Rare processes with top quarks: FCNCs, $t\bar{t}$+X, t+X, $tttt$

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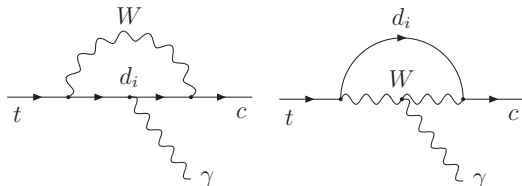
on behalf of the ATLAS and CMS Collaborations

SM@LHC2018, Berlin

Top FCNC Introduction

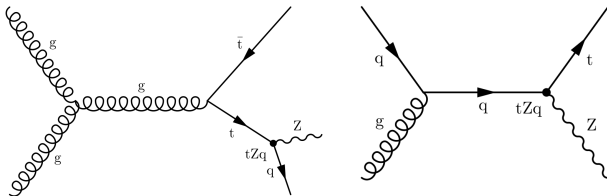**SM FCNC diagrams**

- tree level forbidden
- one-loop suppressed (GIM)

Parametrization as EFT vertices: tqX, $q = u/c$, $X = \gamma/H/g/Z$

- expressed as $t \to qX$ branching ratio BR(tqX): in SM, $10^{-17} \sim 10^{-12}$
- new physics could enhance these vertices $\to$ BR(tqX) up to 10^{-3}

Two modes for searching top FCNC

- $t\bar{t}$ production
- single top (s.t) production


(example feynman diagrams; Z could be other bosons)

tqH ATLAS 13TeV

In $t\bar{t}$ mode with one $t \to Wb$ and the other $t \to qH \to q\gamma\gamma$

- two photons, $m_{\gamma\gamma} \in [100, 160]$GeV

- 0 lepton $\to$ hadronic channel ($W \to qq'$)

- 1 lepton $\to$ leptonic channel ($W \to \ell\nu$)

- mass of FCNC top $\in [152, 190]$GeV

- mass of the other top used for splitting each channel to 2 categories

- bkg: SM Higgs, continuum $\gamma\gamma$, $t\bar{t}\gamma\gamma$
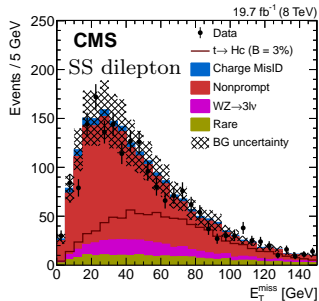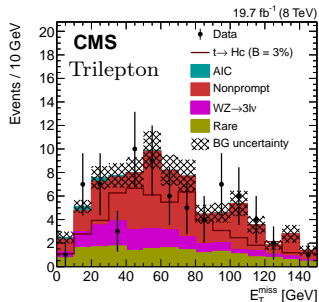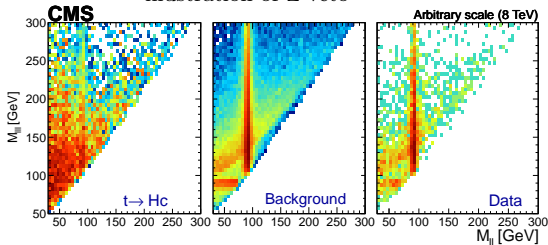
Fit $m_{\gamma\gamma}$ to extract signal

- hadronic channel: MC-based Higgs template and 3rd poly. bkg template

- leptonic channel: event counting

- sys: signal modelling/cross-section

- BR(tuH/tcH) $< 0.24/0.22 \times 10^{-2}$

tqH CMS 8TeV
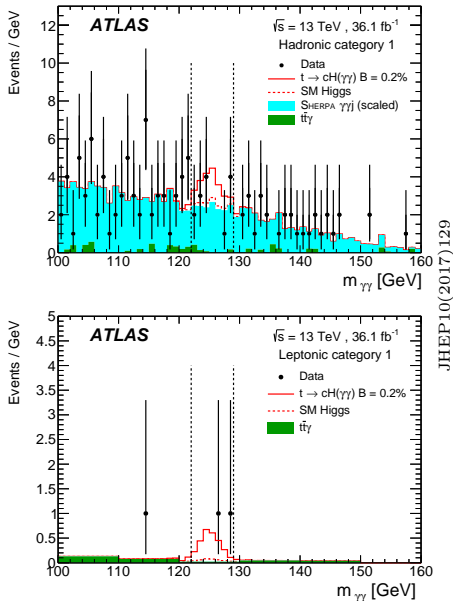
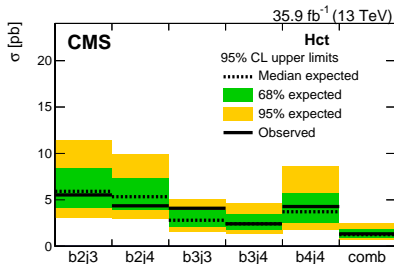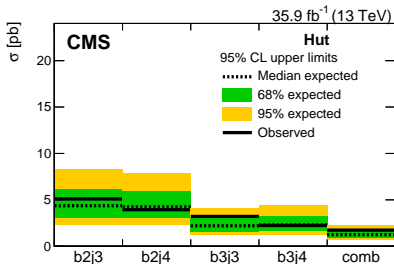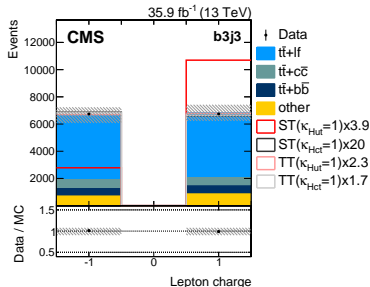**8TeV:** $t\bar{t}$ **mode with one** $t \to \ell\nu b$ **and the other** $t \to qH$

- $H \to \gamma\gamma$: similar as ATLAS

- $H \to b\bar{b}$: upgraded in 13TeV (next slide)

- $H \to WW/ZZ/\tau\tau$: trilepton channel or same sign (SS) dilepton channel
  bkg: non-prompt ℓ, WZ
  sys: non-prompt ℓ normalization

- BR(tuH/tcH) $< 0.55/0.40 \times 10^{-2}$

illustration of Z-veto

JHEP02(2017)079

tqH CMS 13TeV

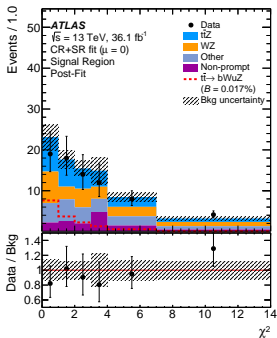**13TeV: $t\bar{t}$ and s.t. modes, $H \to b\bar{b}$**

- first s.t. mode of tqH FCNC search
- 1 lepton, n(j) $\geq$ 3, n(bj) $\geq$ 2
- used BDT to extract signal: e.g. ℓ charge
- 5 categories according to n(j) and n(bj)
- sys: b-tagging, JES, JER
- BR(tuH/tcH) < 0.47/0.47×10^{-2}


arXiv:1712.02399

tqZ ATLAS 13TeV & CMS 8/13TeV

ATLAS: $t\bar{t}$ mode with $t \to \ell\nu b$ and the other $t \to qZ \to q\ell\ell$

- 3 leptons, opposite sign same flavor (OSSF) ℓ pair from Z decay
- bkg: $t\bar{t}Z$, WZ, non-prompt ℓ, tZ
- sys: signal/bkg event modelling
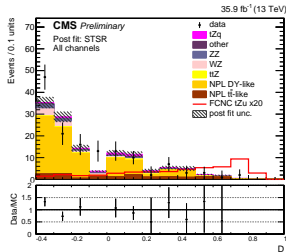- BR(tuZ/tcZ) $< 0.17/0.23 \times 10^{-3}$

CMS: both $t\bar{t}$ **and s.t. modes**

- used BDT to extract signal
- similar selection/bkg as ATLAS
- more non-prompt bkg in 13TeV
- sys: bkg normalization
- 8TeV: BR(tuZ/tcZ) $< 0.22/0.49 \times 10^{-3}$
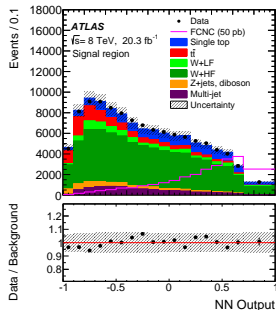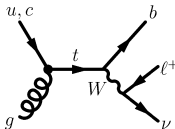- 13TeV: BR(tuZ/tcZ) $< 0.24/0.45 \times 10^{-3}$

ATLAS-CONF-2017-070
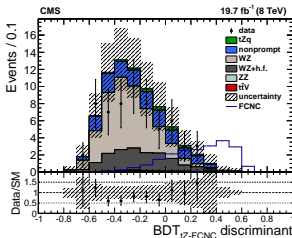
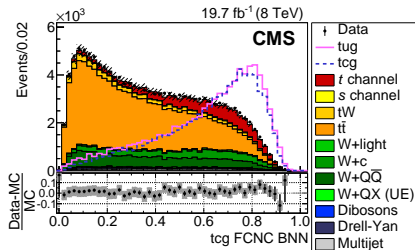JHEP07(2017)003

CMS-PAS TOP-17-017

tqg ATLAS 8TeV & CMS 7/8TeV

ATLAS: "direct" s.t. with $t \to Wb \to \ell\nu b$

- 1 lepton, n(j) = n(bj) = 1, E_T^{miss}
- tight b-tagging WP (50%)
- bkg: $W+$jets, s.t., $t\bar{t}$, non-prompt ℓ
- sys: JER, E_T^{miss}, non-prompt ℓ
- BR(tug/tcg) $< 0.40/2.0 \times 10^{-4}$

**CMS: s.t. t-channel with $t \to \mu\nu b$**

- a forward light-jet
- 1 lepton, n(j) = 2/3, n(bj) $\geq$ 1, n(lj) $\geq$1
- bkg: $t\bar{t}$, s.t., $W+$jets
- sys: NN shape
- BR(tug/tcg) $< 0.20/4.1 \times 10^{-4}$

$tq\gamma$ CMS 8TeV

In s.t. mode with $t \to \mu\nu b$ and one recoil photon

- 1 high p_T photon, 1 muon, E_T^{miss}, n(j) = n(bj) = 1, $\Delta R(\mu/bj, \gamma) > 0.7$, top mass $\in [130,220]$GeV

- bkg: $W\gamma$ and W+jets, estimated via NN templates fit simultaneously

- signal extracted via BDT: e.g. photon pT, lepton charge

- sys: $W\gamma$ and W+jets, pile-up, lepton/photon ID

- BR($tu\gamma/tc\gamma$) < $0.13/1.7 \times 10^{-3}$
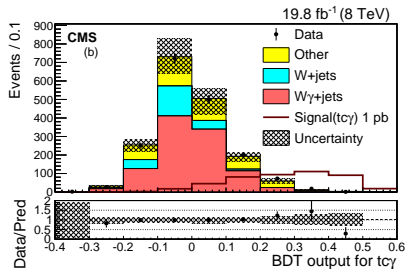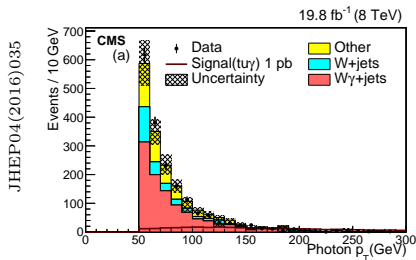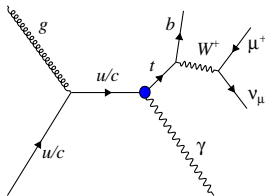
Top FCNC Up-to-date Results
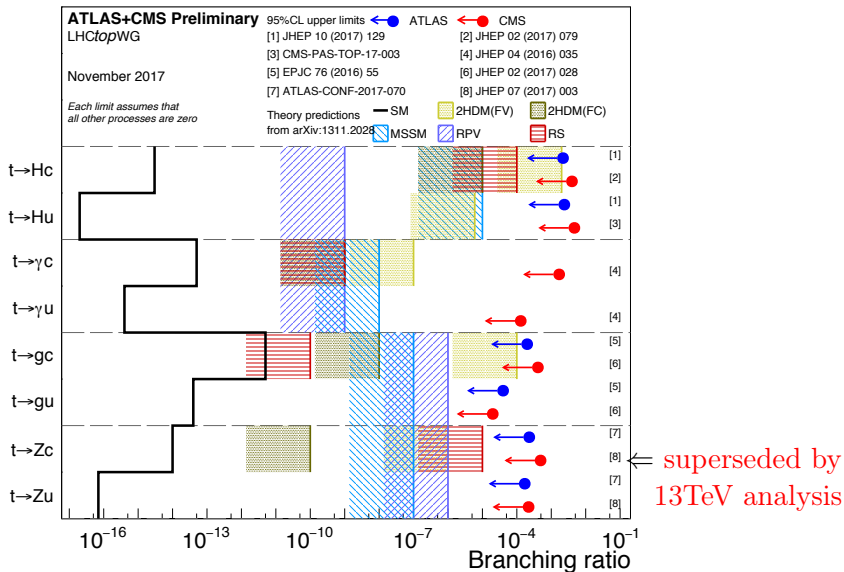
$t\bar{t}Z/W$ ATLAS 13TeV

$t\bar{t}Z$ probes top-Z coupling; $t\bar{t}W$ has BSM sensitivity and is bkg to other analyses

- established at 8TeV by both ATLAS and CMS

- SS dimuon ($t\bar{t}W$), trilepton ($t\bar{t}W$ and $t\bar{t}Z$) and tetralepton ($t\bar{t}Z$) channels

- bkg: WZ and ZZ ($t\bar{t}Z$), non-prompt ℓ ($t\bar{t}W$ and $t\bar{t}Z$)

- sys: non-prompt ℓ ($t\bar{t}W$), lepton ID ($t\bar{t}Z$)

- $\sigma_{t\bar{t}Z} = 0.9 \pm 0.3$ pb, $\sigma_{t\bar{t}W} = 1.5 \pm 0.8$ pb (stat. uncertainty dominates)


EPJC(2017)77:40

$t\bar{t}Z/W$ CMS 13TeV
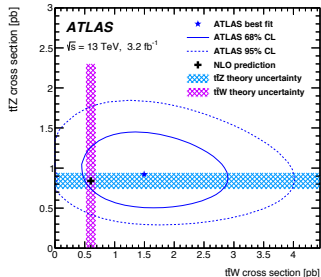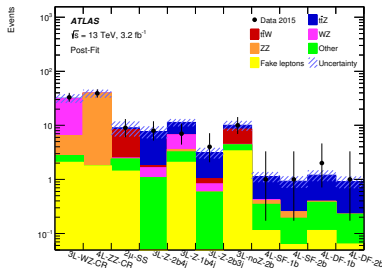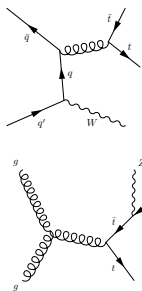
SS dilepton ($t\bar{t}W$)

- BDT used to distinguish signal from bkg
- 20 exclusive regions according to BDT, n(j), n(bj), charge of lepton pair
- bkg: non-prompt ℓ, charge mis-ID
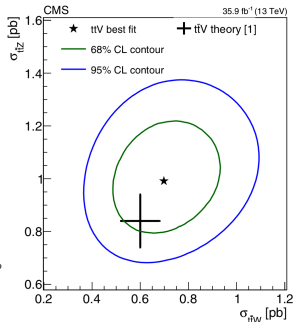- sys: trigger, b-tagging, non-prompt ℓ
- $\sigma_{t\bar{t}Z} = 0.99^{+0.09}_{-0.08}(\text{stat})^{+0.12}_{-0.10}(\text{sys})$ pb, $\sigma_{t\bar{t}W} = 0.77^{+0.12}_{-0.11}(\text{stat})^{+0.13}_{-0.12}(\text{sys})$ pb

Trilepton and tetralepton ($t\bar{t}Z$)

- also in many exclusive regions
- bkg: WZ, ZZ, non-prompt ℓ
- sys: lepton ID, trigger, b-tagging
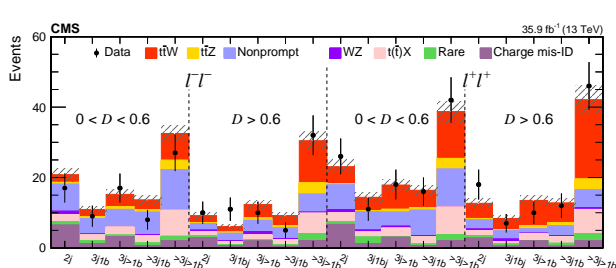
arXiv:1711.02547

$t\bar{t}\gamma$ ATLAS 8TeV & CMS 8TeV

**Probe top-γ coupling** ($t\bar{t} \to \ell +$**jets**)

- $\Delta R(\gamma, \ell/\text{jet})$ cut to suppress radiative decay
- signal extraction: fit photon isolation
- bkg: electronic/hadronic fake photon, $W\gamma$
- Measured vs predicted ATLAS $\sigma_{t\bar{t}\gamma}^{\text{fidu}}$: 137±7(stat)±17(sys) fb vs 151±24 fb
- Measured vs predicted CMS $\sigma_{t\bar{t}\gamma}^{\text{total}}$: 515±108(stat+sys) fb vs 592±77 fb
- $\sigma_{t\bar{t}\gamma}^{\text{fidu}}$ and $\frac{\sigma_{t\bar{t}\gamma}^{\text{fidu}}}{\sigma_{t\bar{t}\text{total}}}$ by CMS and photon pT/η differential $\sigma_{t\bar{t}\gamma}^{\text{fidu}}$ by ATLAS

JHEP11(2017)086

JHEP10(2017)006
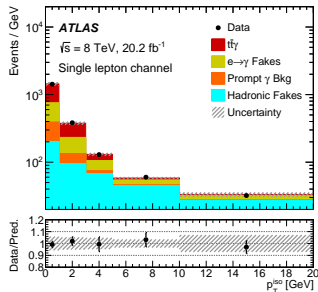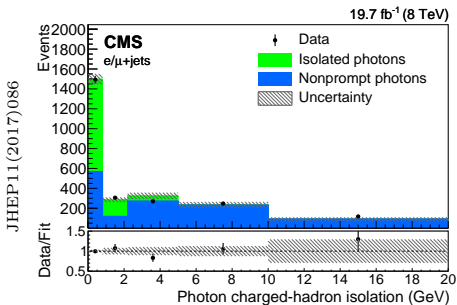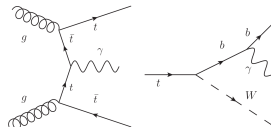
tZ ATLAS 13TeV & CMS 13TeV

Probes top-Z coupling; TGC (WWZ) sensitivity; background to other analyses: e.g. tH and tqZ FCNC

- $t \to Wb \to \ell\nu b$ and $Z \to \ell\ell$

- 3 leptons, OSSF leptons compatible with Z decay, forward light-jet

- bkg/sys: diboson, non-prompt

- ATLAS 4.2σ, CMS 3.7σ
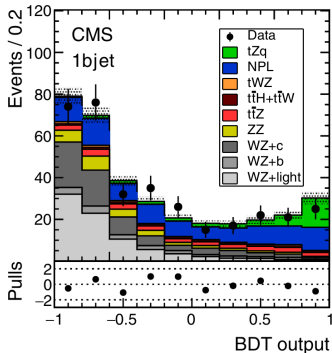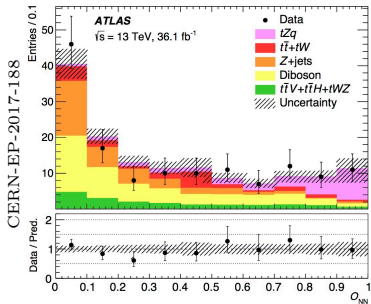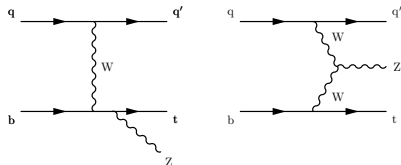
tttt ATLAS 13TeV & CMS 13TeV

Cross-section ∼ 9 fb, sensitive to new physics

- ATLAS $3.2 fb^{-1}$: single $\ell \rightarrow$ cross-section < 190 fb (ATLAS-CONF-2016-020)
  SS dilepton $\rightarrow$ cross-section < 95 fb (ATLAS-CONF-2016-032)

- CMS $2.6 fb^{-1}$: single ℓ and OS di-$\ell \rightarrow$ cross-section < 94 fb (PLB772(2017)336)
  $35.9 fb^{-1}$: SS di-ℓ and ≥3-$\ell \rightarrow$ cross-section < 42 fb (1.6σ) (EPJC(2018)78:140)

- ATLAS interpreted in BSM scenarios e.g. four top contact coupling
  CMS interpreted as constraint on top yukawa coupling

ATLAS-CONF-2016-020

EPJC(2018)78:140
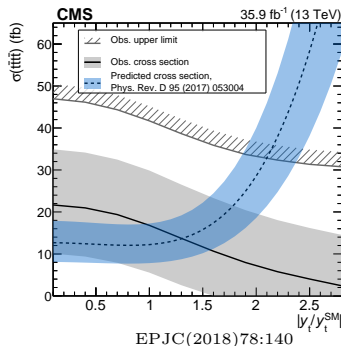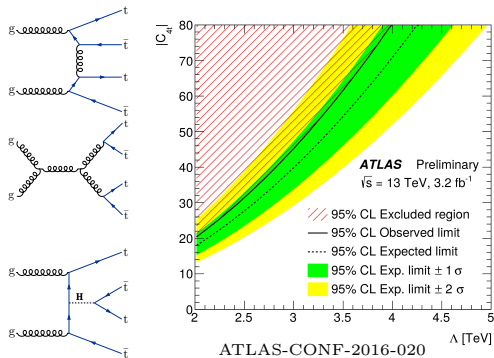
Summary

A selected set of top quark related rare process searches or measurements are presented, with focus on FCNC search

- In general, analyses are performed in many featuring final states, using NN/BDT and performing top reconstruction
- Top FCNC branching ratio limits strongly improved, reaching expected limits for some BSMs (FV 2HDM)
- $t\bar{t}W/Z/\gamma$ established, measured/SM cross-sections agree, not that rare any more
- Evidence of tZ found, yet to be observed
- No evidence of $tttt$ yet

Backup

Top FCNC EFT

$$
\begin{aligned}
-\mathcal{L}^{\text{eff}} &= \frac{g}{2c_W} X_{qt}\, \bar{q}\gamma_\mu(x_{qt}^L P_L + x_{qt}^R P_R)tZ^\mu + \frac{g}{2c_W}\kappa_{qt}\, \bar{q}(\kappa_{qt}^v + \kappa_{qt}^a\gamma_5)\frac{i\sigma_{\mu\nu}q^\nu}{m_t}tZ^\mu \\
&\quad + e\lambda_{qt}\, \bar{q}(\lambda_{qt}^v + \lambda_{qt}^a\gamma_5)\frac{i\sigma_{\mu\nu}q^\nu}{m_t}tA^\mu + g_s\zeta_{qt}\, \bar{q}(\zeta_{tq}^v + \zeta_{qt}^a\gamma_5)\frac{i\sigma_{\mu\nu}q^\nu}{m_t}T^a q G^{a\mu} \\
&\quad + \frac{g}{2\sqrt{2}}g_{qt}\, \bar{q}(g_{qt}^v + g_{qt}^a\gamma_5)tH + \text{H.c.}\,,
\end{aligned}
$$