Latest LHC searches for new interactions with top quarks

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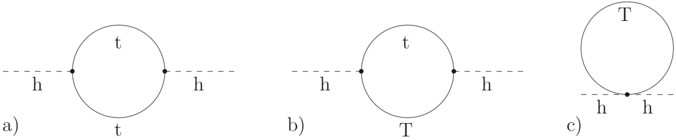
Overview

Search for Beyond the Standard Model (BSM) physics

- Standard Model very successful at explaining experimental data, yet we keep searching beyond it
- Some unanswered questions
  - Nature of dark matter, origin of flavour, neutrino mass, matter-antimatter asymmetry
- Some unsatisfactory (**unnatural**) implications
  - The hierarchy problem, fine-tuning of Higgs mass
- Searching for a theory that will **complete** the theory and do it **elegantly**
  - Guided by "naturalness" principle
  - Experimental hints from SM deviations in flavour sector

New physics and the Top Quark

- **The hierarchy problem**:
  - "Why is gravity so much weaker than other forces?" ($M_{Planck} >> M_{ewk}$)
- Recast - **The fine-tuning problem**
  - Large scale hierarchy induces instability in masses of scalar particles
    - Largest correction from heaviest SM particle - **top quark**
  - Higgs boson mass has to be strongly fine-tuned
- Top partners in BSM theories can cancel out loop corrections and stabilise Higgs mass
  - New particles in many BSM models expected to couple preferentially to top quarks
  - Cancel out loop corrections to Higgs mass



Search for new physics in final states with top quarks

Direct searches

- Resonant or non-resonant production of new particles
- Possible when new physics (NP) scale with reach of collider energy

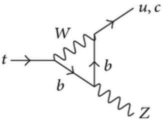
Indirect searches

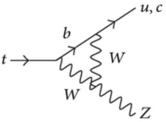
- Search for rare production and decay of top quark
- Deviations from SM in measurements of top properties
- Can be path to discovery even if NP energy scale is very high

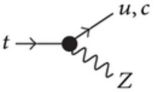
Flavour-changing neutral currents

FCNC in the top quark sector

- FCNC forbidden at tree level in SM. Strongly suppressed at higher order by GIM mechanism
  - $BR_{SM}(t \to Hu) \sim 10^{-17}$;
    $BR_{SM}(t \to Hc) \sim 10^{-15}$
  - $BR_{SM}(t \to Zq) \sim 10^{-14}$;
- Predicted by many BSM models: quark singlet, 2HDM, RPV SUSY
  - $BR_{max}(t \to Hu) \sim 10^{-5}$;
    $BR_{max}(t \to Hc) \sim 10^{-3}$
  - $BR_{max}(t \to Zq) \sim 10^{-4}$;



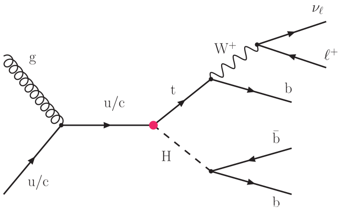


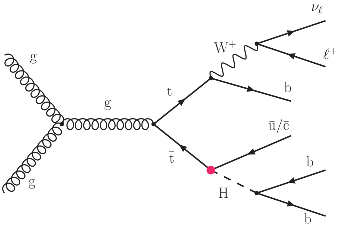


Model:	SM	QS	2HDM	FC 2HDM	MSSM	RPV SUSY	RS	EMF
$\mathcal{B}(t \to qZ)$:	10^{-14}	10^{-4}	10^{-6}	10^{-10}	10^{-7}	10^{-6}	10^{-5}	10^{-6}

[arXiv:1803.09923]

tqH FCNC processes





Production $pp \to tH$

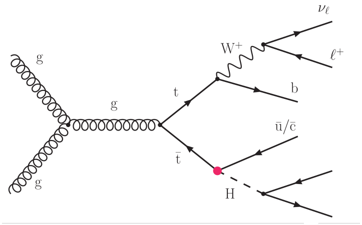
- FCNC single top production
- Only probed by CMS search in $H \to b\bar{b}$ channel

Decay $t \to qH$

- FCNC top decay in $t\bar{t}$ events
- Assume SM semi-leptonic decay of other top in event
- Probed by both ATLAS and CMS searches

$t \to qH$ (ATLAS)

- Searches for rare $t \to uH/t \to cH$ decays
- Several search channels targeting different Higgs decay topologies
- Combination of channels significantly improves sensitivity



$H \to \tau\tau$ $\quad$ $H \to WW$

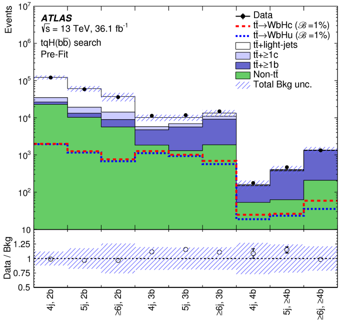
$H \to bb$ $\quad$ $H \to \gamma\gamma$

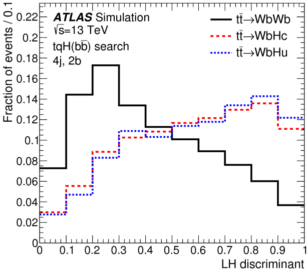
$t \to q(H \to bb)$ (ATLAS)

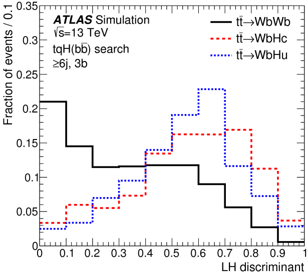
arXiv:1812.11568

- 9 analysis regions categorised by n_{jet} and n_{bjet}
  - Signal sensitive regions: $n_{bjet} = 3$; $n_{jet} = 4\text{-}5$
  - Other regions constrain $t\bar{t}$+jets background & uncertainties
- Fit shape of *likelihood discriminant* **L(x)** constructed from kinematics of lepton, jets, E_T^{miss}

$$L(\mathbf{x}) = \frac{P^{\mathrm{sig}}(\mathbf{x})}{P^{\mathrm{sig}}(\mathbf{x}) + P^{\mathrm{bkg}}(\mathbf{x})},$$





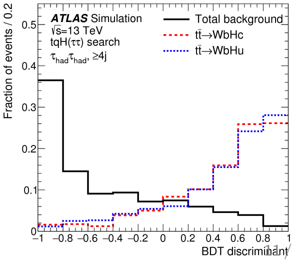


$t \to q(H \to \tau\tau)$ (ATLAS) *arXiv:1812.11568*

- Signals categorised into 4 signal regions by multiplicity of τ_{lep}, τ_{had} and n_{jet}
  - Different event reconstruction quality in each
  - Events inconsistent with hadronic top decays are discarded
- Full event reconstruction performed with χ^2 minimisation
- BDT discriminants trained separately in each region and fit simultaneously across regions
  - Most discriminating variables: $m_{\tau\tau}$, p_T and visible p_T fraction from τ candidates

	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
3j ≥4j	1 lep large E_T^{miss}	0 lep small E_T^{miss}

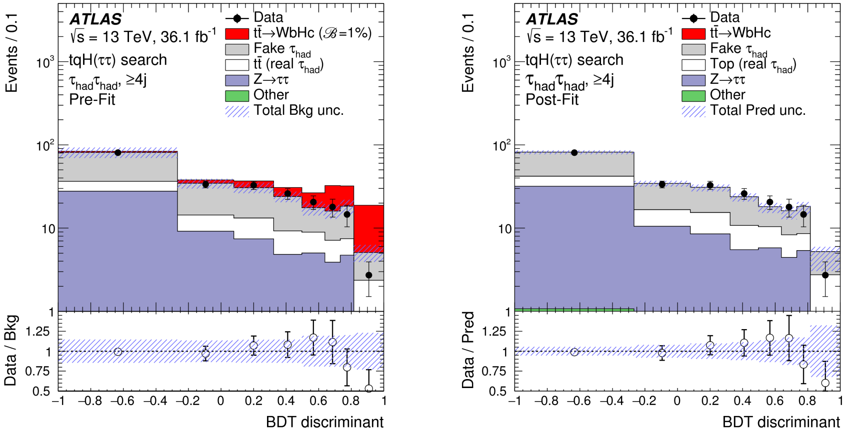
Variable	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ 3j	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ ≥4j	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ 3j	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ ≥4j
$m_{\tau\tau}^{\mathrm{fit}}$	×	×	×	×
m_{Hq}	×	×	×	×
$m_{\mathrm{T,lep}}$	×	×		
$p_{\mathrm{T},1}$	×	×	×	×
$p_{\mathrm{T},2}$	×	×	×	×
$E_{\mathrm{T}}^{\mathrm{miss}}$ ϕ centrality	×	×	×	×
$E_{\mathrm{T},\parallel}^{\mathrm{miss}}$	×	×	×	×
$E_{\mathrm{T},\perp}^{\mathrm{miss}}$	×	×		
m_{bj_1}	×	×	×	×
$m_{\mathrm{lep}j}$	×	×		
$m_{\tau j}$	×	×		
x_1^{fit}	×	×	×	×
x_2^{fit}	×	×	×	×
$m_{bj_1j_2}$		×		×



$t \to q(H \to \tau\tau)$ (ATLAS)

arXiv:1812.11568

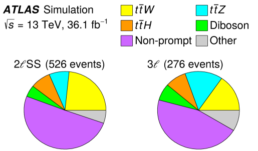
- BDT discriminant well modelled before and after profile likelihood fit
- No evidence of deviation from SM predictions

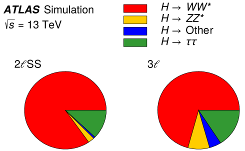


$t \to q(H \to WW)$ (ATLAS)

arXiv:1805.03483

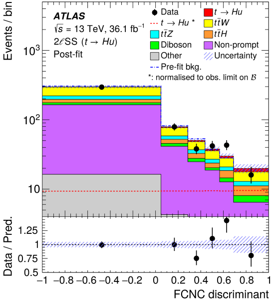
- Target events with same-sign (SS) $2l$ / $3l$ ($l = e/\mu$)
  - Signal events arise mostly from $H \to WW^*$
  - Secondary contributions from $H \to \tau_l \tau_l$, $H \to ZZ^*$
- Data-driven estimation of dominant non-prompt lepton background (mainly $t\bar{t}$)
- ttV/ttH background from simulation
- Signal discriminated by fit to BDT discriminant

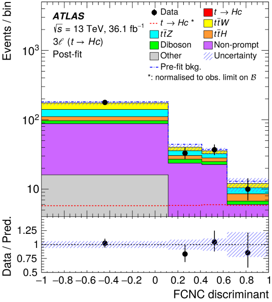


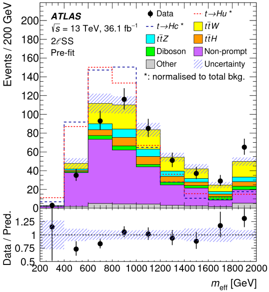


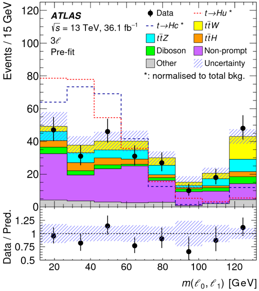
Variable	2ℓSS	3ℓ
p_T of higher-p_T lepton	×	
p_T of lower-p_T lepton	×	
p_T of lepton ℓ_0		×
p_T of lepton ℓ_1		×
p_T of lepton ℓ_2		×
Dilepton invariant masses (all combinations)	×	×
Trilepton invariant mass		×
Best Z candidate invariant mass		×
Maximum lepton $\lvert\eta\rvert$	×	
Lepton flavor	×	
Number of jets	×	×
Number of b-tagged jets	×	×
p_T of highest-p_T jet		×
p_T of second highest-p_T jet		×
p_T of highest-p_T b-tagged jet		×
$\Delta R(\ell_0, \ell_1)$		×
$\Delta R(\ell_0, \ell_2)$		×
ΔR(higher-p_T lepton, closest jet)	×	
ΔR(lower-p_T lepton, closest jet)	×	
$\Delta R(\ell_1$, closest jet)		×
Smallest $\Delta R(\ell_0$, b-tagged jet)		×
E_T^{miss}	×	
m_{eff}	×	×

- Most discriminating observables:
  - 2*l*SS SR: m_{eff}
  - 3*l* SR: dilepton invariant mass
- Best-fit FCNC branching ratios compatible with zero



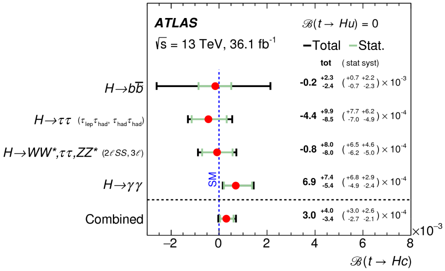


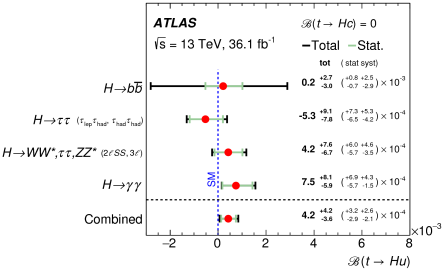




Combination of all ATLAS $t \to qH$ searches *arXiv:1812.11568*

- Best fit for each of $BR(t \to uH)$ and $BR(t \to cH)$ obtained first assuming the other to be zero
- Results from all channels compatible with SM prediction
- Combination across channels leads to large reduction in uncertainty

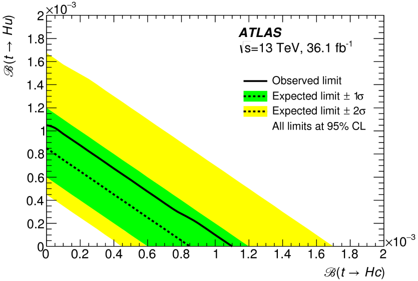


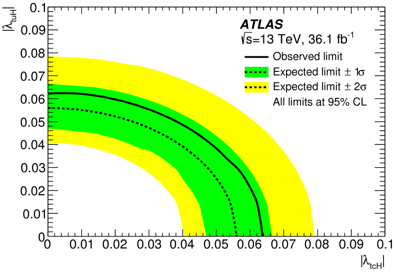


Combination of all ATLAS $t \to qH$ searches *arXiv:1812.11568*

- Limits produced by simultaneously varying $BR(t \to uH)$ and $BR(t \to cH)$ in likelihood function
- Also translated into limits on non-diagonal Yukawa couplings λ_{tuH} and λ_{tcH}

$$|\lambda_{tqH}| = (1.92 \pm 0.02)\sqrt{\mathscr{B}(t \to Hq)}.$$

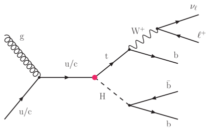




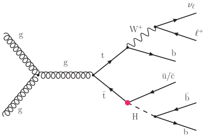
$pp \to tH$ / $t \to qH$ (CMS)

arXiv:1712.02399

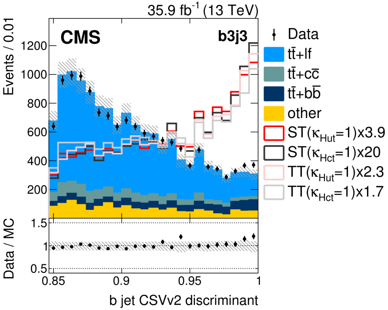
Single-top production

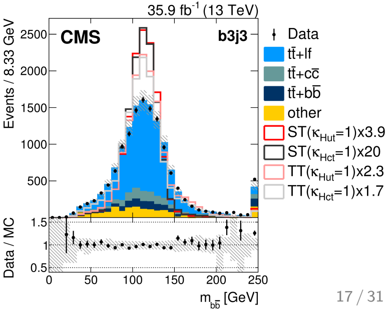


FCNC decay in $t\bar{t}$

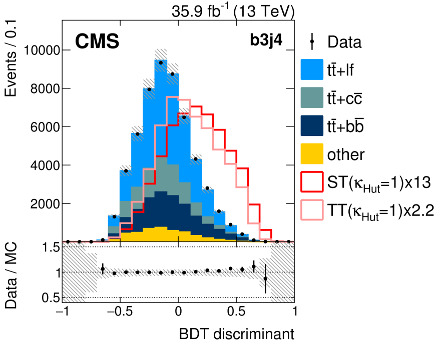


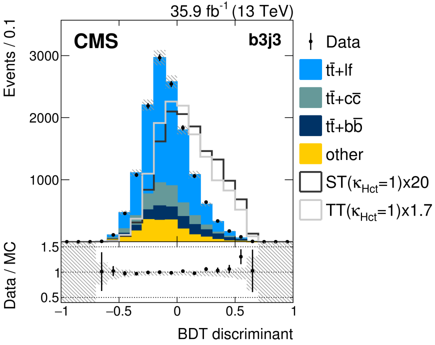
- First result on FCNC $pp \to tH$ production
    - Improved sensitivity to tuH coupling
- Search in single-lepton channel, $H \to b\bar{b}$
- 5 signal regions categorised by $n_{jet}(3,\geq 4)$ and $n_{bjet}(2,3,\geq 4)$
- BDT discriminant constructed from kinematic observables after full reconstruction of event

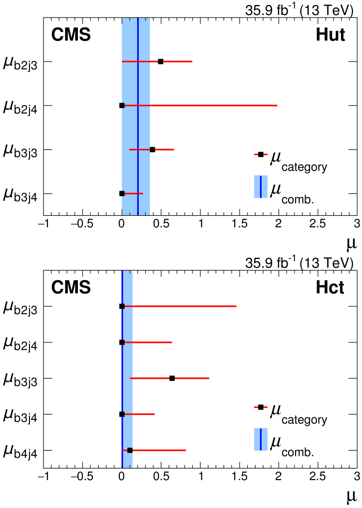




- Separate BDT discriminants trained for *tuH* and *tcH* signals in different signal regions
- No significant deviation observed compared to SM



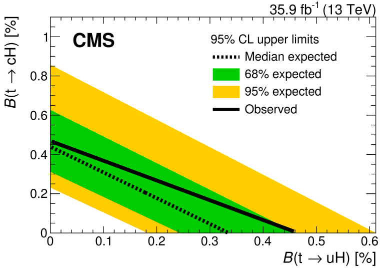


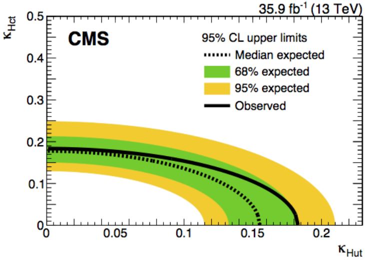


- Bets fit signal strengths for *tuH* and *tcH* for individual regions and their combinations
- Demonstrates individual region importance for each process
- Fitted branching fractions compatible with zero

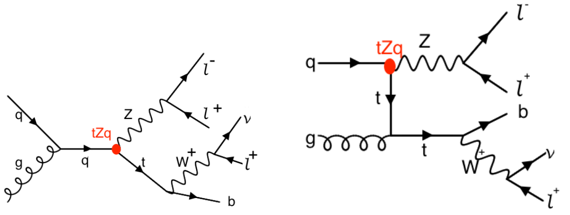
- Limit on branching fractions:
- Comparable to ATLAS result in $b\bar{b}$ channel
- $BR(t \to uH)$ limits benefit from addition of production channel
- BR limits translated also to limits on coupling

$$\kappa_{\mathrm{Hut}}^2 = \mathcal{B}(\mathrm{t} \to \mathrm{uH})\frac{\Gamma_\mathrm{t}}{\Gamma_{\mathrm{Hut}}},$$
$$\kappa_{\mathrm{Hct}}^2 = \mathcal{B}(\mathrm{t} \to \mathrm{cH})\frac{\Gamma_\mathrm{t}}{\Gamma_{\mathrm{Hct}}},$$

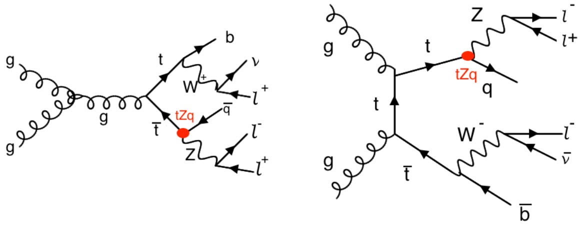




$t \to qZ$



Production vertices (CMS)



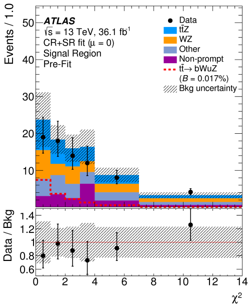
Decay vertices (ATLAS ; CMS)

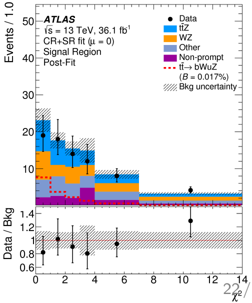
$t \to qZ$ (ATLAS)

arXiv:1803.09923

- Events categorised into signal sensitive and background control regions
- Main background sources: ttZ, WZ, non-prompt leptons in $t\bar{t}$ and Z+jets
- Reconstruct full event by minimising χ^2
  - Signal discriminant used in signal region
  - Simultaneous fit performed with other observables in control regions

Selection	$t\bar{t}Z$ CR	WZ CR	ZZ CR	Non-prompt lepton CR0 (CR1)	SR
No. leptons	3	3	4	3	3
OSSF	Yes	Yes	Yes	Yes	Yes
$\lvert m_{\ell\ell}^{\rm reco} - 91.2\ \mathrm{GeV}\rvert$	< 15 GeV	< 15 GeV	< 15 GeV	> 15 GeV	< 15 GeV
No. jets	≥ 4	≥ 2	≥ 1	≥ 2	≥ 2
No. b-tagged jets	2	0	0	0 (1)	1
$E_{\rm T}^{\rm miss}$	> 20 GeV	> 40 GeV	> 20 GeV	> 20 GeV	> 20 GeV
$m_{\rm T}^{\ell\nu}$	-	> 50 GeV	-	-	-
$\lvert m_{\ell\nu}^{\rm reco} - 80.4\ \mathrm{GeV}\rvert$	-	-	-	-	< 30 GeV
$\lvert m_{j\ell\nu}^{\rm reco} - 172.5\ \mathrm{GeV}\rvert$	-	-	-	-	< 40 GeV
$\lvert m_{j\ell\ell}^{\rm reco} - 172.5\ \mathrm{GeV}\rvert$	-	-	-	-	< 40 GeV

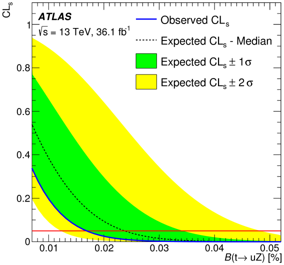


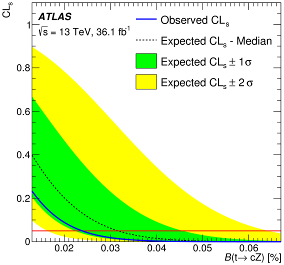


$t \to qZ$ (ATLAS)

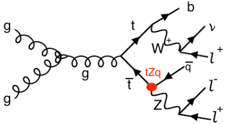
arXiv:1803.09923

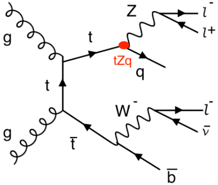
- 95% CL upper limits on FCNC branching fractions:
  - $BR(t \to uZ) < 1.7 \times 10^{-4}$
  - $BR(t \to cZ) < 2.4 \times 10^{-4}$





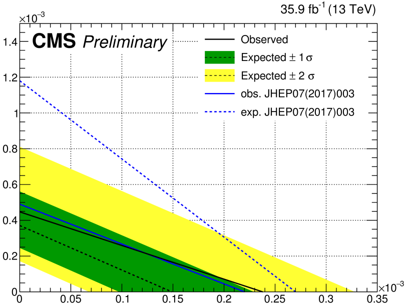
- Events categorised into signal-sensitive and background control regions
- Channels separated by lepton flavour
- Similar background composition as ATLAS search
- BDT discriminants separately trained for FCNC production and decay processes
  - Uses reconstructed observables: invariant masses, angles, *b*-tagging

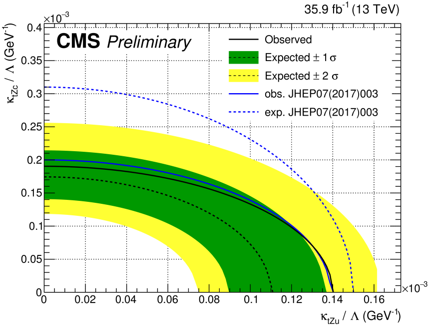




	WZ control region (WZCR)	single top quark signal region (STSR)	top quark pair signal region (TTSR)	single top quark control region (STCR)	top quark pair control region (TTCR)
Number of jets	$\geq 1, \leq 3$	1	$\geq 2, \leq 3$	1	$\geq 2, \leq 3$
Number of b jets	0	1	≥ 1	1	≥ 1
$\lvert M(Z_{reco}) - M_Z \rvert < 7.5$ GeV	Yes	Yes	Yes	No	No

- 95% CL upper limits on FCNC branching fractions:
  - $BR(t \to uZ) < 2.4 \times 10^{-4}$
  - $BR(t \to cZ) < 4.5 \times 10^{-4}$

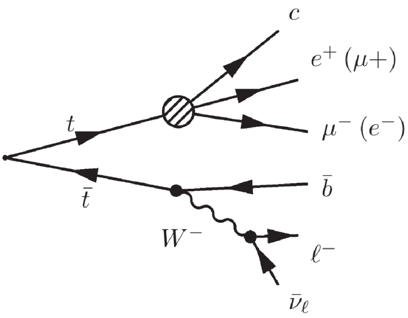




Lepton flavour violation (LFV)

LFV in top quark decay (ATLAS)

- Predicted by GUT theories, SUSY, technicolor
- Scale of new physics (NP) is unknown
  - EFT approach appropriate if NP scale is higher than what is experimentally probed
- LFV top couplings relatively unconstrained by experiments
- Presenting first direct search for $t \to ll'q$



$t\bar{t}$ LFV (ATLAS)

ATLAS-CONF-2018-044

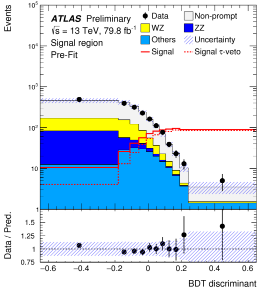
- Search for $t \to ll'q$ in $t\bar{t}$ production
- Signal region required to have 3 light leptons (e, μ)
  - opposite-sign, different-flavour (OSDF) lepton pair
  - Events with OSSF lepton pair with $|m_{ll} - m_Z| <10$ GeV discarded
- Fit to shape of BDT discriminant in signal region
- Main backgrounds $t\bar{t}/Z + j$ with non-prompt lepton, WZ/ZZ

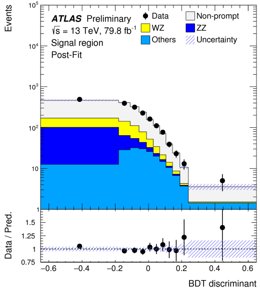
Variable	Separation (%)
OSSF lepton pair invariant mass	11
cLFV top mass	10
p_T of the electron associated to the cLFV decay	9.1
p_T of the muon associated to the cLFV decay	8.5
p_T of the lepton associated to the SM decay	8.3
Scalar mass of all jets and leptons in the event	7.6
Same-sign electron pair invariant mass	6.9
Missing transverse momentum	6.8
Number of b-jets	6.7
W transverse mass associated to the SM top lepton	6.6
ΔR between the cLFV electron and the cLFV light jet	6.5
SM top mass	6.4
ΔR between the cLFV muon and the cLFV light jet	6.3
BDT discriminant	44

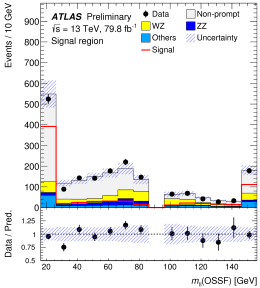
$t\bar{t}$ LFV (ATLAS)

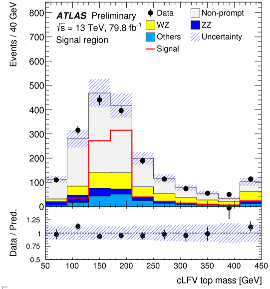
ATLAS-CONF-2018-044

- No evidence of signal
- Observed (expected) upper limit on $BR(t \to ll'q)$ 1.86×10^{-5} (1.36×10^{-5})
- Improves previous indirect limits on $BR(t \to e\mu q)$ by $\sim$3 orders of magnitude









Summary

Summary

- Presented several LHC searches for new physics through rare top quark production and decay processes
- No evidence for BSM physics found in searches
- Limits on FCNC and LFV processes have been strengthened in Run 2
- All results presented were on partial Run-2 (2015+2016) data
- Threefold increase in luminosity for full Run-2 data (2015-2018)
    - Stay tuned for new results!

BACKUP

b-tagging working points

Analysis	b-efficiency	lqg-rejection	c-rejection
ATLAS $tqH(bb)$	60%	1500	34
CMS $tH/tqH(bb)$	70%	100	10
ATLAS $tqH(\tau\tau)$	70%	380	12
ATLAS $tqH(WW^*)$	70%	380	12
ATLAS tqZ	77%	134	6
CMS tZ/tqZ	77%	134	6
$t\bar{t} \to ll'$	77%	134	6

Lepton/jet selection and non-prompt lepton background

Analysis	p_T^e [GeV]	p_T^μ [GeV]	p_T^j [GeV]
ATLAS $tqH(bb)$	30	30	25
CMS $tH/tqH(bb)$	35	30	30
ATLAS $tqH(\tau\tau)$	15	10	30
ATLAS $tqH(WW^*)$	10	10	25
ATLAS tqZ	15	15	25
CMS tZ/tqZ	35	30	30
ATLAS $t\bar{t} \to ll'$	10	10	25

- CMS tqZ/tZ analyses directly constrains NPL background by fitting m_T^W distribution in control regions
- ATLAS analyses:
  - tqZ analysis: NPL rate determined in fake lepton control regions and derived SF applied to all regions entering fit
  - Background from hadronic jets faking leptons estimated with matrix method in all other analyses
  - Charge mis-identification background estimated from OS control region using charge flip rate estimated from $Z \to ee$ sample.

Hadronic τ identification and fake-τ background estimation

- Reconstructed from collimated calorimeter clusters with 1/3 associated charged tracks
  - Total electric charge ± 1
- Discriminated from light quark/gluon jets using BDT
  - Track momentum balance, impact parameter, calorimeter energy, electromagnetic fraction are the most discriminant input variables
  - "Medium" WP used: 55%(45%) efficiency for 3-prong(1-prong) τ_h
  - Reject any τ_h candidate that is also *b*-tagged
- Estimate fake τ_{had} background control region:
  - τ_{had} candidate required to pass loose criteria but fail "medium" WP, OR same charge for both τ in event
  - Use to creat fake τ_{had} template to be used in the signal region

$t \to q(H \to WW)$ (ATLAS) Signal Regions *arXiv:1805.03483*

- $2lSS$ region:
  - $n_{jet} \geq 4$, $n_{bjet} = 1\text{-}2$
- $3l$ region:
  - $n_{jet} \geq 2$, $n_{bjet} \geq 1$
  - $\sum_q (l_0 l_1 l_2) = 1$
  - Z-mass veto for each OSSF lepton pair, and for $3l$ system
- Main discriminating variables:
  - From ttV: N_{bjets}, m_{eff}, E_T^{miss}, $p_T^{leadlep}$
  - From non-prompt lepton background: $\Delta R(l_0, l_1)$, $m(l_0 l_{1,2})$, $m_{OSSF}(ll)$, N_{bjets}, m_{eff}
- Separate training for $t \to Hu/t \to Hc$ only for $3l$ SR

Past FCNC searches (8 TeV)

- CMS tbW anomalous coupling and FCNC tqg: PAS-TOP-14-007
- CMS tqH; $H \to ff, VV$: TOP-13-007
- CMS $tq\gamma$: TOP-14-003