Searches for flavour violation and flavour changing neutral currents in top quark final states

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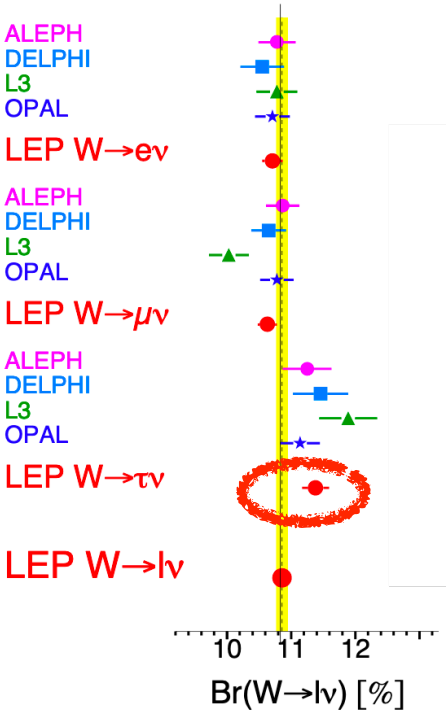
on behalf of the ATLAS collaboration

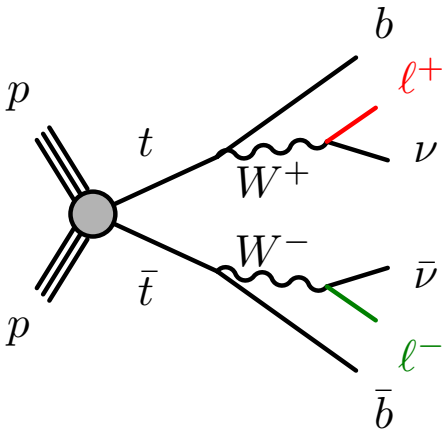
Lepton flavour universality

- The Standard Model predicts that the charged leptons ($e/\mu/\tau$) only differ in their mass
- Under the electroweak force, they interact universally
- Lepton flavour universality
- I.e. all the charged leptons of different flavours have the same coupling strength to the *W* boson
- *W* boson decays have been precisely measured at LEP
- However, in $\mathcal{BR}(W \to \tau\nu)$, a deviation $> 2\sigma$ from the SM prediction was observed
- Measuring $\mathcal{BR}(W \to \tau\nu)/\mathcal{BR}(W \to \mu\nu)$ with a precision of 1-2% would either prove LEP discrepancy or rule it out



Phys.Rept. 532 (2013) 119-244

Analysis strategy



- Exploiting the $t\bar{t}$ final state, a large unbiased sample of *W* bosons can be obtained
- Thereby, one decaying top is used to trigger the event (tag lepton) while the other one provides the (unbiased) *W* boson used in the measurement (probe lepton)
- Can go as low in transverse momentum as reconstruction works
- Only look at leptonic tau decays to profit from smaller reconstruction uncertainties
- Main task: distinguish prompt muons from taus decaying into muons

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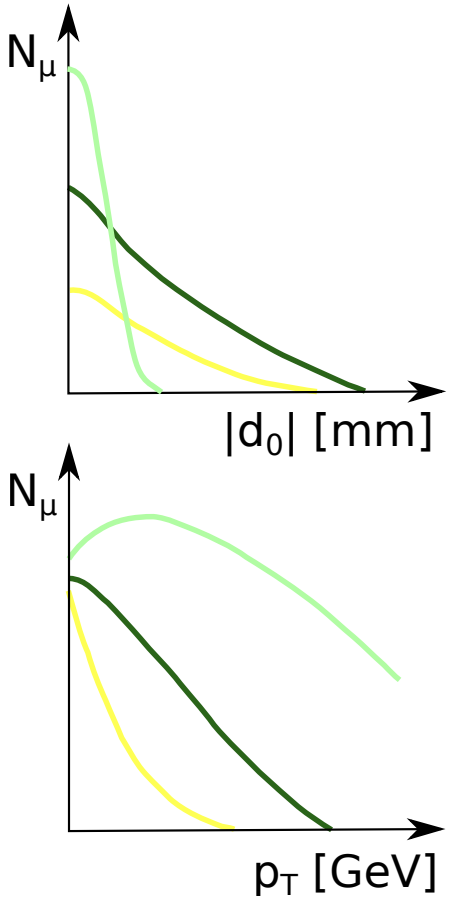

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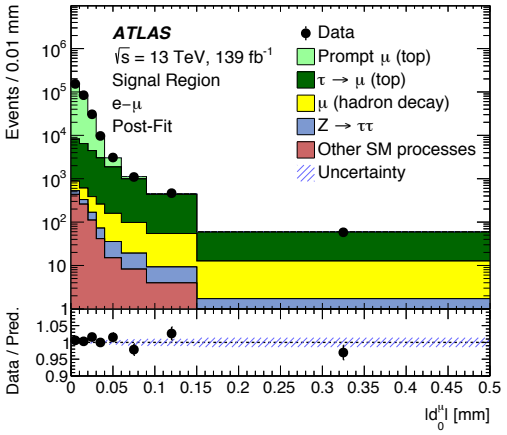
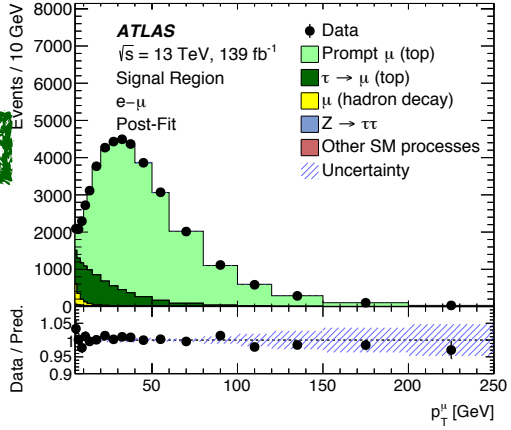
- Main task: distinguish prompt muons from taus decaying into muons
- Use muon transverse momentum and unsigned transverse impact parameter with respect to beamline
- Allows to also distinguish leptonic tau decays from muons from hadron decays

arXiv:2007.14040





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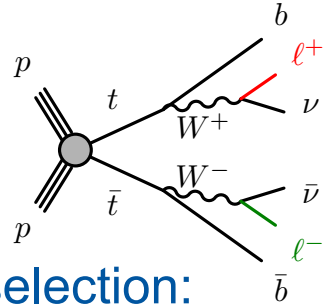
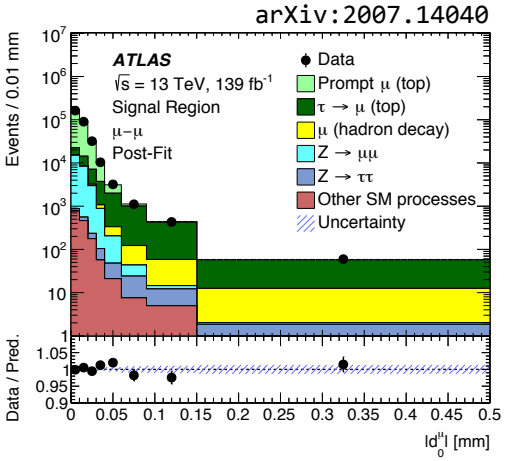
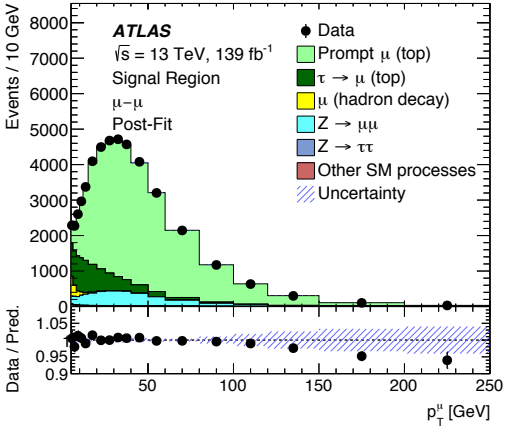






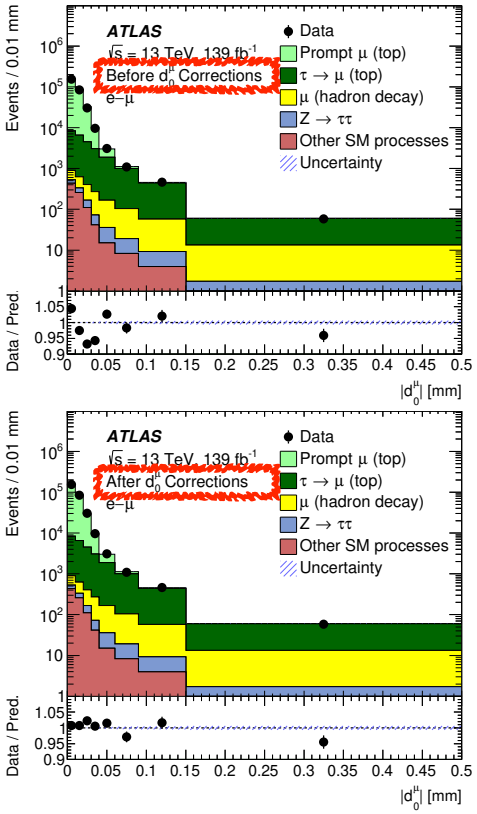
- Applying standard $t\bar{t}$ (di-lepton, $e\mu/\mu\mu$) selection:
  - 2 *b*-tagged jets, 2 oppositely charged leptons, *Z* boson veto for di-muon channel
- Tag lepton must pass trigger requirement
- Probe muon must have p_T > 5GeV
  - Allows to probe a large p_T range
- Remaining backgrounds for the measurement:
  - Hadrons decaying into muons
  - *Z*+2*b*-tagged jets in di-muon channel

The transverse impact parameter d_0

- Distance of closest approach of muon tracks in the transverse plane
- Defined with respect to the beamline (process independent)
- Determine shape of $|d_0|$ in 33 kinematic bins ($p_{\mathrm{T}}^{\mu}, |\eta^{\mu}|$) from Data using $Z \to \mu\mu$ selection
- Subtract remaining backgrounds estimated in MC
- Use shapes as prompt muon templates in signal region
- Systematic uncertainty due to application of $|d_0|$ shape from Z boson decays to $t\bar{t}$ signal region:
  - Estimated by ratio of $|d_0|$ between $t\bar{t}$ and $Z \to \mu\mu$
  - Rescale Data by applying ratio to calculate systematic uncertainty (done separately for core and tail of $|d_0|$ distribution)

Pre-Fit plots, only normalisation applied

arXiv:2007.14040



Muons from *b*-/*c*-hadron decays

- *b*- and *c*-hadrons decaying into muons constitute largest background at large $|d_0|$
- Estimate normalisation in same sign (SS) control region:
  - Shape of $|d_0|$ in SS region taken from MC
  - Subtract prompt contribution $(t\bar{t} + V)$ from $p_T > 30$ GeV region
  - Apply Data/MC ratio in SS region to signal region
- Modelling differences between SS and OS taken from MC
- ➢ Good Data/MC agreement gives confidence that the distributions are well modelled in signal region
- Uncertainties arising from limited statistics of SS region, MC modelling and p_T threshold for prompt contribution

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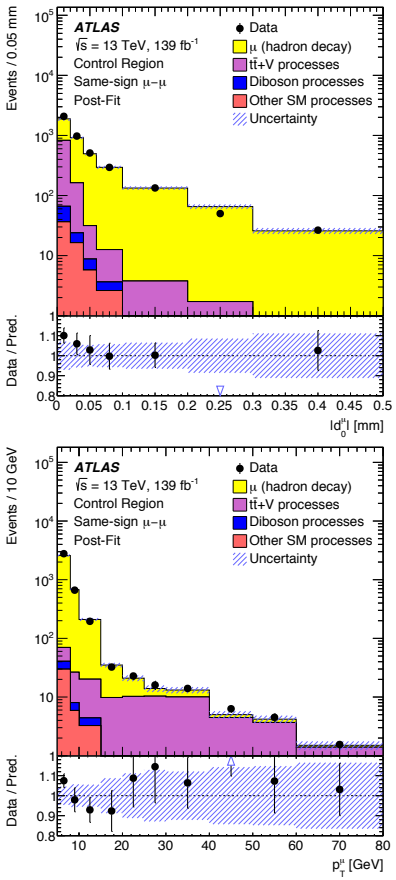

Remaining Z boson background in di-muon channel

- Although Z veto is applied in di-muon channel, residual contribution from Z+2b-tagged jets is left
- Estimate its normalisation from Data by removing Z veto
- Fit $m_{\mu\mu}$ distribution between 50 GeV and 140 GeV with convolution of Breit-Wigner and Gaussian for $Z \to \mu\mu$ and 3rd-order Chebychev polynomial for background
  - Normalisation factor: 1.36 ± 0.01
- Use other fit functions to estimate systematic uncertainty

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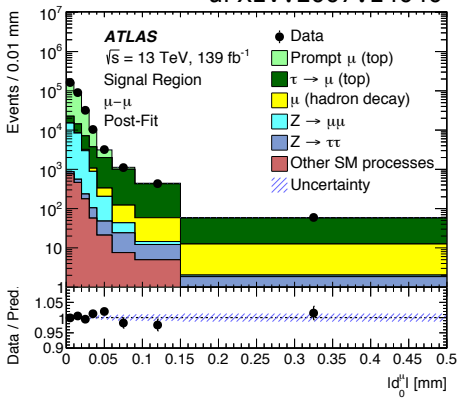
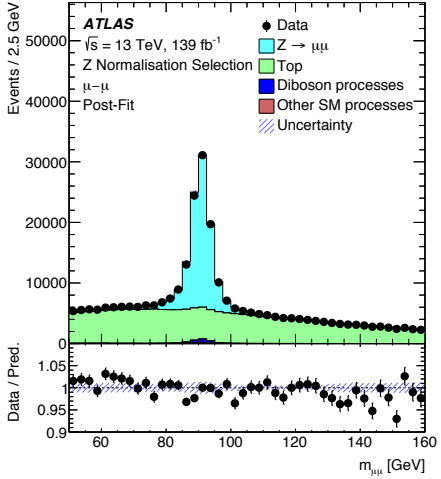
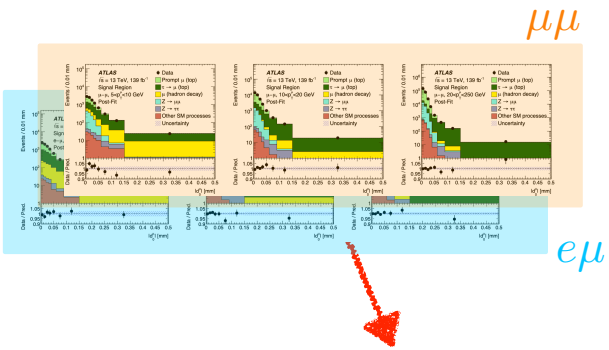




Statistical interpretation

- For both channels (tag electron/muon), perform 2D profile likelihood fit in muon
  - $|d_0|$: [0, 0.01, 0.02, 0.03, 0.04, 0.06, 0.09, 0.15, 0.5] mm
  - p_T : [5, 10, 20, 250] GeV
- Freely floating parameters:
  - $\mathcal{BR}(W \to \tau\nu)/\mathcal{BR}(W \to \mu\nu)$
  - Scaling factor for top processes (applied to both prompt muons and leptonic tau decays)
- Many uncertainties are correlated between prompt muons and leptonic tau decays
  - ▶ Mostly cancel out for probe muons
- Observe excellent Data/MC agreement in each signal region bin



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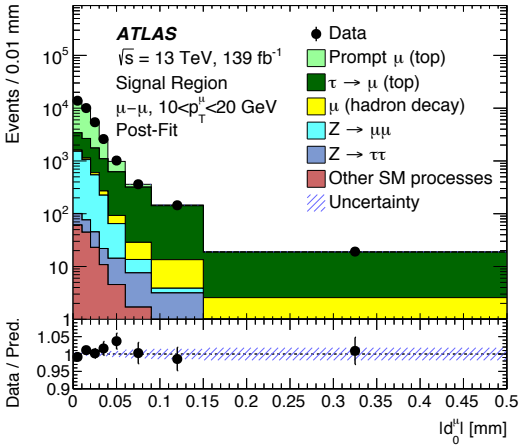

Systematic uncertainties

- Uncertainty of measurement dominated by systematic uncertainty
- Leading one is the extrapolation uncertainty on the prompt $|d_0|$ templates
- Theoretical modelling uncertainties (such as parton shower or scale variations)
- Hadron to muon decay background normalisation in SS region, i.e. due to MC generator used in estimate
- Muon isolation requirements efficiency and low-p_T muon reconstruction efficiency

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Source	**Impact on $R(\tau/\mu)$**
Prompt d_0^μ templates	0.0038
$\mu_{(prompt)}$ and $\mu_{(\tau\to\mu)}$ parton shower variations	0.0036
Muon isolation efficiency	0.0033
Muon identification and reconstruction	0.0030
$\mu_{(had.)}$ normalisation	0.0028
$t\bar{t}$ scale and matching variations	0.0027
Top p_T spectum variation	0.0026
$\mu_{(had.)}$ parton shower variations	0.0021
Monte Carlo statistics	0.0018
Pile-up	0.0017
$\mu_{(\tau\to\mu)}$ and $\mu_{(had.)}$ d_0^μ shape	0.0017
Other detector systematic uncertainties	0.0016
Z+jet normalisation	0.0009
Other sources	0.0004
$B(\tau \to \mu\nu_\tau\nu_\mu)$	0.0023
Total systematic uncertainty	0.0109
Data statistics	0.0072
Total	**0.013**

Lepton flavour universality - Results

New!

- The measured value of $\mathcal{BR}(W \to \tau\nu)/\mathcal{BR}(W \to \mu\nu)$ is:
  0.992 ± 0.013 [± 0.007(stat) ± 0.011(syst)]
- Very good agreement with SM expectation
- Almost twice the precision of the combination of the LEP results
- Most precise measurement to date

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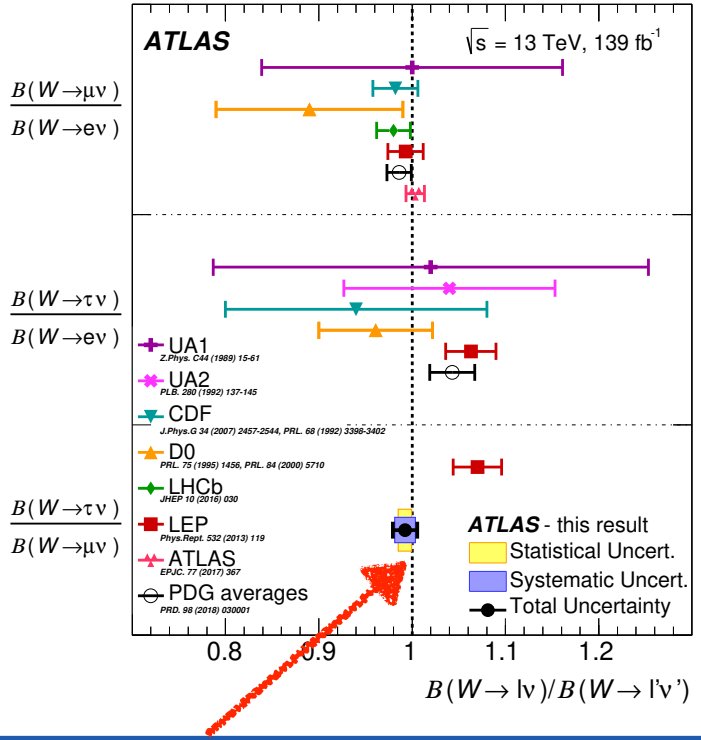

Flavour-changing neutral currents

- Flavour-changing neutral currents (FCNCs) are forbidden at tree level in the Standard Model
- Strongly suppressed at higher orders via the GIM mechanism

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- Several extensions to the SM predict processes involving FCNCs:

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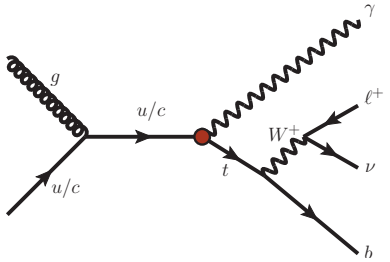
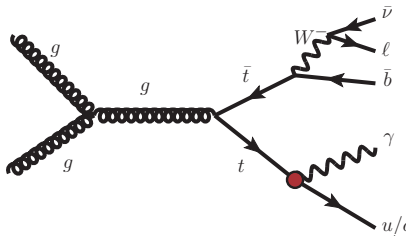
- Many models predict the branching ratios of top quark decays via FCNC to be significantly larger
- Will present 2 searches for FCNCs involving top quarks

Final states with a top quark and a photon

- Analysis focusses on models with FCNC: $u/c \to t + \gamma$
- Can occur in production or decay of top quarks
- In both cases, one photon and one top quark signature
- Only considering leptonic top quark decay
- Require exactly 1 photon, lepton and *b*-tagged jet and $E_{\mathrm{T}}^{\mathrm{miss}}$
- Consider models with left-handed (LH) and right-handed (RH) couplings
- Apply neural network (NN) trained on kinematic properties of photon/lepton/jet and $E_{\mathrm{T}}^{\mathrm{miss}}$
- Separate trainings for LH/RH and *u*/*c* quark coupling





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Background estimation

- Dominating backgrounds are $W+\gamma+$ jets and $Z+\gamma+$jets
- Estimate normalisation from Data in control regions
  - *W*: require a non-*b*-tagged jet and $m_{\ell\gamma}$ outside the *Z* peak to suppress *Z*+jets
  - *Z*: require 2 leptons of same flavour and opposite charge, no additional requirements on jets or $E_{\mathrm{T}}^{\mathrm{miss}}$
- Dedicated estimates from Data for number of electrons/ hadrons misidentified as photons
  - Electrons: measured in *Z* boson decays
  - Photons: modified photon criteria with respect to signal region

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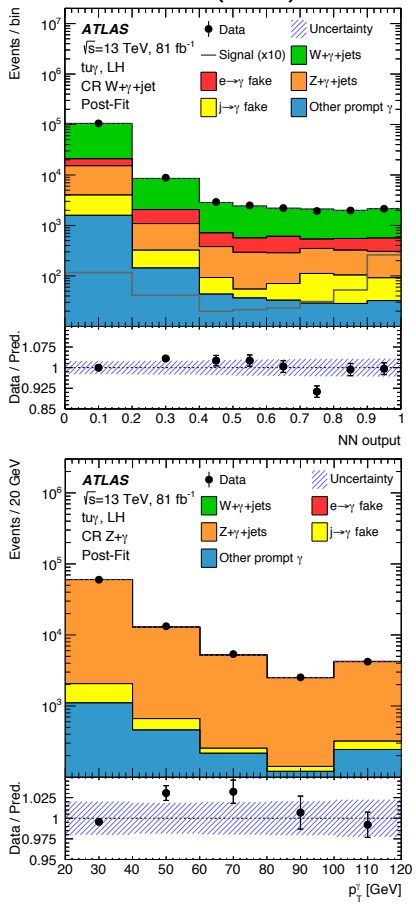

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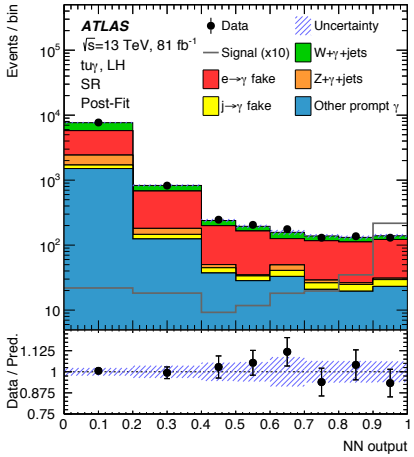
Results

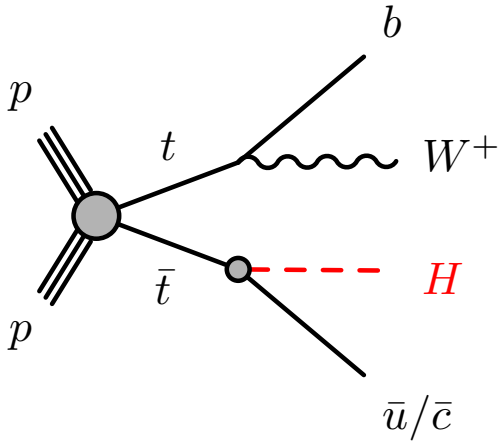
- Perform simultaneous binned profile likelihood fit to the NN output
- No significant FCNC contributions are observed
- Limits on the effective coupling parameters are calculated
- Can be translated into limits on the production cross section and branching ratios



Observable	Vertex	Coupling	Obs.	Exp.
$\left\lvert C_{uW}^{(13)*} + C_{uB}^{(13)*} \right\rvert$	$tu\gamma$	LH	0.19	$0.22^{+0.04}_{-0.03}$
$\left\lvert C_{uW}^{(31)} + C_{uB}^{(31)} \right\rvert$	$tu\gamma$	RH	0.27	$0.27^{+0.05}_{-0.04}$
$\left\lvert C_{uW}^{(23)*} + C_{uB}^{(23)*} \right\rvert$	$tc\gamma$	LH	0.52	$0.57^{+0.11}_{-0.09}$
$\left\lvert C_{uW}^{(32)} + C_{uB}^{(32)} \right\rvert$	$tc\gamma$	RH	0.48	$0.59^{+0.12}_{-0.09}$
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	LH	36	52^{+21}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	RH	78	75^{+31}_{-21}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	LH	40	49^{+20}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	RH	33	52^{+22}_{-14}
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	LH	2.8	$4.0^{+1.6}_{-1.1}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	RH	6.1	$5.9^{+2.4}_{-1.6}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	LH	22	27^{+11}_{-7}
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	RH	18	28^{+12}_{-8}

FCNC interaction between Higgs boson, top and light quark

- Since Higgs boson is lighter than the top quark, FCNC $t \to H + q$ decays become possible
- Their branching ratio is largely enhanced by some beyond SM scenarios, i.e. in the $t \to H + c$ decay
- In $t\bar{t}$ production, expect one top quark decaying into *b*+*W* and the other one into $t \to H + q$



- Since largest branching fraction of Higgs boson is into $b\bar{b}$ and $\tau^+\tau^-$, looking for $tqH(b\bar{b})$ and $tqH(\tau^+\tau^-)$ final states
- Can be combined with searches with $H \to ZZ^*$, $H \to WW^*$ and $H \to \gamma\gamma$ decays (not covered in this talk)
- Looking for 1(0) lepton and at least 3 jets in $b\bar{b}$ / $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ ($\tau_{\mathrm{had}}\tau_{\mathrm{had}}$) channel

$t \to H + q$ search strategy

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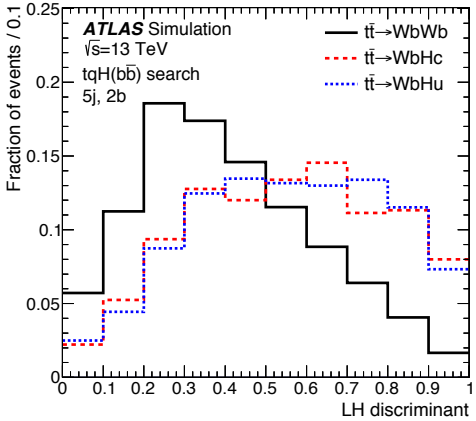

- Main background after preselection: $t\bar{t}$
- All backgrounds involving prompt leptons in decays are estimated from MC
- $tqH(b\bar{b})$ final state:
  - Multijet background estimated in matrix method
  - Require at least 2 *b*-tagged jets
  - Categorise in regions with different (*b*-tag) jet multiplicities
  - Use likelihood discriminant based four-momentum vectors of all final-state particles (including *b*-tagging information)

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  - Use likelihood discriminant based four-momentum vectors of all final-state particles (including *b*-tagging information)
- $tqH(\tau^+\tau^-)$ final state:
  - Fake τ_{had} background estimated from Data via loosened τ_{had} requirement or flipped charge
  - Use boosted decision tree trained on invariant masses of combination of decay products, p_T of leptons, momentum fractions carried by the visible decay products of the taus

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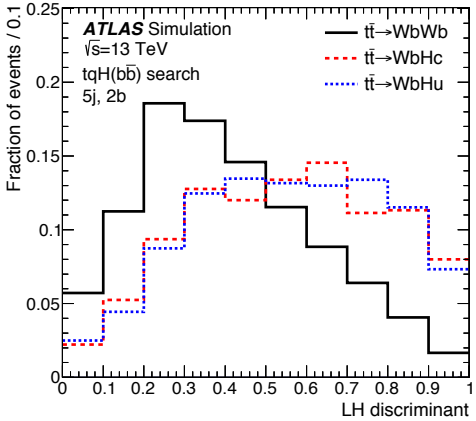

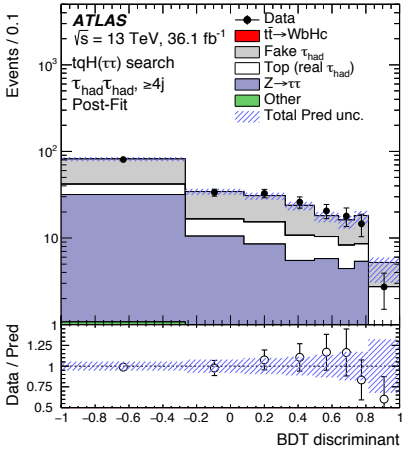

$t \to H + q$ results

- For both final states, use binned likelihood fit on all final discriminant distributions across all analysis regions
- No significant excess above SM expectation found
- Set limits on branching rations to *u* and *c* quarks
- Combine with searches for $H \to ZZ^*$, $H \to WW^*$ and $H \to \gamma\gamma$ decays

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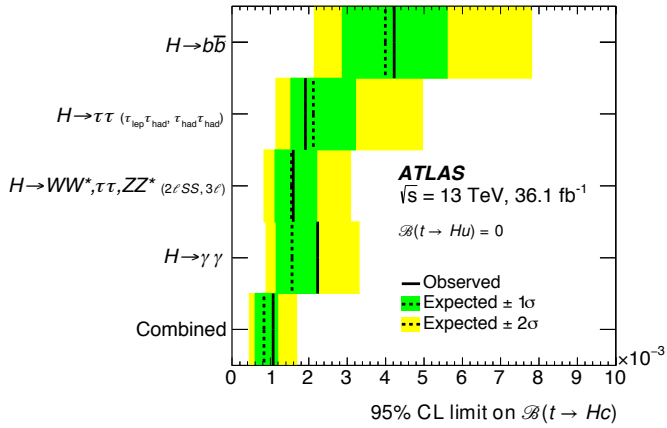
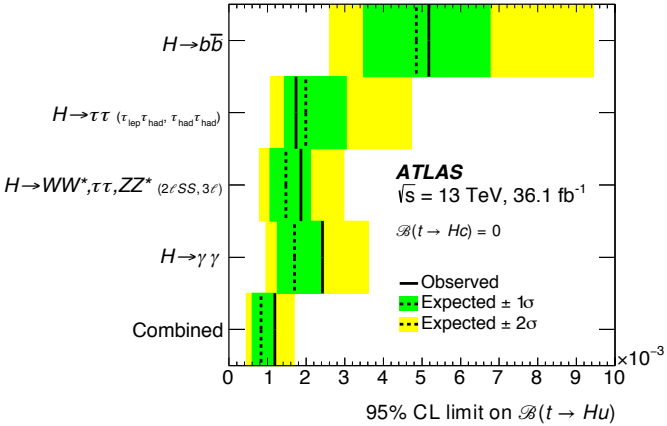


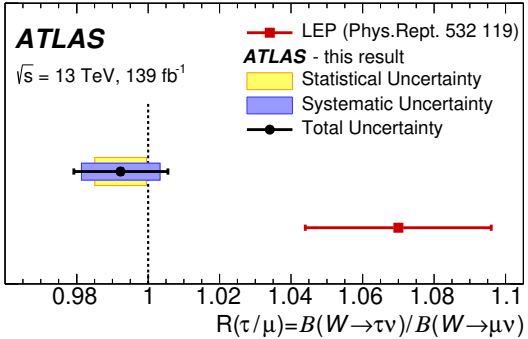


Summary

- Presented measurement of $\mathcal{BR}(W \to \tau\nu)/\mathcal{BR}(W \to \mu\nu)$
- Perfect agreement with SM expectation
  - Improved LEP precision by almost a factor of 2

- Shown 2 searches for FCNC in top quark final states
- Targeting a variety of beyond SM models
- FCNCs from top quark to light quark involving photon or Higgs boson
- Key ingredient is background suppression
  - Usage of machine learning techniques
- No sign for FCNCs involving top quarks found

arXiv:2007.14040



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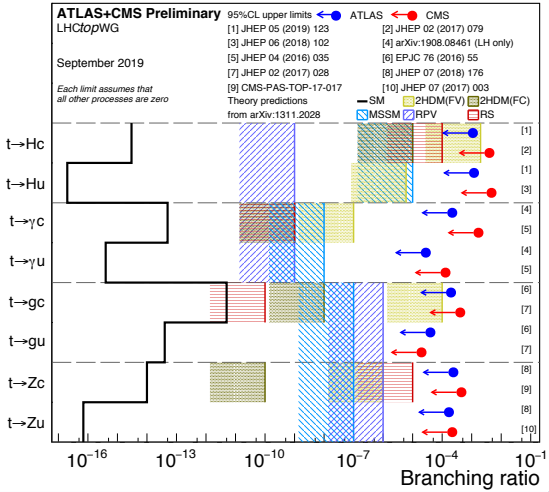
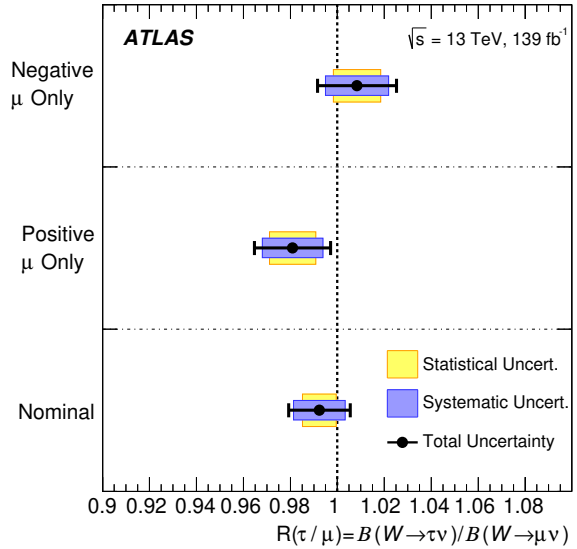


Backup

Lepton flavour universality in $t\bar{t}$ decays

- Cross checks have been performed separating by probe charge and tag flavour
  - Reasonable agreement observed



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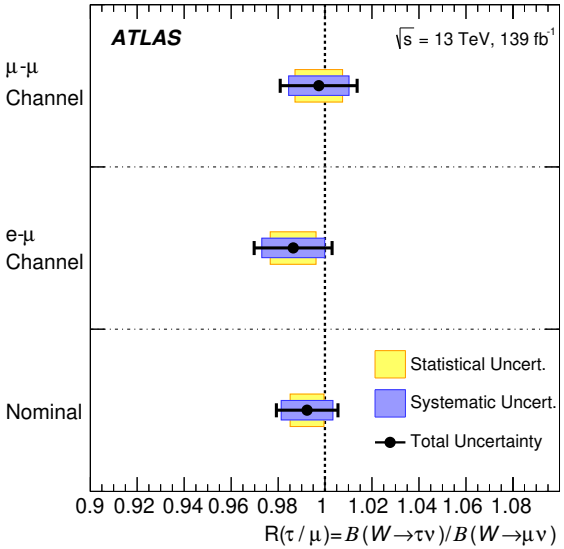
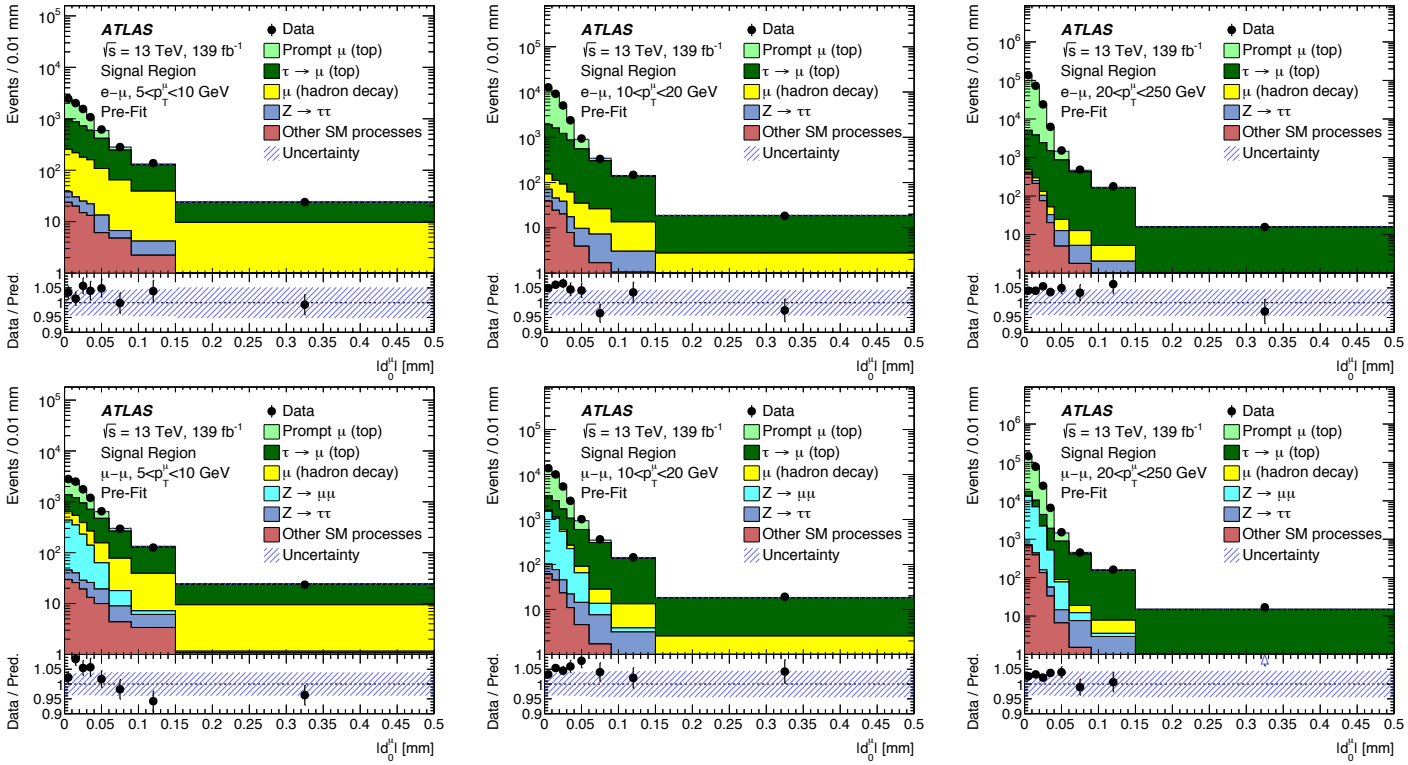


Lepton flavour universality in $t\bar{t}$ decays

- Pre-Fit distributions



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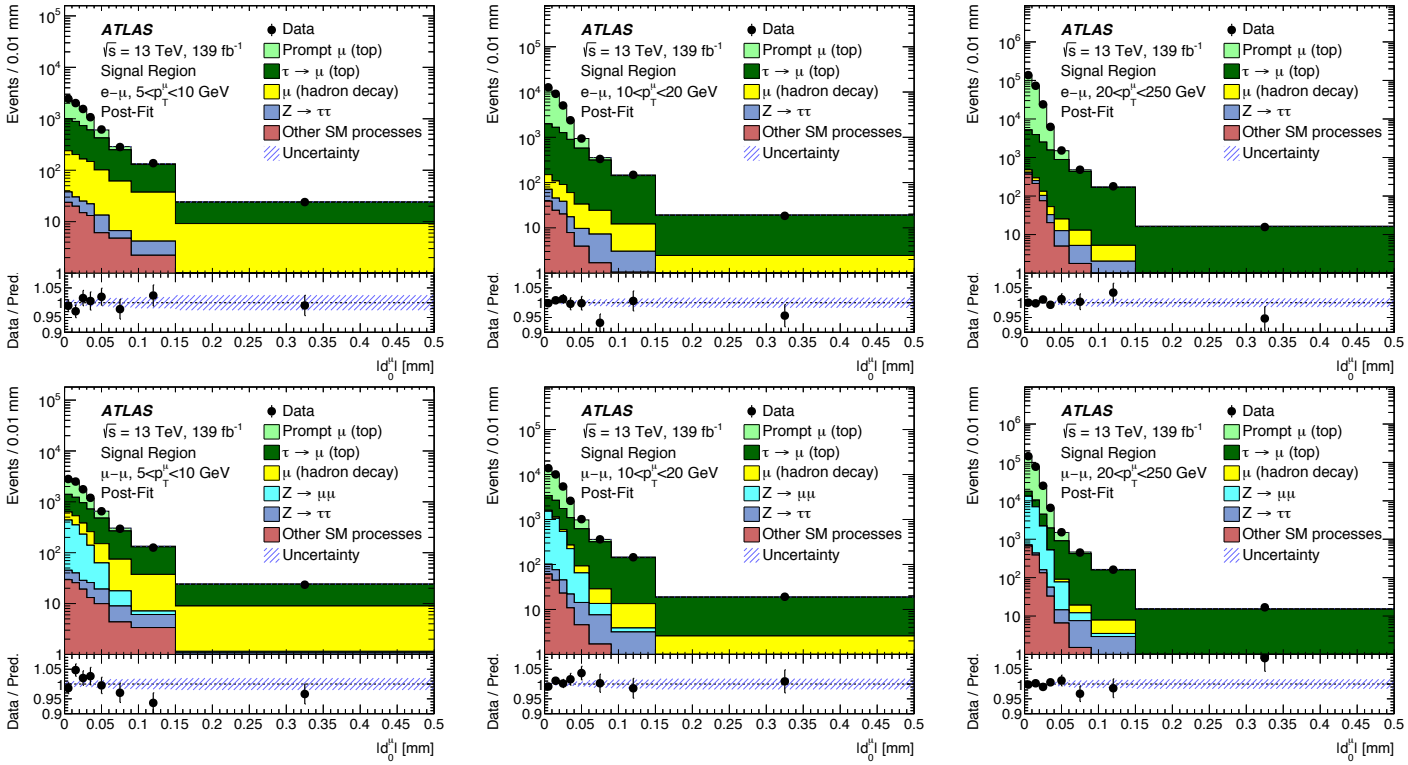
Lepton flavour universality in $t\bar{t}$ decays

- Post-Fit distributions



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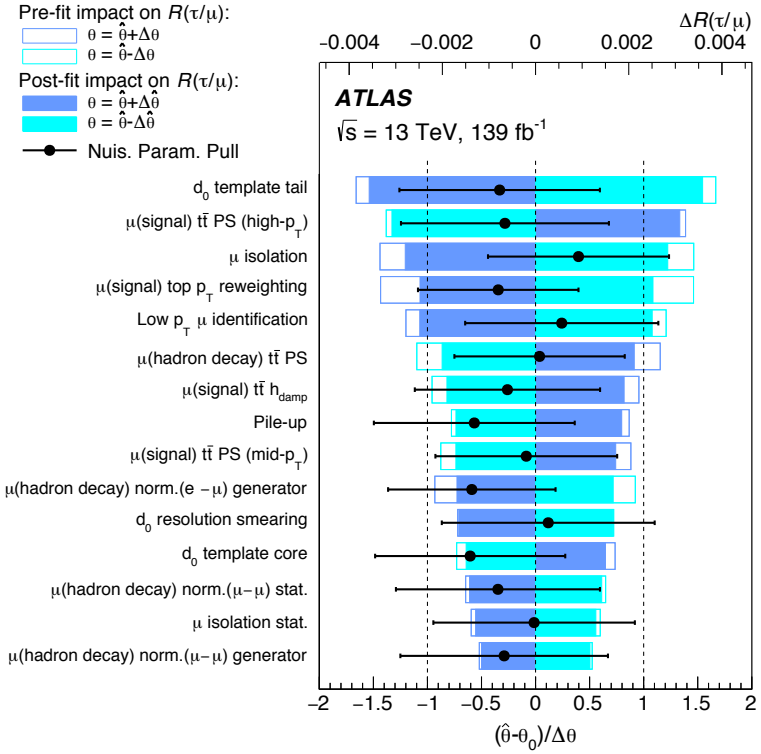
Systematic uncertainties

- Uncertainty of measurement dominated by systematic uncertainty
- Leading one is the extrapolation uncertainty on the prompt |d0| templates
- Theoretical modelling uncertainties (such as parton shower or scale variations)
- Hadron to muon decay background normalisation in SS region, i.e. MC modelling
- Muon isolation requirements efficiency and low-p_T muon reconstruction efficiency

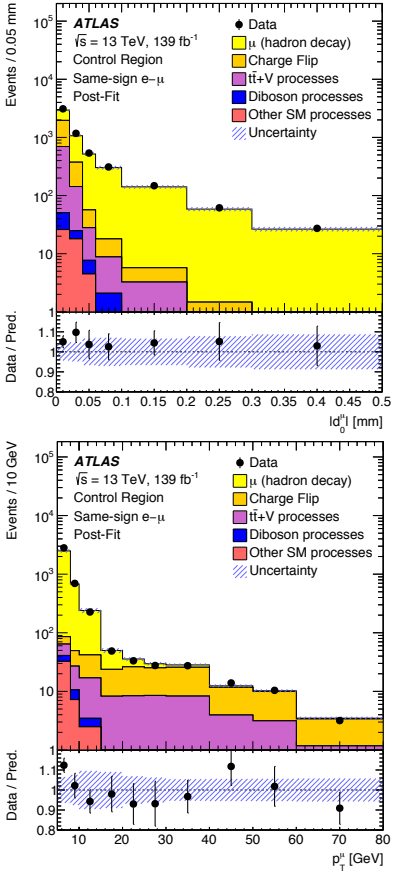
arXiv:2007.14040



Muons from *b*-/*c*-hadron decays

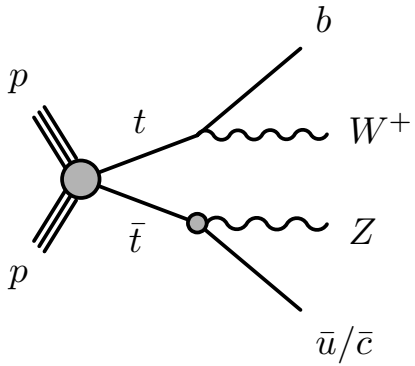
- *b*- and *c*-hadrons decaying into muons constitute largest background at large $|d_0|$
- Estimate normalisation in same sign (SS) control region:
  - Shape of $|d_0|$ in SS region taken from MC
  - Subtract prompt contribution ($t\bar{t} + V$) from $p_T > 30$ GeV region
  - Apply Data/MC ratio in SS region to signal region
- Modelling differences between SS and OS taken from MC
- ➢ Good Data/MC agreement gives confidence that the distributions are well modelled in signal region
- Uncertainties arising from limited statistics of SS region, MC modelling and p_T threshold for prompt contribution

arXiv:2007.14040



FCNC interaction between *Z* boson, top and light quark

Model:	SM	QS	2HDM	FC 2HDM	MSSM	RPV SUSY	RS	EMF
$\mathcal{B}(t \to qZ)$:	10^{-14}	10^{-4}	10^{-6}	10^{-10}	10^{-7}	10^{-6}	10^{-5}	10^{-6}



- Some extensions of the SM significantly increase the branching fraction of the top quark into *Z* boson and a light quark
- Looking for one top quark decay into *b*+*W* and one into *Z*+*q*
- Final states with 3 leptons and 2 jets (1*b*-tagged jet) and $E_{\mathrm{T}}^{\mathrm{miss}}$
- Reconstruct *Z* boson candidate from leptons with invariant mass closest to *Z* mass
- Determine longitudinal component of the neutrino momentum from decay particles by minimising

$$\chi^2 = \frac{\left(m^{\mathrm{reco}}_{j_a \ell_a \ell_b} - m_{t_{\mathrm{FCNC}}}\right)^2}{\sigma^2_{t_{\mathrm{FCNC}}}} + \frac{\left(m^{\mathrm{reco}}_{j_b \ell_c \nu} - m_{t_{\mathrm{SM}}}\right)^2}{\sigma^2_{t_{\mathrm{SM}}}} + \frac{\left(m^{\mathrm{reco}}_{\ell_c \nu} - m_W\right)^2}{\sigma^2_W}$$

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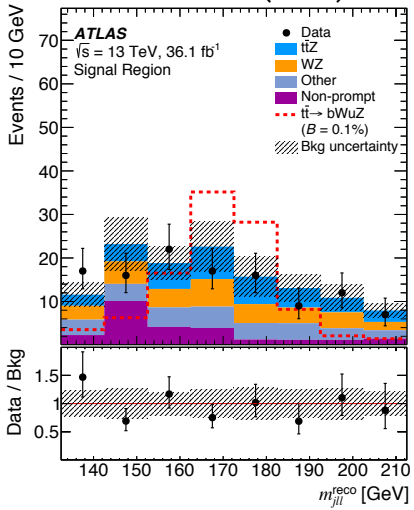
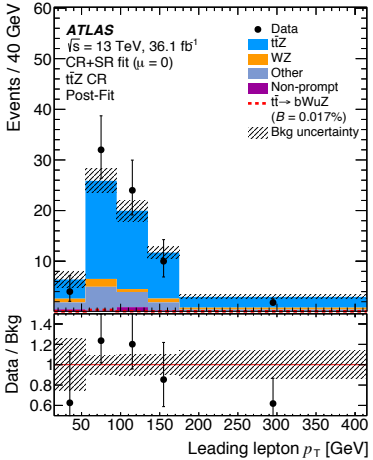
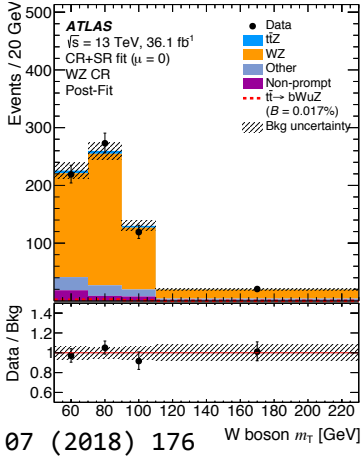


$t \to Z + q$ backgrounds

- Main backgrounds: di-boson, $t\bar{t} + Z$ and $t + Z$
- Estimated from Data in control regions:
  - $t\bar{t} + Z$: require 3 leptons and 2 *b*-tagged jets
  - *WZ*: 3 leptons, $E_{\mathrm{T}}^{\mathrm{miss}}$ > 40 GeV, $m_{\mathrm{T}}^{\ell\nu} > 50$ GeV
  - *ZZ*: 4 leptons, at least 1 (not *b*-tagged) jet
- Backgrounds from events containing at least one non-prompt lepton estimated by semi-data-driven technique
  - Improves Data/MC agreement significantly





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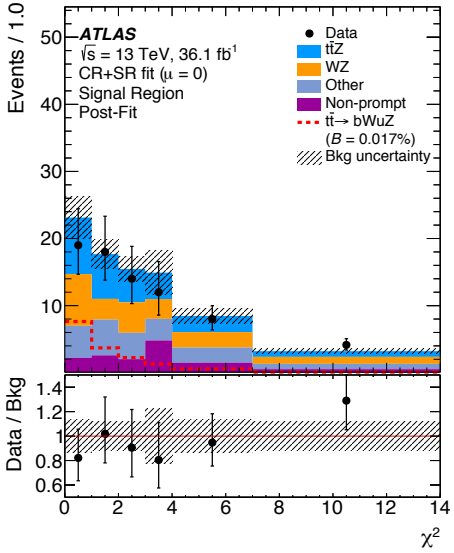
$t \to Z + q$ results

- Perform maximum-likelihood fit in χ^2 and lepton p_T
- Main uncertainties: theoretical normalisation uncertainties and uncertainties in the modelling of background processes in the simulation
- No evidence of a FCNC signal found
- Upper limits on branching rations can be converted into upper limits on EFT operators contributing to the FCNC decay



	$\mathcal{B}(t \to uZ)$	$\mathcal{B}(t \to cZ)$
Observed	1.7×10^{-4}	2.4×10^{-4}
Expected -1σ	1.7×10^{-4}	2.2×10^{-4}
Expected	2.4×10^{-4}	3.2×10^{-4}
Expected $+1\sigma$	3.4×10^{-4}	4.6×10^{-4}

Operator	Observed	Expected
$\lvert C_{uB}^{(31)} \rvert$	0.25	0.30
$\lvert C_{uW}^{(31)} \rvert$	0.25	0.30
$\lvert C_{uB}^{(32)} \rvert$	0.30	0.34
$\lvert C_{uW}^{(32)} \rvert$	0.30	0.34