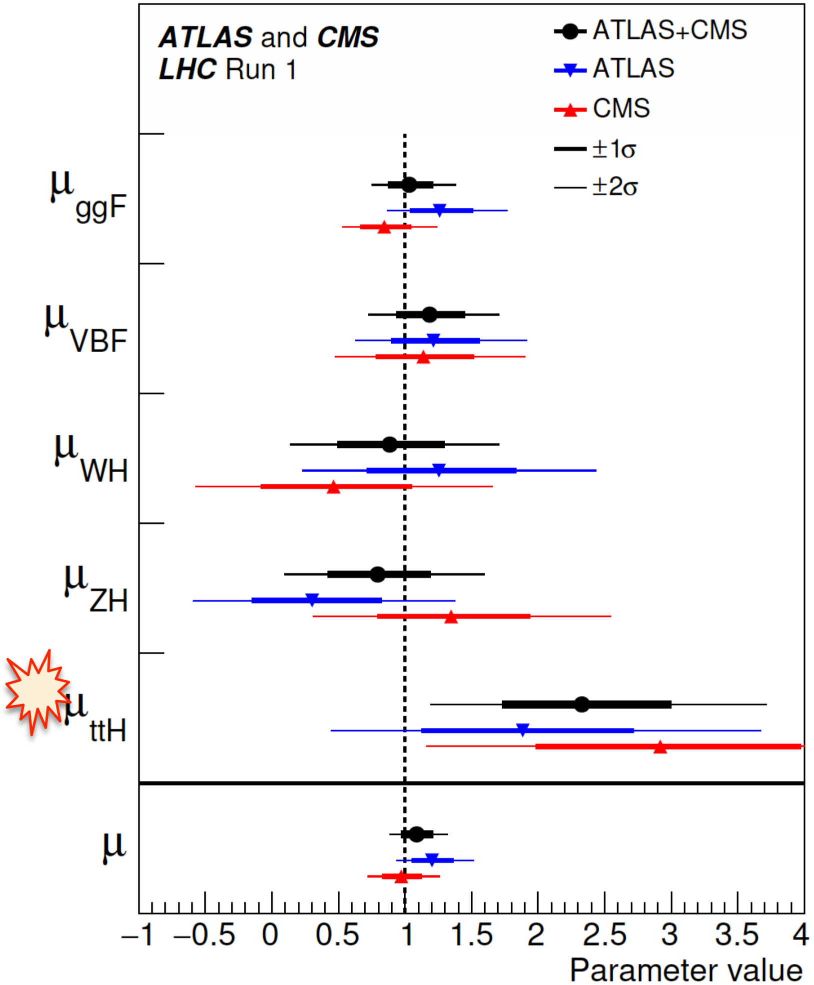


One of the highlights of Run 2 physics program



Hint of ttH signal

JHEP08(2016)045



Projections with full 2015+2016 dataset: very close to ttH evidence (3σ) !

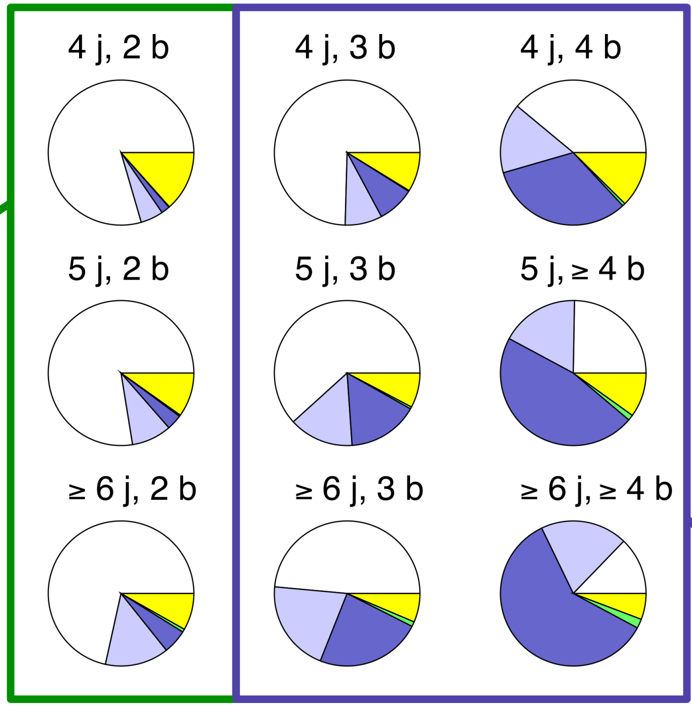
→ Now, analysing it !!!

ttH (H→bb) signal produces 1 or 2 leptons and 6 or 4 jets, 4 of them b-jets

- Very challenging final state affected by large systematics:
  tt+jets, tt+heavy flavour modelling, *b*-tagging, JES
- Categorize events according to the # jets and b-jets → **control and signal regions**
- Build **multivariate discriminant** in signal-enriched regions
- Signal-depleted channels play a key role constraining systematic uncertainties
- Analysis relies on a profiled likelihood fit, in order to constrain in-situ the leading systematics

Background composition
Single lepton

high statistics, constraint on overall ttbar normalisation and modelling



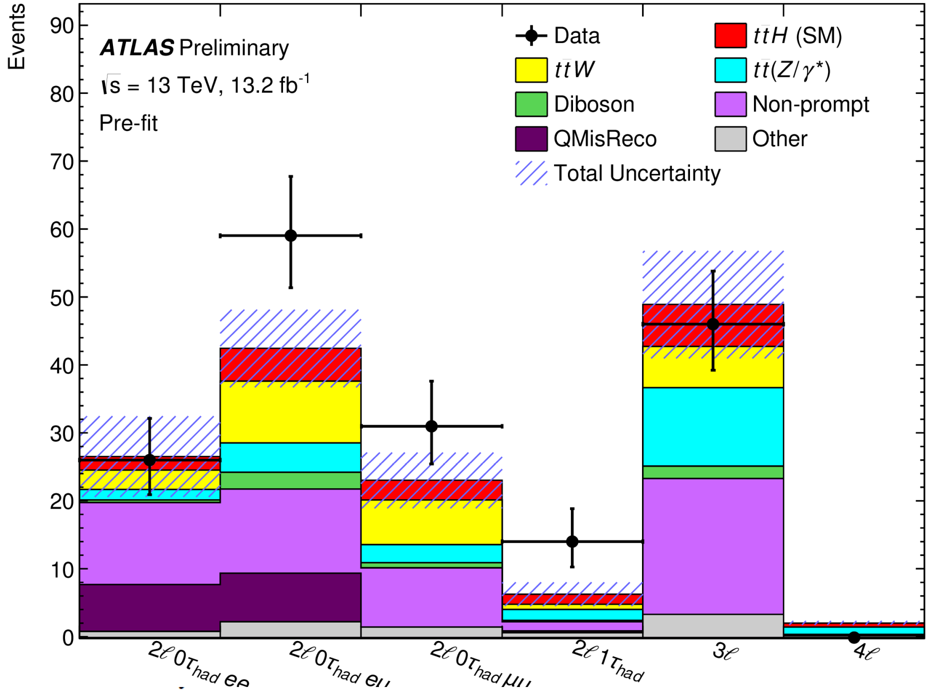
ATLAS Simulation

m_H = 125 GeV
$\sqrt{s}$ = 8 TeV
$t\bar{t}$+light
$t\bar{t}+c\bar{c}$
$t\bar{t}+b\bar{b}$
$t\bar{t}$+V
non-$t\bar{t}$

constraint uncertainties on ttbb and ttcc normalisations

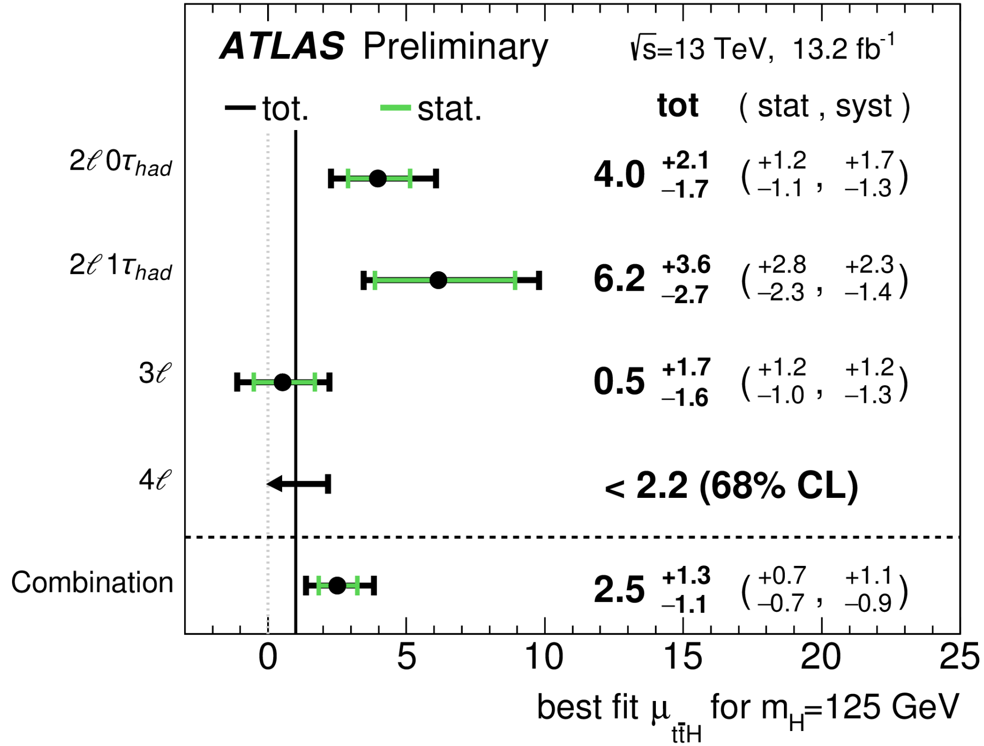
Search for *tt+H* (H→multilepton)

Prefit predictions and observed data events



Uncertainty Source	$\Delta\mu$	
Non-prompt leptons and charge misreconstruction	+0.56	−0.64
Jet-vertex association, pileup modeling	+0.48	−0.36
$t\bar{t}W$ modeling	+0.29	−0.31
$t\bar{t}H$ modeling	+0.31	−0.15
Jet energy scale and resolution	+0.22	−0.18
$t\bar{t}Z$ modeling	+0.19	−0.19
Luminosity	+0.19	−0.15
Diboson modeling	+0.15	−0.14
Jet flavor tagging	+0.15	−0.12
Light lepton (e, μ) and $\tau_{\rm had}$ ID, isolation, trigger	+0.12	−0.10
Other background modeling	+0.11	−0.11
Total systematic uncertainty	+1.1	−0.9

Best fit values of the tt+H signal strength

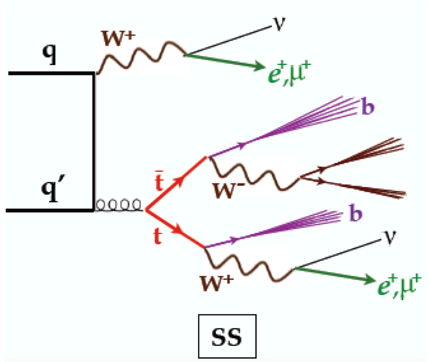


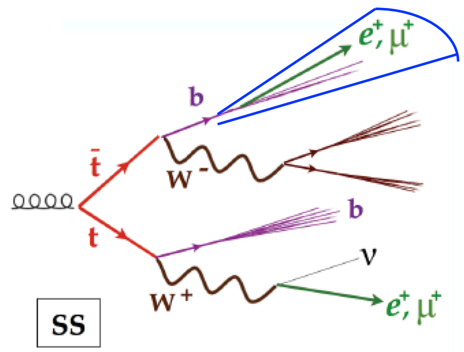
- Most analyses are still statistically limited, main syst. from non-prompt and charge misID
- Run1: $\mu=2.1^{+1.4}_{-1.2}$ (excess in μμ and 3ℓ)
- Reinterpretation of results as a BSM signal? multilepton+bjets+MET final states

Top coupling to vector bosons: tt+Z/W

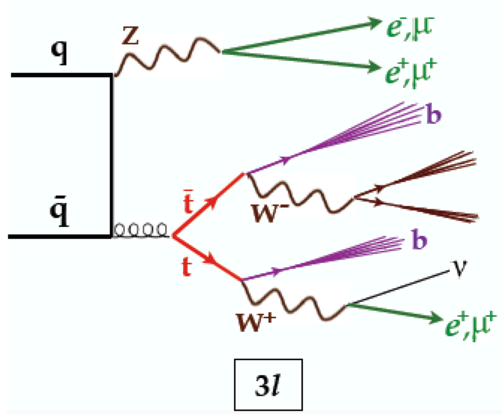
Sample statistics, S/B ratio and dominant backgrounds vary across different channels
for each of them, several SRs (lepton flavour/charge, nJets, nBjets) and CRs (Z+jets, WZ, ZZ)

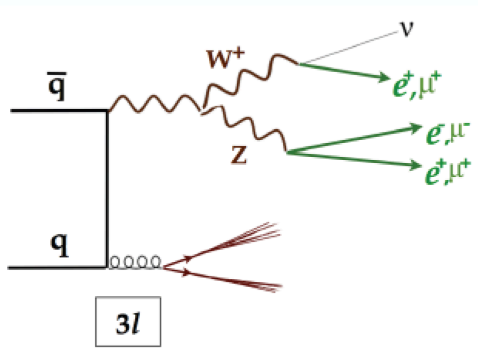
Channel	Sub-channels	Characteristics	Main cuts	Main background
SS dilepton	μμ	targets ttW	≥2 b-tags	fake leptons derived from matrix method (DD) in control sample with 2l OS+SS and looser lepton requirements
Trilepton	ttZ (ttW) enriched	small sample size, good S/B	≥1 b-tag	leptonic decay WZ, (fake leptons) One WZ CR is included in the fit; another is defined for validation
Tetralepton	tt→ same (diff.) flavour	very small sample size, excellent S/B	1-2 OSSF pairs	leptonic decay ZZ (rare SM) One ZZ CR is included in the fit;





non-prompt ℓ (from $t\bar{t}$)





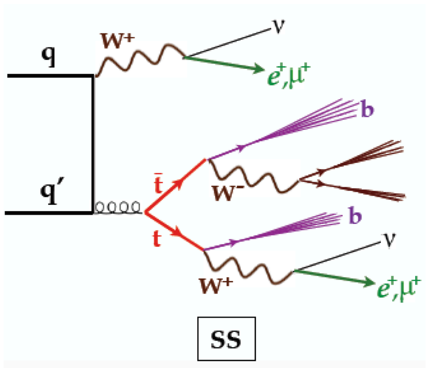
WZ(+HF)

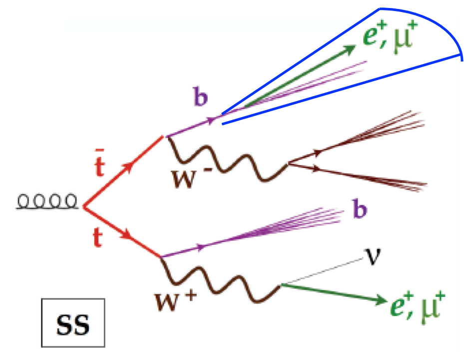
Top coupling to vector bosons: tt+Z/W

Sample statistics, S/B ratio and dominant backgrounds vary across different channels

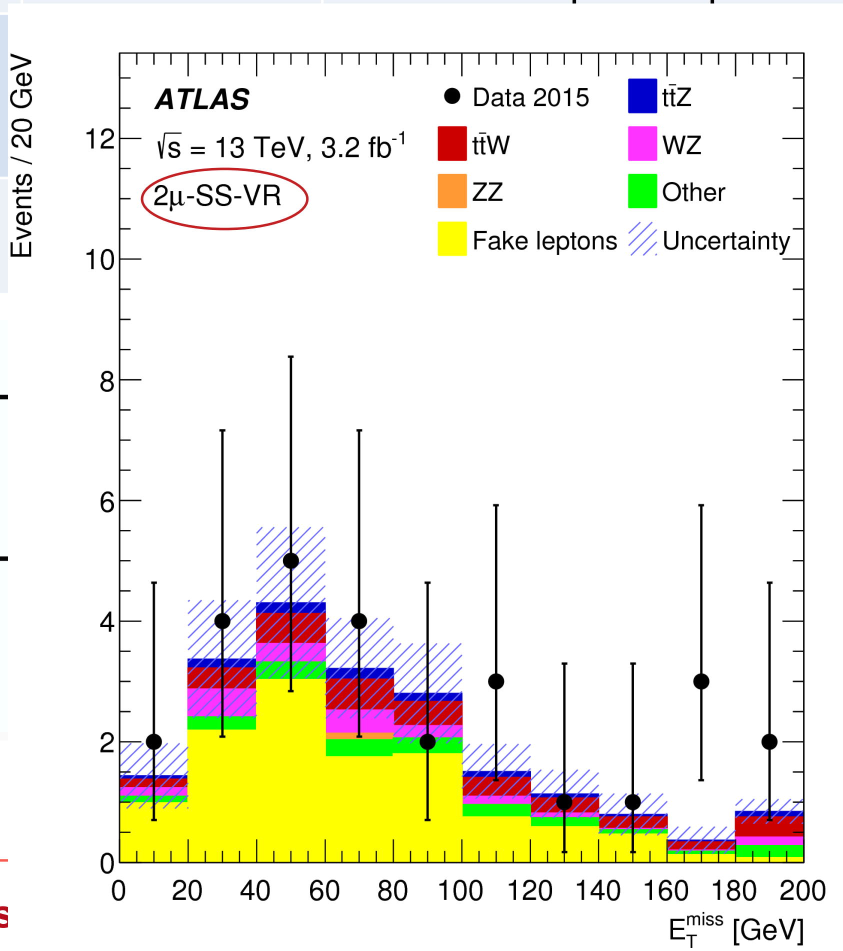
for each of them, several SRs (lepton flavour/charge, nJets, nBjets)   and CRs (Z+jets, WZ, ZZ)

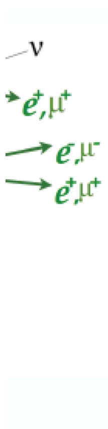
Channel	Sub-channels	Characteristics	Main cuts	Main background
SS dilepton	μμ	targets ttW	≥2 b-tags	fake leptons (from ttbar events) derived from matrix method (DD) in control sample with 2l OS+SS and looser lepton requirements
Trilepton	ttZ (ttW) enriched	small sample size, good S/B		tons) e fit; ion
Tetralepton	tt→ same (diff.) flavour	very small sample size, excellent S/B		e fit;





non-prompt ℓ (from tt̄)





Top coupling to vector bosons: tt+Z/W

Sample statistics, S/B ratio and dominant backgrounds vary across different channels

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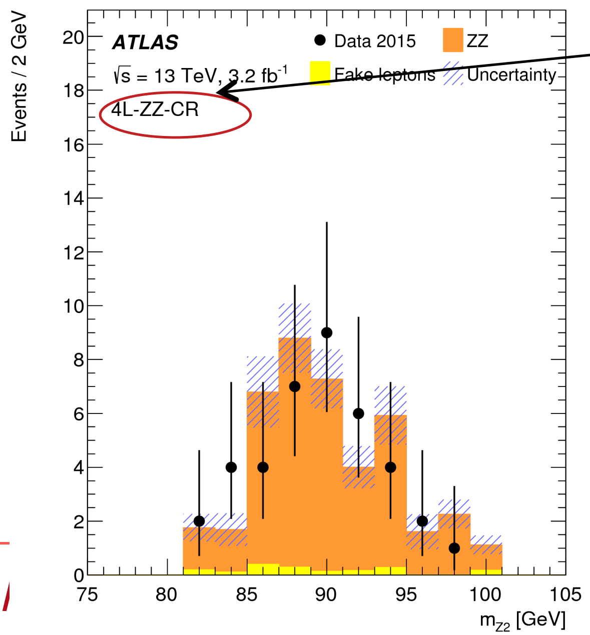
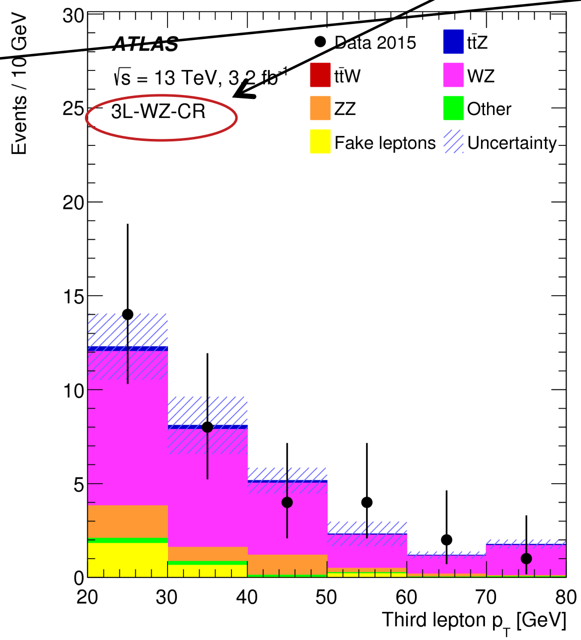
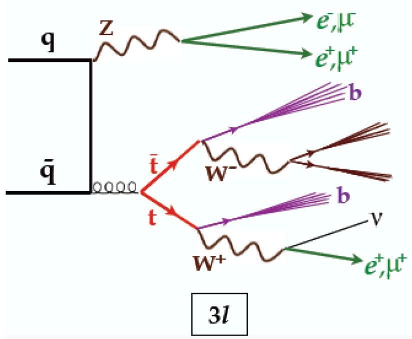
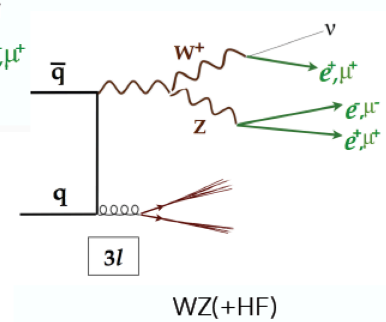
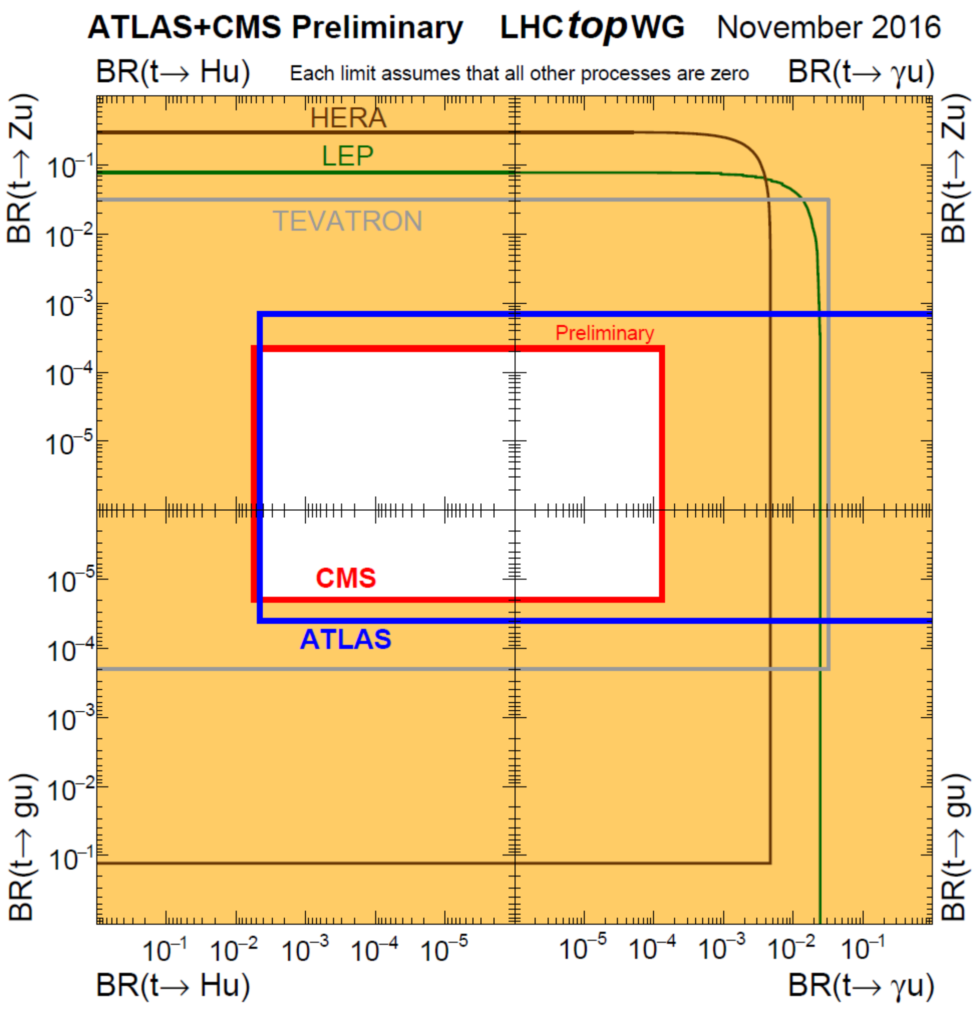
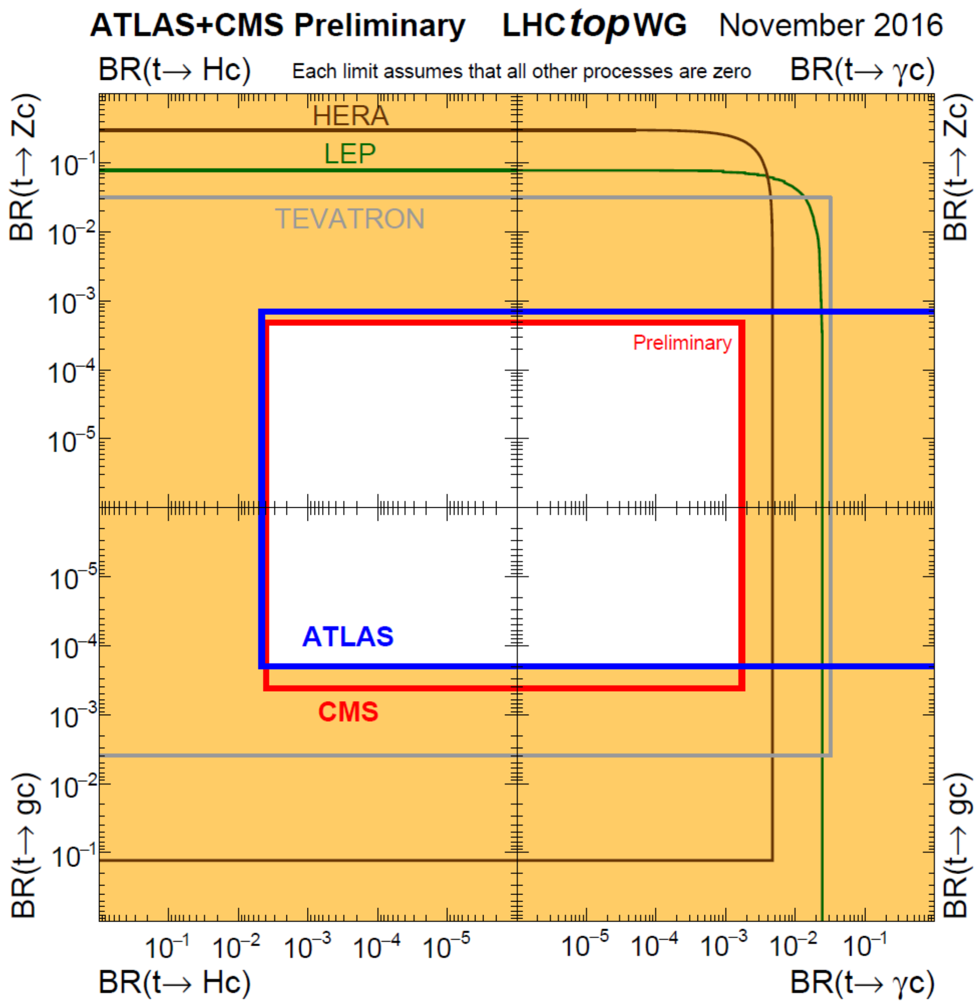









ATLAS+CMS Preliminary
LHCtopWG
November 2016
BR(t→ Hu)
Each limit assumes that all other processes are zero
BR(t→ γu)
BR(t→ Zu)
BR(t→ gu)
HERA
LEP
TEVATRON
Preliminary
CMS
ATLAS


ATLAS+CMS Preliminary
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BR(t→ γc)
BR(t→ Zc)
BR(t→ gc)
HERA
LEP
TEVATRON
Preliminary
ATLAS
CMS

FCNC QCD Lagrangian: anom. coupl.

Run I LHC FCNC results are expressed in the framework of anomalous couplings:

$$\begin{aligned}
\mathcal{L}_{FCNC} = \sum_{q=u,c} \Big[\; & \frac{\sqrt{2}}{2} g_s \frac{\kappa_{gqt}}{\Lambda} \cdot \bar{t}\sigma^{\mu\nu}\left(f^L_{gq}P_L + f^R_{gq}P_R\right) q G^a_{\mu\nu} && \text{tensor} \\
+ & \frac{\sqrt{2}}{2} e \frac{\kappa_{\gamma qt}}{\Lambda} \cdot \bar{t}\sigma^{\mu\nu}\left(f^L_{\gamma q}P_L + f^R_{\gamma q}P_R\right) q A_{\mu\nu} && \text{tensor} \\
+ & \frac{1}{\sqrt{2}} \eta_{hqt} \cdot \bar{t}\left(f^L_{hq}P_L + f^R_{hq}P_R\right) q H && \text{scalar} \\
+ & \frac{\sqrt{2}}{4} \frac{g}{\cos\theta_W} \frac{\kappa_{zqt}}{\Lambda} \cdot \bar{t}\sigma^{\mu\nu}\left(f^L_{zq}P_L + f^R_{zq}P_R\right) q Z_{\mu\nu} && \text{tensor} \\
+ & \frac{1}{4} \frac{g}{\cos\theta_W} \zeta_{zqt} \cdot \bar{t}\gamma^{\mu}\left(\tilde{f}^L_{zq}P_L + \tilde{f}^R_{zq}P_R\right) q Z_{\mu} \Big] + h.c && \text{vector}
\end{aligned}$$

Top decay	κ_{gqt}/Λ	$\kappa_{\gamma qt}/\Lambda$	κ_{zqt}/Λ	ζ_{zqt}	η_{hqt}
t→g q	X				
t→γ q		X			
t→Z q			X	x NLO	
t→h q					X

Single top	κ_{gqt}/Λ	$\kappa_{\gamma qt}/\Lambda$	κ_{zqt}/Λ	ζ_{zqt}	η_{hqt}
p p → t (g)	X				
p p → t γ	X	X			
p p → t Z	X		X	X	
p p → t h	X				X

X: considered
X: usually neglected

Assumptions

Example of conventions

$$\sqrt{\left|f^L_{xq}\right|^2 + \left|f^R_{xq}\right|^2} = 1 \qquad \frac{\kappa_{xqt}}{\Lambda},\ \zeta_{xqt},\ \text{and}\ \eta_{xqt} > 0$$

$$\sqrt{\left|\tilde{f}^L_{xq}\right|^2 + \left|\tilde{f}^R_{xq}\right|^2} = 1$$

Simplifications

f^R_{xq} =0 & f^L_{xq} =1

f^R_{xq} =1 & f^L_{xq} =0