Highlights of top quark properties measurements at ATLAS

XXIII International Workshop QFTHEP

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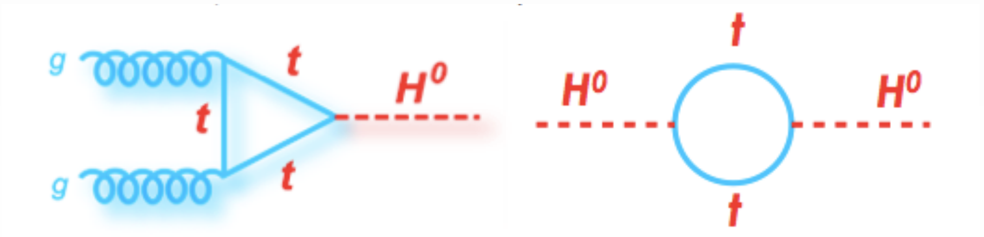
on behalf of the ATLAS Collaboration

Yaroslavl, Russia 29/06/2017

What makes top quark interesting?

Heaviest fundamental particle in the SM

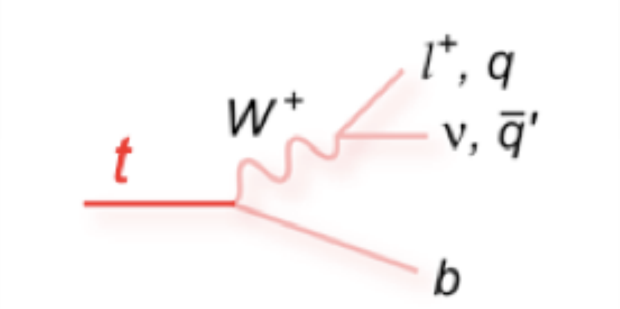
Larger mass → Larger coupling to SM Higgs + m_{top} is a fundamental parameter in SM



Allows for Self-Consistency Checks of SM Post Higgs Discovery

Short lifetime (~10^{-25}s)

Decays before hadronization – Unique among the quarks!



Access to Polarization and Spin Correlations

Processes including tops are backgrounds for new physics

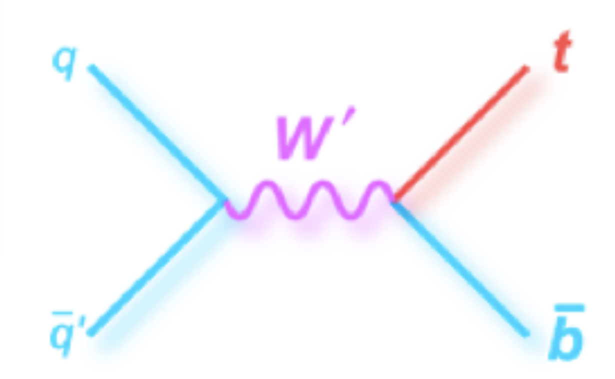
e.g. $H \rightarrow b\bar{b}$

$H \rightarrow WW$

+ Exotics and SUSY

Good Understanding → Improvements in Searches

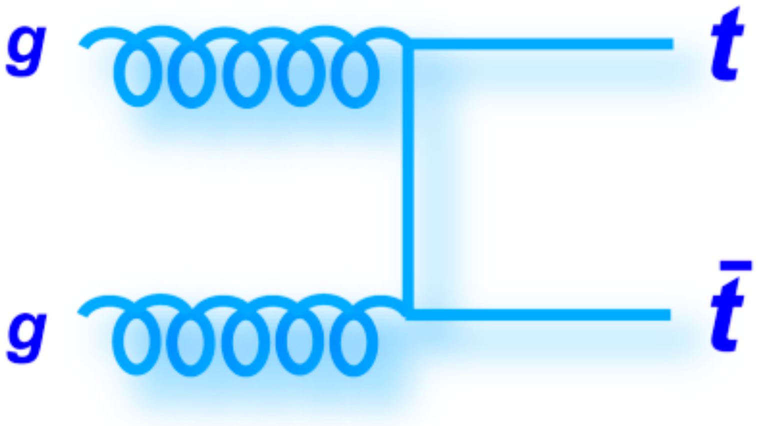
Hints of new/BSM physics

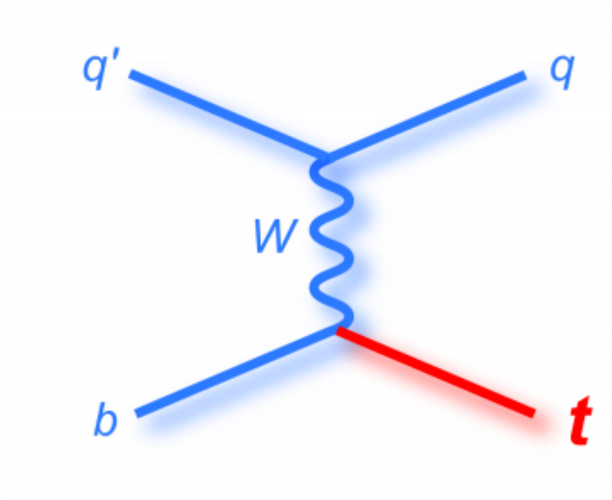


Exotic Particles Could Decay Preferentially to Top Quarks

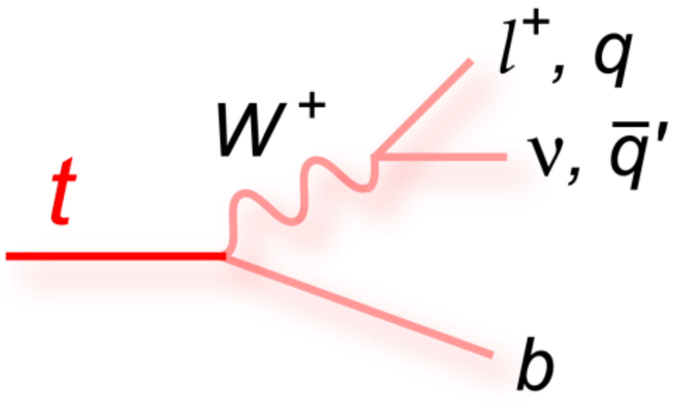
Top production and decay

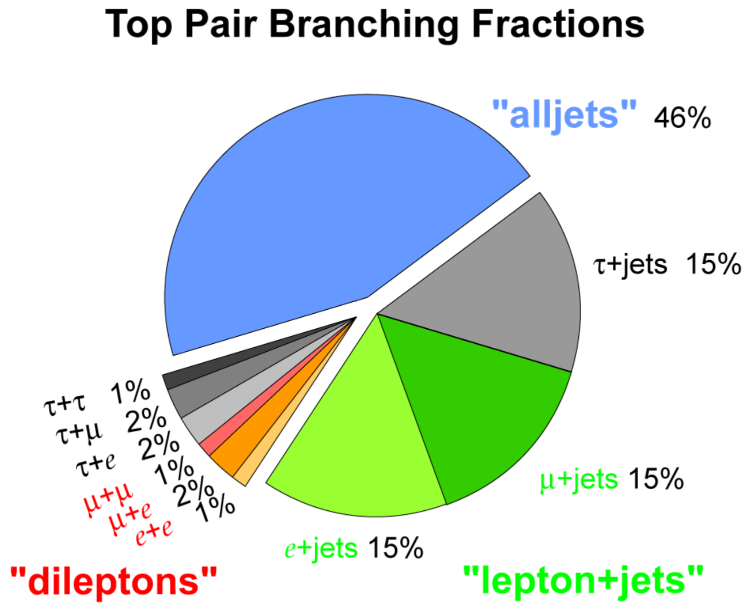
- ★ In *pp* collisions top production is dominated by QCD production in top and anti-top pairs.
- ★ EW production provides direct access to Wtb vertex



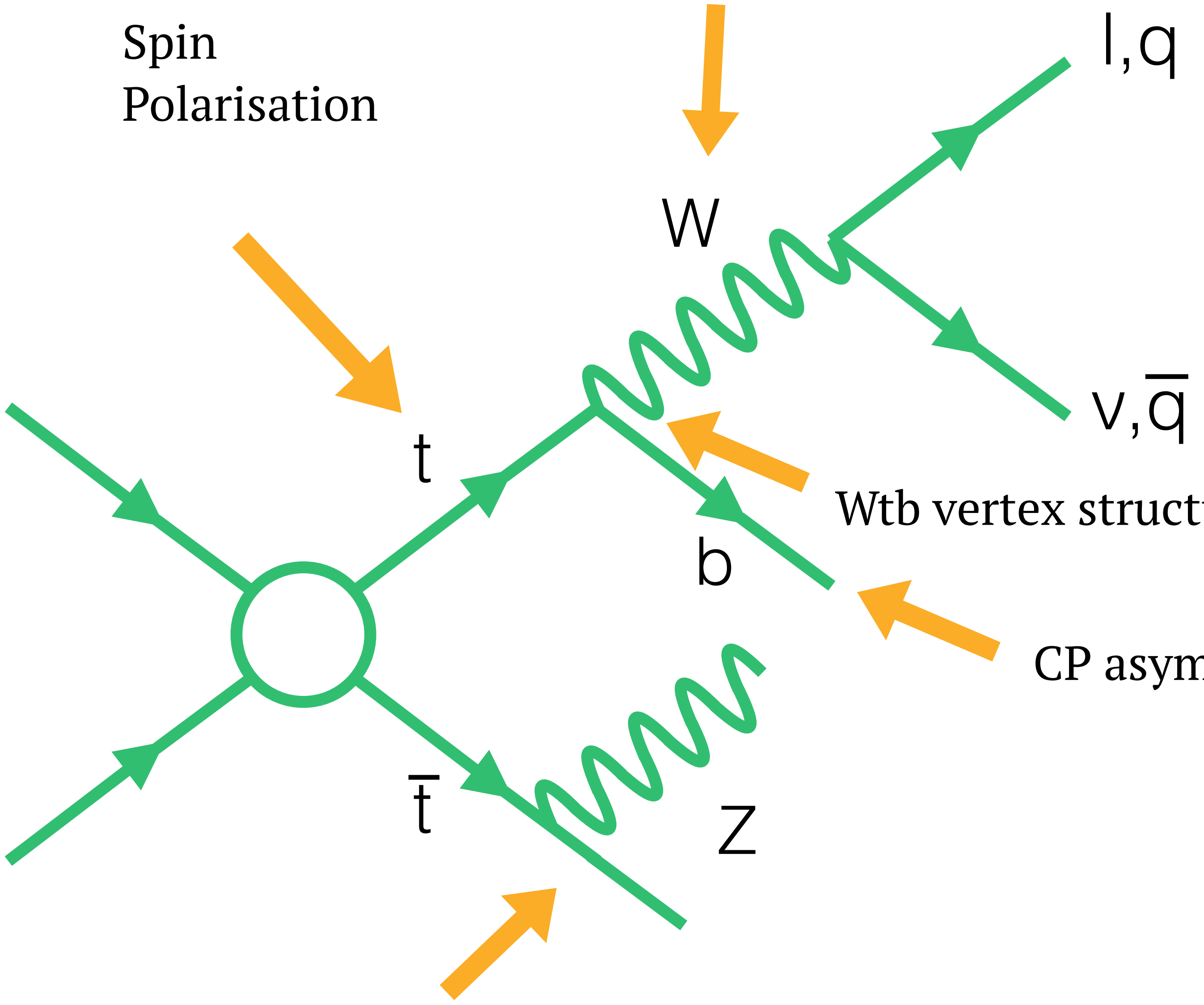


- ★ In the SM, top decays to Wb





Topics covered in this talk



Mass
Spin
Polarisation

Polarisation
Helicity

Wtb vertex structure

CP asymmetry

$t\bar{t}Z$, $t\bar{t}W$, $tt\gamma$ production

Topics covered in this talk

Top mass	arXiv:1702.07546 Phys.Lett. B 761 (2016) 350
Top spin	JHEP 03 (2017) 113
Wtb vertex structure	JHEP 04 (2017)124
W polarisation	Eur.Phys.J. C (2017)77:264
CP asymmetries	JHEP 02 (2017) 071
$t\bar{t}X$ production	Eur.Phys.J. C (2017)77:40 arXiv:1706.03046

Top quark mass

★ Motivations

- EW precision calculations depend on m_t
- EW vacuum stability involve m_t
- m_t is large → connection with high energy theories
- Unique opportunity to study a (almost) bare quark

★ Methods: Confinement → quark masses are not observables → what is m_t?

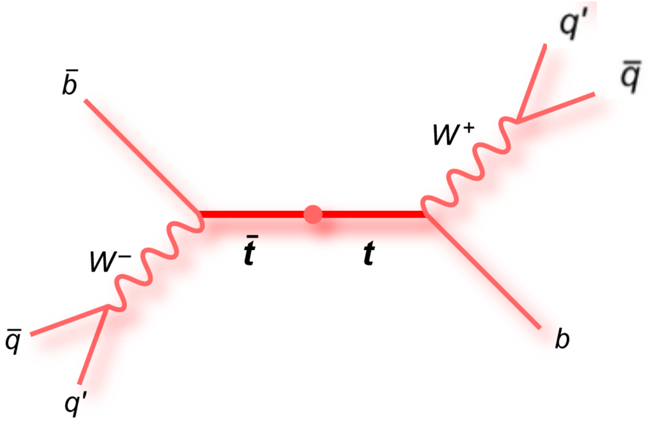
- **Top decay products invariant mass m_t^{MC}: Direct measurements**
  - Choose detector-level observables (O_i) which depend on the top quark mass
  - Generate MC with varied m_t^{MC} values
  - From MC, parameterise $O_i(m_t^{MC})$
  - Take value of m_t^{MC} which best describes data
- **theory parameter in the lagrangian m_t^{pole} (in pole mass scheme) Cross section measurements**
  - Take at least a NLO calculation (fix scheme)
  - Obtain (differential also) $\sigma_{t\bar{t}+X}(m_t^{pole})$
  - Compare measured $\sigma^{exp}_{t\bar{t}+X}$ with theory
  - Choose the value of m_t^{pole} which best match $\sigma^{exp}_{t\bar{t}+X}$
  - m_t^{pole} well-defined theoretically

★ Topologies

Newest ATLAS result		Most precise ATLAS result	
$t\bar{t}$ all-hadronic	$t\bar{t}$ semileptonic	$t\bar{t}$ dileptonic	single-t (t leptonic)
• 6 jets (2 b-jets)	• 4 jets (2 b-jets)	• 2 b-jets	• 2 jets (1 b-jet)
• no leptons	• 1 lepton	• 2 leptons	• 1 lepton
• no E_T^{miss}	• $E_T^{miss} > 30$ GeV	• $E_T^{miss} > 60$ GeV	• $E_T^{miss} > 30$ GeV

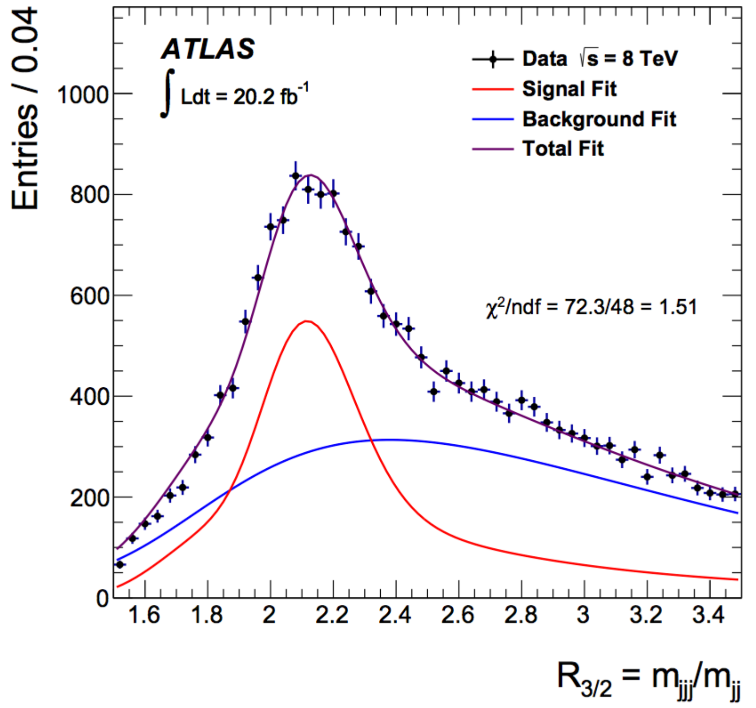
arXiv:1702.07546

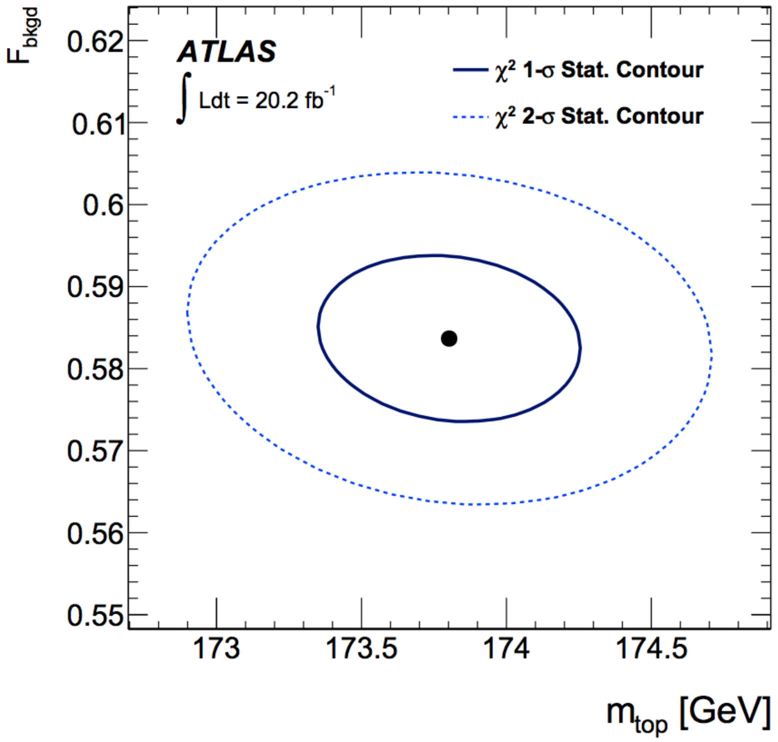
Top quark mass in the all-hadronic channel



- ★ Largest branching ratio (46%) among the possible top quark decay channels
- ★ Challenging because of the large multijet background
- ★ m_{top} extracted from a template fit to the distribution of the ratio of three-jet to dijet masses, $R_{3/2}=m_{jjj}/m_{jj}$ (reduced dependence on the jet energy scale uncertainty)
- ★ The dominant source of systematic uncertainty come from the jet energy scale, hadronisation modelling and the b-jet energy scale.
- ★ with a relative precision of 0.7%, it is about 40% more precise than the previous measurement performed by ATLAS in the all-hadronic channel at 7 TeV.

$$m_{top} = 173.72 \pm 0.55 \text{ (stat.)} \pm 1.01 \text{ (syst.) GeV}$$





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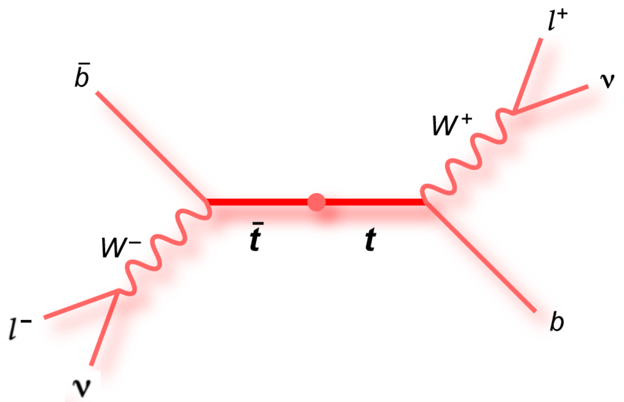
Top quark mass in the dilepton channel

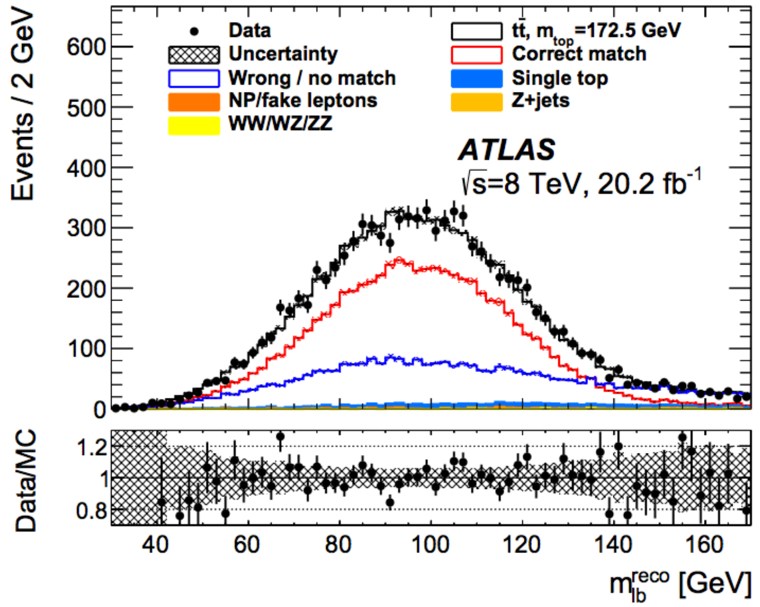


- The analysis uses a template fit to m_{lb}
- An unbinned maximum likelihood fit gives the m_{top} value that best describes de data
- Biggest uncertainties come from the jet energy scale and the relative b-to-light-jet energy scale
- The result is the most precise single result in this decay channel to date (40% more precise than the one obtained with 7 TeV data)

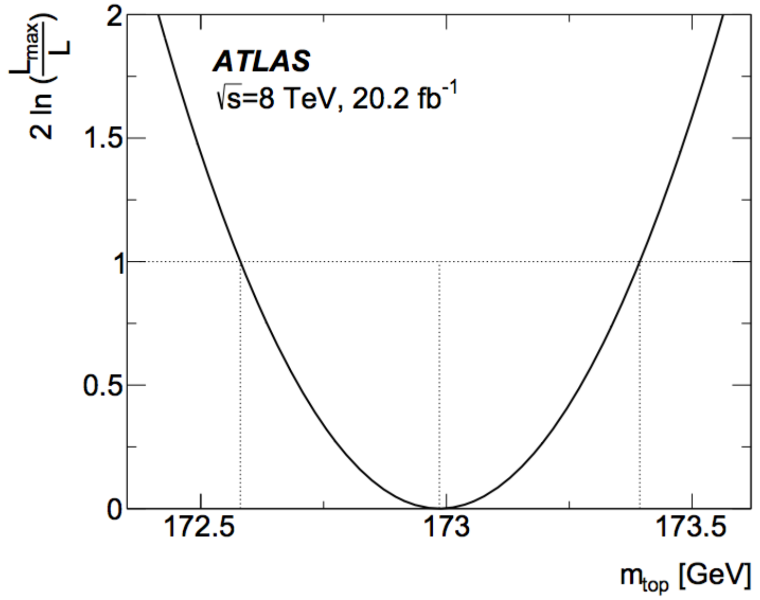
$$m_{top} = 172.99 \pm 0.41(\text{stat}) \pm 0.74(\text{syst})\text{GeV}$$

- The result is combined with ATLAS m_{top} measurements in the lepton+jets channel and the dilepton channel @ 7 TeV with a relative precision of 0.4%

$$m_{top} = 172.84 \pm 0.34(\text{stat}) \pm 0.61(\text{syst})\text{GeV}$$



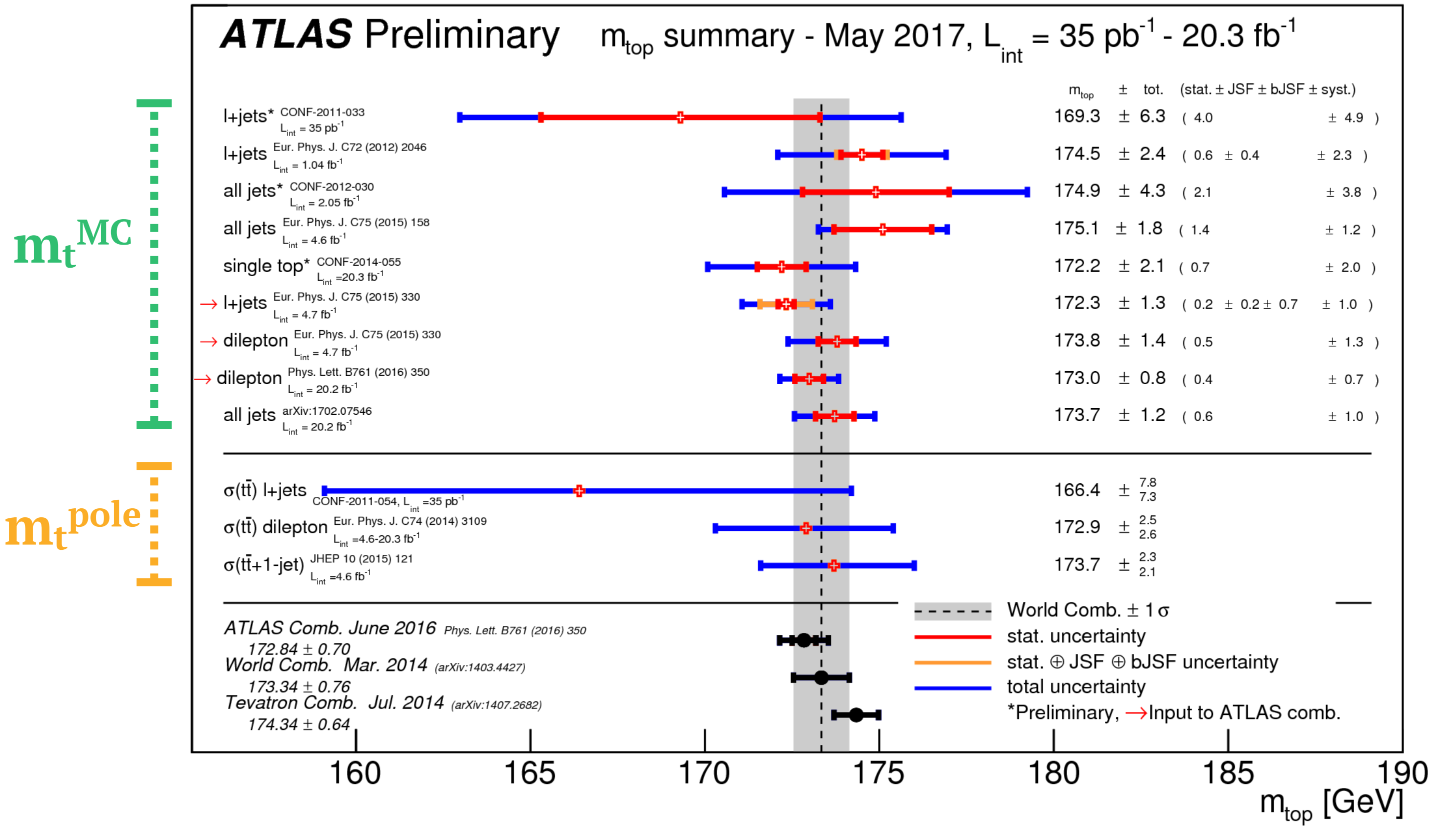
(b) $m_{\ell b}^{reco}$ in data and simulation



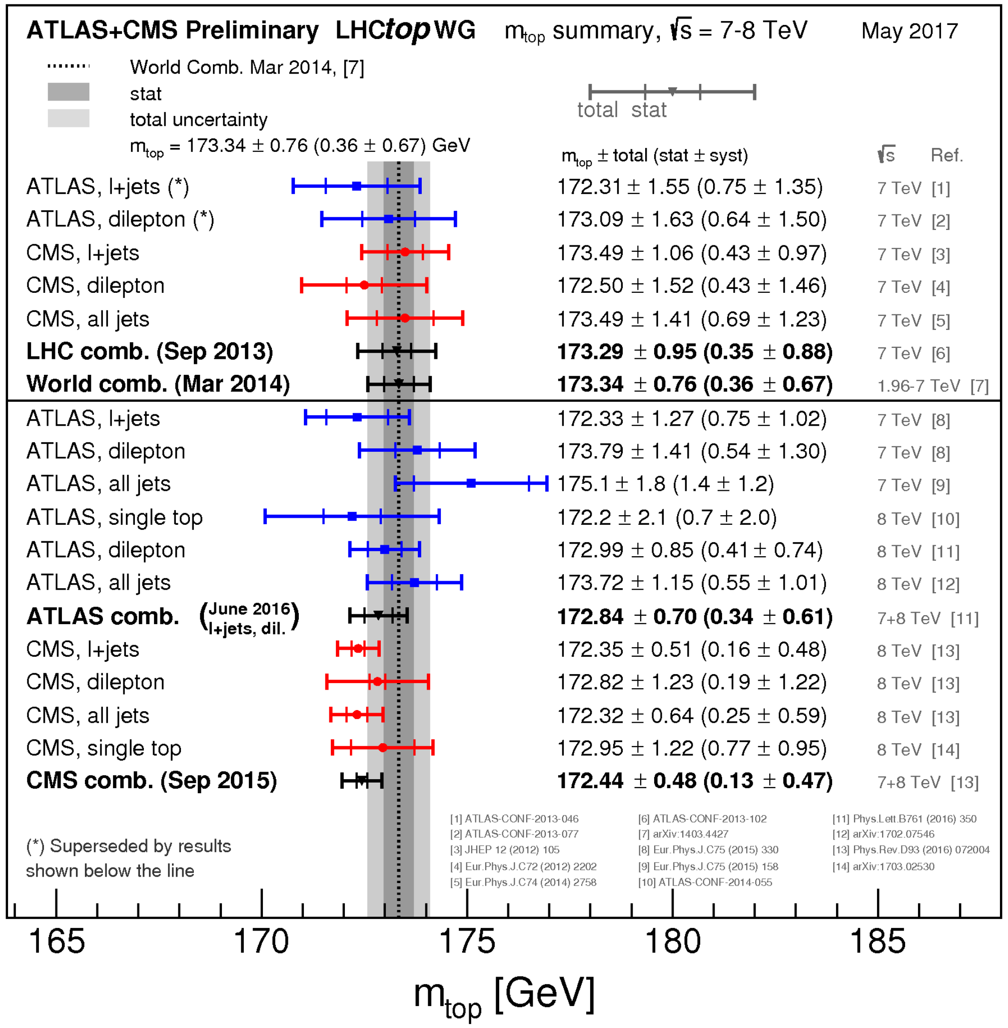
(d) Logarithm of the likelihood

Top quark mass summary

ATLAS public results



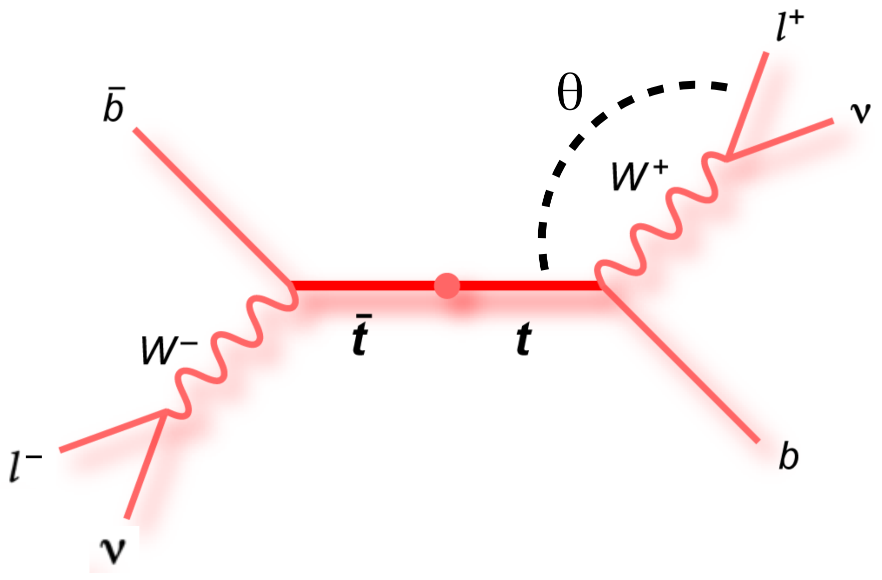
ATLAS public results



- ★ Main gain in precision of top mass measurements lays in the combination of the results
- ★ Uncertainties are dominated by systematics (JES, b-JES and modelling)
- ★ m_t^{MC} and m_t^{pole} are obtained with different techniques and therefore the results are not directly comparable, specially the uncertainties

Top quark spin observables in $t\bar{t}$ production

- ★ In the SM, top quarks produced in pairs are unpolarised
- ★ The **spins of the top and the antitop are correlated** and the information is transferred to their decay products, thus affecting their angular distributions.
- ★ Use $t\bar{t}$ dilepton events (ee, μμ, eμ)
- ★ The spin density matrix can be expressed in terms of **15 spin observables** using 3 orthogonal spin quantisation axes:
  - 3 polarisation coefficients for the top quark
  - 3 polarisation coefficients for the antitop quark
  - 9 spin correlation coefficients
- ★ Results are provided at **parton level** in the full phase-space and at stable-particle level in a fiducial phase-space.



Three axes:
- **k**: helicity axis
- **n**: transvers axis
- **r**: orthogonal to k & n

θ: angle between the momentum of a decay particle and a quantisation axis

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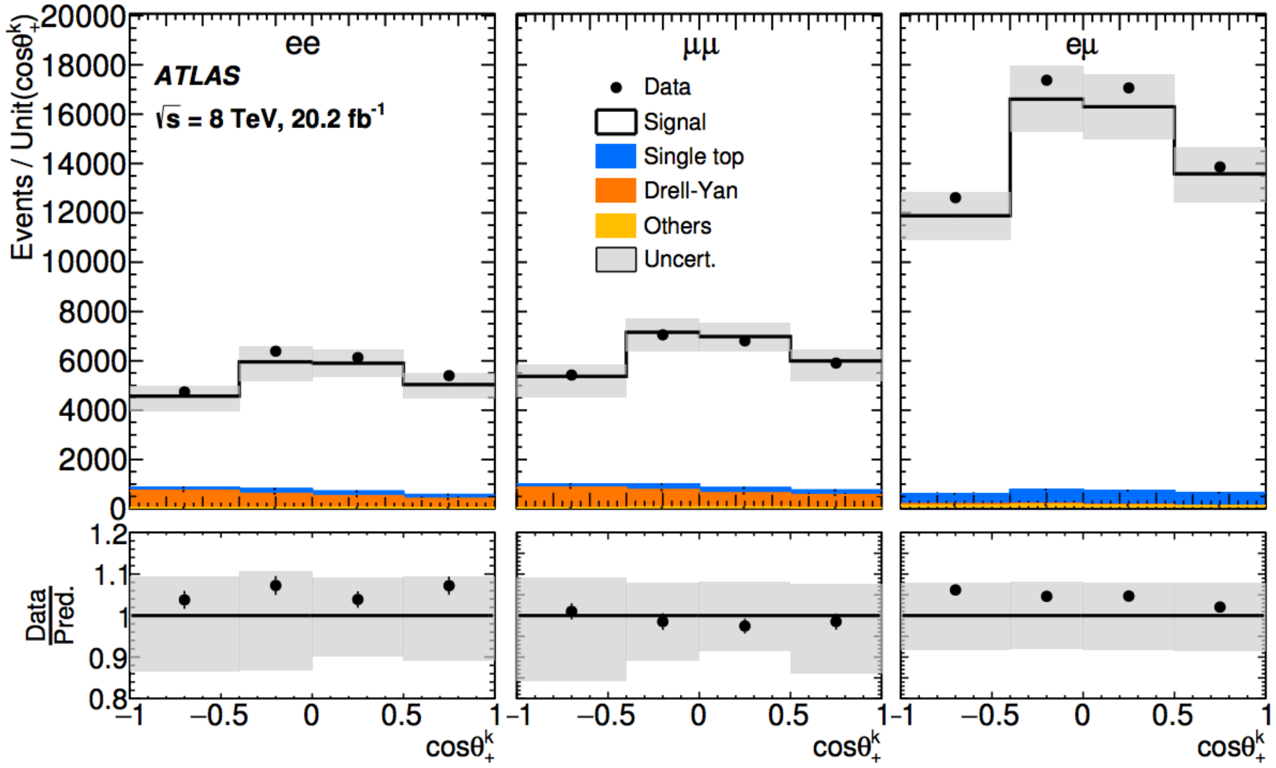
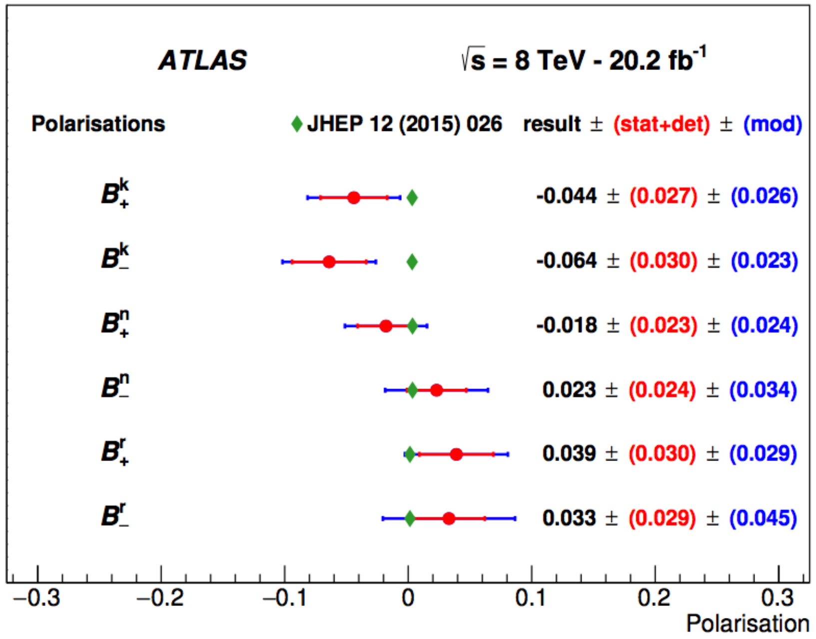
Top quark spin observables in $t\bar{t}$ production

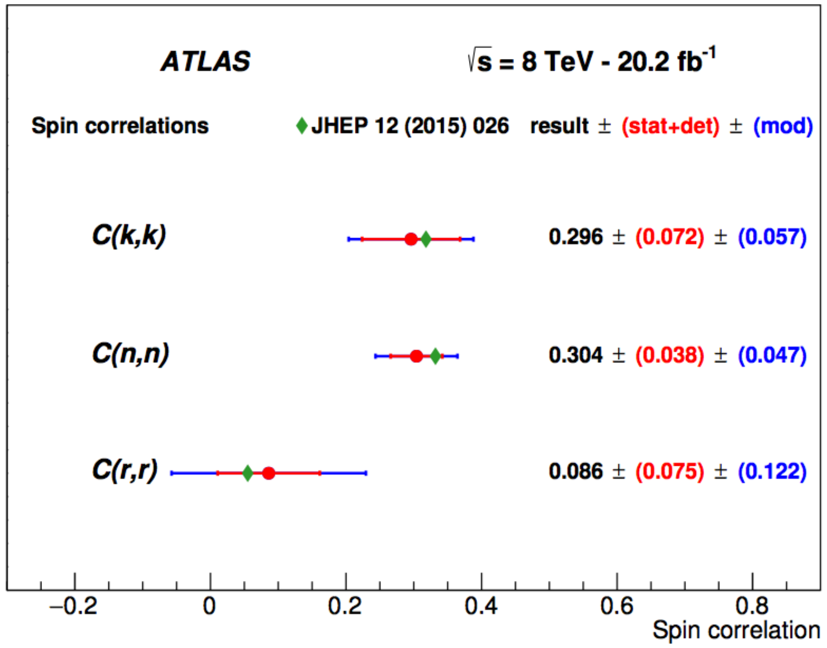


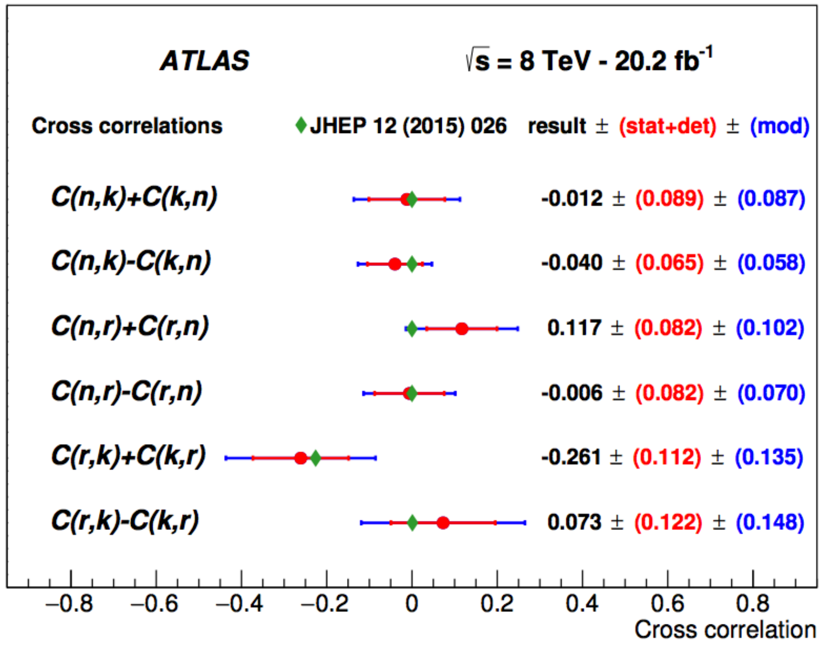
$$\frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos\theta_+^a\,\mathrm{d}\cos\theta_-^b} = \frac{1}{4}\left(1+\boxed{B_+^a}\cos\theta_+^a+\boxed{B_-^b}\cos\theta_-^b-\boxed{C}(a,b)\cos\theta_+^a\cos\theta_-^b\right)$$

B: (anti)top polarisation
C: spin correlations
(-)+:(anti)top
k: helicity axis
n: transvers axis
r: orthogonal to k & n

★ The dominant source of systematic uncertainties comes from the modelling of the signal, which can represent up to 85% of the total uncertainty.







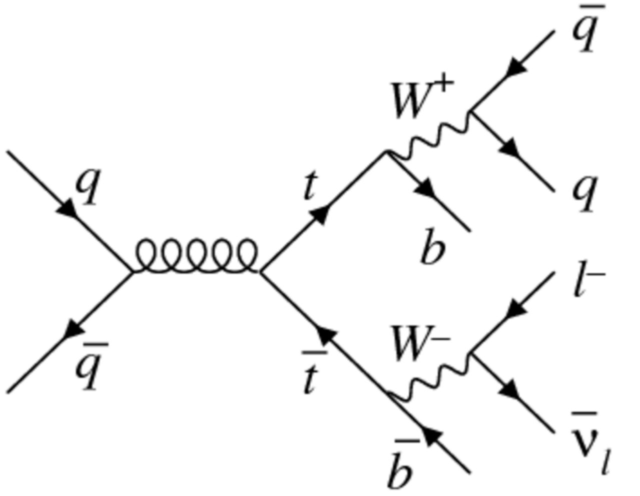
★ Results at parton level

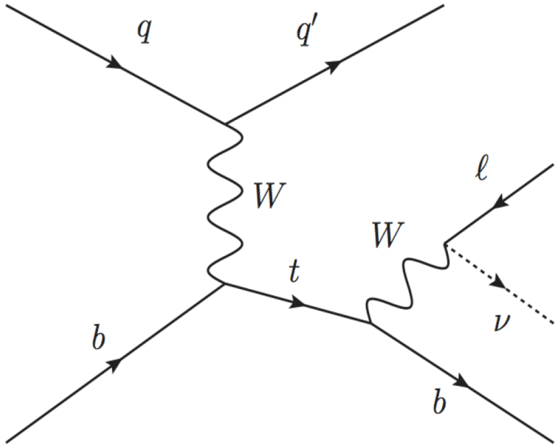
Wtb vertex

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}}\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}\left(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}}\right)tW_{\mu}^{-} + \mathrm{h.c.}$$

In the **SM**: $V_L \sim 1$, $V_R = g_L = g_R = 0$ → **Limits** set to: **$\mathrm{Re}(V_R)$, $\mathrm{Re}(g_L)$, $\mathrm{Re}(g_R)$**; **$\mathrm{Im}(g_R)$**; **$\mathrm{Re}[g_R/V_L]$, $\mathrm{Im}[g_R/V_L]$, $|V_R/V_L|$**

- ★ **W boson polarisation**: **top pairs production, lepton+jets**
- ★ **W boson spin observables**: **t-channel single top production, lepton channel**
- ★ **Top quark polarisation**: t-channel single top production, lepton channel
- ★ **Triple-differential angular decay rates**: **t-channel single top production, lepton channel**





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

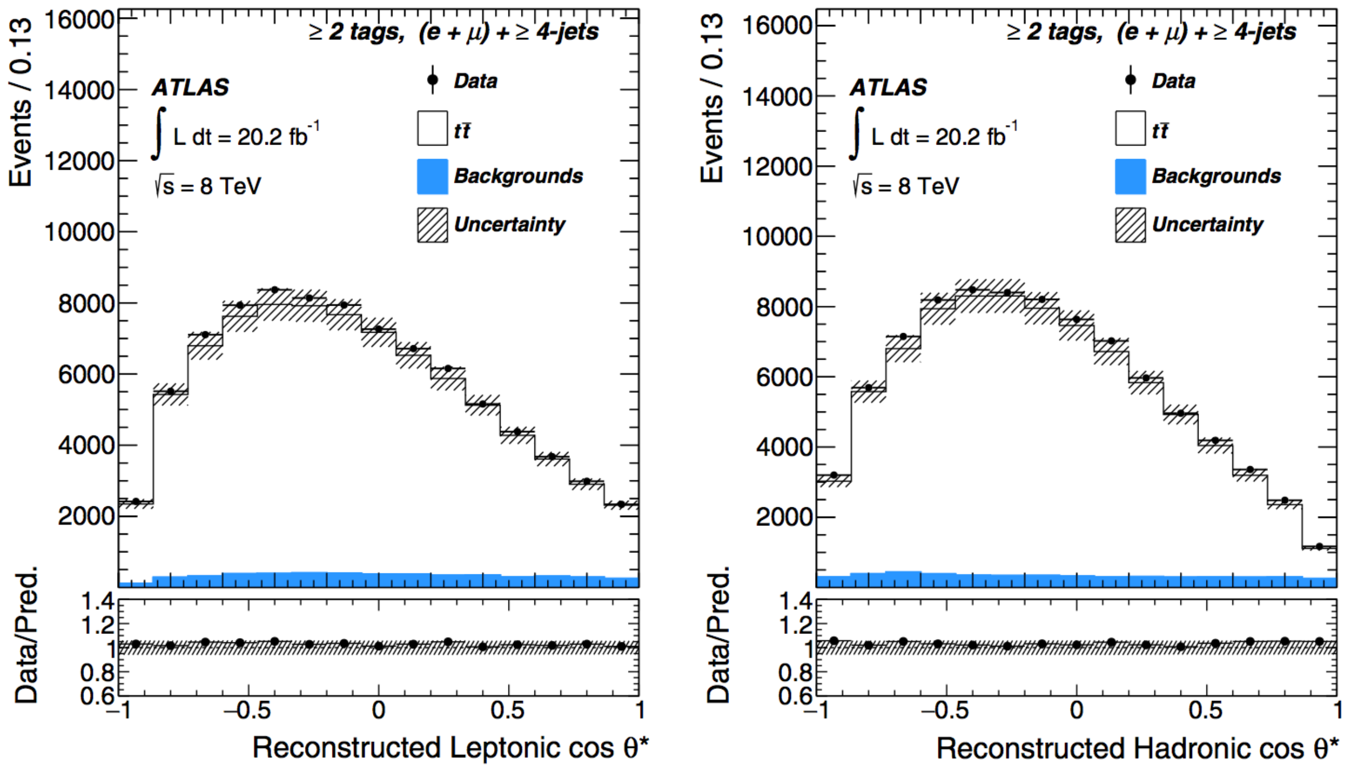
W polarisation in $t\bar{t}$ semileptonic events

- W boson helicity fractions can be accessed via angular distribution of polarisation analysers:
  - Leptonic decay: charged lepton
  - Hadronic decay: down-type quark

Predictions at NNLO in QCD
$F_L = 0.311 \pm 0.005$
$F_R = 0.0017 \pm 0.0001$
$F_0 = 0.687 \pm 0.005$

- The down-type quark is identified using a kinematic likelihood fitter (KLFitter), using the weight of the b-jet tagging algorithm
- Template fit of the distribution $cos\theta^*$ (angle between the analyser and the reversed direction of flight of the b-quark from the top quark decay in the W boson rest frame) for the full phase-space

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



Hadronic analyser (1 b-tag + ≥2 b-tags)
$F_0 = 0.659 \pm 0.010$ (stat.+bkg. norm.) $^{+0.052}_{-0.054}$ (syst.)
$F_\mathrm{L} = 0.281 \pm 0.021$ (stat.+bkg. norm.) $^{+0.063}_{-0.067}$ (syst.)
$F_\mathrm{R} = 0.061 \pm 0.022$ (stat.+bkg. norm.) $^{+0.101}_{-0.108}$ (syst.)

Leptonic analyser (≥2 b-tags)
$F_0 = 0.709 \pm 0.012$ (stat.+bkg. norm.) $^{+0.015}_{-0.014}$ (syst.)
$F_\mathrm{L} = 0.299 \pm 0.008$ (stat.+bkg. norm.) $^{+0.013}_{-0.012}$ (syst.)
$F_\mathrm{R} = -0.008 \pm 0.006$ (stat.+bkg. norm.) ± 0.012 (syst.)

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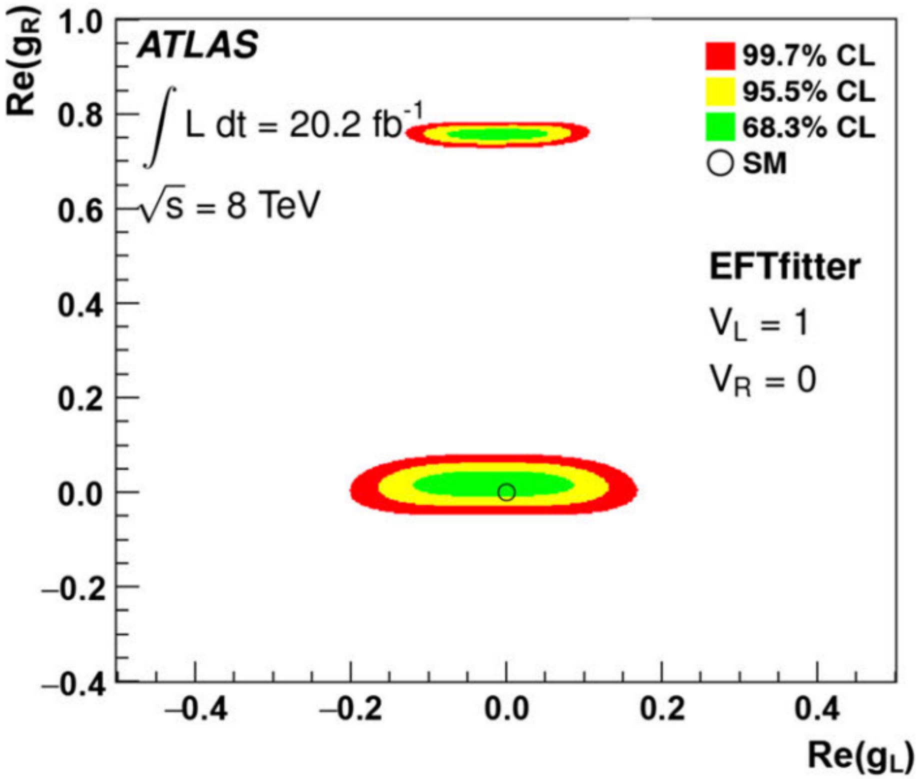
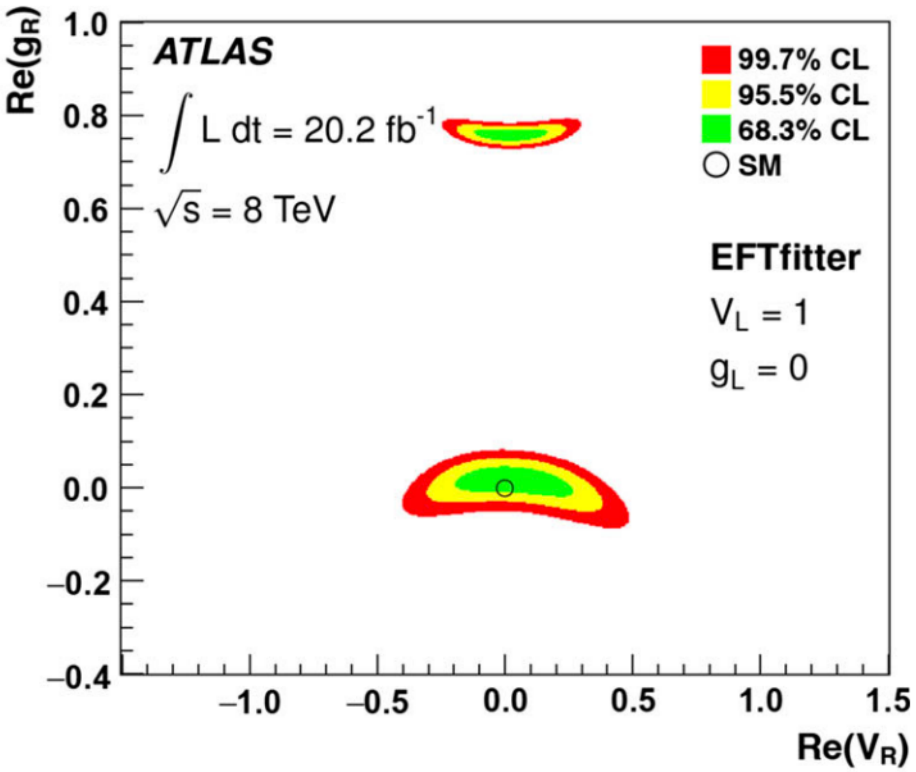
W polarisation in $t\bar{t}$ semileptonic events





- ★ Limits on the anomalous couplings are set assuming these to be real, corresponding to the CP-conserving case.
  - V_L is fixed to the SM prediction of one.
  - Only one anomalous coupling is allowed to vary at a time, while the rest of them are fixed to their SM predictions

Coupling	95% CL interval
V_R	[−0.24, 0.31]
g_L	[−0.14, 0.11]
g_R	[−0.02, 0.06], [0.74, 0.78]

- ★ Main uncertainty sources:
  - Leptonic analyser: jet energy scale and resolution and MC template statistics
  - Hadronic analyser: b-tagging uncertainty, jet energy resolution and ttbar modelling

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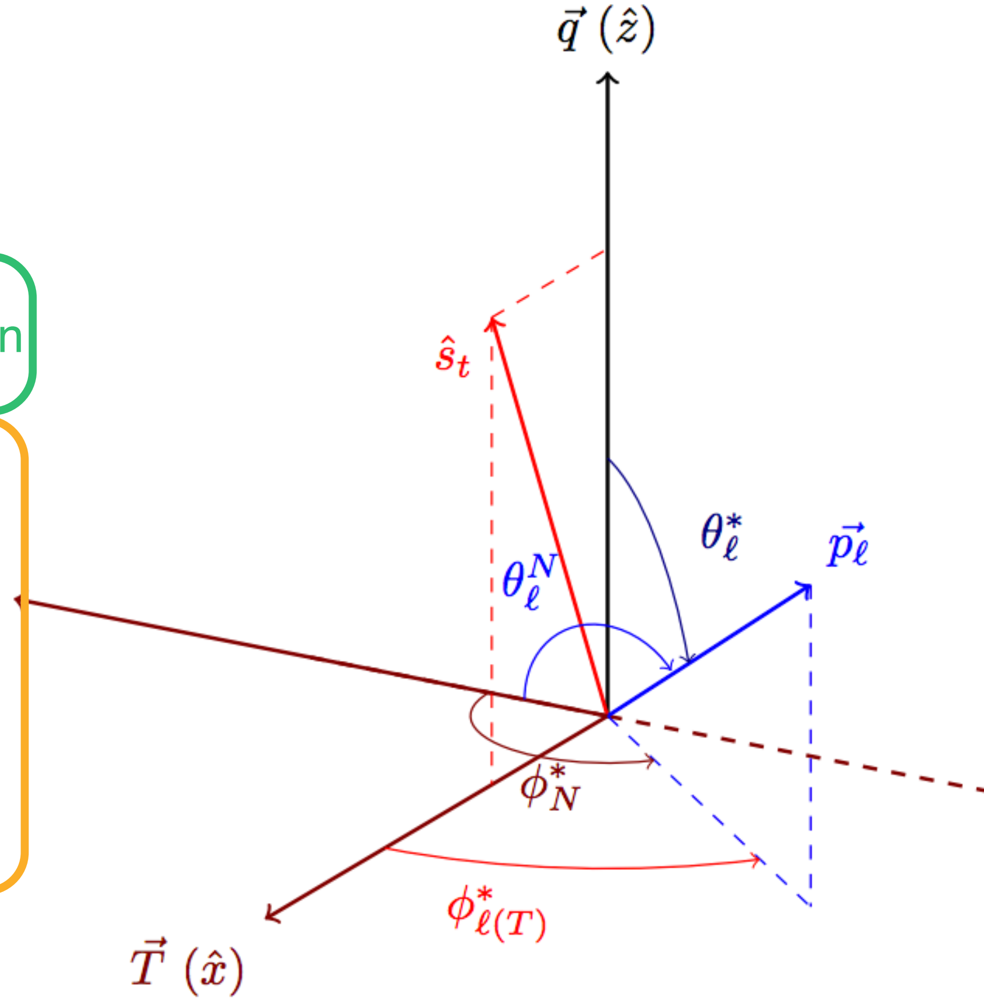
Wtb vertex at production and decay in t-channel events

- ★ ***Wtb* vertex at production:** the information about the **top polarisation** can be measured from asymmetries in the angular distributions of the decay products reconstructed in the top quark rest frame.
- ★ ***Wtb* vertex at decay:** the spin density matrix elements for the W boson helicity components 0, ±1 resulting from the decay of polarised top-quarks can be parameterised in terms of expected values of six independent **W spin observables** which are **sensitive to anomalous Wtb couplings**. These can be extracted from asymmetries in the angular distributions of the charged lepton reconstructed in the W boson rest frame.

Asymmetry	Angular observable	Polarisation observable	SM prediction
A_{FB}^{ℓ}	$\cos\theta_\ell$	$\frac{1}{2}\alpha_\ell P$	0.45
A_{FB}^{tW}	$\cos\theta_W \cos\theta_\ell^*$	$\frac{3}{8}P\,(F_{\mathrm{R}}+F_{\mathrm{L}})$	−0.10
A_{FB}	$\cos\theta_\ell^*$	$\frac{3}{4} < S_3 >$	−0.23
A_{EC}	$\cos\theta_\ell^*$	$\frac{3}{8}\sqrt{\frac{3}{2}} < T_0 >$	−0.20
A_{FB}^{N}	$\cos\theta_\ell^N$	$-\frac{3}{4} < S_2 >$	0
A_{FB}^{T}	$\cos\theta_\ell^T$	$\frac{3}{4} < S_1 >$	0.34
$A_{\mathrm{FB}}^{N,\phi}$	$\cos\theta_\ell^* \cos\phi_N^*$	$\frac{2}{\pi} < A_2 >$	0
$A_{\mathrm{FB}}^{T,\phi}$	$\cos\theta_\ell^* \cos\phi_T^*$	$-\frac{2}{\pi} < A_1 >$	−0.14

Production

Decay



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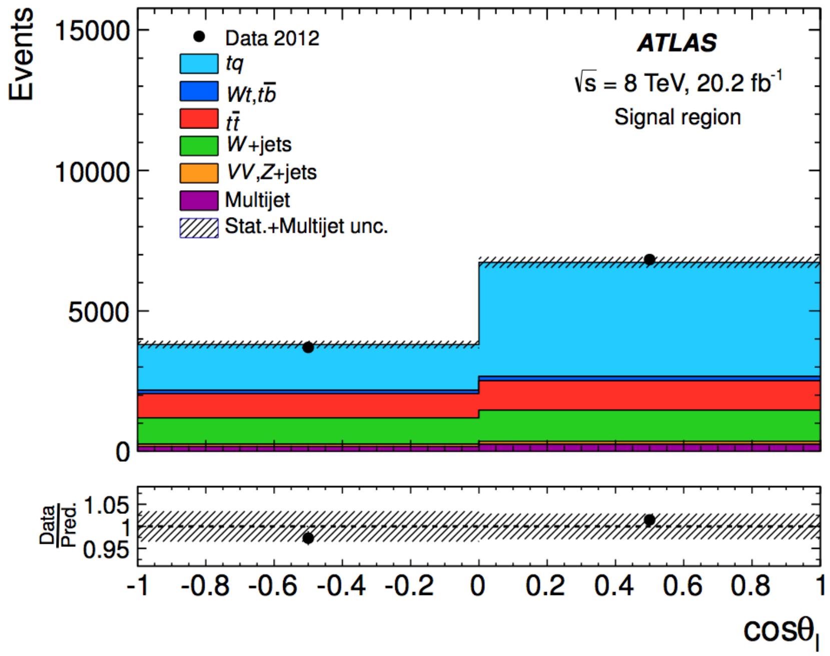
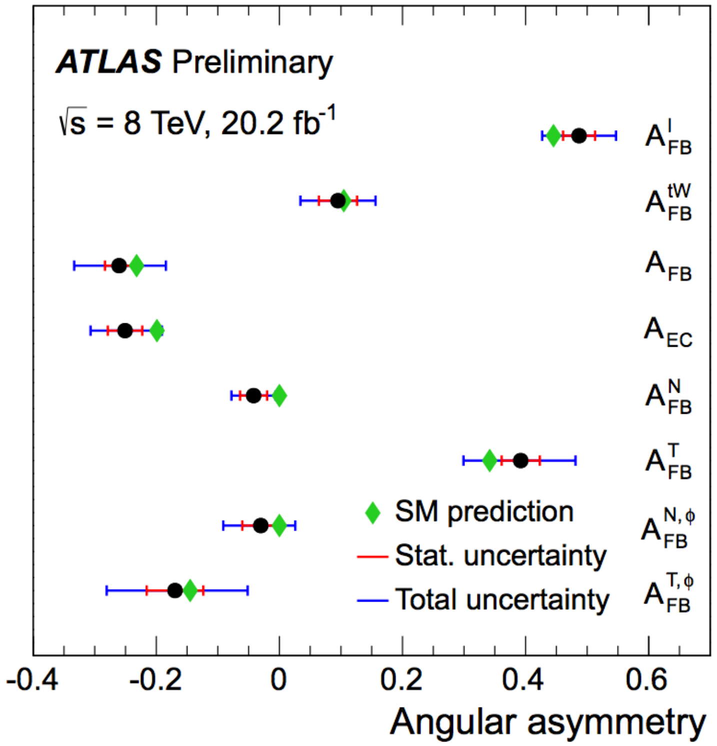
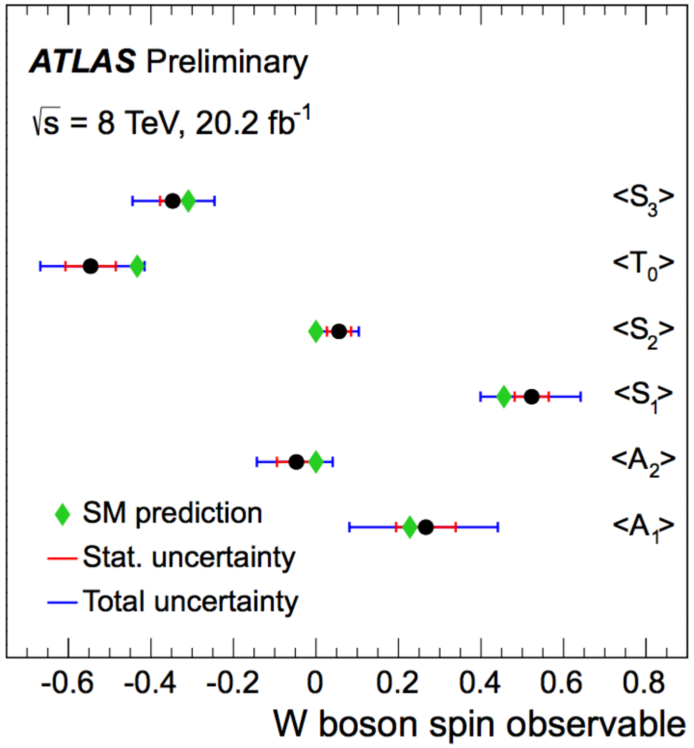
Wtb vertex at production and decay in t-channel events

- ⭑ W boson spin observables and top polarisation related observables obtained via the measurement of asymmetries assuming SM couplings in the unfolding procedure: **consistency check of the SM**.







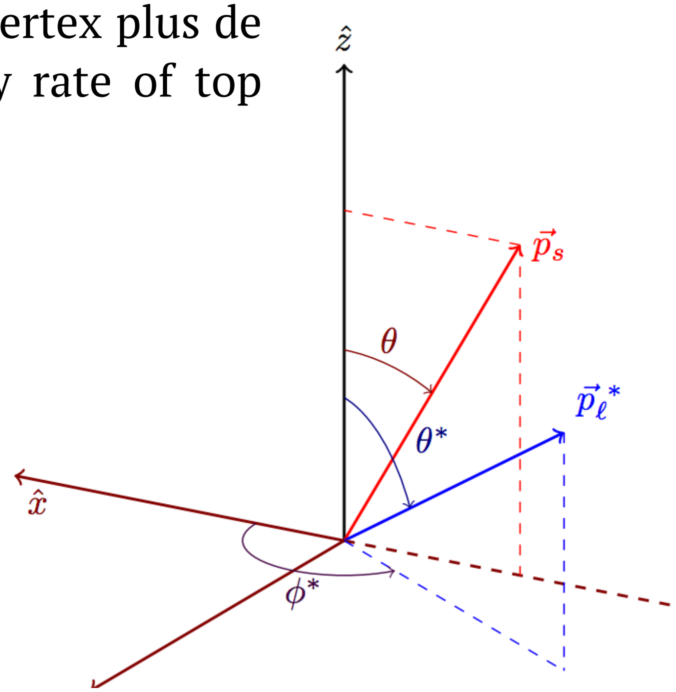
- ⭑ Two of the asymmetries, A_{FB}^{N} (which has the highest sensitivity to **Im g_R**) and A_{FB}^{l}, have been used to extract **limits** on this coupling. For this computation, the rest of the couplings were assumed to have SM values.

$$\mathrm{Im}\; gR \in [-0.18, 0.06] \text{ at the 95\% CL}$$

- ⭑ The dominant sources of systematic uncertainties are the modelling of the t-channel and $t\bar{t}$ processes, and the jet reconstructions and energy scale.

Wtb vertex: three angle analysis

- Complete description of the full space of anomalous couplings governing the Wtb vertex plus de top-quark polarisation by using the normalised triple-differential (θ,θ*,Φ*) decay rate of top quarks.

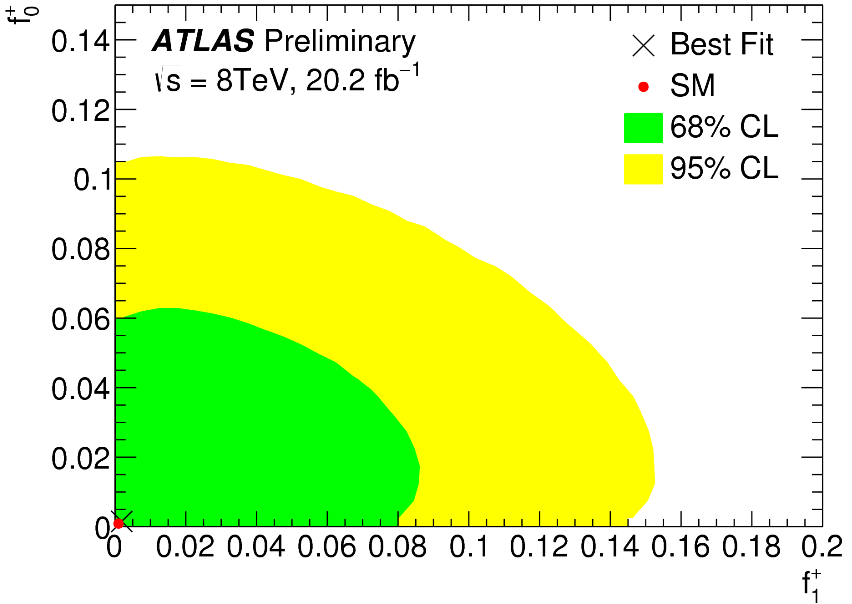


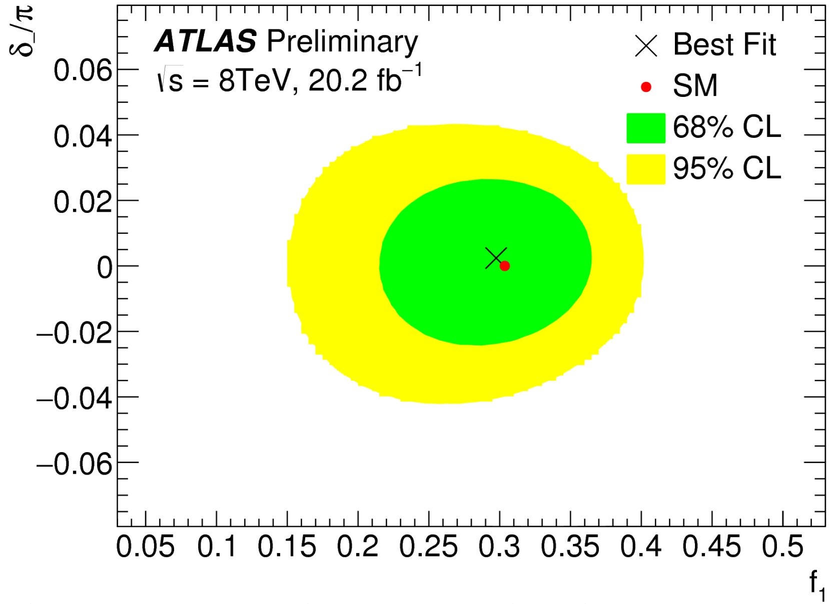
$$\begin{aligned}\varrho(\theta,\theta^*,\phi^*;P)=\frac{1}{N}\frac{d^3N}{d(\cos\theta)d\Omega^*} &= \frac{1}{8\pi}\Bigg\{\frac{3}{4}\left|A_{1,\frac{1}{2}}\right|^2(1+P\cos\theta)\,(1+\cos\theta^*)^2\\ &+\frac{3}{4}\left|A_{-1,-\frac{1}{2}}\right|^2(1-P\cos\theta)\,(1-\cos\theta^*)^2\\ &+\frac{3}{2}\left(\left|A_{0,\frac{1}{2}}\right|^2(1-P\cos\theta)+\left|A_{0,-\frac{1}{2}}\right|^2(1+P\cos\theta)\right)\sin^2\theta^*\\ &-\frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*\,(1+\cos\theta^*)\,\mathrm{Re}\left[e^{i\phi^*}A_{1,\frac{1}{2}}A^*_{0,\frac{1}{2}}\right]\\ &-\frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*\,(1-\cos\theta^*)\,\mathrm{Re}\left[e^{-i\phi^*}A_{-1,-\frac{1}{2}}A^*_{0,-\frac{1}{2}}\right]\Bigg\}=\sum_{k=0}^{2}\sum_{l=0}^{2}\sum_{m=-l}^{l}a_{k,l,m}M^m_{k,l}(\theta,\theta^*,\phi^*)\end{aligned}$$

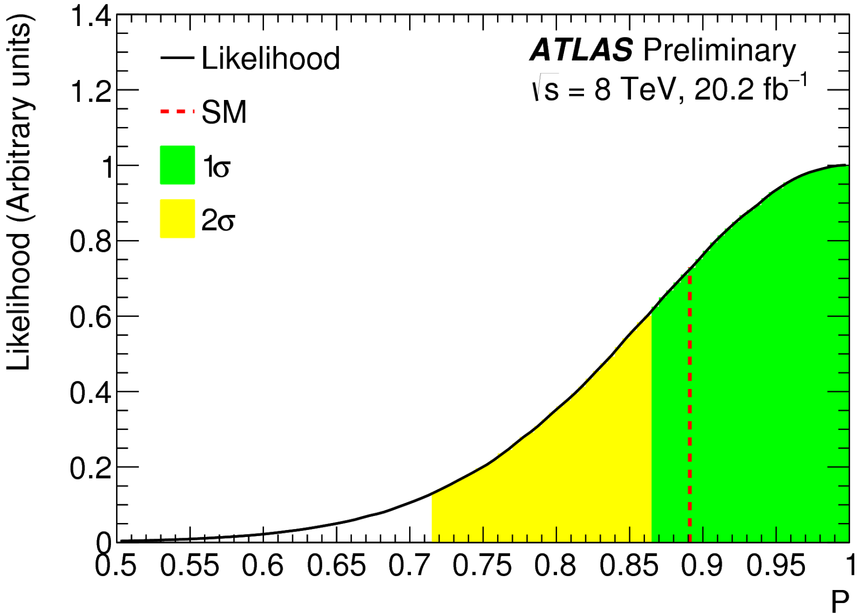
- Only nine of the coefficients $A_{k,l,m}$ are nonzero and can be parameterised by three amplitude fractions and and two phases:
  - 3 observable amplitude fractions: f_1,f_{1+},f_{0+}
  - 1 observable phase: δ-
  - 1 likely unobservable phase: δ+
  - 1 observable nuisance parameter: P
- Detector effects are deconvolved from data by measuring differential rates using Fourier techniques
- All amplitudes and phases (and couplings) + P are determined simultaneously and include all correlations

Wtb vertex: three angle analysis

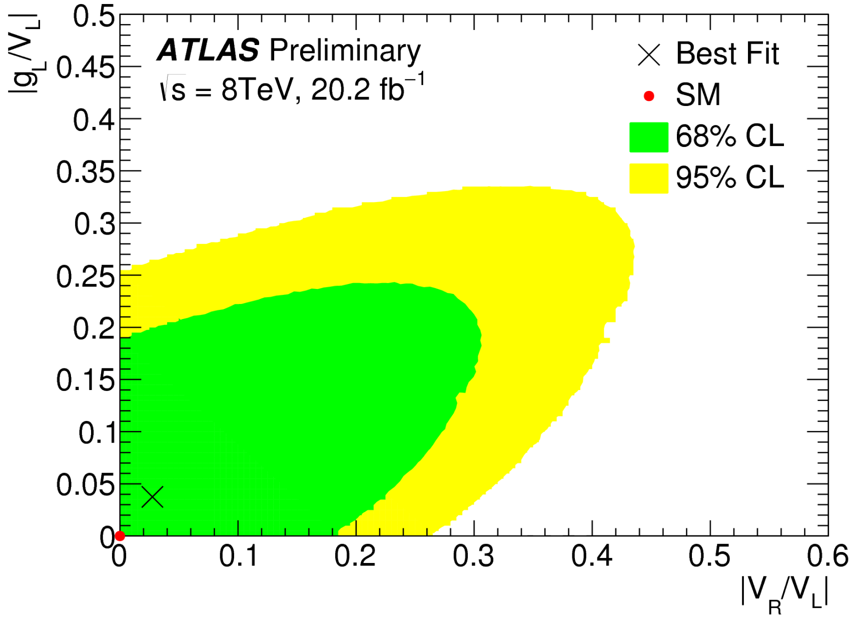
- ★ Global fit: Likelihood function with all correlations (covariance matrix)
  - Distributions are obtained from numerical calculations of the likelihood function

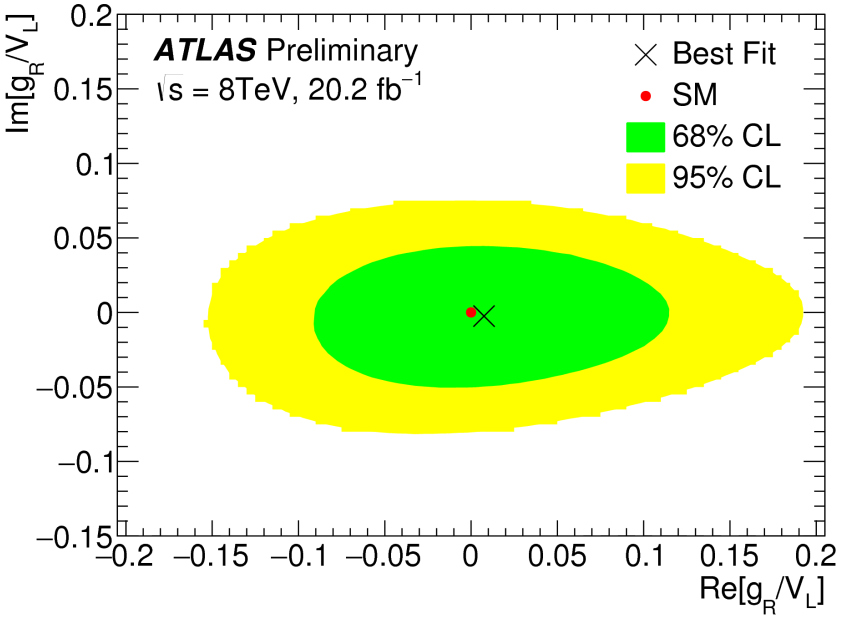


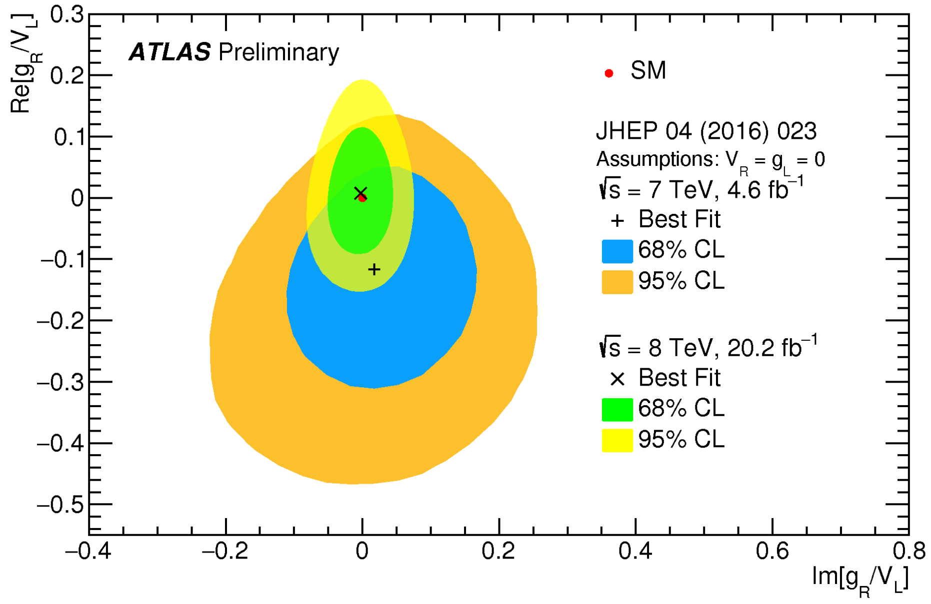




- ★ Interpretation in terms of anomalous couplings by propagating the statistical and systematic uncertainties
  - Limits are placed simultaneously on the possible complex values of the ratio of the anomalous couplings
  - No assumptions on values of the other anomalous couplings







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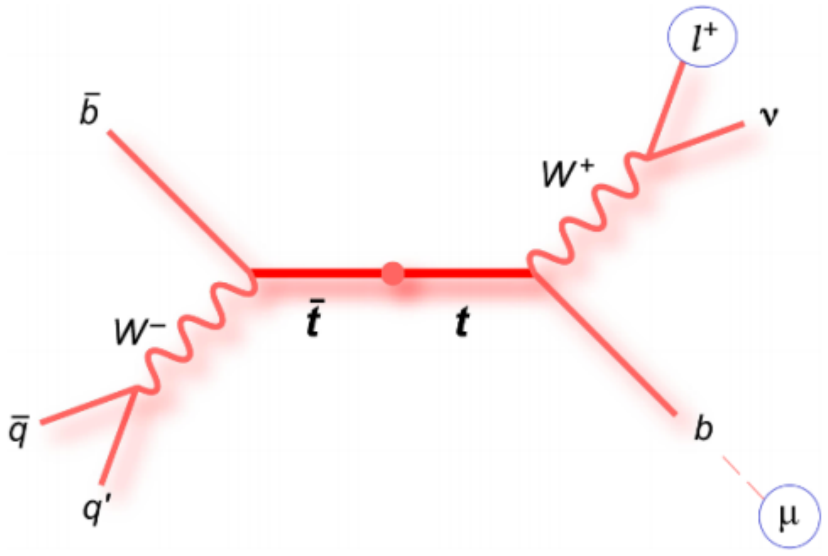
CP asymmetry in $t\bar{t}$ dileptonic events

- CP asymmetries in heavy-flavour mixing and decay from *b*-hadrons from top quark decays.
- Measurement of same- and opposite-sign charge asymmetries from the probabilities for an initial (anti)*b*-quark to decay via either a positively or negatively charged muon.
- Measurement of CP asymmetries which relate to B_q-$\bar{B}_q$ mixing and direct CP-violating *b*- and *c*-decays
- Asymmetries unfolded to a well-defined fiducial region



$$A^{ss} = \frac{P(b \to \ell^+) - P(\bar{b} \to \ell^-)}{P(b \to \ell^+) + P(\bar{b} \to \ell^-)}$$

$$A^{os} = \frac{P(b \to \ell^-) - P(\bar{b} \to \ell^+)}{P(b \to \ell^-) + P(\bar{b} \to \ell^+)}$$

$$A^{b\ell}_{\text{mix}} = \frac{\Gamma\left(b \to \bar{b} \to \ell^+ X\right) - \Gamma\left(\bar{b} \to b \to \ell^- X\right)}{\Gamma\left(b \to \bar{b} \to \ell^+ X\right) + \Gamma\left(\bar{b} \to b \to \ell^- X\right)},$$

$$A^{bc}_{\text{mix}} = \frac{\Gamma\left(b \to \bar{b} \to \bar{c} X\right) - \Gamma\left(\bar{b} \to b \to c X\right)}{\Gamma\left(b \to \bar{b} \to \bar{c} X\right) + \Gamma\left(\bar{b} \to b \to c X\right)},$$

$$A^{b\ell}_{\text{dir}} = \frac{\Gamma\left(b \to \ell^- X\right) - \Gamma\left(\bar{b} \to \ell^+ X\right)}{\Gamma\left(b \to \ell^- X\right) + \Gamma\left(\bar{b} \to \ell^+ X\right)},$$

$$A^{c\ell}_{\text{dir}} = \frac{\Gamma\left(\bar{c} \to \ell^- X_L\right) - \Gamma\left(c \to \ell^+ X_L\right)}{\Gamma\left(\bar{c} \to \ell^- X_L\right) + \Gamma\left(c \to \ell^+ X_L\right)},$$

$$A^{bc}_{\text{dir}} = \frac{\Gamma\left(b \to c X_L\right) - \Gamma\left(\bar{b} \to \bar{c} X_L\right)}{\Gamma\left(b \to c X_L\right) + \Gamma\left(\bar{b} \to \bar{c} X_L\right)},$$

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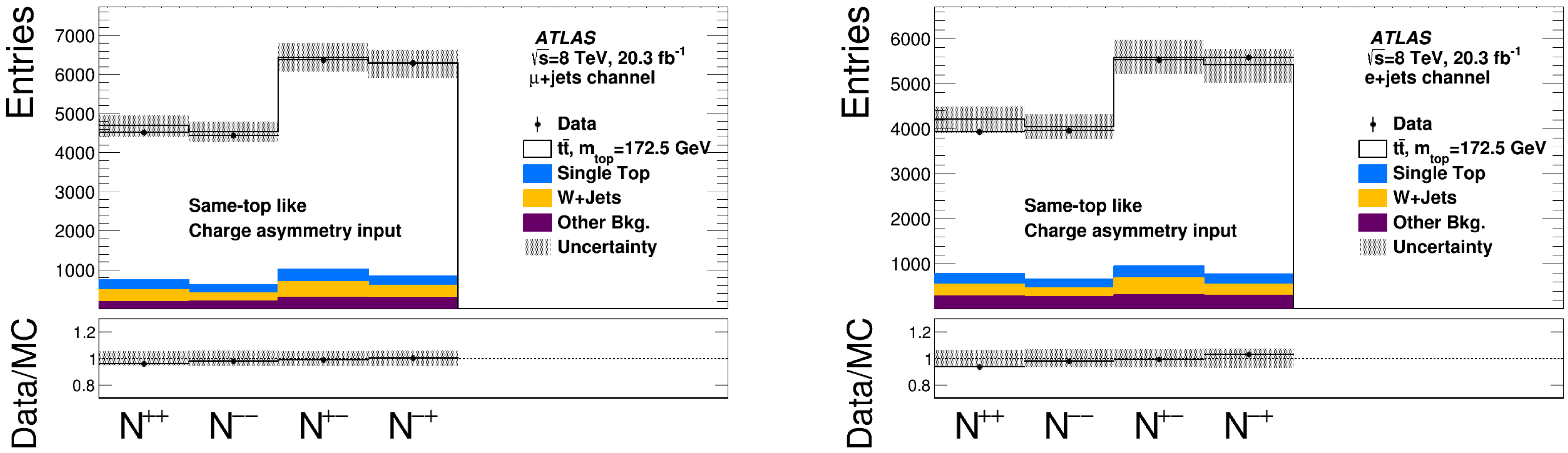
CP asymmetry in $t\bar{t}$ dileptonic events



	Data (10^{-2})	MC (10^{-2})	Existing limits (2σ) (10^{-2})	SM prediction (10^{-2})
A^{ss}	-0.7 ± 0.8	0.05 ± 0.23	-	$< 10^{-2}$
A^{os}	0.4 ± 0.5	-0.03 ± 0.13	-	$< 10^{-2}$
A^{b}_{mix}	-2.5 ± 2.8	0.2 ± 0.7	< 0.1	$< 10^{-3}$
$A^{b\ell}_{dir}$	0.5 ± 0.5	-0.03 ± 0.14	< 1.2	$< 10^{-5}$
$A^{c\ell}_{dir}$	1.0 ± 1.0	-0.06 ± 0.25	< 6.0	$< 10^{-9}$
A^{bc}_{dir}	-1.0 ± 1.1	0.07 ± 0.29	-	$< 10^{-7}$

- ★ The main contribution to systematic uncertainties come from the modelling of additional radiation and PDF uncertainties, the jet energy scale and the lepton energy resolution.

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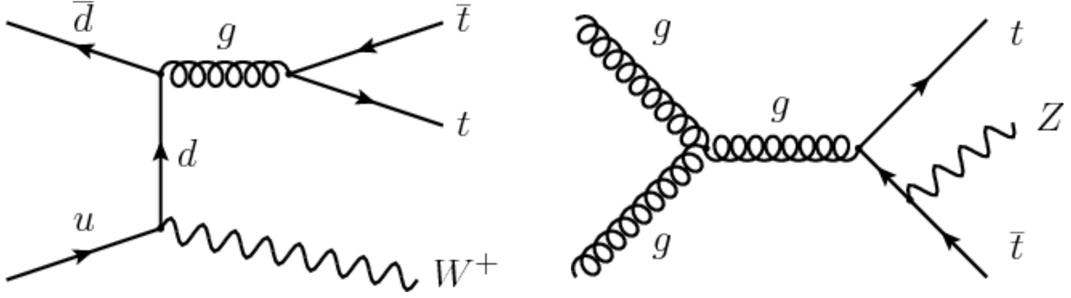
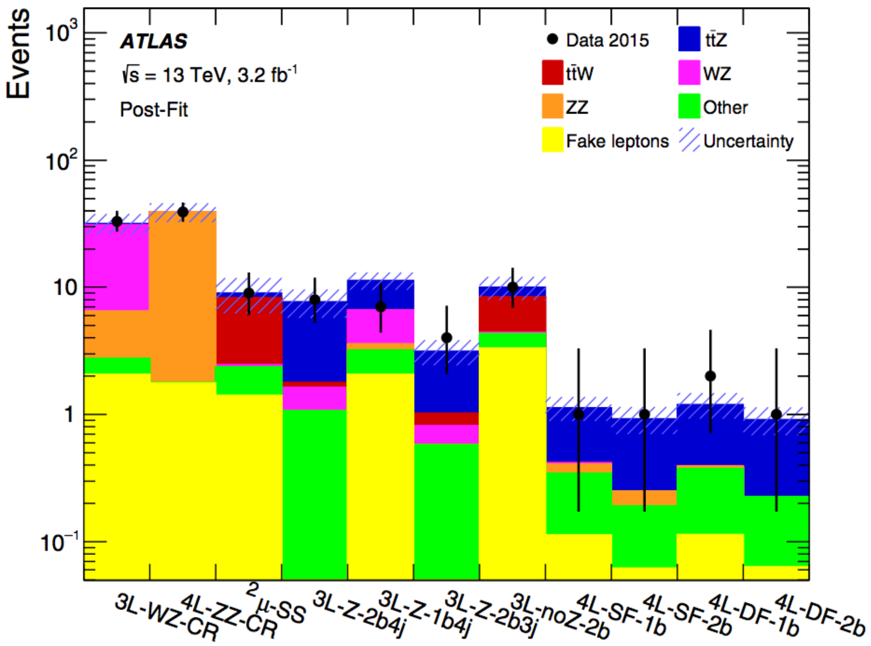
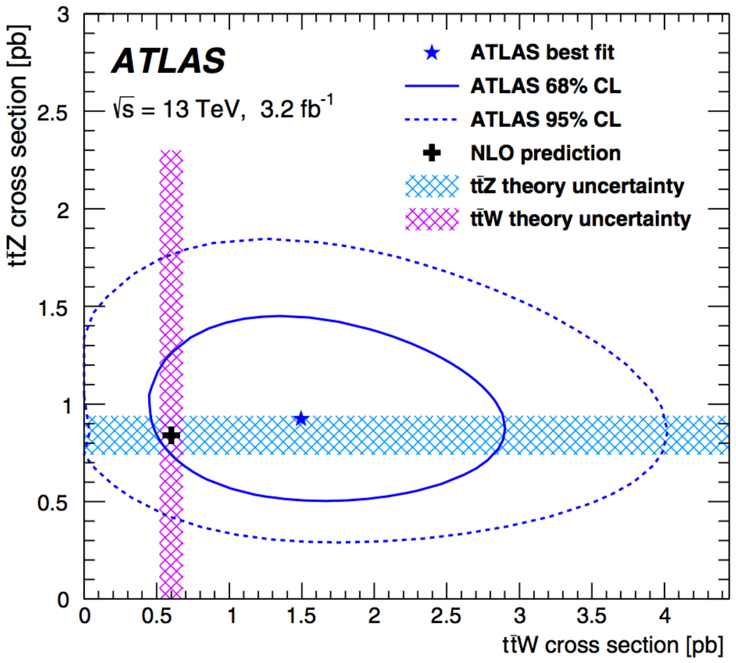
$t\bar{t}V$ production in multilepton final states

- ★ Large datasets give access to rate $t\bar{t}$+W and $t\bar{t}$+Z processes
  - $t\bar{t}Z$: information about neutral-current coupling to the top quark.
  - Sensitive to the presence of BSM physics (vector-like quarks, strongly coupled Higgs boson, technicolor)
- ★ σ_{ttW} and σ_{ttZ} are fitted simultaneously in nine signal regions and two control regions
  - Definition based on the number, charge and flavour of leptons and on the number of jets and b-jets.



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



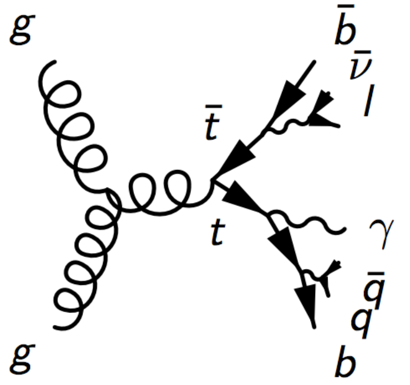


σ_{ttZ} = 0.9 ± 0.3 pb
(SM: 0.84 ± 12%)

σ_{ttW} = 1.5 ± 0.8 pb
(SM: 0.5 ± 12%)

arXiv:1706.03046

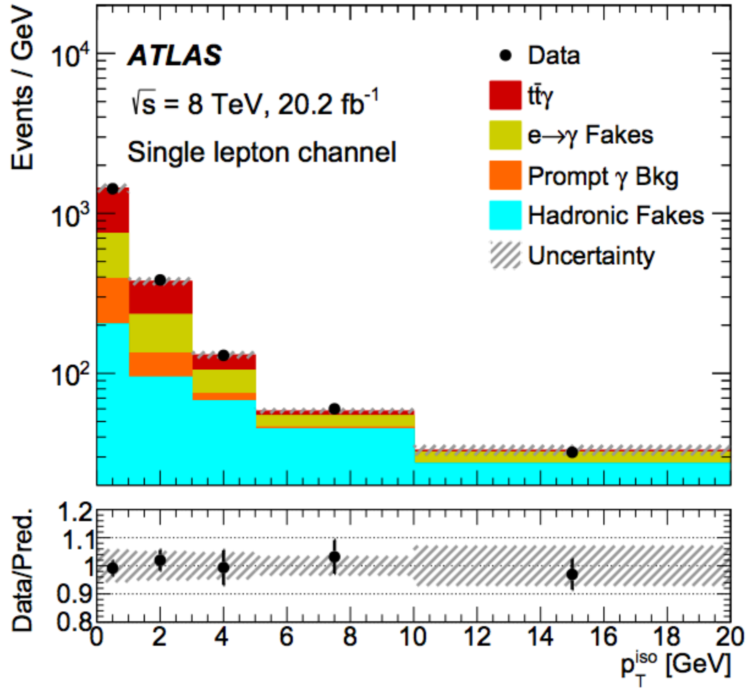
$t\bar{t}\gamma$ production in multilepton final states

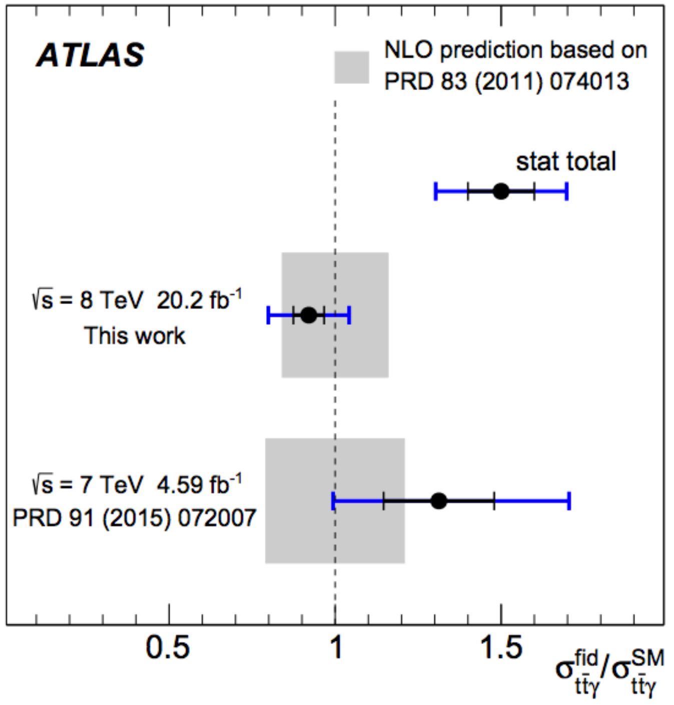


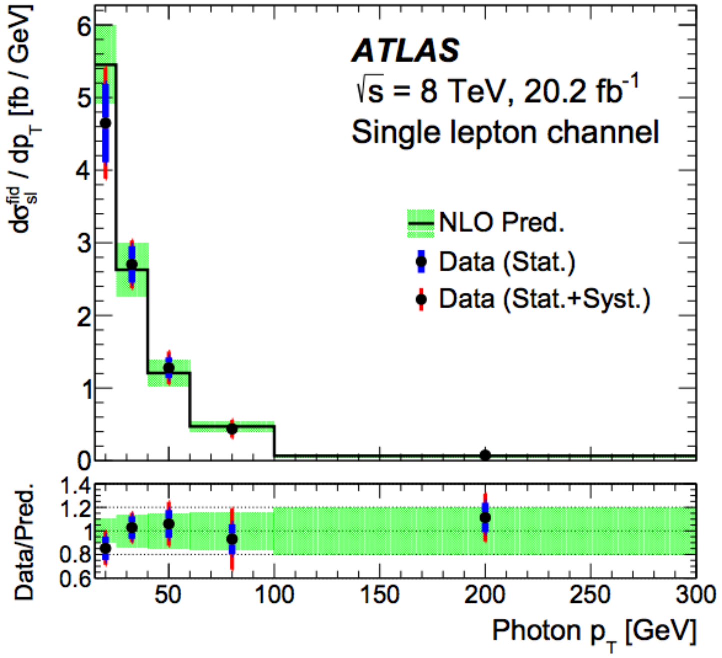
- ★ Probe the tγ electroweak coupling
- ★ Fiducial cross section of top-quark pair events in association with a photon
- ★ Differential cross sections *wrt*. photon p_T and η are measured.
- ★ Measurement based on the minimisation of a profile likelihood ratio, using the photon track isolation as the discriminating variable.
- ★ The dominant source of systematic uncertainty come from the hadron-fake template and the template describing electrons misidentified as photons

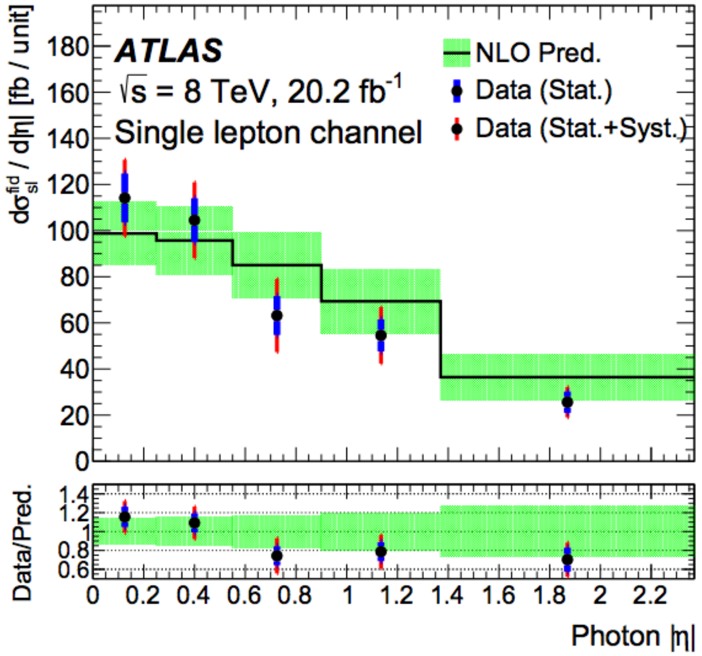
$$\sigma_{\rm sl}^{\rm fid} = 139 \pm 7(\text{stat}) \pm 17(\text{syst})\,\text{fb}$$

$$\sigma(\text{NLO prediction}) = 151 \pm 24\,\text{fb}$$









Conclusion

- ★ The top quark provides a potential window to new physics.
- ★ Its properties are studied with great precision at ATLAS experiment
- ★ Most of the precision measurements with Run1 data @ 8TeV are finished
- ★ All top quark properties are consistent with SM with current precision
- ★ Main sources of uncertainties come from jet and b-jet energy scale and the modelling of the ttbar processes
- ★ Starting to look at Run2 data @ 13TeV with larger statistics