# CP violation and flavour changing neutral currents in the top sector


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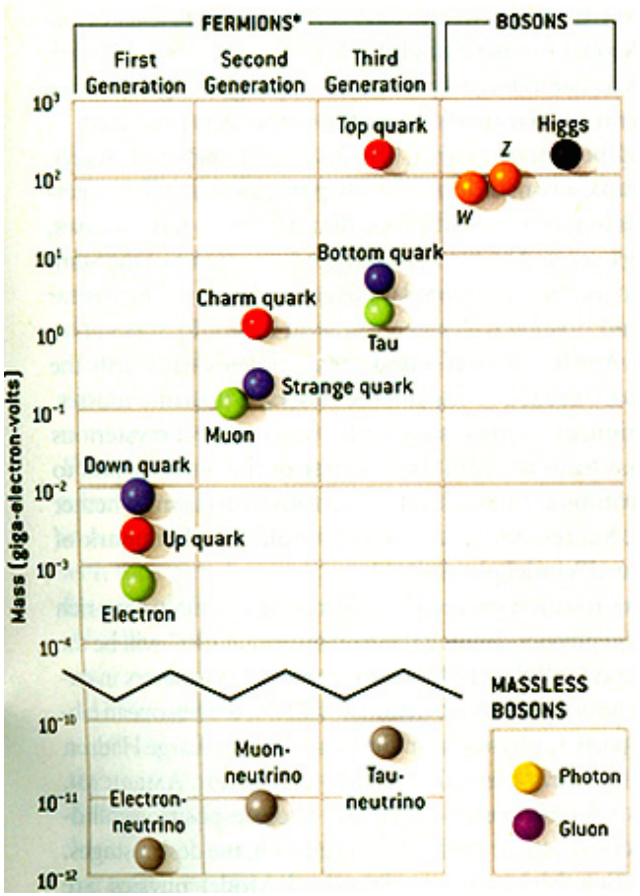
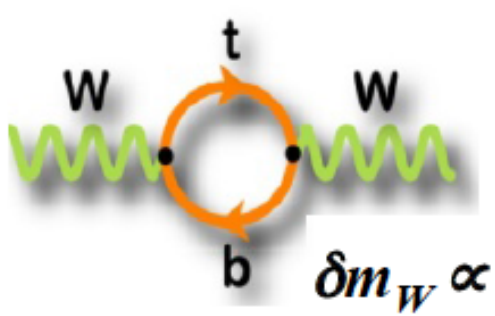
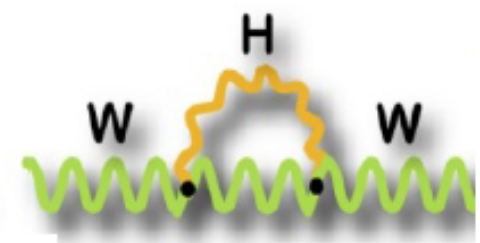
# Why bother about top?

- Special from many accounts
  - Heaviest among all known elementary particles
  - Has the strongest coupling with the Higgs boson
  - Decays before it can hadronize unlike its peers
  - Allows to directly study own properties



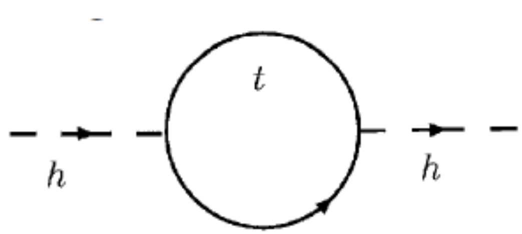

- An excellent benchmark to check self-consistency of the standard model (SM)

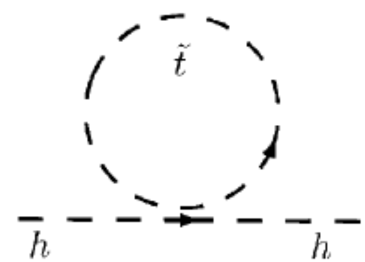



$\delta m_W \propto m_t^2$ $\delta m_W \propto \ln(m_H)$

- Expected to have a good connection with new physics (NP)



# What will this talk cover?

- Public results from ATLAS and CMS mostly appearing between CKM2016 in Mumbai and now

- CP asymmetry in b-hadron decays using top pair events **JHEP 02 (2017) 071**
- CP violation via triple product asymmetry in top pair events **JHEP 03 (2017) 101**
- FCNC decays $t \to qZ$ in top pair events **JHEP 07 (2018) 176**
- FCNC production of tZq **JHEP 07 (2017) 003**
- FCNC involving a top quark and a Z boson **CMS PAS TOP-17-017**
- FCNC decays $t \to qH$ in the multilepton channel **PRD 98 (2018) 032002**
- FCNC decays $t \to qH$, with $H \to \gamma\gamma$ in top pair events **JHEP 10 (2017) 129**
- Higgs-mediated FCNC in top pair events **JHEP 02 (2017) 079**
- FCNC interaction of the top quark and the Higgs boson **JHEP 06 (2018) 102**
- Single top quark production via the qgt FCNC process **EPJ C76 (2016) 55**
- tqg FCNC in *t*-channel single top quark events **JHEP 02 (2017) 028**

# Why CP violation in the top sector?

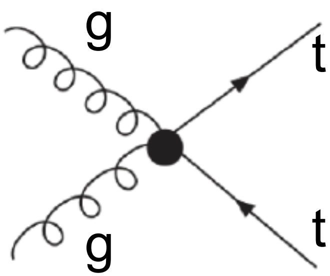
- A crucial ingredient for explaining matter-antimatter asymmetry
  - So far, it has been observed in the quark sector, that to only in the kaon and B-meson system
  - Falls short by ~10 orders of magnitude to account for the observed preponderance of matter over antimatter

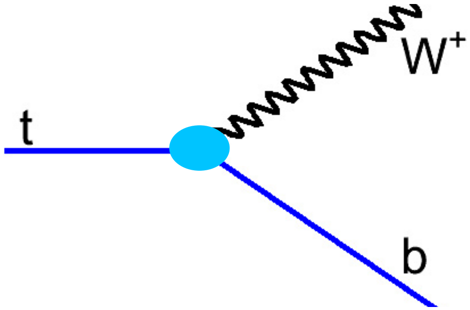
- Top provides another avenue to look for CP violation
  - Expected to be negligible within the SM
  - A probe for NP, e.g. chromo-electric dipole moment that could alter the production and decay vertices

**Atwood et al., PR 347 (2001) 1**

**Gupta and Valencia, PRD 81 (2010) 034013**

**Gupta, Mete and Valencia, PRD 80 (2009) 034013**




- LHC being a top factory is an ideal setting towards this goal

# CP asymmetry in b-hadron decays

- Top pair events offer an alternative avenue to study CP violation in b-hadron decays ➔ complementary to the resonant production of $b\bar{b}$ pairs at Belle and BaBar or hadroproduction (mostly at LHC)

- A unique aspect of the study is a method by which the b-quark charge in top pair events can be determined both at its production and decay
  - Hard lepton from W decay in the semileptonic $t\bar{t}$ sample allows determination of charge of the accompanying b-quark: $t \to bW^+ \to bl^+\nu$
  - Charge of the soft muon in $b \to X\mu\nu$ can probe the decay chain ➔ tag the jets with soft muon ("soft muon tagging" or SMT)

- By using inclusive top decay chains that produce two leptons, one can probe CP violation in $B_q$–$\bar{B}_q$ (q = d, s) mixing, semileptonic b and c decays as well as in $b \to c$ transition

<u>Same sign</u>

$$t \to \ell^+\nu\,(b \to \bar{b}) \to \ell^+\ell^+X$$
$$t \to \ell^+\nu\,(b \to c) \to \ell^+\ell^+X$$
$$t \to \ell^+\nu\,(b \to \bar{b} \to c\bar{c}) \to \ell^+\ell^+X$$

<u>Opposite sign</u>

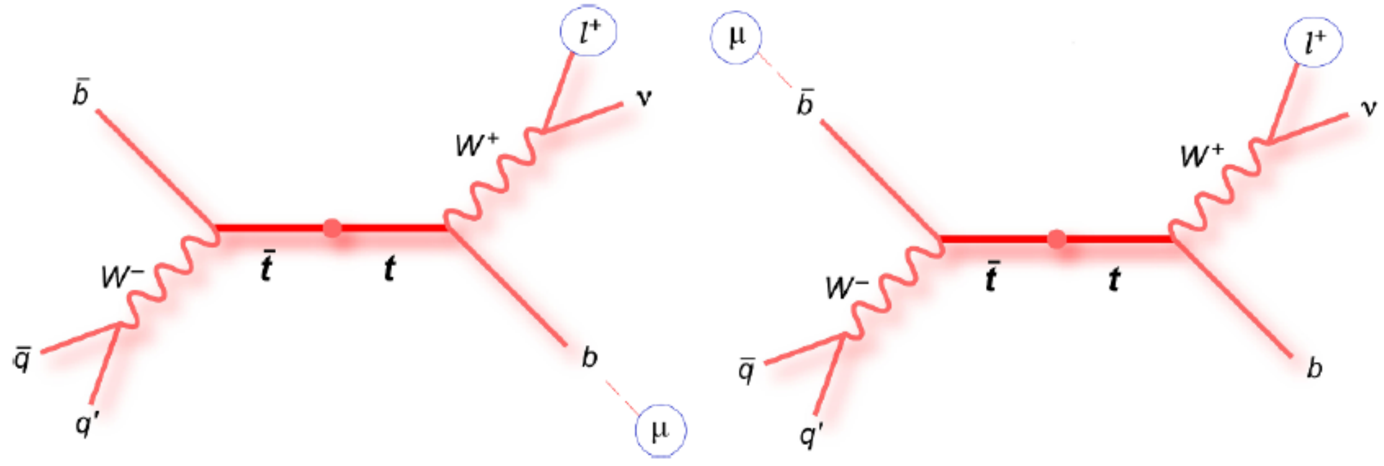
$$t \to \ell^+\nu b \to \ell^+\ell^-X$$
$$t \to \ell^+\nu\,(b \to \bar{b} \to \bar{c}) \to \ell^+\ell^-X$$
$$t \to \ell^+\nu\,(b \to c\bar{c}) \to \ell^+\ell^-X$$

**Gedelia et al., PRL 110 (2013) 232002**

# CP asymmetry in b-hadron decays

- Opposite- or same-sign muons arise if the SMT muon is from the same or different top quark

**JHEP 02 (2017) 071**

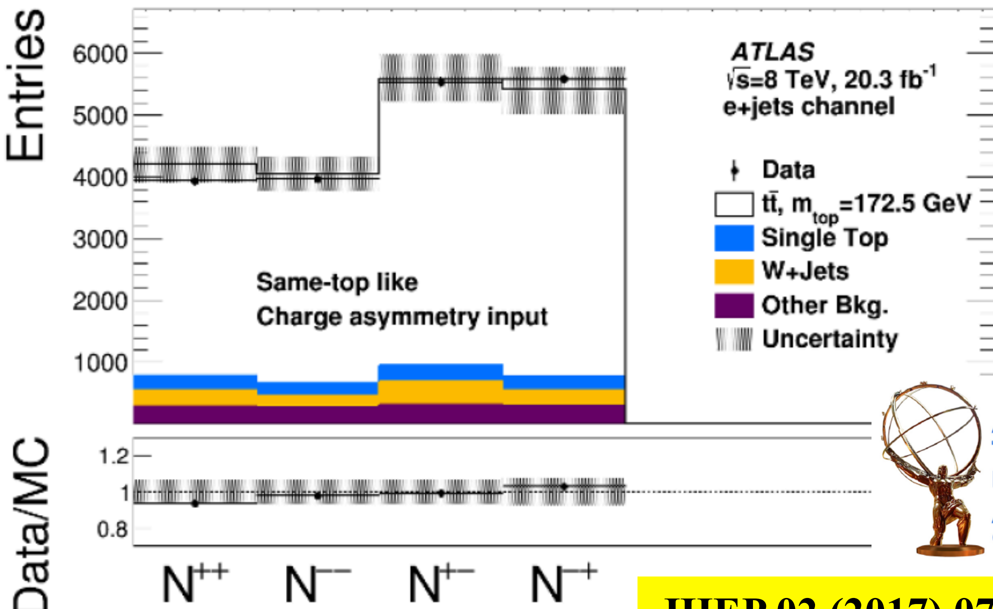


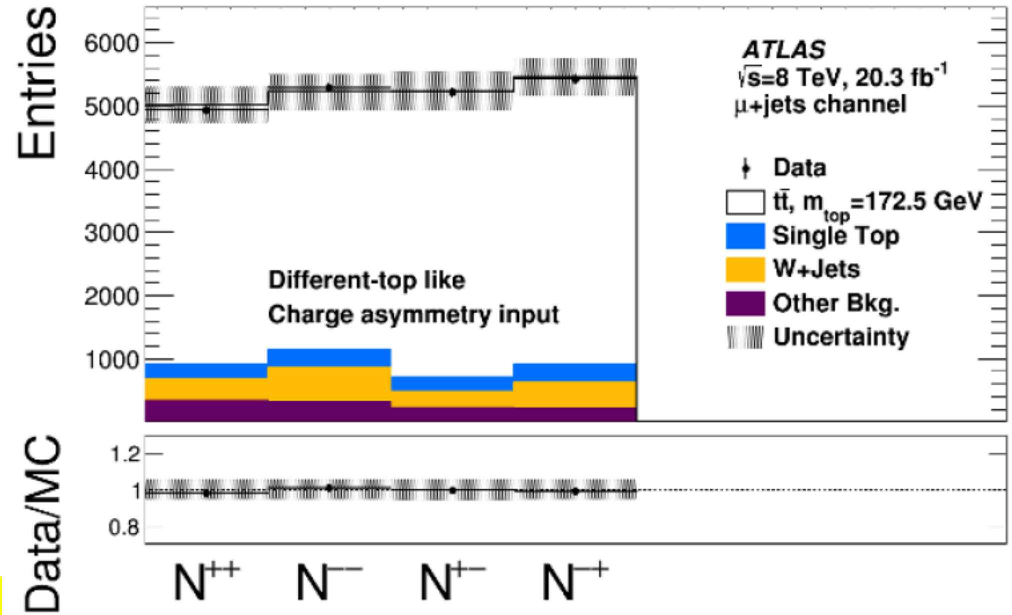

- Measure same- and opposite-sign charge asymmetries as:

$$A^{\rm SS} = \frac{\left(\frac{N^{++}}{N^{+}} - \frac{N^{--}}{N^{-}}\right)}{\left(\frac{N^{++}}{N^{+}} + \frac{N^{--}}{N^{-}}\right)} \qquad A^{\rm OS} = \frac{\left(\frac{N^{+-}}{N^{+}} - \frac{N^{-+}}{N^{-}}\right)}{\left(\frac{N^{+-}}{N^{+}} + \frac{N^{-+}}{N^{-}}\right)}$$

- $N^{\alpha\beta}$ is the number of SMT muons found with a charge β in conjunction with a W-boson lepton (electron or muon) of charge α
- $N^+$ ($N^{++} + N^{+-}$) and $N^-$ ($N^{-+} + N^{--}$) are the total number of positively and negatively charged W-boson leptons, respectively

# CP asymmetry in b-hadron decays




**JHEP 02 (2017) 071**

| | Data $(10^{-2})$ | MC $(10^{-2})$ | Existing limits $(2\sigma)$ $(10^{-2})$ | | SM prediction $(10^{-2})$ | |
|---|---|---|---|---|---|---|
| $A^{ss}$ | $-0.7 \pm 0.8$ | $0.05 \pm 0.23$ | - | | $< 10^{-2}$ | [19] |
| $A^{os}$ | $0.4 \pm 0.5$ | $-0.03 \pm 0.13$ | - | | $< 10^{-2}$ | [19] |
| $A^{b}_{mix}$ | $-2.5 \pm 2.8$ | $0.2 \pm 0.7$ | $< 0.1$ | [95] | $< 10^{-3}$ | [95, 96] |
| $A^{b\ell}_{dir}$ | $0.5 \pm 0.5$ | $-0.03 \pm 0.14$ | $< 1.2$ | [94] | $< 10^{-5}$ | [19, 94] |
| $A^{c\ell}_{dir}$ | $1.0 \pm 1.0$ | $-0.06 \pm 0.25$ | $< 6.0$ | [94] | $< 10^{-9}$ | [19, 94] |
| $A^{bc}_{dir}$ | $-1.0 \pm 1.1$ | $0.07 \pm 0.29$ | - | | $< 10^{-7}$ | [97] |

- Results are consistent with SM, albeit statistically limited ➔ scope for Run 2
- First ever measurement of direct $A^{bc}$ and tightened $2\sigma$ limit on $A^{cl}$

# CP violation via triple-product asymmetry

- Use a set of T-odd observables, $v_1.(v_2 \times v_3)$, where $v_i$ is the spin or momentum of the *i*-th daughter particle
  - Change sign under time reversal, consequently odd under CP transformation
  - Underlying assumption here is CPT conservation
- CPV would be manifested via a nonzero value of the following asymmetry:

$$\boxed{A_{\mathrm{CP}}(O_i) = \frac{N_{\text{events}}(O_i > 0) - N_{\text{events}}(O_i < 0)}{N_{\text{events}}(O_i > 0) + N_{\text{events}}(O_i < 0)}}$$

  - Asymmetry correcting for detector effects as well as without corrections
  - As NP could potentially impact these corrections, or dilution factors
- Study performed in the lepton+jet final state of $\mathrm{t\bar{t}}$ events

$$O_2 = \epsilon(P, p_{\mathrm{b}} + p_{\bar{\mathrm{b}}}, p_\ell, p_{j_1}) \xrightarrow{\text{lab}} \propto (\vec{p}_{\mathrm{b}} + \vec{p}_{\bar{\mathrm{b}}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1})$$

$$O_3 = Q_\ell\, \epsilon(p_{\mathrm{b}}, p_{\bar{\mathrm{b}}}, p_\ell, p_{j_1}) \xrightarrow{\mathrm{b\bar{b}\,CM}} \propto Q_\ell\, \vec{p}_{\mathrm{b}} \cdot (\vec{p}_\ell \times \vec{p}_{j_1})$$

$$O_4 = Q_\ell\, \epsilon(P, p_{\mathrm{b}} - p_{\bar{\mathrm{b}}}, p_\ell, p_{j_1}) \xrightarrow{\text{lab}} \propto Q_\ell\, (\vec{p}_{\mathrm{b}} - \vec{p}_{\bar{\mathrm{b}}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1})$$

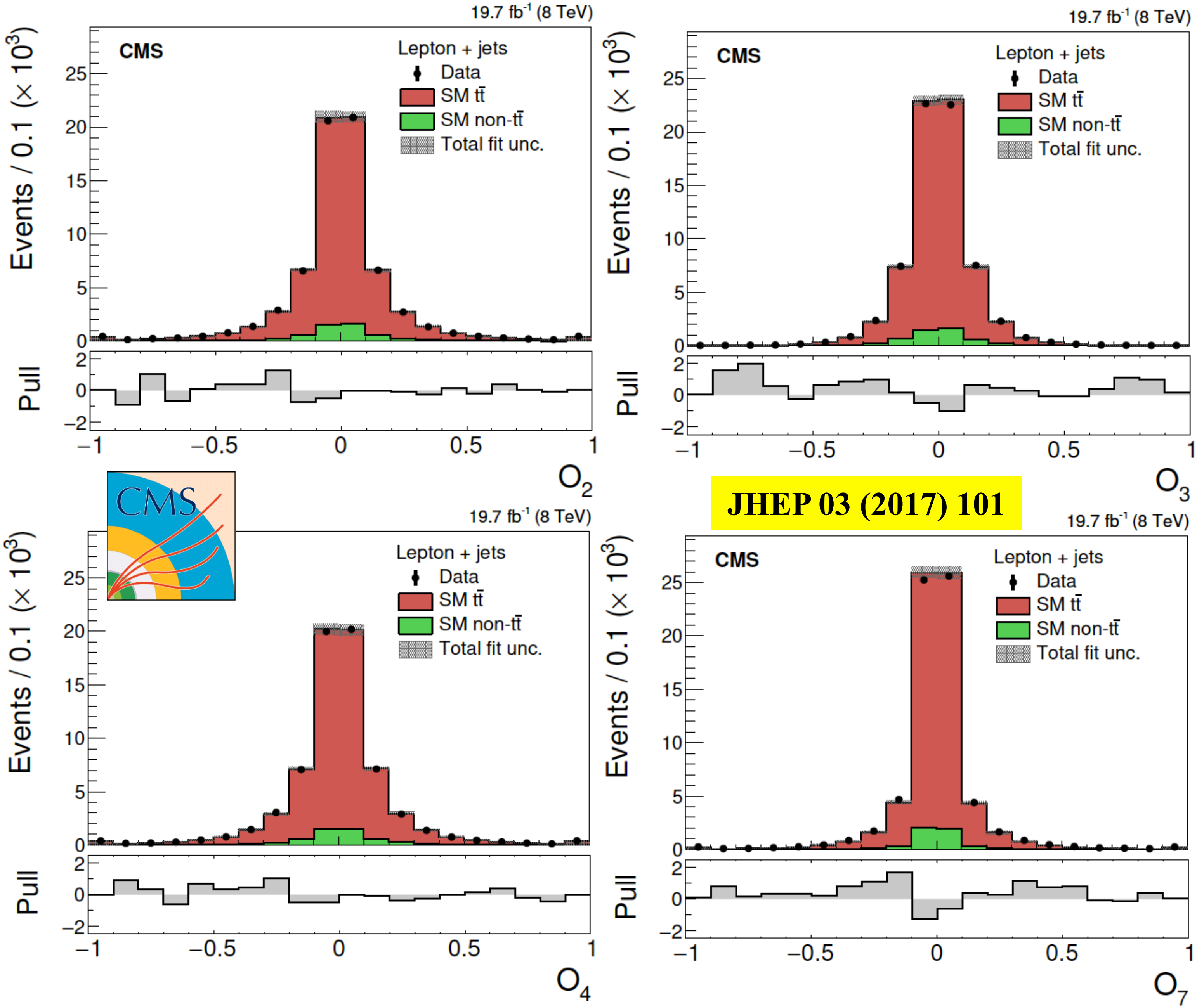
$$O_7 = q \cdot (p_{\mathrm{b}} - p_{\bar{\mathrm{b}}})\, \epsilon(P, q, p_{\mathrm{b}}, p_{\bar{\mathrm{b}}}) \xrightarrow{\text{lab}} \propto (\vec{p}_{\mathrm{b}} - \vec{p}_{\bar{\mathrm{b}}})_z (\vec{p}_{\mathrm{b}} \times \vec{p}_{\bar{\mathrm{b}}})_z$$

  - $A_{\mathrm{CP}}$ could range from 0.4% in $O_{2,7}$ to 8.0% in $O_{3,4}$

**JHEP 03 (2017) 101**

**Hayreter and Valencia PRD 93 (2016) 014020**

# CP violation via triple-product asymmetry




JHEP 03 (2017) 101

$A'_{\mathrm{CP}}$ (%)

| | $\ell$ + jets |
|---|---|
| $O_2$ | $+0.16 \pm 0.42 \pm 0.44$ |
| $O_3$ | $-0.31 \pm 0.42 \pm 0.44$ |
| $O_4$ | $-0.13 \pm 0.42 \pm 0.44$ |
| $O_7$ | $+0.06 \pm 0.42 \pm 0.44$ |

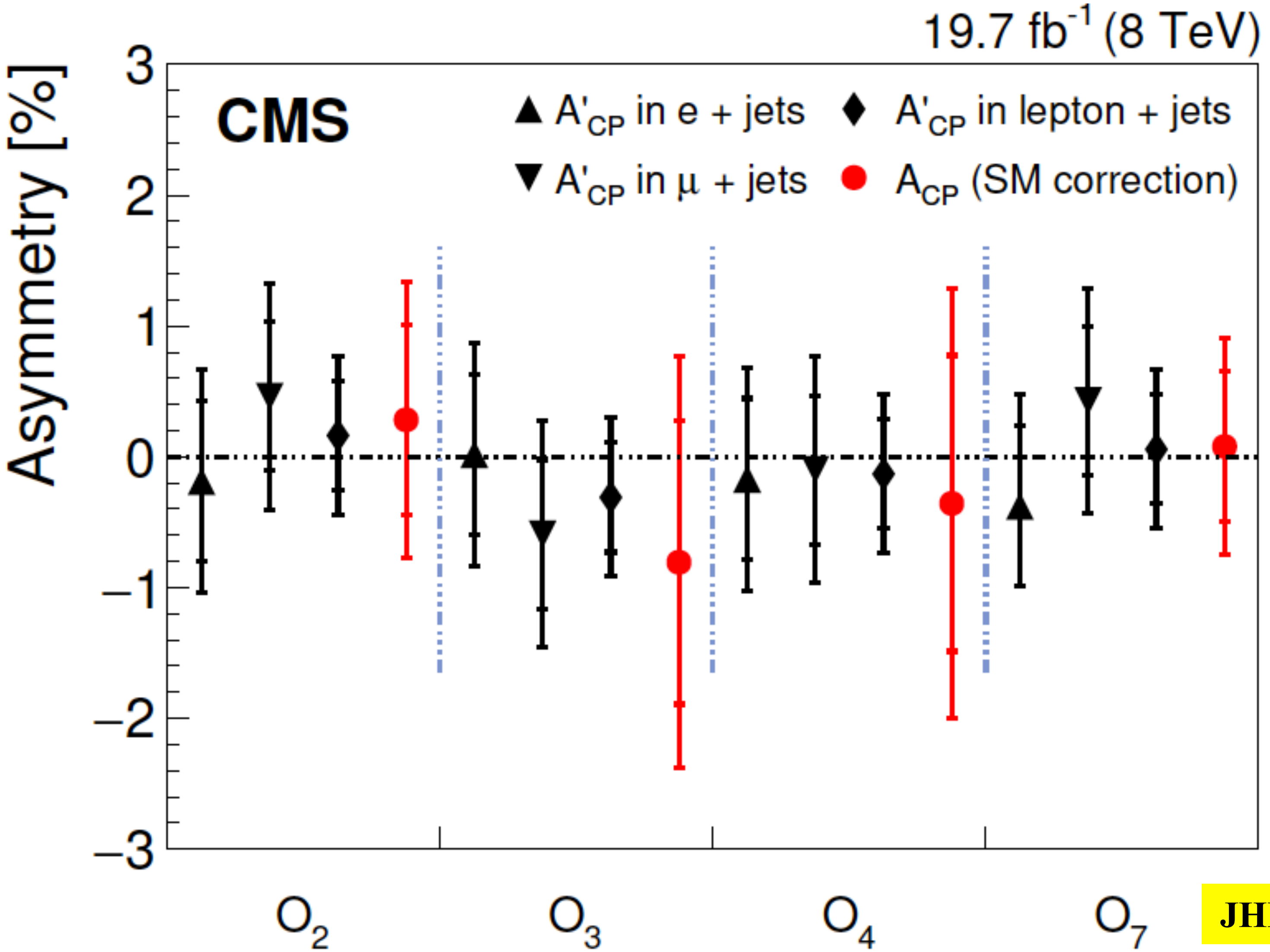
- Intrinsic detector bias is the largest systematic source

$A_{\mathrm{CP}}$ (%)

| | $\ell$ + jets |
|---|---|
| $O_2$ | $+0.3 \pm 1.1$ |
| $O_3$ | $-0.8 \pm 1.6$ |
| $O_4$ | $-0.4 \pm 1.7$ |
| $O_7$ | $+0.1 \pm 0.8$ |

- Each of the above observables is given in units of $(m_t)^3$

# CP violation via triple-product asymmetry



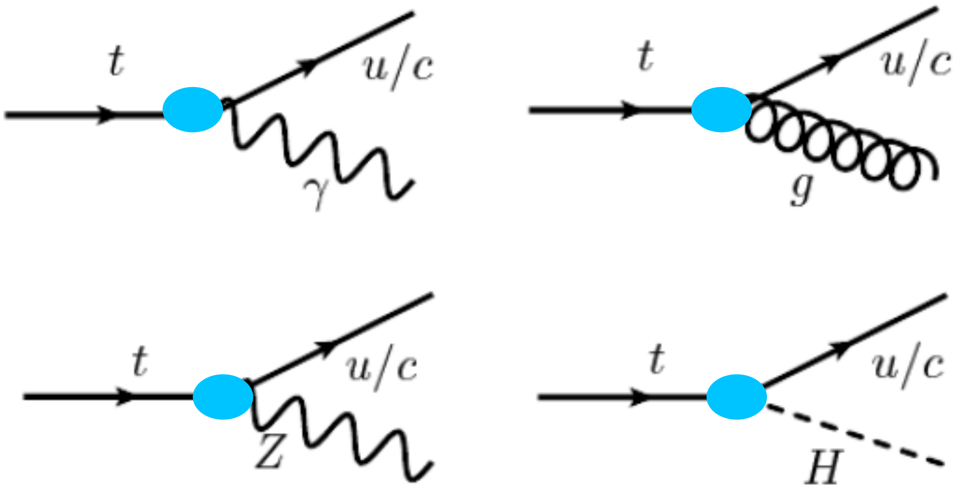

JHEP 03 (2017) 101

- Both uncorrected and corrected asymmetries are consistent with zero
- Good agreement with the SM prediction

# FCNC in top: what & why?

- Flavour Changing Neutral Current (FCNC) changes the flavour of a fermionic current without altering its electric charge
- Such processes are forbidden at tree level in the SM, but could occur at higher orders via loop-induced diagrams

- In the top quark sector, these can occur in a number of ways:




| Process | Branching ratio |
|---|---|
| $t \to u + \gamma$ | $4 \times 10^{-16}$ |
| $t \to c + \gamma$ | $5 \times 10^{-14}$ |
| $t \to u + Z$ | $7 \times 10^{-17}$ |
| $t \to c + Z$ | $1 \times 10^{-14}$ |
| $t \to u + g$ | $4 \times 10^{-14}$ |
| $t \to c + g$ | $5 \times 10^{-12}$ |
| $t \to u + H$ | $2 \times 10^{-17}$ |
| $t \to c + H$ | $3 \times 10^{-15}$ |

➢ This guarantees any measurable branching ratio for a top FCNC process is NP

# FCNC in top: how large NP could be?

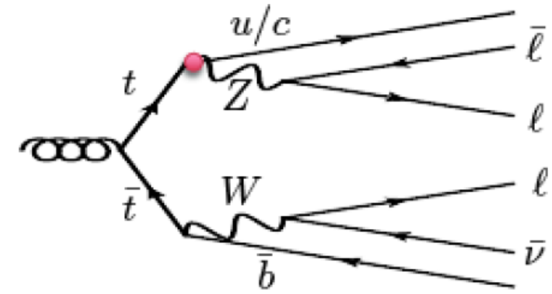
- Many NP models predict top FCNC contributions that are several orders of magnitude above SM expectations
- For example, see where a large branching ratio is expected from NP

**Aguilar-Saaverda, ACTA Phys. Pol. B 35 (2004) 2695**

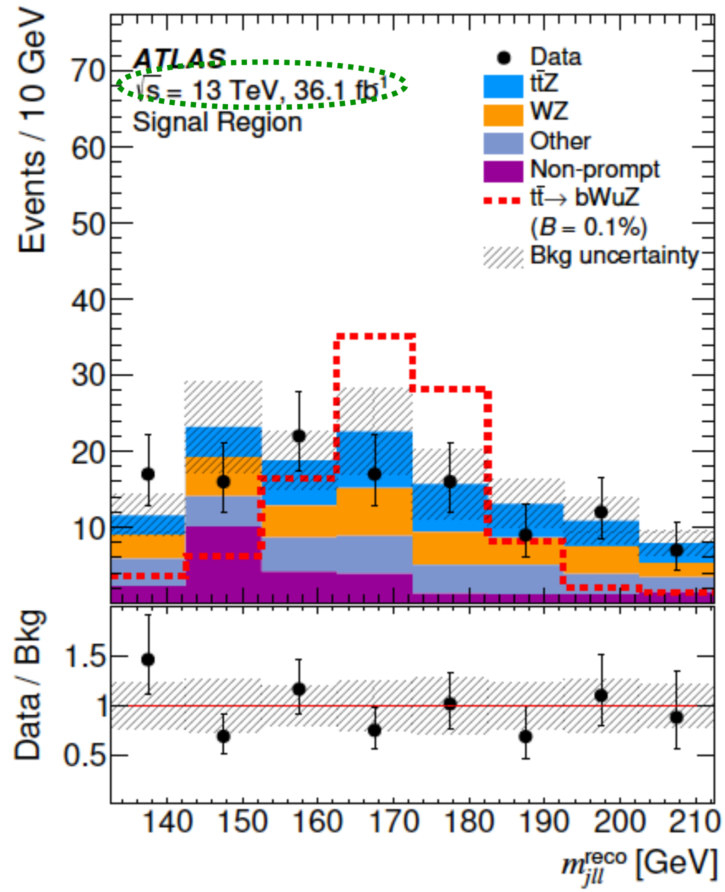
| Process | SM | 2HDM(FV) | 2HDM(FC) | MSSM | RPV | RS |
|---|---|---|---|---|---|---|
| $t \to u + \gamma$ | $4 \times 10^{-16}$ | - | - | $\leq 10^{-8}$ | $\leq 10^{-9}$ | - |
| $t \to c + \gamma$ | $5 \times 10^{-14}$ | $\leq 10^{-7}$ | $\leq 10^{-9}$ | $\leq 10^{-8}$ | $\leq 10^{-9}$ | $\leq 10^{-9}$ |
| $t \to u + Z$ | $7 \times 10^{-17}$ | - | - | $\leq 10^{-7}$ | $\leq 10^{-6}$ | - |
| $t \to c + Z$ | $1 \times 10^{-14}$ | $\leq 10^{-6}$ | $\leq 10^{-10}$ | $\leq 10^{-7}$ | $\leq 10^{-6}$ | $\leq 10^{-5}$ |
| $t \to u + g$ | $4 \times 10^{-14}$ | - | - | $\leq 10^{-7}$ | $\leq 10^{-6}$ | - |
| $t \to c + g$ | $5 \times 10^{-12}$ | $\leq 10^{-4}$ | $\leq 10^{-8}$ | $\leq 10^{-7}$ | $\leq 10^{-6}$ | $\leq 10^{-10}$ |
| $t \to u + H$ | $2 \times 10^{-17}$ | $6 \times 10^{-6}$ | - | $\leq 10^{-5}$ | $\leq 10^{-9}$ | - |
| $t \to c + H$ | $3 \times 10^{-15}$ | $2 \times 10^{-3}$ | $\leq 10^{-5}$ | $\leq 10^{-5}$ | $\leq 10^{-9}$ | $\leq 10^{-4}$ |

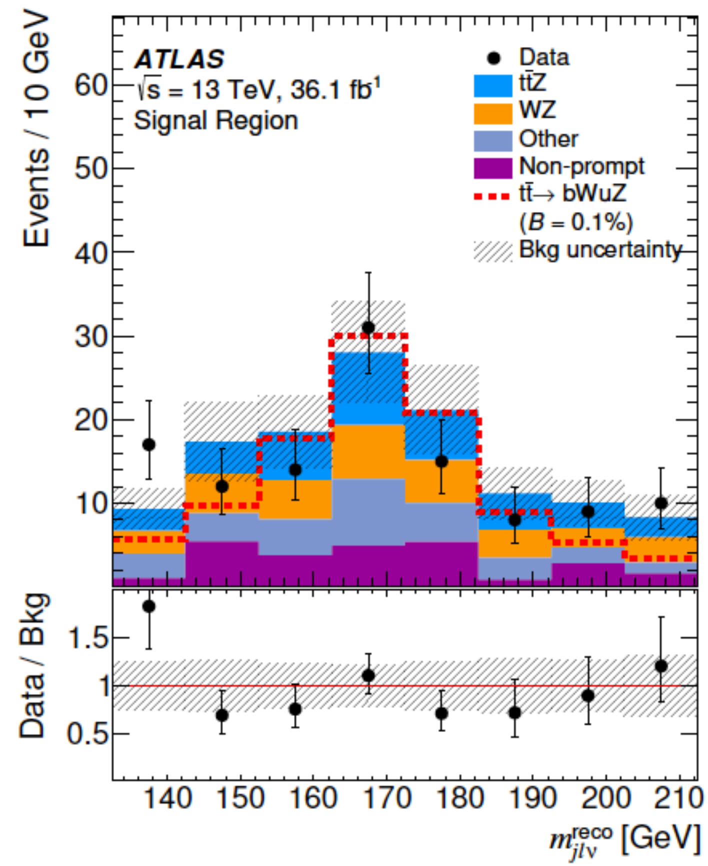
# FCNC in top: t→qZ (q = u, c)

- Final state: three isolated charged leptons, at least two jets of which one is b-tagged, and missing transverse energy (MET) due to the undetected neutrino
- Background: dominantly tt̄Z and WZ; all estimated in dedicated control regions




**JHEP 07 (2018) 176**

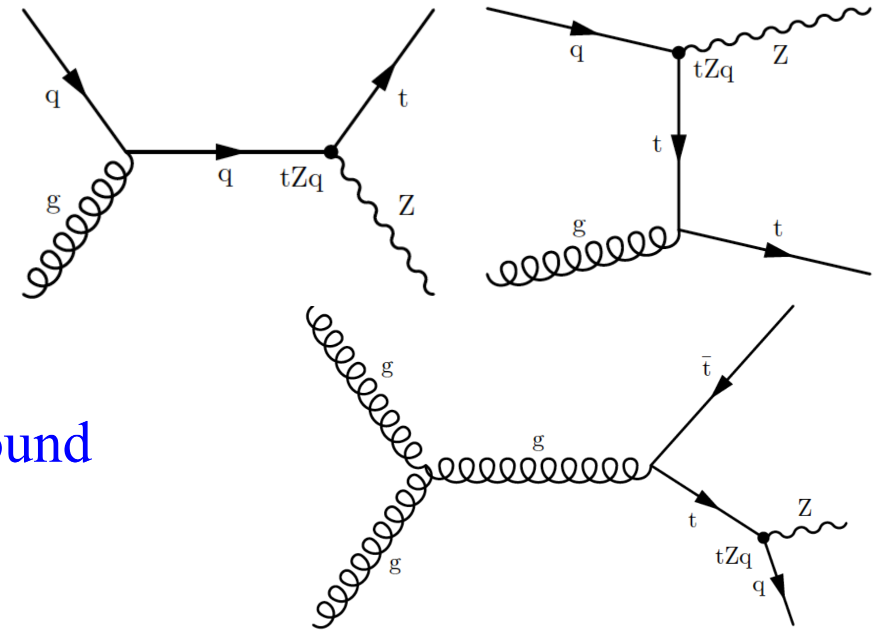


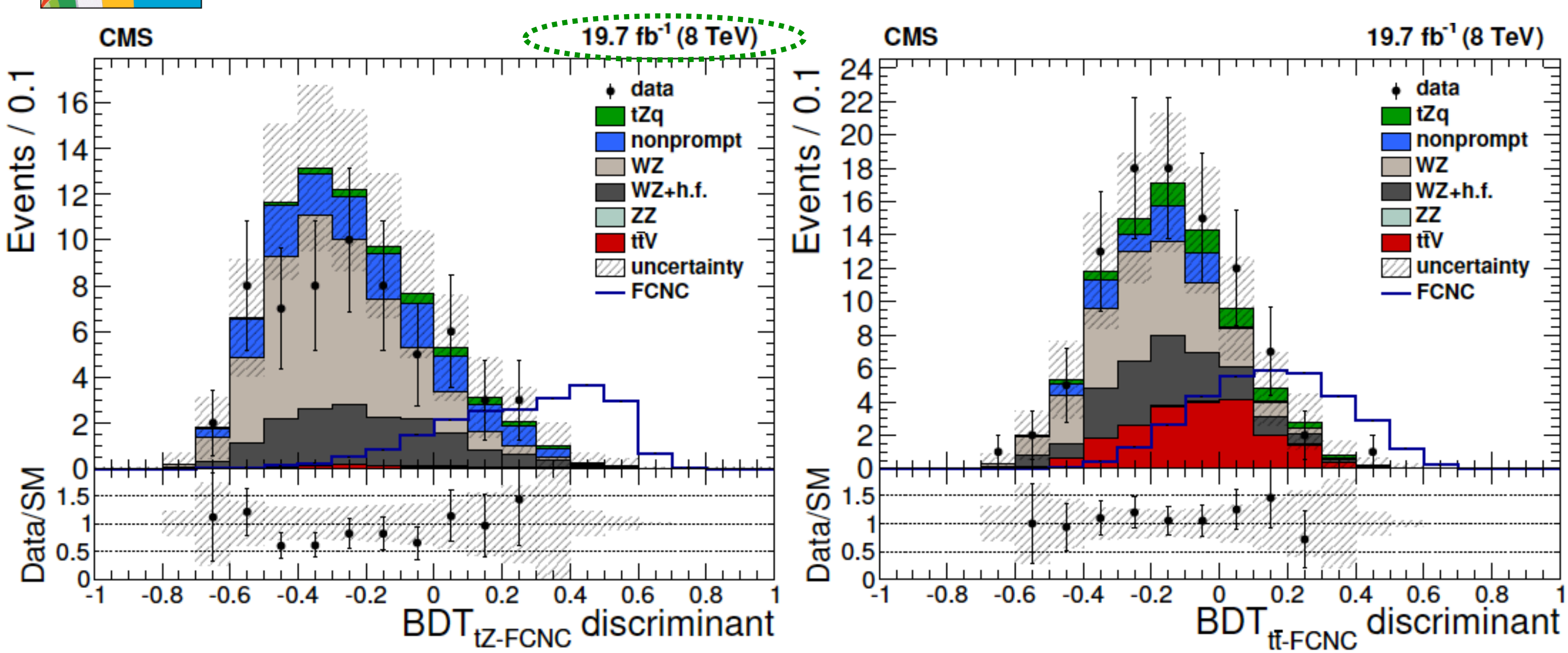

- Data consistent with the SM background expectations
- 95% CL upper limit on BR of t→qZ: 1.7 (2.4)×10$^{-4}$ for q = u (c)

# FCNC production of tZq (q = u, c)

- Search performed combining single top and top pair production channels
- Final state comprises three leptons (muons and/or electrons), a b-jet and MET; an extra jet needed in the top pair channel
- SM tZq process is the key irreducible background



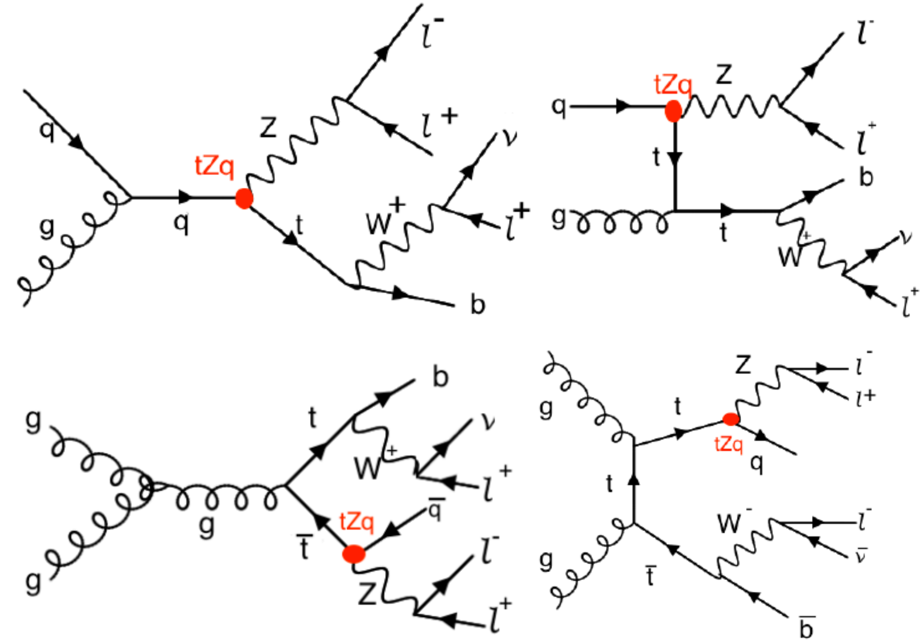

**JHEP 07 (2017) 003**

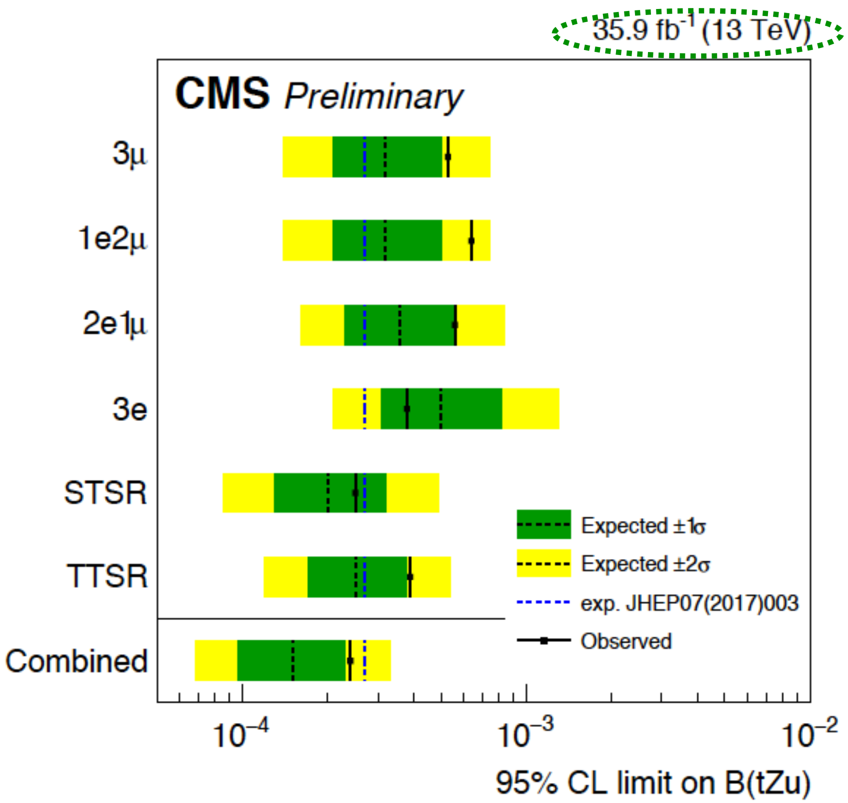


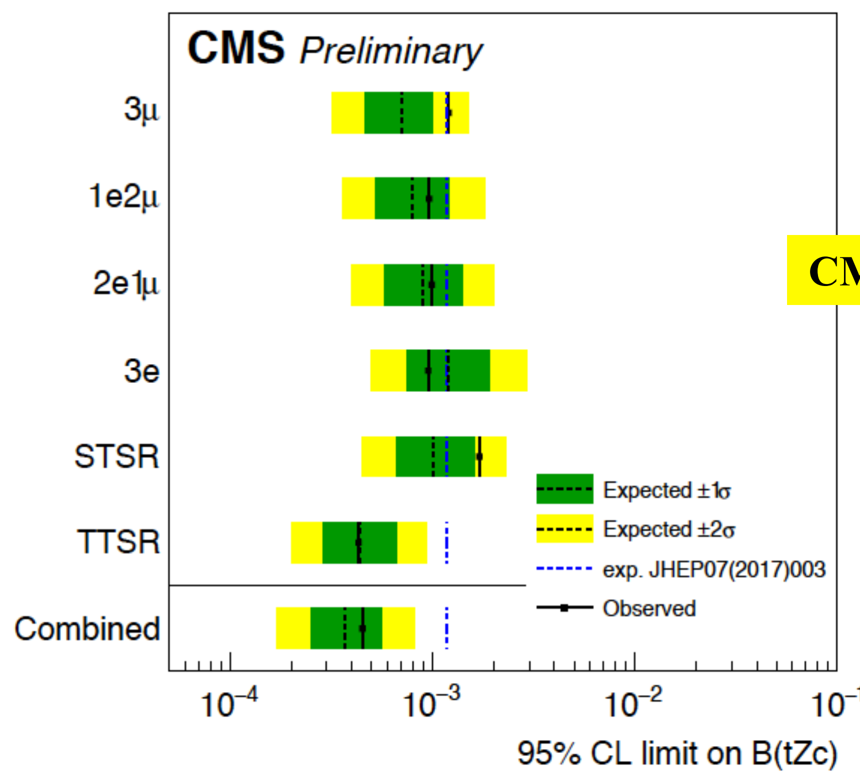

- No evidence for FCNC tZq production is found
- Set 95% CL limits: $B(t \rightarrow Zu) < 0.022\%$ and $B(t \rightarrow Zc) < 0.049\%$

# FCNC production of tZq (q = u, c)

- ❑ Search focuses on single top and top pair events in the three lepton final state
- ❑ Must contain two opposite sign leptons of same flavour, between one to three jets and MET
- ➢ Limit for $B(t \rightarrow Zu)$ is compatible with the 8-TeV result, while the $B(t \rightarrow Zc)$ limit is improved w.r.t. latter



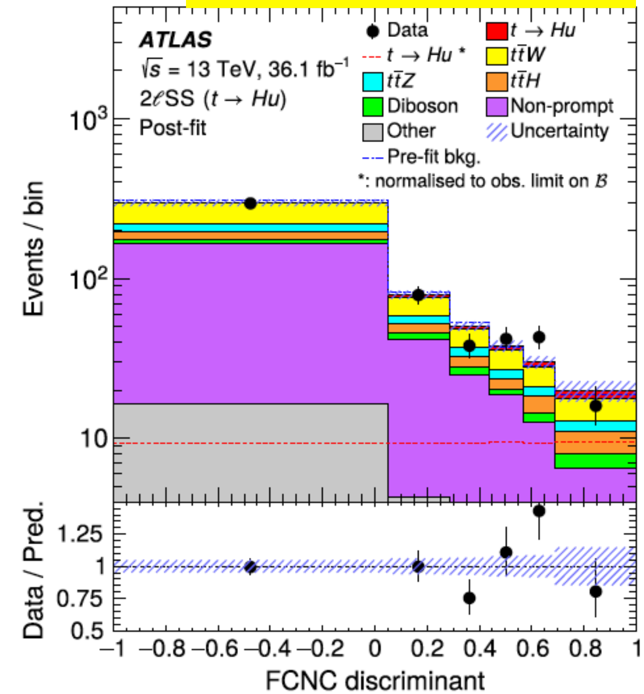




CMS PAS TOP-17-017

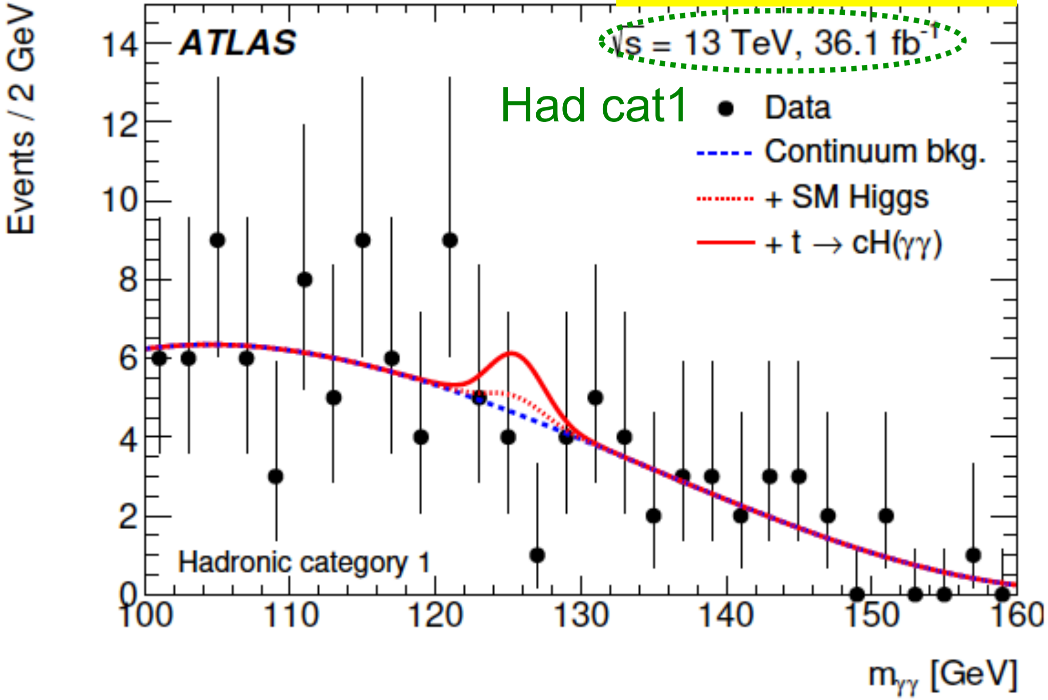
# FCNC in top: t→Hq (q = u, c)

- Use $t\bar{t}$ events with one top decaying to Hq (q = u, c) and the Higgs to WW*, ZZ* or ττ (leptonic) ➔ final state comprises llb3q2ν or lllbq3ν
- BDT based analysis to separate t→Hc and t→Hu signal from SM backgrounds
- ➢ In absence of any signal, 95% CL limits are set on $B$(t→Hc) < 0.16% and $B$(t→Hu) < 0.19%

**PRD 98 (2018) 032002**




**JHEP 10 (2017) 129**

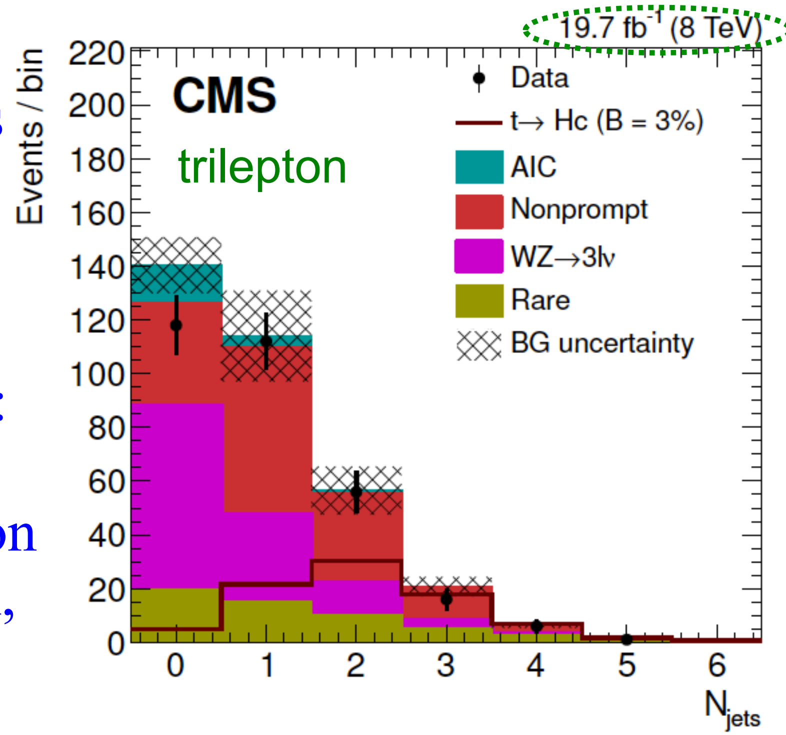



- One top with hadronic or leptonic W decay; in other top (→Hq) the Higgs boson decays into two photons
- Two event categories: cat1 has both t and $\bar{t}$ lying in the $m_t$ window, whereas cat2 has the Hq system satisfying it

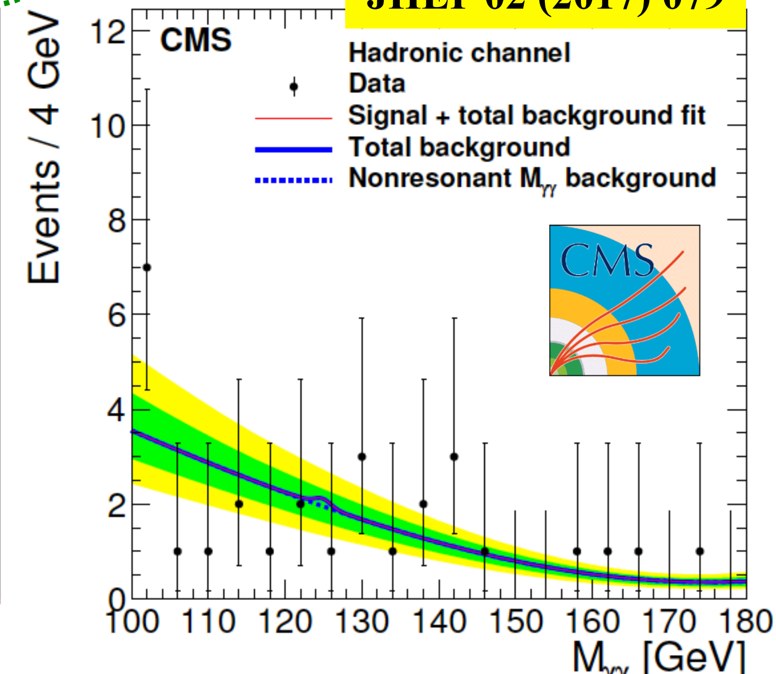
➢ No evidence for a signal; 95% CL limits are set on $B$(t→Hc) < 0.22% and $B$(t→Hu) < 0.24%

# FCNC in top: $t \to Hq$ (q = u, c)

- $t\bar{t}$ events are used, where the Higgs is assumed to decay into dibosons or difermions ($b/\tau$)
- 6 event categories: trilepton, dilepton same sign, diphoton + hadron or lepton, and b-jet + lepton

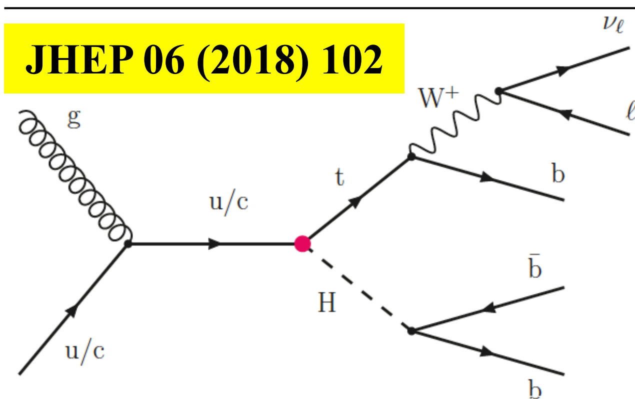


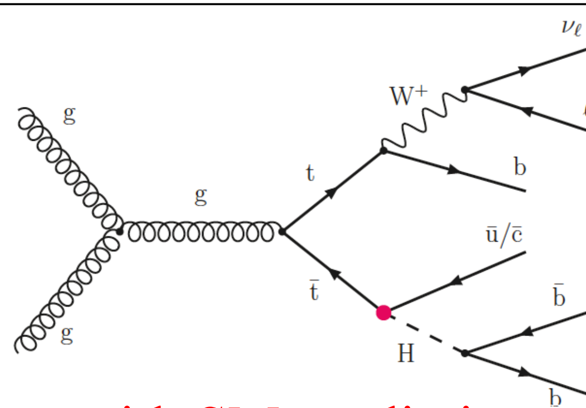

JHEP 02 (2017) 079

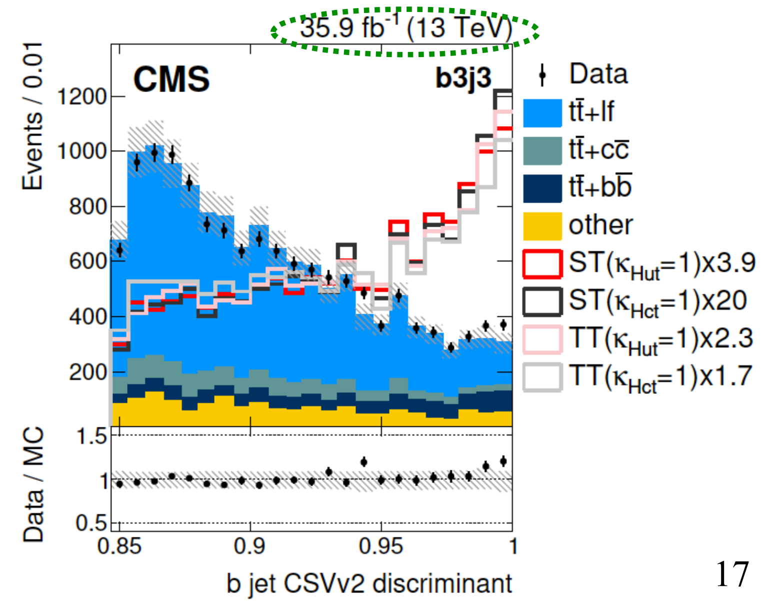



➢ No significant excess above background in any of these channels; 95% CL limits on $B(t \to Hc) < 0.40\%$ and $B(t \to Hu) < 0.55\%$

JHEP 06 (2018) 102

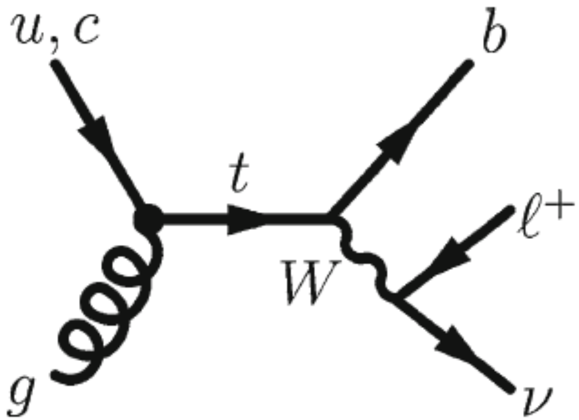


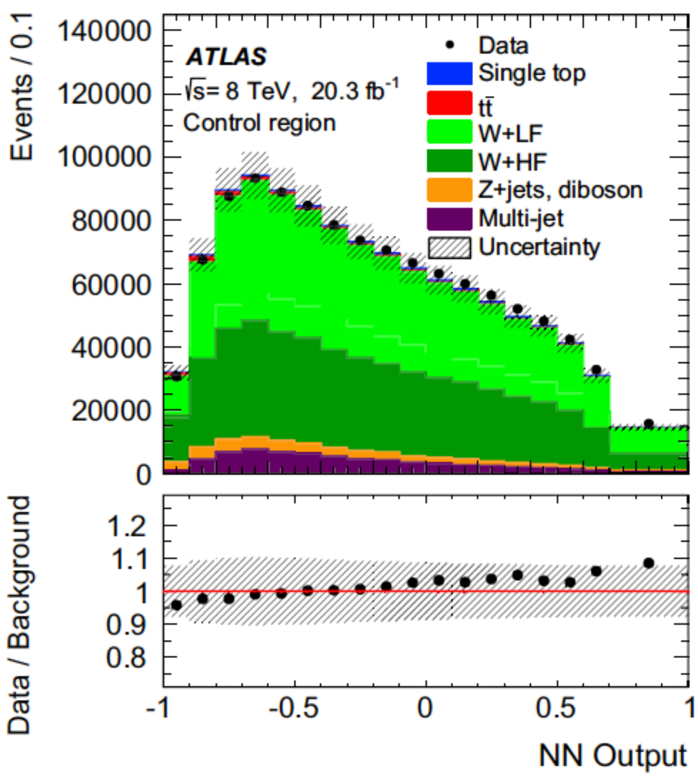

➢ With data being consistent with SM prediction, 95% CL limits set on $B(t \to Hc/u) < 0.47\%$

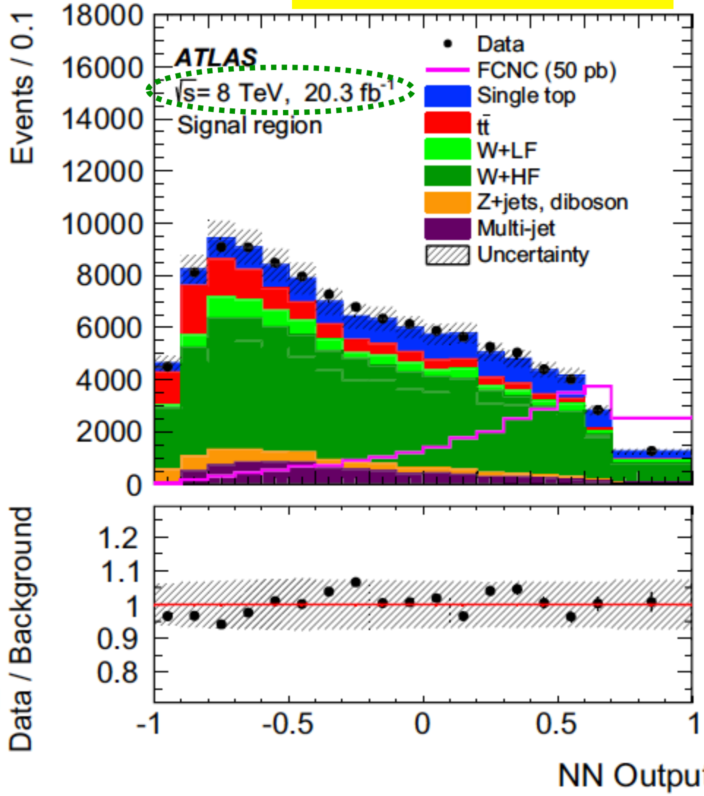
# Single top via FCNC qgt process (q = u, c)



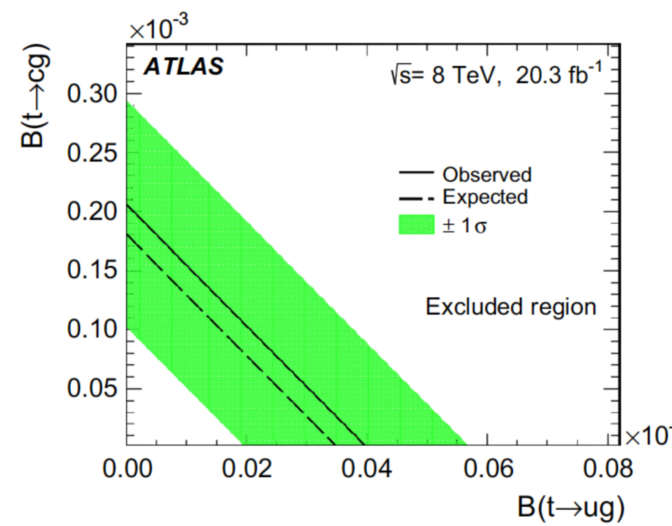

- Final state comprises an isolated charged lepton (muon or electron), a b-jet and MET
- The process of interest can be distinguished from SM single top production owing to the absence of any accompanying additional jets
- Events are classified as signal or SM backgrounds with a neural network that relies mostly on kinematics

**EPJ C76 (2016) 55**

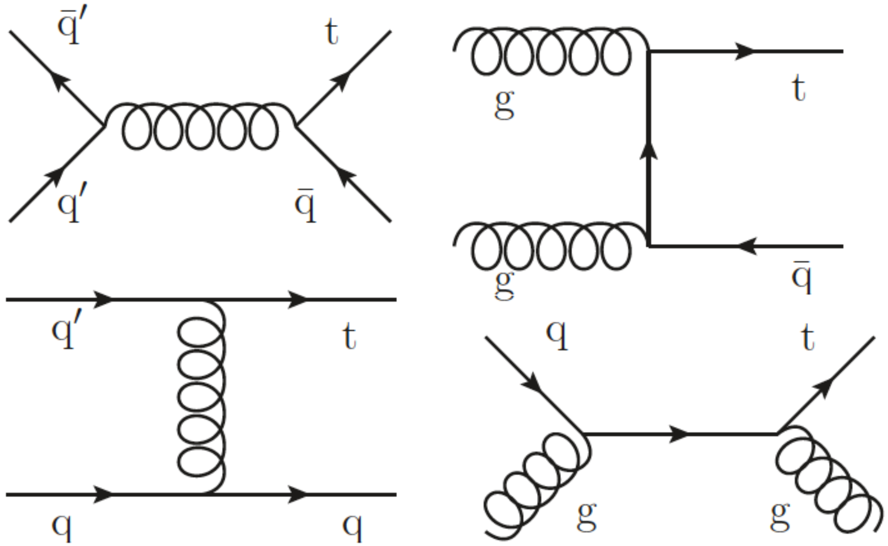



- Without any signal, 95% CL limit on production x-section (subsequently on BR) is set



# FCNC in top: t→qg (q = u, c)




- Single top quark events in the *t* channel are used in this search
- Final state comprises 1 muon and 2-3 jets, while a Bayesian neural network (BNN) is used to identify signal from backgrounds

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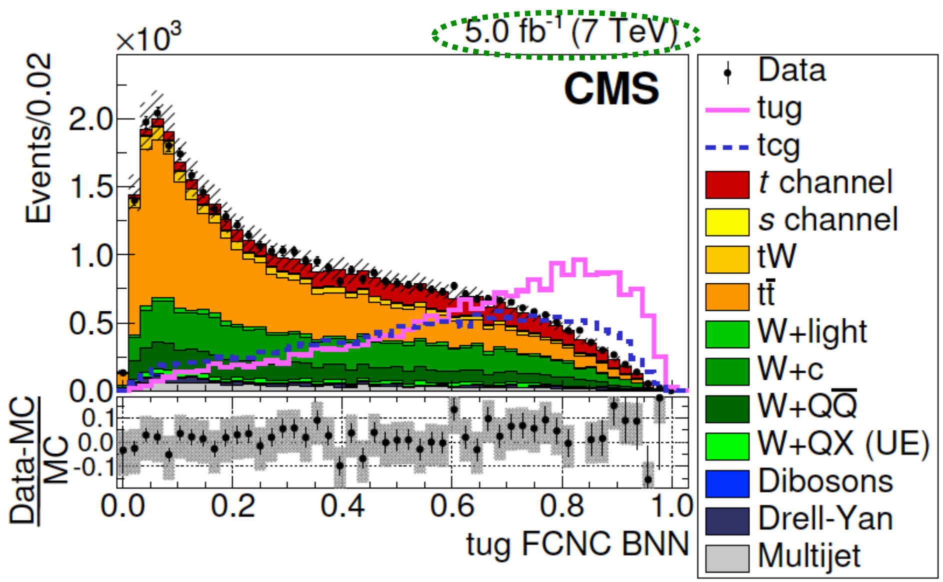
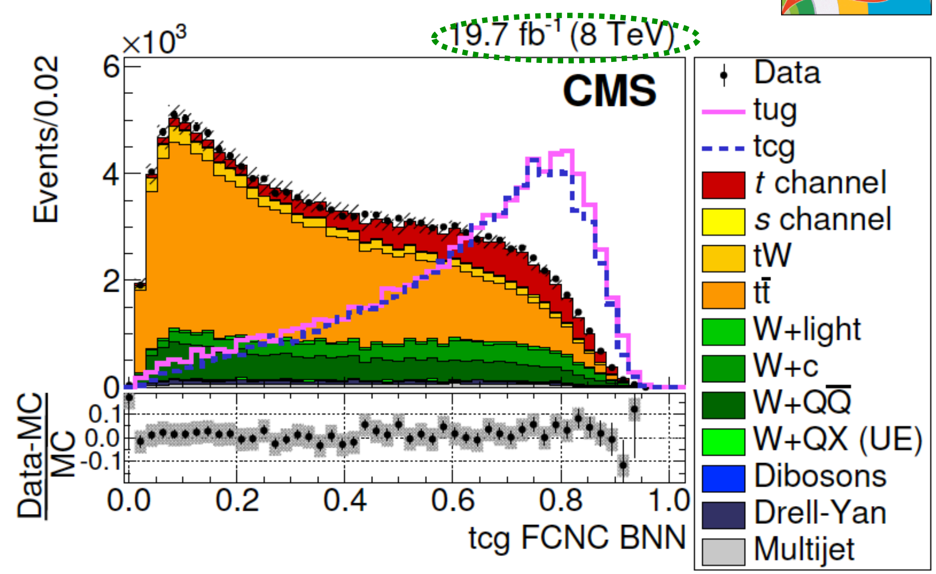
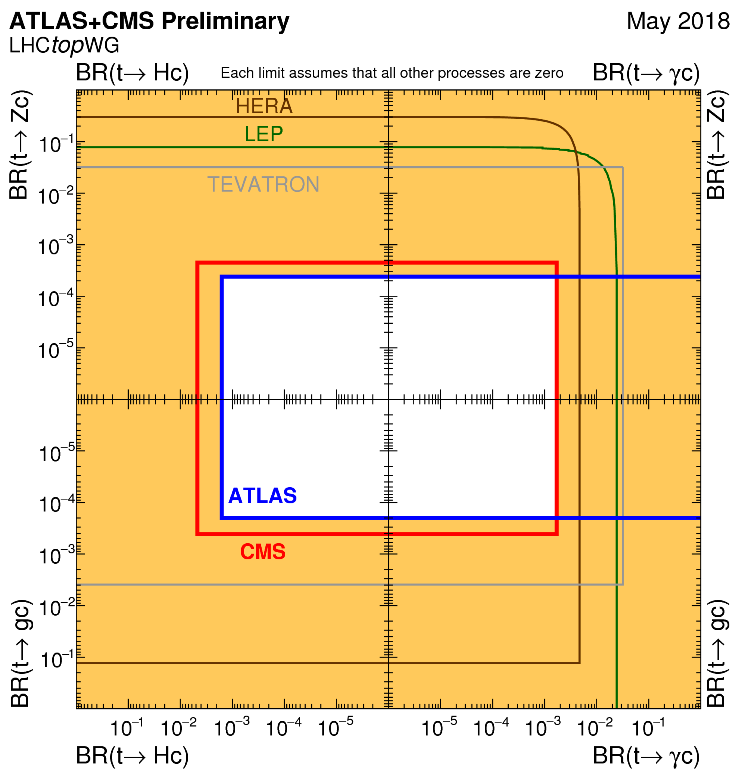


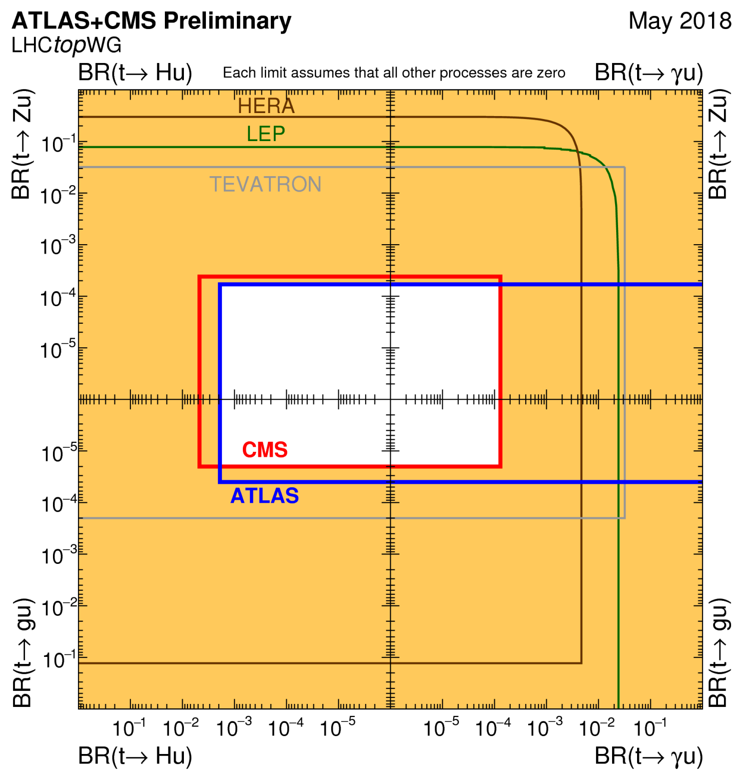




- Set 95% CL upper limits on FCNC coupling strength $|\kappa_{tug}|/\Lambda < 4.1\times10^{-3}$ TeV$^{-1}$ and $|\kappa_{tcg}|/\Lambda < 1.8\times10^{-2}$ TeV$^{-1}$, where $\Lambda$ is the NP scale
- These can be translated to $B(t\rightarrow ug) < 2.0\times10^{-5}$ and $B(t\rightarrow cg) < 4.1\times10^{-4}$

# Summary

- Presented results on two exciting sectors (CP violation and FCNC) related to the single top and top quark pair production at the LHC
  - Though the first isn't as much explored as the kaon or B-meson system, it has a great future ahead, thanks to the "top factory" *aka* LHC
  - The second is the sole preserve of the LHC at the moment




- Though there is no evidence for new physics, we must continue to explore till the "nature gives in"