# $tqH$ FCNC in production and decay at ATLAS and CMS

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Boston University

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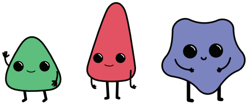


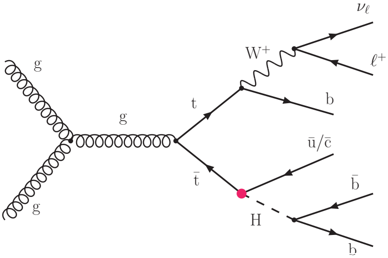
# Flavor changing neutral currents

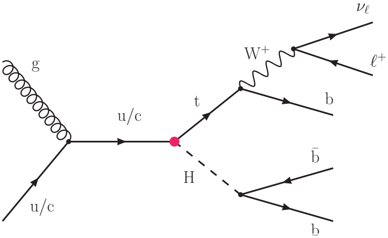
Many theories which include new physics at a scale $\Lambda$ well above LHC energies predict enhanced **flavor changing neutral currents**, giving rise to potentially observable $tHq$ vertices

FCNC is **forbidden at tree level** in SM and highly suppressed in loop corrections ($t \to Hc = 3 \times 10^{-15}$)

Such vertices can appear on the **decay side** in $t\bar{t}$ production

Also can appear in non-SM $tH$ **single-top production**



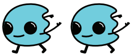
# BSM theories with FCNC

Models commonly considered in FCNC experimental papers (listing $t \to Hc$ BR, summarized from 1311.2028, from Snowmass 2013):

- **Two-Higgs doublet models**: produce tree-level $tHq$ couplings in flavor-violating models ($2 \times 10^{-3}$)
- 2HDM can also give observable $tHq$ couplings via loops with charged Higgs in **flavor-conserving 2HDM** ($\leq 10^{-5}$, most optimistic case)
- **SUSY**: flavor violation with light squarks, however advancing squark mass limits suppress loop-induced branching ratios ($\leq 10^{-5}$ for $m_{\tilde{q}} = 1\,\mathrm{TeV}$)
- **Warped extra dimensions** (RS): large coupling of $t$ to KK-excited gauge bosons can induce FC loops ($\leq 10^{-4}$)

$\sqrt{s} = 13\,\text{TeV}$

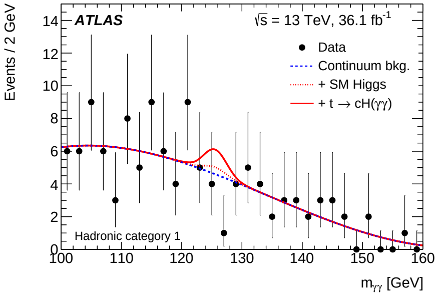
Events with **2 photons**,
$p_T > 40, 30\,\text{GeV}$,
$100 < m_{\gamma\gamma} < 160\,\text{GeV}$

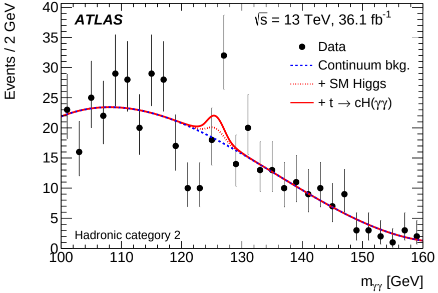


Data divided into **4 categories**:
2 hadronic categories—no identified leptons, 4 jets, at least 1 $b$-tagged.

*top 1* and *top 2* candidates from 6-body (4-jet, 2-photon) system:

1. passing inv. mass cuts on *top 1* and *top 2* (above)
2. failing inv. mass cut on *top 2* (below)



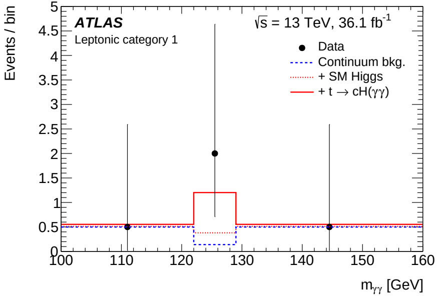
$\sqrt{s} = 13\,\text{TeV}$

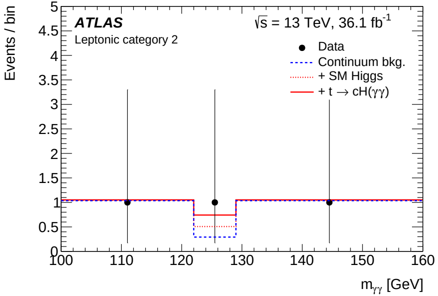
2 leptonic categories—exactly 1 identified lepton (10, 15 GeV for electrons, muons), 2 or more jets

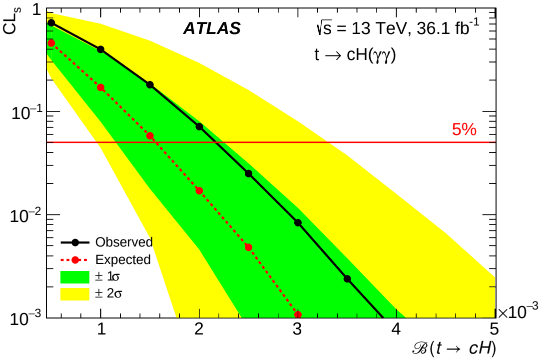
Two photons + one jet form *top 1*, remaining jet, lepton, $E_{\text{T}}^{\text{miss}}$ with $m_W$ constraint form *top 2*:

1. passing inv. mass cuts on *top 1* and *top 2* (above)
2. failing inv. mass cut on *top 2* (below)

**Fit** performed to **di-photon mass** with signal function at $m_H$, backgrounds (primarily $\gamma\gamma j$ and $t\bar{t}\gamma$) from sideband fit






$\sqrt{s} = 13\,\mathrm{TeV}$

**Upper limit** (95% CL) on $t \to cH$ branching ratio set to 0.22% (0.16% expected)

$t \to Hu$ has slightly lower acceptance than $t \to Hc$ (feature in several analyses with $b$-tagging)

**Upper limit** on $t \to uH$ branching ratio set to 0.24% (0.17% expected)

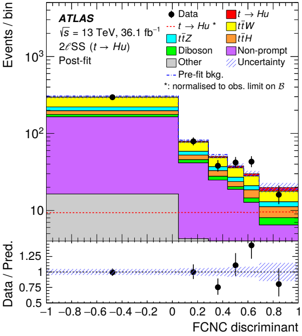
Searches for $\tau\tau$, $WW^*$, $ZZ^*$ decays of the $H$ in **2 channels**:

$\sqrt{s} = 13\,\text{TeV}$

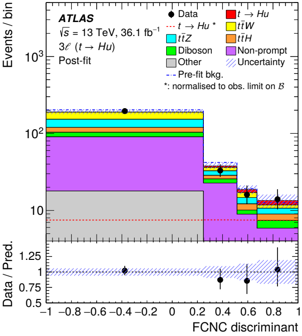
- $2\ell$ same-sign, $\geq 4$ jets, 1 or 2 $b$-jets (a,c)
- $3\ell$, $\geq 2$ jets, $\geq 1$ $b$-jet (b,d)

Make use of $t\bar{t}H$ data, analysis optimized for FCNC signal: (PRD 97 (2018) 072003), SM $t\bar{t}H$ treated as background, new BDT and BG estimates

$t \to Hu$ (a,b) and $t \to Hc$ (c,d) branching fractions are extracted individually in fits to BDT discriminants combining $2\ell$SS and $3\ell$ channels




(a)




(b)

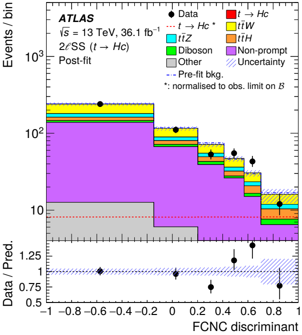
Searches for $\tau\tau$, $WW^*$, $ZZ^*$ decays of the $H$ in **2 channels**:

$\sqrt{s} = 13\,\text{TeV}$

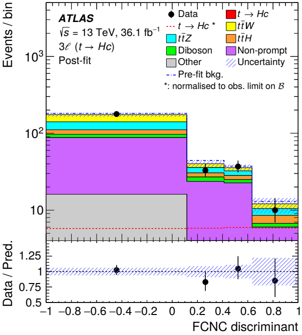
- $2\ell$ same-sign, $\geq 4$ jets, 1 or 2 $b$-jets (a,c)
- $3\ell$, $\geq 2$ jets, $\geq 1$ $b$-jet (b,d)

Make use of $t\bar{t}H$ data, analysis optimized for FCNC signal: (PRD 97 (2018) 072003), SM $t\bar{t}H$ treated as background, new BDT and BG estimates

$t \to Hu$ (a,b) and $t \to Hc$ (c,d) branching fractions are extracted individually in fits to BDT discriminants combining $2\ell$SS and $3\ell$ channels




(c)

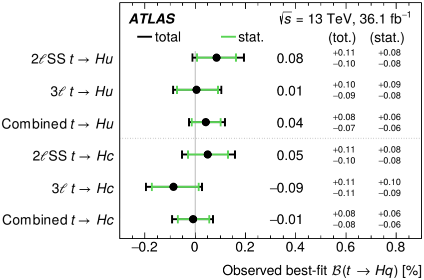


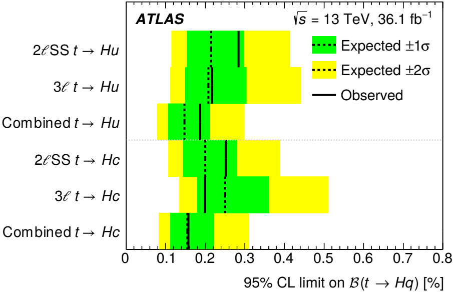

(d)

# $t \to Hq$ FCNC with multileptons

PRD 98 (2018) 032002

Best-fit and upper limits obtained for $u$ and $c$ signals, $2\ell$SS and $3\ell$ channels $\sqrt{s} = 13$ TeV




Limits from ATLAS multileptons:

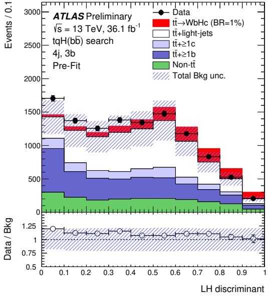
$$B(t \to uH) < 0.19\% (0.15\%)$$
$$B(t \to cH) < 0.16\% (0.15\%)$$

$\sqrt{s} = 13$ TeV

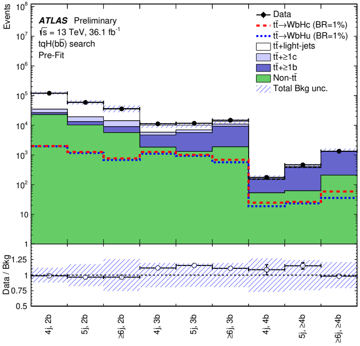
## $H \to b\bar{b}$

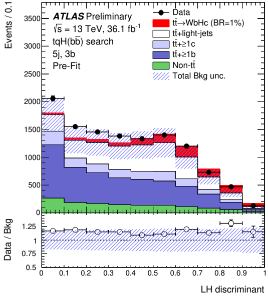
Lepton+jets split into nine analysis regions by $n$-jet $m$–$b$-jet, as shown

Likelihood (LH) discriminant is constructed to separate signals and backgrounds




Most sensitive regions are 5j,3b and 4j,3b



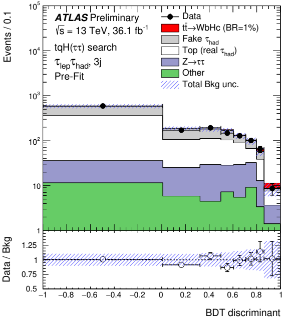
$\sqrt{s} = 13\,\text{TeV}$

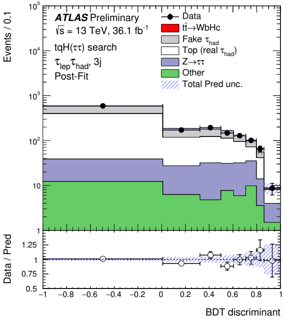
$H \to \tau^+\tau^-$

Four SRs designated: $(\tau_{\text{lep}}, \tau_{\text{had}}, 3\text{j})$, $(\tau_{\text{lep}}, \tau_{\text{had}}, \geq 4\text{j})$, $(\tau_{\text{had}}, \tau_{\text{had}}, 3\text{j})$, $(\tau_{\text{had}}, \tau_{\text{had}}, \geq 4\text{j})$

Events with a reconstructed fully-hadronic top decay are rejected, $\chi^2$ kinematic reconstruction of $H \to \tau\tau$ decay performed

BDT trained on $t\bar{t} \to W(qq)bH(\tau\tau)q$ signal against total background



# $t \to Hq$ FCNC with $H \to b\bar{b}, \tau^+\tau^-$



$\sqrt{s} = 13\,\text{TeV}$

$H \to \tau^+\tau^-$

Four SRs designated: $(\tau_{\text{lep}}, \tau_{\text{had}}, 3\text{j})$, $(\tau_{\text{lep}}, \tau_{\text{had}}, \geq 4\text{j})$, $(\tau_{\text{had}}, \tau_{\text{had}}, 3\text{j})$, $(\tau_{\text{had}}, \tau_{\text{had}}, \geq 4\text{j})$

Events with a reconstructed fully-hadronic top decay are rejected, $\chi^2$ kinematic reconstruction of $H \to \tau\tau$ decay performed

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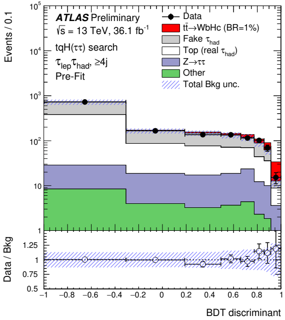
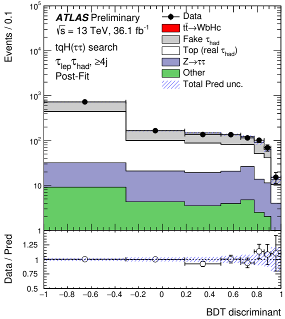
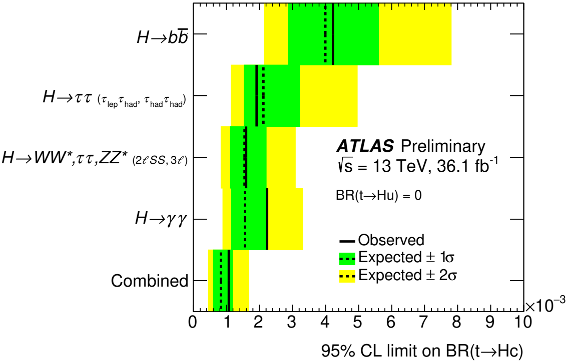


$\sqrt{s} = 13\,\text{TeV}$

Limits (expected) at 95% C.L.:
From $H \to b\bar{b}$ analysis,
$B(t \to uH) < 0.52\%(0.49\%)$
$B(t \to cH) < 0.42\%(0.40\%)$

From $H \to \tau\tau$ analysis,
$B(t \to uH) < 0.17\%(0.20\%)$
$B(t \to cH) < 0.19\%(0.21\%)$




**Combination** of $H \to b\bar{b}, \tau^+\tau^-$ with multilepton, $H \to \gamma\gamma$

Full likelihood combination of 4 ATLAS searches

Limits set on individual $tHu$, $tHc$ couplings, also in BR$(t \to Hc)$, BR$(t \to Hu)$ plane

# $tHq$ FCNC prod. and decay with $H \to b\bar{b}$

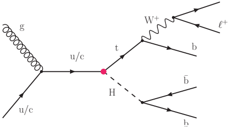
JHEP 06 (2018) 102

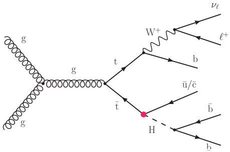
$\sqrt{s} = 13$ TeV

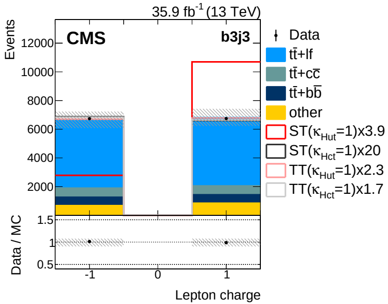
Search in 2 channels for **production** of a single $t$ in association with $H$ (ST) and $t\bar{t}$ lepton+jets with FCNC in **decay** (TT), with $H \to b\bar{b}$ decays considered

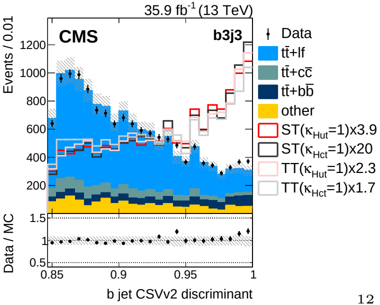
Events with exactly 1 isolated lepton, $\geq 3$ jets, $\geq 2$ $b$-jets, are selected

Five signal regions are defined based on number of jets, $b$-jets



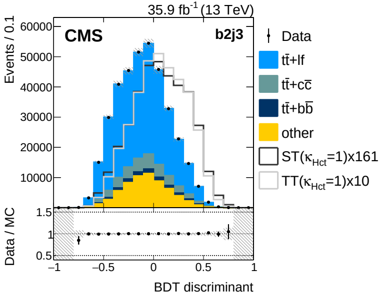
# $tHq$ FCNC prod. and decay with $H \to b\bar{b}$

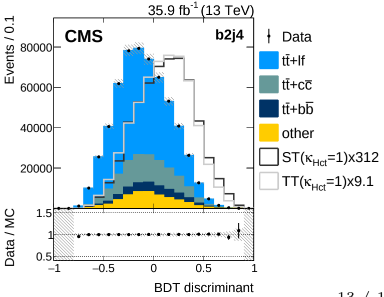
JHEP 06 (2018) 102

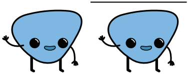
$\sqrt{s} = 13\,\text{TeV}$

BDT trained for each signal region, for $c$ and $u$ analyses, to determine correct $b$ jet permutation (b4j4 only used for $Hct$)

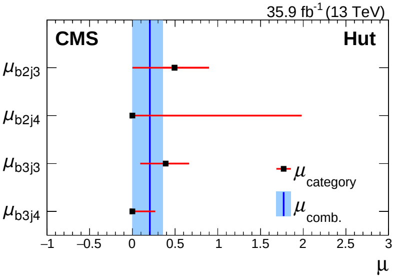
Full kinematic reconstruction of event is performed, assign $b$-jets to $t$ or $H$ by picking greatest BDT discriminant value, $\approx 75\%$ correct assignment

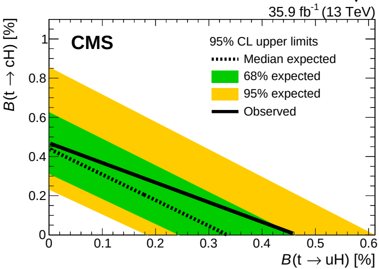


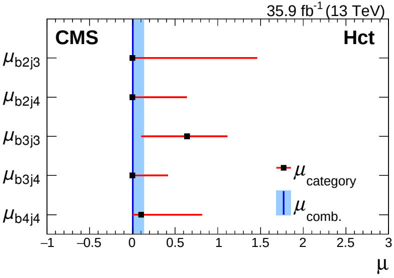



$\sqrt{s} = 13$ TeV




Inclusion of the ST production results in $\approx 20\%$ improvement of $Hut$ limit




Limit on $B(t \to uH)$ (with $B(t \to cH) = 0$): 0.47%

expected 0.34%

Limit on $B(t \to cH)$ (with $B(t \to uH) = 0$): 0.47%

expected 0.44%

$\sqrt{s} = 13\,\text{TeV}$

Systematic uncertainties—comparison with ATLAS $H \to b\bar{b}$ analysis:

CMS analysis:

- $b$-tagging scale factors (8–30% yield variation)
- ren. fac. scales ($\approx 20\%$ yield variation)
- Powheg ME/PS matching (1–5% effect)
- Jet energy scale ($\approx 8\%$ yield variation)

ATLAS analysis:

- $c$-tagging calibration ($\Delta B \approx 1.5 \times 10^{-3}$)
- $t\bar{t}$ +light jets PS/Had. ($\Delta B \approx 1.2 \times 10^{-3}$)
- $t\bar{t}+ \geq 1$b 4Fs/5Fs comparison ($\Delta B \approx 0.5$–$1.0 \times 10^{-3}$)
- JES flavor dependnce ($\Delta B \approx 0.5$–$1.0 \times 10^{-3}$)
- $t\bar{t}+ \geq 1c$ norm.($\Delta B \approx 0.5$–$1.0 \times 10^{-3}$)

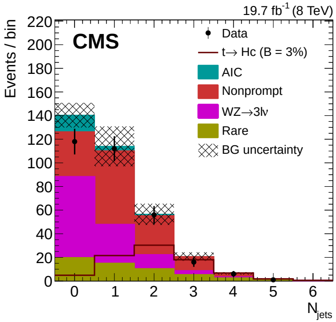
$\sqrt{s} = 8\,\text{TeV}$

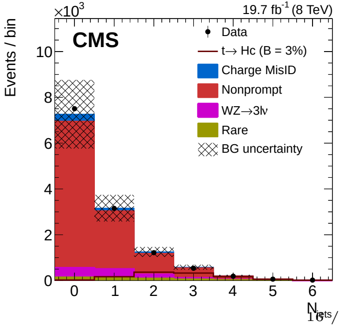
Three independent analyses searching for $t \to Hq$ FCNC in decay:

- **Multilepton ($2\ell$SS and $3\ell$), sensitive to $H \to WW, ZZ, \tau\tau$**
- $\gamma\gamma$ + jets ($1\ell$ and $0\ell$)
- single lepton + $\geq 4$ jet, $\geq 3$ $b$-jets, sensitive to $H \to b\bar{b}$

Multilepton backgrounds include charge mis-identification, mis-identified or non-prompt leptons—estimated with data-driven techniques

3 SS regions and 4 trilepton signal regions are designated



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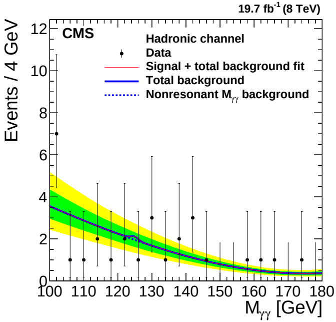
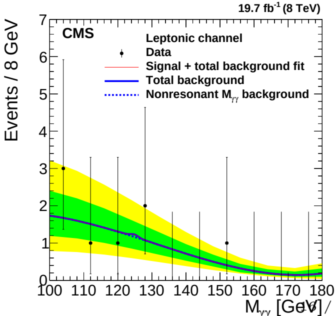
Diphoton signal region defined by tight $m_{\gamma\gamma}$ windows nominal $H$ peak position

Non-resonant diphoton and small SM $H \to \gamma\gamma$ are included as backgrounds



$\sqrt{s} = 8\,\text{TeV}$

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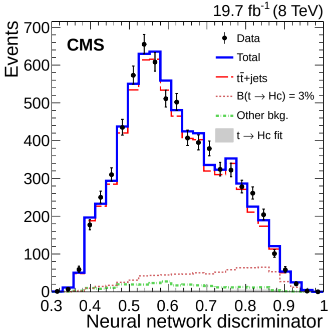
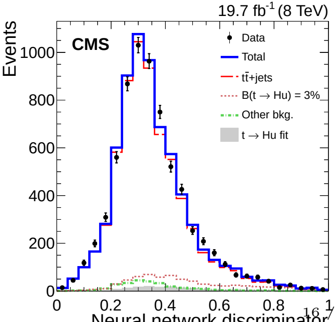
- Multilepton ($2\ell$SS and $3\ell$), sensitive to $H \to WW, ZZ, \tau\tau$
- $\gamma\gamma$ + jets ($1\ell$ and $0\ell$)
- **single lepton + $\geq 4$ jet, $\geq 3$ $b$-jets, sensitive to $H \to b\bar{b}$**

MVA analysis determines best assignment of jets for $t$,$H$ reconstruction, correct assignment in $\approx 54\%$ of events

Same classifier used for $u$ and $c$ analyses



$\sqrt{s} = 8\,\mathrm{TeV}$

| | $\mathcal{B}_{obs}$(t → Hc) | $\mathcal{B}_{exp}$(t → Hc) | $\mathcal{B}_{exp}+\sigma$ | $\mathcal{B}_{exp}-\sigma$ |
|---|---|---|---|---|
| Trilepton | 1.26 | 1.33 | 1.87 | 0.95 |
| Same-sign dilepton | 0.99 | 0.93 | 1.26 | 0.68 |
| Multilepton combined | 0.93 | 0.89 | 1.22 | 0.65 |
| Diphoton hadronic | 0.67 | 0.82 | 1.19 | 0.63 |
| Diphoton leptonic | 1.59 | 1.92 | 2.8 | 1.58 |
| Diphoton combined | 0.47 | 0.67 | 1.06 | 0.44 |
| b jet + lepton | 1.16 | 0.89 | 1.37 | 0.60 |
| Full combination | 0.40 | 0.43 | 0.64 | 0.30 |

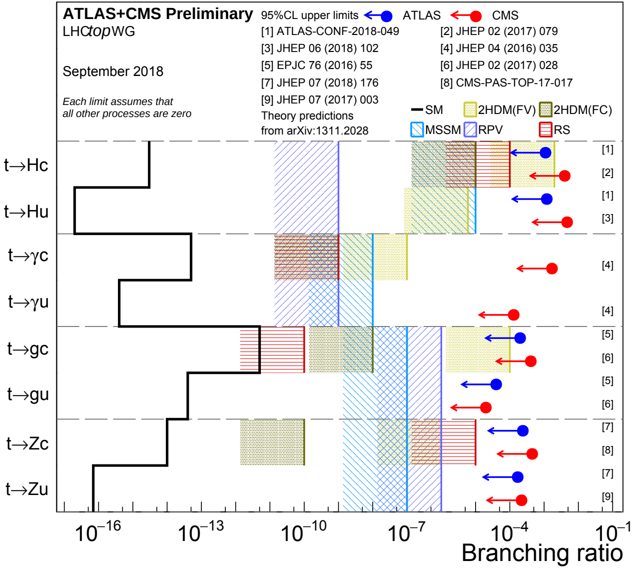
| | $\mathcal{B}_{obs}$(t → Hu) | $\mathcal{B}_{exp}$(t → Hu) | $\mathcal{B}_{exp}+\sigma$ | $\mathcal{B}_{exp}-\sigma$ |
|---|---|---|---|---|
| Trilepton | 1.34 | 1.47 | 2.09 | 1.05 |
| Same-sign dilepton | 0.93 | 0.85 | 1.16 | 0.62 |
| Multilepton combined | 0.86 | 0.82 | 1.14 | 0.60 |
| Diphoton hadronic | 0.57 | 0.72 | 1.05 | 0.57 |
| Diphoton leptonic | 1.56 | 1.89 | 2.69 | 1.55 |
| Diphoton combined | 0.42 | 0.60 | 0.96 | 0.39 |
| b jet + lepton | 1.92 | 0.84 | 1.31 | 0.57 |
| Full combination | 0.55 | 0.40 | 0.58 | 0.27 |

Simultaneous fit of data in 12 channels is performed, determining $t \to Hu$ and $t \to Hc$ branching ratios

Upper limits set at:
$B(t \to Hu) = 0.55\%(0.40\%)$

$B(t \to Hc) = 0.40\%(0.43\%)$

# Summary of LHC limits on FCNC




Best limits (before this workshop) come from:

- ATLAS: PRD 98 (2018) 032002
- CMS: JHEP 02 (2017) 079, JHEP 06 (2018) 102

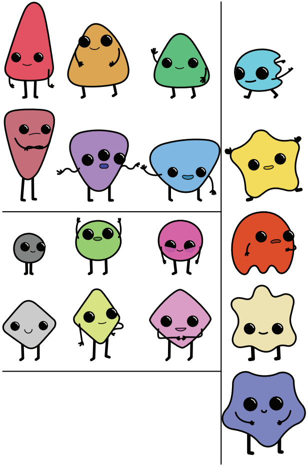
Preliminary ATLAS combination moves best limits from:
0.19% → 0.12% ($tHu$)
and
0.16% → 0.11% ($tHc$)

# Conclusion

Searches for FCNC continue to provide a promising area to test BSM physics predictions

Best LHC limits are starting to probe phase space of particular BSM models

Promising area of study for run-3 and HL-LHC!



Artwork credit: Mallory Brangan

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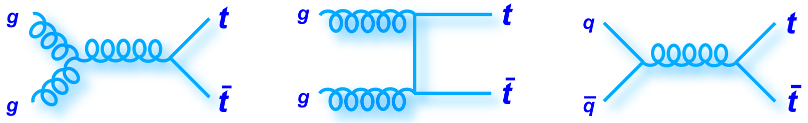
# Production of top quarks at the LHC

Top quarks are produced predominantly via **pair production**, but single top quarks can also be produced weakly

At the LHC, $t\bar{t}$ pairs are produced mainly in gluon fusion diagrams (c.f. the Tevatron, where quark-initiated diagrams dominate), quark-initiated diagrams contribute roughly 10% of the total production at 14 TeV (JHEP07(2013)167)



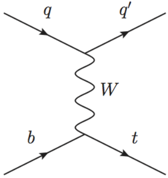

The $t\bar{t}$ production cross section at $\sqrt{s} = 13\,\text{TeV}$ is $\approx$ **830 pb** (Ref)

# Production of top quarks at the LHC

Single top quark production: **cross-sections given for $\sqrt{s} = 13\,\text{TeV}$** (Ref)

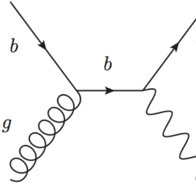
## $t$-channel ($tq$) production

Largest cross-section and cleanest signal of single-top processes-
ATLAS measurements at 7,8,13 TeV
$\boldsymbol{\sigma_{t-\text{ch}} \approx 220\,\text{pb}}$



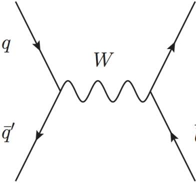

## $tW$ production

Large quantum interference with $t\bar{t}$ production due to identical $WWbb$ final state, ATLAS measurements at 7,8,13 TeV
$\boldsymbol{\sigma_{tW} \approx 70\,\text{pb}}$



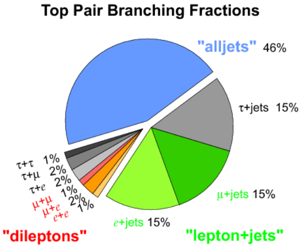

## $s$-channel ($tb$) production

Very small cross-section at LHC
ATLAS searches at 7,8 TeV
$\boldsymbol{\sigma_{s-\text{ch}} \approx 10\,\text{pb}}$

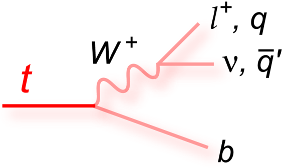


The top quark decays via charged weak current, so its decay products depend on the **CKM matrix**

In a global fit assuming CKM unitarity, the element $V_{tb}$ is determined to be $0.99915 \pm 0.00005$ (Ref), so we safely assume $t \to Wb$ 100% of the time for most purposes




The subsequent decay of the $W$ thus determines the final state, for $t\bar{t}$: dilepton, lepton+jets, all-hadronic, tau+X



# Search for FCNC in $t \to Hq$ in multilepton final states

| Variable | $2\ell$SS | $3\ell$ |
|---|---|---|
| $p_T$ of higher-$p_T$ lepton | × | |
| $p_T$ of lower-$p_T$ lepton | × | |
| $p_T$ of lepton $\ell_0$ | | × |
| $p_T$ of lepton $\ell_1$ | | × |
| $p_T$ of lepton $\ell_2$ | | × |
| 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 | | × |
| $\Delta R(\ell_0, \ell_1)$ | | × |
| $\Delta R(\ell_0, \ell_2)$ | | × |
| $\Delta R$(higher-$p_T$ lepton, closest jet) | × | |
| $\Delta R$(lower-$p_T$ lepton, closest jet) | × | |
| $\Delta R(\ell_1$, closest jet) | | × |
| Smallest $\Delta R(\ell_0$, $b$-tagged jet) | | × |
| $E_T^{miss}$ | × | |
| $m_{eff}$ | × | × |

Variables used to construct the BDT discriminants for the 2lSS and 3l categories. The symbol “x” indicates that this variable is used in the respective BDT. The “best Z candidate” is the opposite-charge lepton pair with same flavor with invariant mass closest to 91.2 GeV; if no such pair exists, zero is assigned for the invariant mass

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

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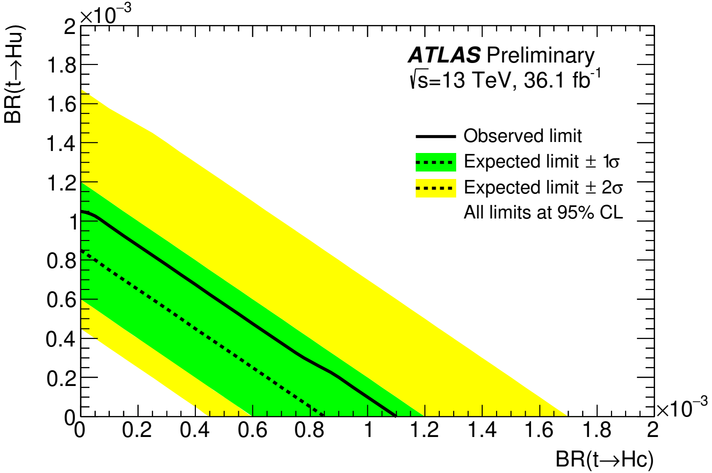
# ATLAS combination of $t \to Hq$ FCNC searches

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# $t \to Hq$ FCNC with multileptons

| | Best-fit $\mathcal{B}(t \to Hu)$ [%] | | Observed (Expected) Upper Limit on $\mathcal{B}(t \to Hu)$ [%] | |
|---|---|---|---|---|
| | stat. | stat. + syst. | stat. | stat. + syst. |
| $2\ell$SS | $0.08\,^{+0.08}_{-0.08}$ | $0.08\,^{+0.11}_{-0.10}$ | 0.23 (0.15) | 0.28 (0.21) |
| $3\ell$ | $0.01\,^{+0.09}_{-0.08}$ | $0.01\,^{+0.10}_{-0.09}$ | 0.20 (0.18) | 0.22 (0.21) |
| Combined | $0.04\,^{+0.06}_{-0.06}$ | $0.04\,^{+0.08}_{-0.07}$ | 0.17 (0.12) | 0.19 (0.15) |

| | Best-fit $\mathcal{B}(t \to Hc)$ [%] | | Observed (Expected) Upper Limit on $\mathcal{B}(t \to Hc)$ [%] | |
|---|---|---|---|---|
| | stat. | stat. + syst. | stat. | stat. + syst. |
| $2\ell$SS | $0.05\,^{+0.08}_{-0.08}$ | $0.05\,^{+0.11}_{-0.10}$ | 0.22 (0.15) | 0.25 (0.20) |
| $3\ell$ | $-0.09\,^{+0.10}_{-0.09}$ | $-0.09\,^{+0.11}_{-0.11}$ | 0.19 (0.23) | 0.20 (0.25) |
| Combined | $-0.01\,^{+0.06}_{-0.06}$ | $-0.01\,^{+0.08}_{-0.08}$ | 0.15 (0.13) | 0.16 (0.15) |

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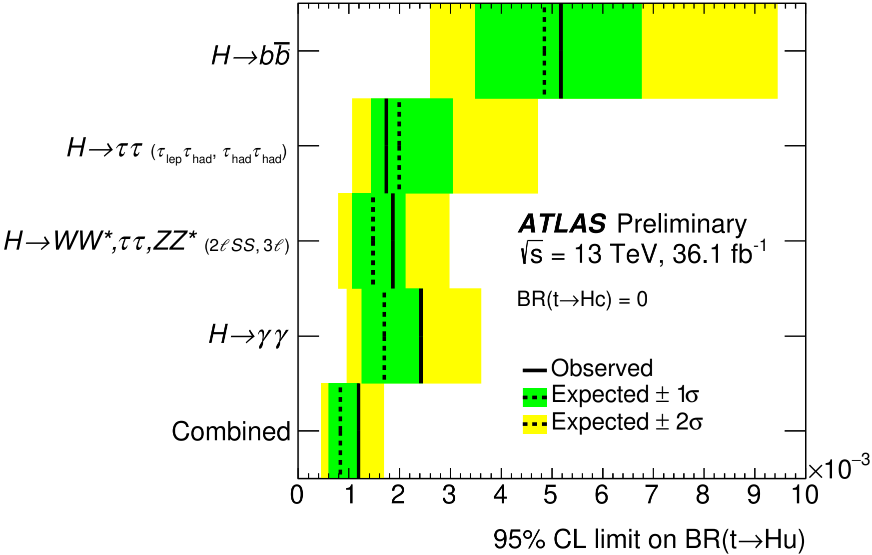

H→bb̄
H→ττ (τlepτhad, τhadτhad)
H→WW*,ττ,ZZ* (2ℓSS, 3ℓ)
H→γγ
Combined
ATLAS Preliminary
√s = 13 TeV, 36.1 fb-1
BR(t→Hc) = 0
Observed
Expected ± 1σ
Expected ± 2σ
×10-3
0
1
2
3
4
5
6
7
8
9
10
95% CL limit on BR(t→Hu)


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multivariate analysis TMVA [41]. The input BDT variables that are used for the ST and TT hypotheses correspond to the reconstructed invariant mass of two b jets associated with the Higgs boson decay, the reconstructed invariant mass of a b jet ($m_{b\bar{b}}$), lepton and neutrino associated with the top quark decay ($m(t^{\ell})$), its transverse momentum ($p_T(t^{\ell})$), $\Delta R$ between the reconstructed Higgs boson and the top quark. In case of the hypothesis of the background $t\bar{t}$ events the following variables are used: $m(t^{\ell})$, $m(t^{h})$, $\Delta R(t^{\ell}, t^{h})$, and $p_T(t^{\ell})$, where $t^{h}$ corresponds to the reconstructed top quark hadronic decay from one b-tagged and two non b-tagged jets. The BDT classifier is trained to distinguish the correct from the wrong b jet assignments. The train-

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