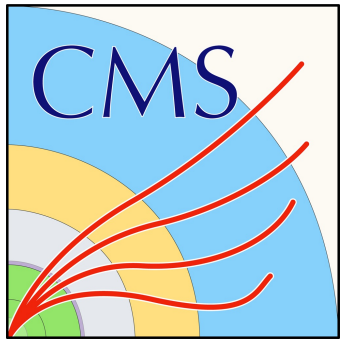
Comparisons of FCNC results from ATLAS and CMS

What did we learn, where can we improve?

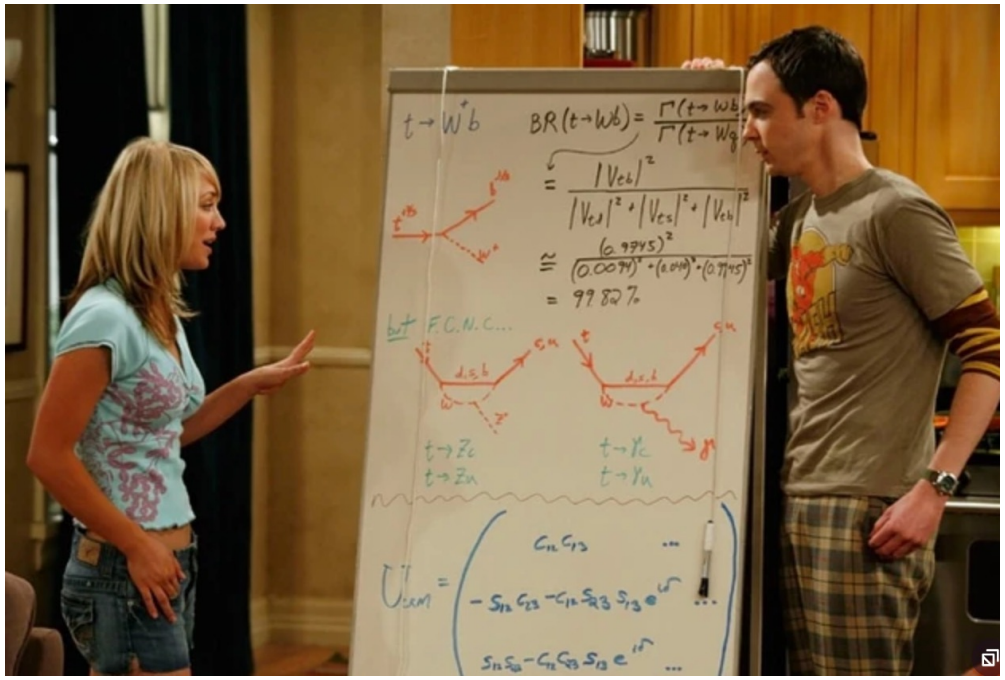
Jeremy Andrea (IPHC-Strasbourg) on behalf of the ATLAS and CMS collaborations



Special thanks to
Gauthier Durieux and
Wolfgang Wagner

Introduction

- Flavour Changing Neutral Currents (FCNC) :
  - Forbidden at tree level,
  - Exist in the SM via loops, but heavily suppressed => GIM mechanism, ($Br(t \to qX) < 10^{-11}$),
  - Can be largely enhanced in the presence of new physics $Br(t \to qX) \approx 10^{-10} - 10^{-3}$.



- Interests in top-FCNC searches, both on the experimental and theory sides, since decades (HERA, LEP2, Tevatron, LHC).

- A lot of progresses at the LHC :
  - High luminosity and $(t\bar{t})$ cross section => large boost of sensitivity,
  - More elaborate data-analysis techniques,
  - Higgs discovery => top-FCNC involving a Higgs boson, large variety of decay channels.

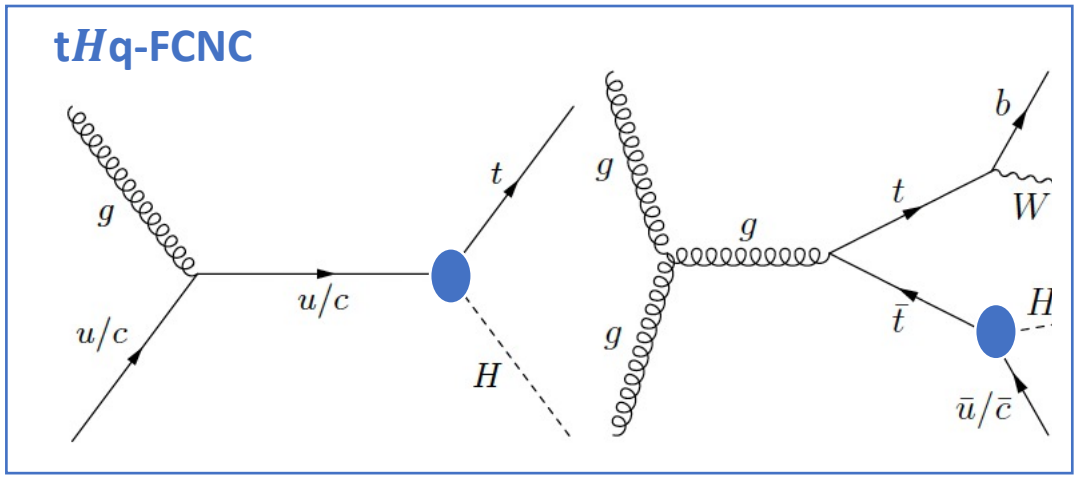
- Outline :
  - Discussions on theoretical framework and interpretations,
  - Overview of top-FCNC analyses, ATLAS-CMS comparisons,
  - Discussions.

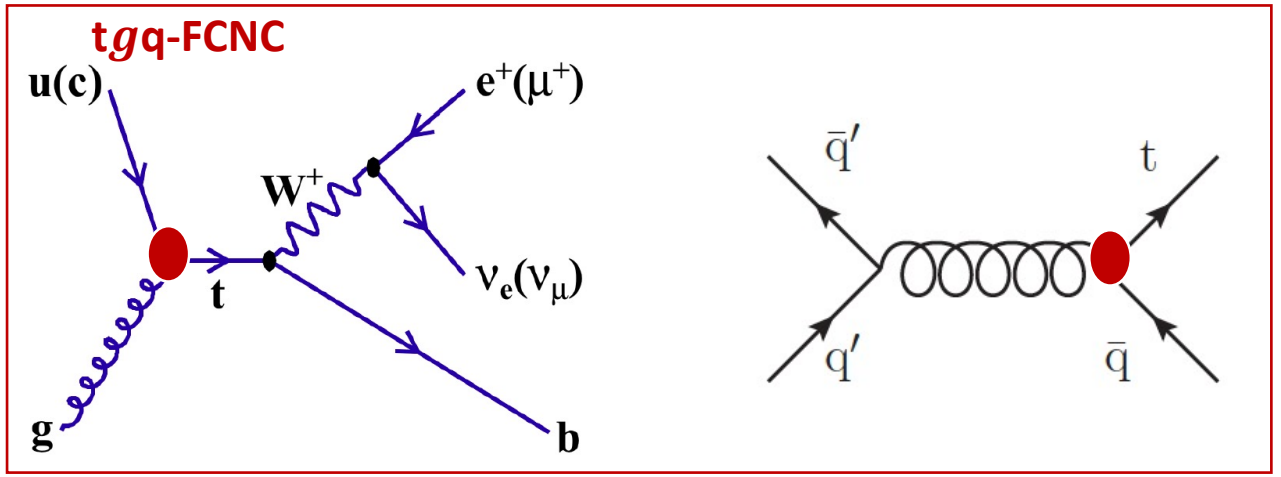
Top-FCNC signatures

- Top-FCNC implying a SM neutral boson. Signatures with possible BSM boson not considered here.

- Two diagram "classes" considered.
  - **At decay** : in $t\bar{t}$ events, SM produced, one top quark decays with FCNC, the other one decays as in the SM.
  - **At production (single top)**: sensitive to quark content of the proton, charge asymmetries in $tXu/tX\bar{u}$, lower cross sections for $tXc - tX\bar{c}$, lower "relative to $t\bar{t}$-FCNC" cross sections at 13 TeV compared to 7/8 TeV.
  - tgq not searched for in the $t\bar{t}$ events, highly unfavourable S/B.

- Large variety of signatures : Single lepton, multi-leptons, multi (b) jets, tau leptons, photons etc…





Theoretical framework(s)

FCNC Models and MC generation (1)

- **ATLAS** :
  - Latest results with an **EFT interpretation**,
  - Madgraph model at NLO (QCD),
  - Left-right couplings lead to same cross-sections/Br, only slightly different angular distributions. **Usually neglected**.

Exemple for tHq

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{q=u,c} \left[\frac{C_{u\phi}^{qt}}{\Lambda^2} O_{u\phi}^{qt} + \frac{C_{u\phi}^{tq}}{\Lambda^2} O_{u\phi}^{tq} \right]$$

$$C_{u\phi}^{qt,tq} = \frac{C_{u\phi}^{qt} + C_{u\phi}^{tq}}{2}$$

- **CMS** :
  - **Anomalous couplings interpretation**,
  - Madgraph model at LO,
  - Left-right couplings leads to same cross-sections/Br, only slightly different angular distributions. **Always neglected**.
  - Limits on Br can be eventually re-interpretated within the EFT framework (at LO).

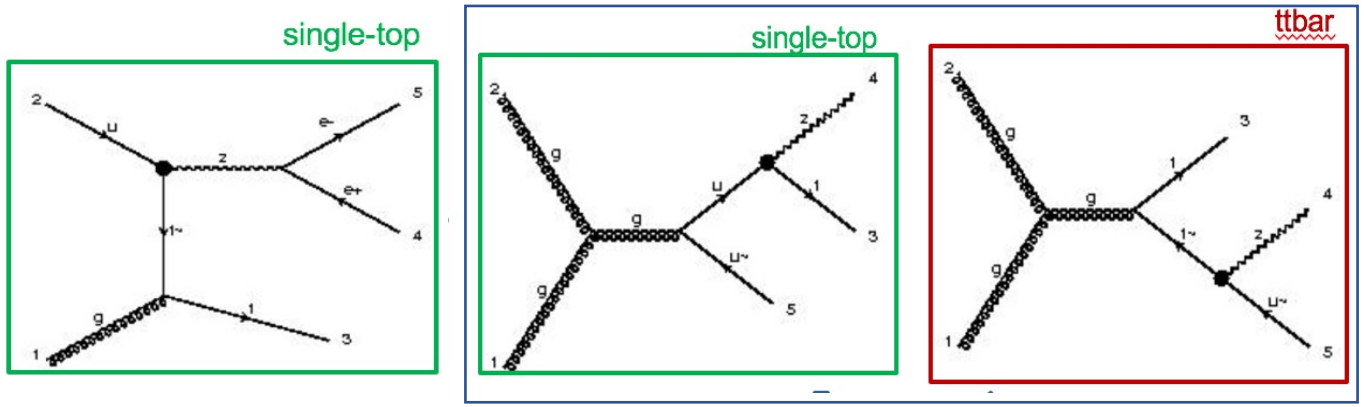
Exemple for tHq

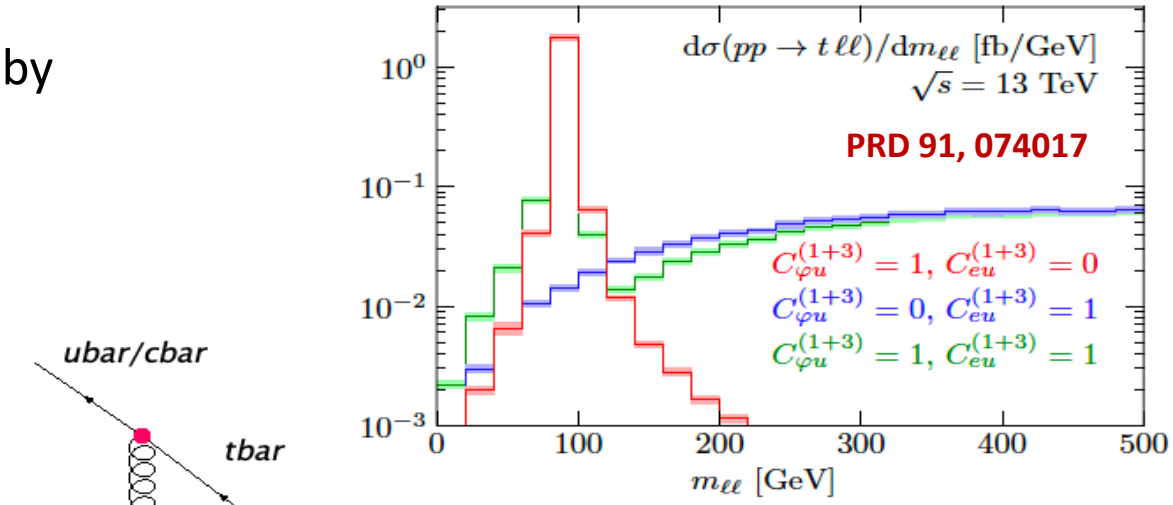
$$\mathcal{L} = \sum_{\mathrm{q=u,c}} \frac{g}{\sqrt{2}} \bar{\mathrm{t}}\, \kappa_{\mathrm{Hqt}} (f_{\mathrm{Hq}}^{\mathrm{L}} P_{\mathrm{L}} + f_{\mathrm{Hq}}^{\mathrm{R}} P_{\mathrm{R}}) \mathrm{qH} + \mathrm{h.c.}$$

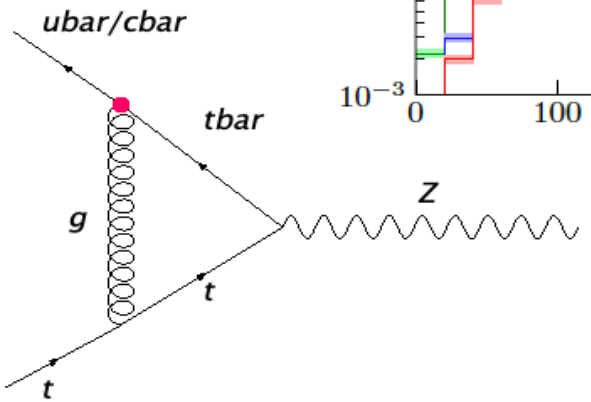
MC generation : separate generations of $t\bar{t}$ (normalized at NNLO SM cross section× $\mathcal{B}r(FCNC)$), and single top FCNC events.

FCNC Models and MC generation (2)

- Interferences between single top and $t\bar{t}$ FCNC.
- Interferences taken as negligible in analyses.
- Approximation confirmed at LO (E.P.J.Plus 135 (2020) 339), what about at NLO ?
- EFT model also predict 4-fermions interactions, not covered by experimental FCNC searches.
- Challenges for interpretation at NLO (QCD).
  - Top-FCNC appear **at loop level**,
  - **Mixing** of FCNC couplings,
  - Full picture (and optimal sensitivity ?) through **a global fit** (G. Durieux&al).
- Top-FCNC to set limits on specific BSM models and other interpretations (arXiv:1311.202, PLB 850 (2024)138548).

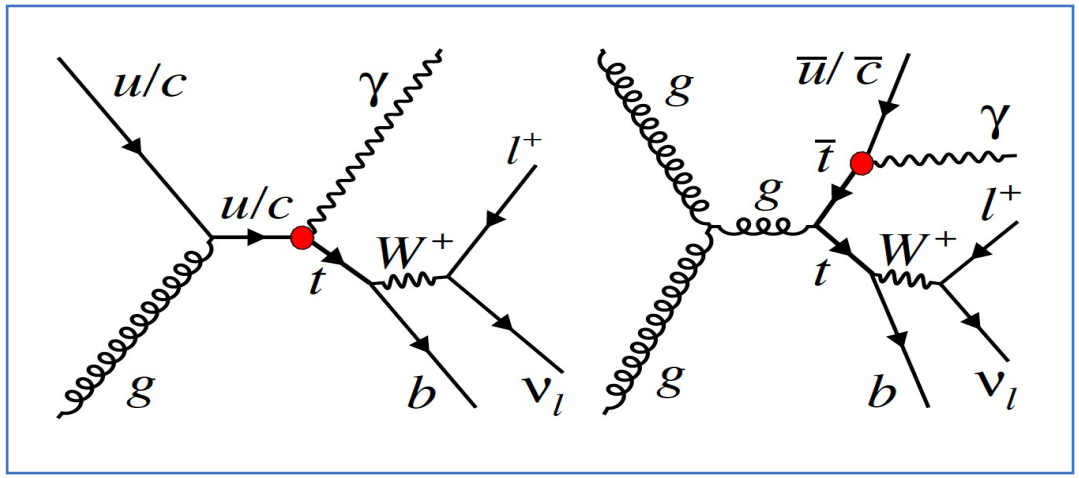




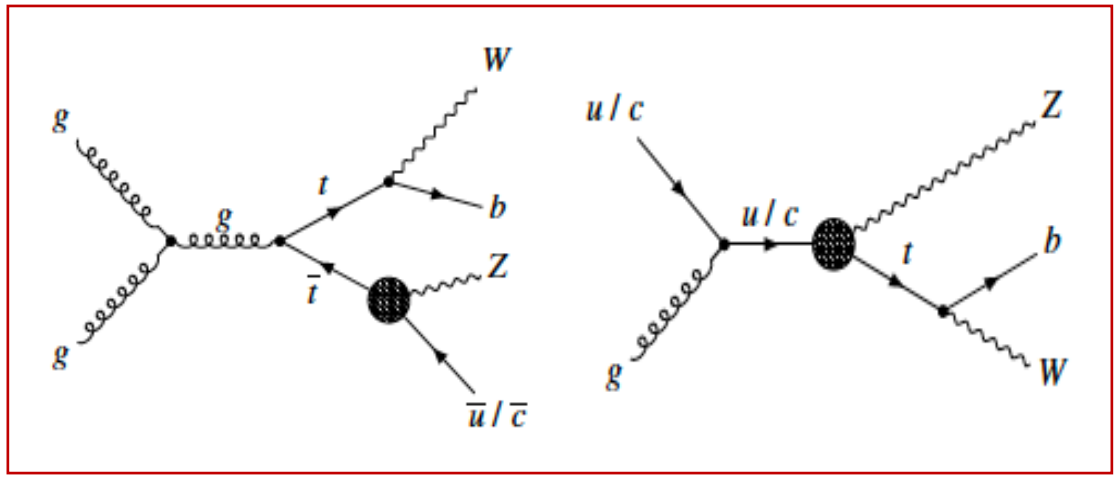


$t\gamma q$ and tZq FCNC

tγq-FCNC



tZq-FCNC



tγ-FCNC

PLB 842 (2023) 137379

PRD109 (2024) 072004

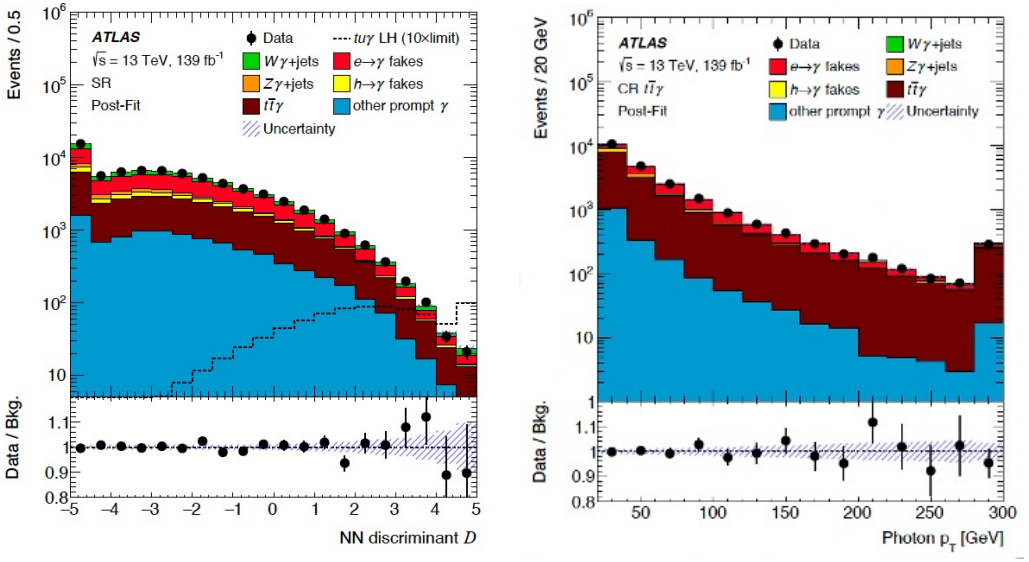
Single lepton (e, μ), N_l=1, 1 photon, $N_j \geq 1$, $N_b \geq 1$ b-tag jet. Missing pT cut.

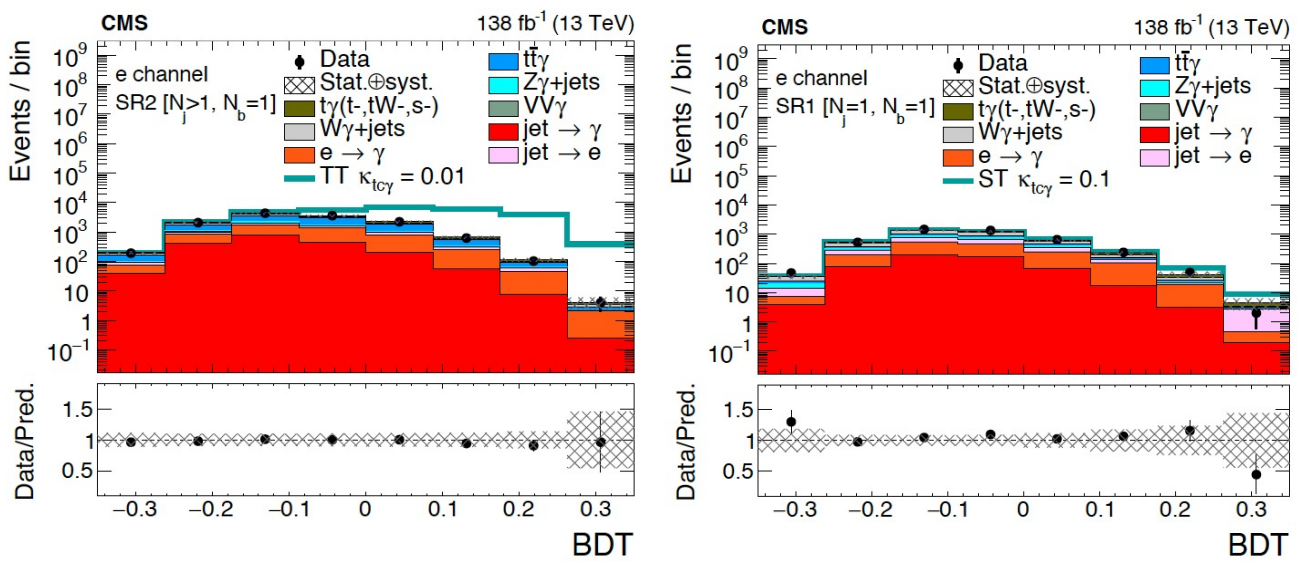
- 1 SR (N_b =1) and 2 CR : $t\bar{t}\gamma$ ($N_j \geq 4$, $N_b \geq 2$) and $W\gamma$+j (N_j=1, N_b =1, tight b-tag veto).
- Data-driven methods for fake photons.
- NN for SR and pT of the photon for CRs.

$$Br(t \to u\gamma) < 0.85 \cdot 10^{-5}\ (0.88 \cdot 10^{-5}),$$
$$Br(t \to c\gamma) < 4.20 \cdot 10^{-5}\ (3.40 \cdot 10^{-5})$$

- 4 SR : decay channel, single top (N_j=1, N_b =1) and $t\bar{t}$ ($N_j \geq 1$, N_b=1).
- Data-driven methods for fake photons and fake leptons.
- Fit of the SR using BDT discriminants.

$$Br(t \to u\gamma) < 0.95 \cdot 10^{-5}\ (1.2 \cdot 10^{-5}),$$
$$Br(t \to c\gamma) < 1.51 \cdot 10^{-5}\ (1.54 \cdot 10^{-5})$$





tZ-FCNC

PRD 108 (2023) 032019

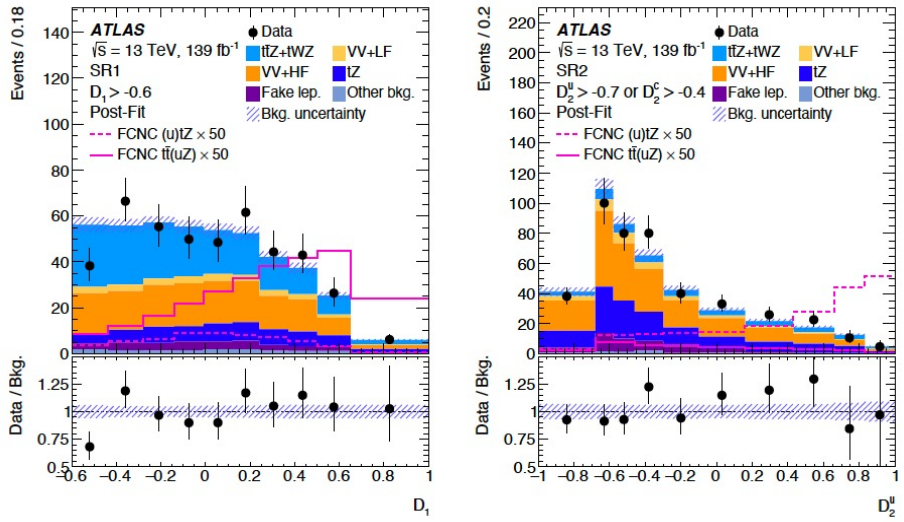
JHEP 07 (2017) 003

Search in the 3 leptonic channels : N_l=3, $N_j \geq$1, $N_b \geq$1, OSSF Dilepton compatible with Z mass.

Run 1 !

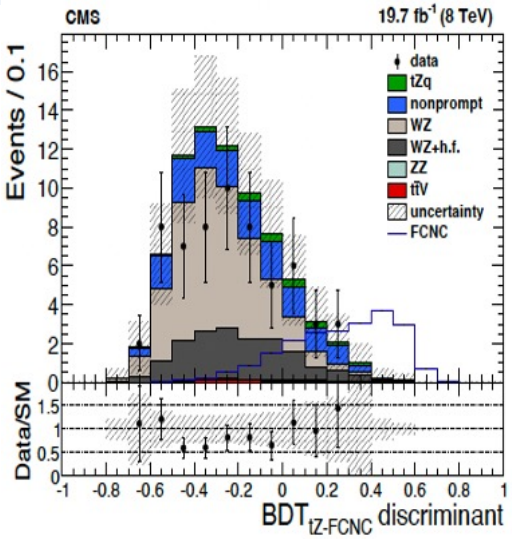
- top masses (top_{SM} and top_{FCNC}) reconstruction with kinfit.
- SRs : $t\bar{t}$-FCNC ($N_j \geq$2, N_b =1), single top ($N_j \geq$=1-2, N_b =1, orthogonality with m_{top} cut).
- C-tagging for a specific tZq category in $t\bar{t}$-FCNC.
- CRs : $t\bar{t}$ -SM (Z-veto), $t\bar{t}Z$($N_j \geq 4$, N_b =2), m_{top} "sidebands". All backgrounds shapes from simulations.
- Signal extracted from GBDTs, left and right handed.

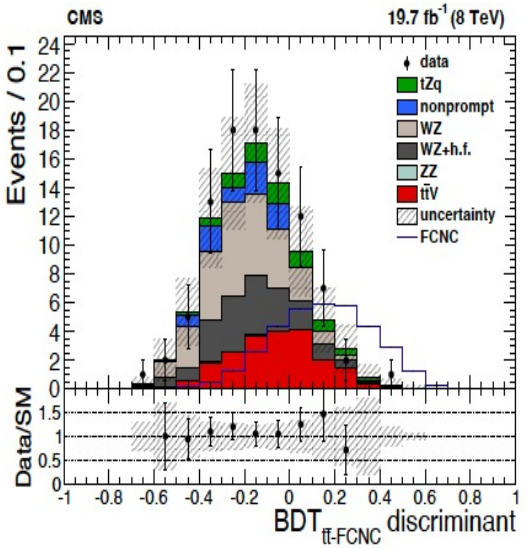
$$\boldsymbol{Br(t \to uZ) < 6.2 \cdot 10^{-5}\ (4.9 \cdot 10^{-5})},$$
$$\boldsymbol{Br(t \to cZ) < 13 \cdot 10^{-5}\ (10 \cdot 10^{-5})}$$



- top masses (top_{SM} and top_{FCNC}) reconstruction,
- SR: $t\bar{t}$-FCNC ($N_j \geq$2, N_b =1), single top (N_j=1, N_b =1), $m_T(W)$ and E_T-miss,
- CRs (non-prompt lepton, VV, N_b=0, low $m_T(W)$).
- Non prompt lepton estimated from data.
- Signal extracted from BDTs. 2D contours provided without extrapolations.

$$\boldsymbol{Br(t \to uZ) < 2.2 \cdot 10^{-4}\ (2.7 \cdot 10^{-4})},$$
$$\boldsymbol{Br(t \to cZ) < 4.9 \cdot 10^{-4}\ (11.8 \cdot 10^{-4})}$$





Moving forward with tZ(γ)q-FCNC

$$-\frac{g_W}{2c_W}\begin{cases} v_{tq}^Z \\ -a_{tq}^Z \end{cases} = \frac{-e}{2s_W c_W}\frac{m_t^2}{\Lambda^2}\left[C_{\varphi u}^{(a+3)*} \pm C_{\varphi q}^{-(a+3)*}\right],$$

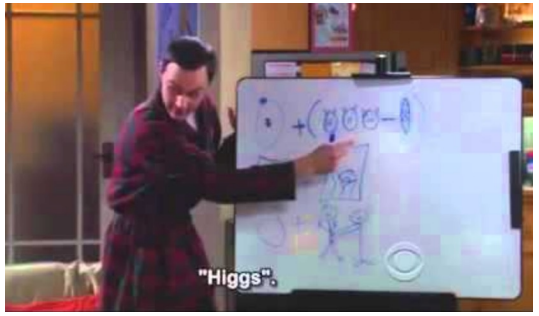
$$-e\frac{\kappa_{tq}^\gamma}{\Lambda}\begin{cases} f_{tq}^\gamma \\ ih_{tq}^\gamma \end{cases} = e\frac{m_t}{\Lambda^2}\left[(C_{uB}^{(3a)} + C_{uW}^{(3a)}) \pm (C_{uB}^{(a3)} + C_{uW}^{(a3)})^*\right],$$

$$-\frac{g_W}{2c_W}\frac{\kappa_{tq}^Z}{\Lambda}\begin{cases} f_{tq}^Z \\ ih_{tq}^Z \end{cases} = \frac{-e}{s_W c_W}\frac{m_t}{\Lambda^2}\left[(s_W^2\, C_{uB}^{(3a)} - c_W^2\, C_{uW}^{(3a)}) \pm (s_W^2\, C_{uB}^{(a3)} - c_W^2\, C_{uW}^{(a3)})^*\right]$$

PRD 91, 074017

- Multiple EFT operators can contribute to the same signatures.
- Example : tensor couplings for tZq and $t\gamma q$ FCNC-couplings are linear combinations of the same Wilson coefficients (at LO).

- In the EFT framework, tZ and $t\gamma$ should be searched for together (similar to $t\bar{t}Z$-$t\bar{t}\gamma$).
- Requirements :
  - Have coherent MC (EFT) based model and MC samples,
  - Not a combination results : perform a simultaneous fit of tZ and $t\gamma$ SRs and CRs.
- First possible step toward a global fit approach ? Accounting of the $tqll$?



tHq FCNC

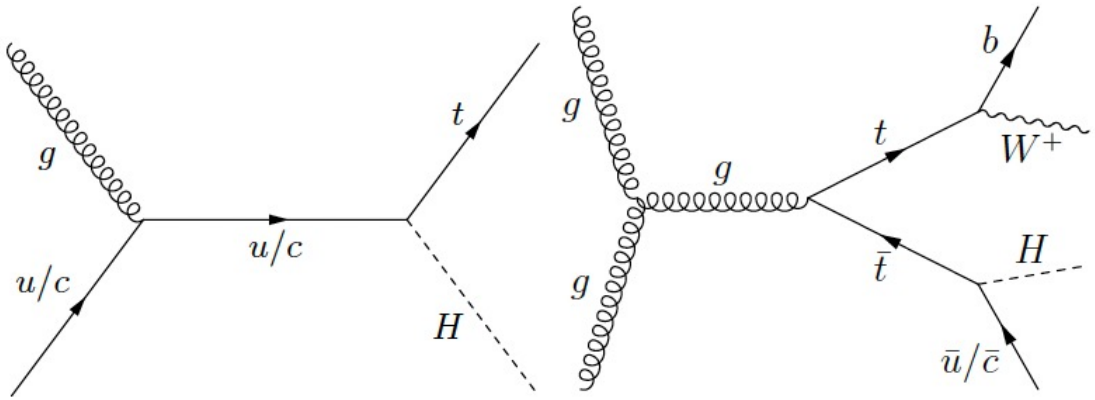
Not covered

ATLAS : JHEP 05 (2019) 123
CMS : JHEP 02 (2022) 169

tHq-FCNC : $H \rightarrow \gamma\gamma, \tau\tau, b\bar{b}, WW, ZZ$

Not covered

JHEP 06 (2023) 155



tH-FCNC, H→ $\gamma\gamma$

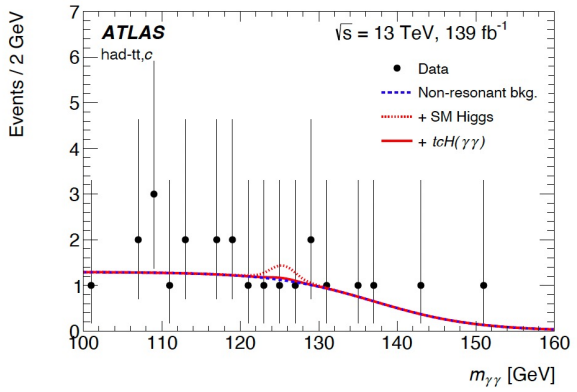
JHEP 12 (2023) 195

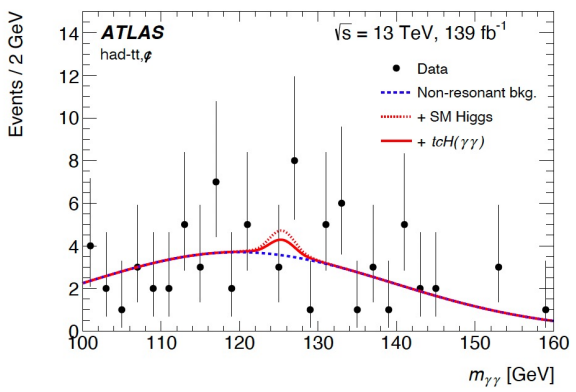
PRL 129 (2022) 032001

2 photons, $N_j \geq 1$, $N_b \geq 1$. Presence of high p_T lepton => Hadronic and leptonic channel.

- m_{top} for $t_{FCNC}(j\gamma\gamma)$ and $t_{SM}(jjb$ or $lvj)$ => check consistency with m_{top}.
- Single top vs tt FCNC (selection on N_j or compatibility of t_{SM} with true top mass).
- tcH and tuH separation based on c-tagging.
- Fit of $\gamma\gamma$ mass after cut on a BDT.
- Non H resonant background from side bands.

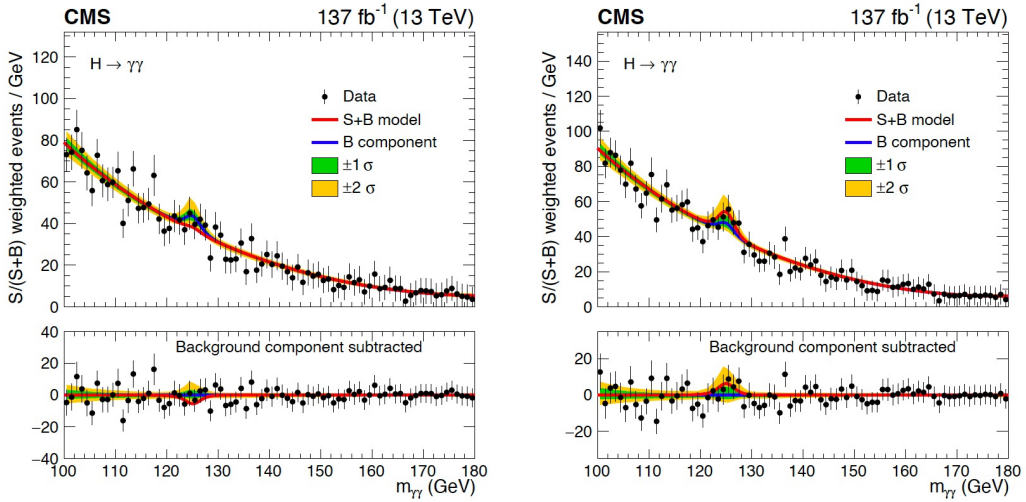
$$\boldsymbol{Br(t \to uH) < 4.0 \cdot 10^{-4}\ (2.4 \cdot 10^{-4});}$$
$$\boldsymbol{Br(t \to cH) < 5.8 \cdot 10^{-4}\ (3.0 \cdot 10^{-4})}$$





- m_{top} for $t_{FCNC}(j\gamma\gamma)$ and $t_{SM}(jjb$ or $lvj)$ => best jets combination from NN and kin fit.
- BDTs for trained for tcH and tuH, ST and TT, res. and non-res based on BDT => categorisation.
- Fit of $\gamma\gamma$ mass for each BDT categories.
- Fake photons shape from data-driven.

$$\boldsymbol{Br(t \to uH) < 1.9 \cdot 10^{-4}\ (3.1 \cdot 10^{-4});}$$
$$\boldsymbol{Br(t \to cH) < 7.3 \cdot 10^{-4}\ (5.1 \cdot 10^{-4})}$$



tH-FCNC, multi-leptons

EPJC 84(2024) 757

2407.15172, subm. to PRD

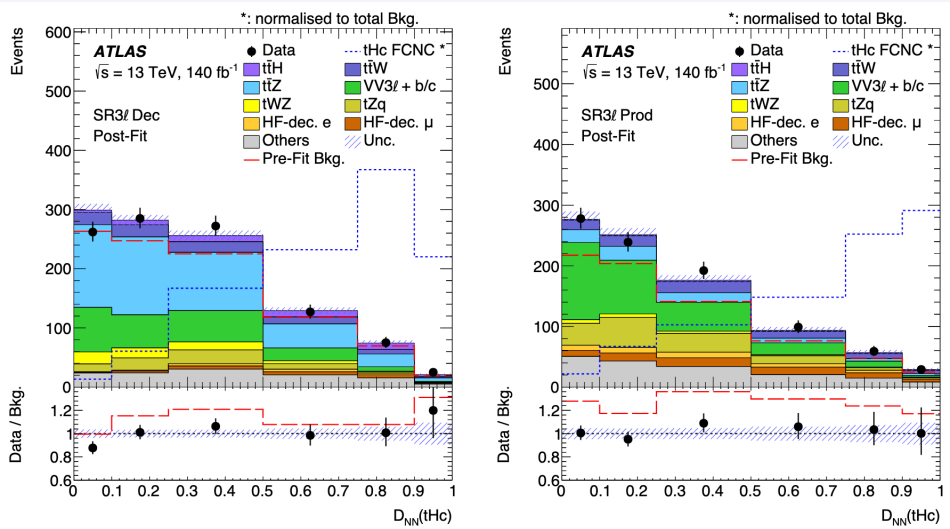
Dilepton-same sign (e, μ) and 3 leptons, ≥1 jets, ≥1 bjets, Z mass veto.

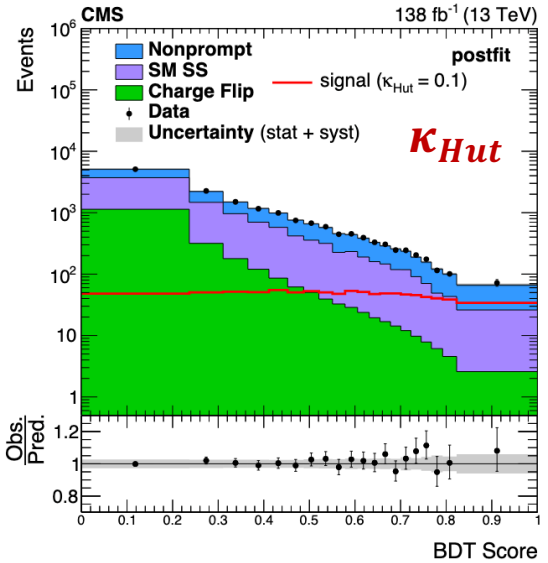
- 2lss vs 3l categories with N_j and N_b selections.
- CR for no-prompt leptons (low p_T lepton selection) and prompt lepton backgrounds ($t\bar{t}W$, $t\bar{t}Z$, 2 b-jets, Z-mass selection) normalisation.
- Charge mis-reco background from SS at the Z mass.
- Events reconstruction and fit of NN discriminants for signal regions, events yields and lepton p_T in control regions.

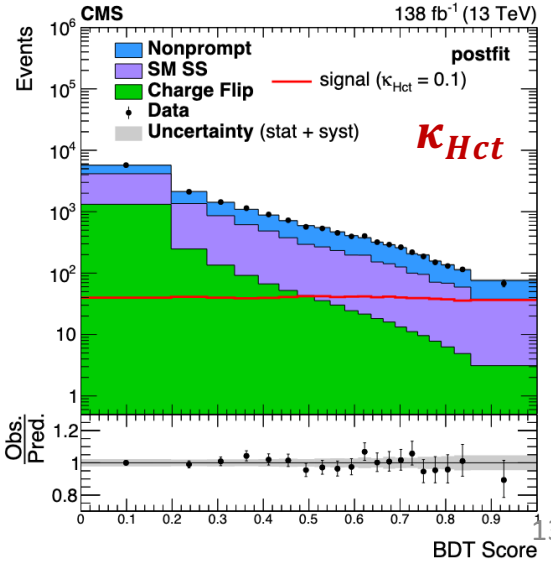
$$\boldsymbol{Br(t \to uH) < 2.8 \cdot 10^{-4}\ (3.0 \cdot 10^{-4})},$$
$$\boldsymbol{Br(t \to cH) < 3.3 \cdot 10^{-4}\ (3.8 \cdot 10^{-4})}$$

- Events SR definition from a BDT, with optimised binning.
- Non-prompt backgrounds fully estimated from data.
- Charge mis-reco estimated from simulation, found small impact on yields.

$$\boldsymbol{Br(t \to uH) < 7.2 \cdot 10^{-4}\ (5.9 \cdot 10^{-4})},$$
$$\boldsymbol{Br(t \to cH) < 4.3 \cdot 10^{-4}\ (6.2 \cdot 10^{-4})}$$







Combinations

EPJC 84(2024) 757

2407.15172, subm. to PRD

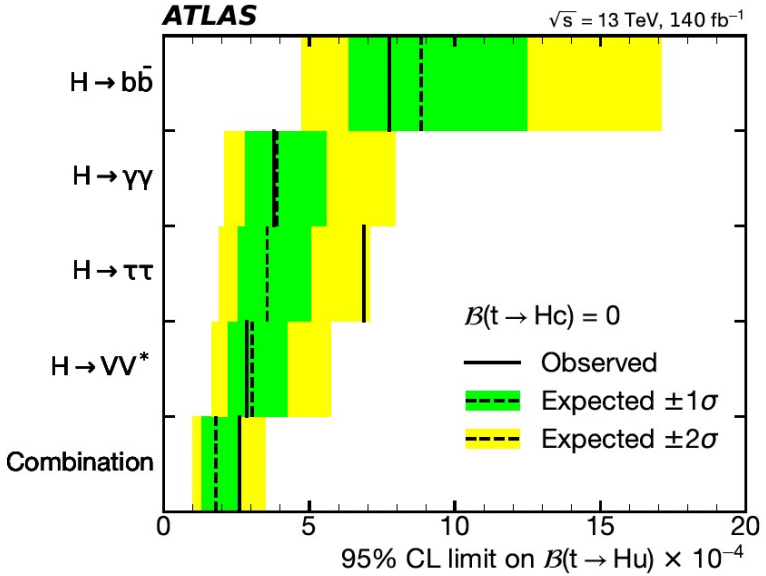
- ATLAS : dominated by multilepton. CMS : dominated by diphoton.

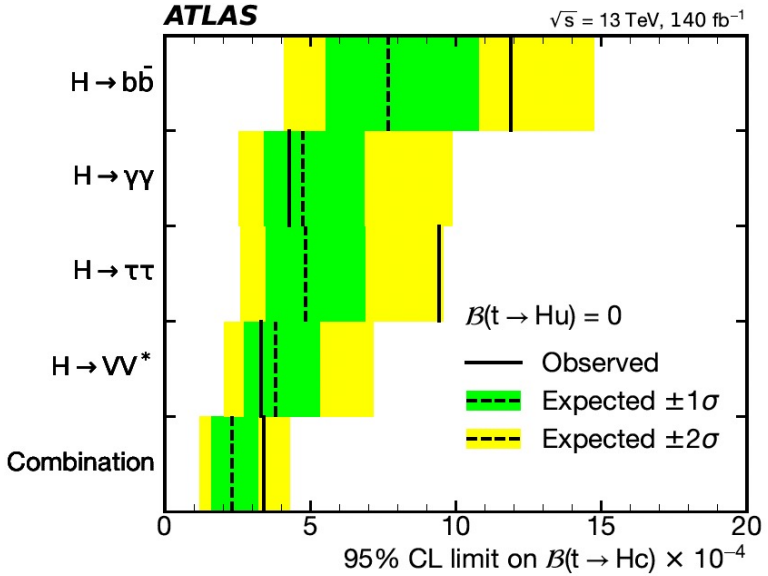
- Key point : choice of correlations, not always done fully coherently (because done at different times).

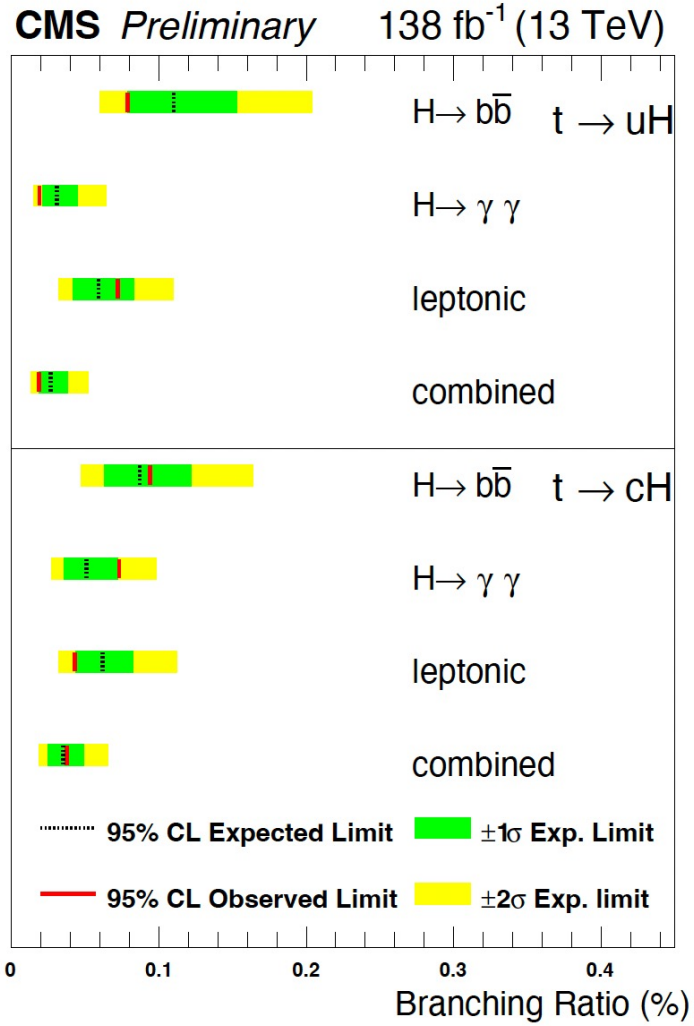
- Could we foresee ATLAS+CMS combinations ?

$$Br(t \to uH) < 2.6 \cdot 10^{-4}\ (1.8 \cdot 10^{-4}),$$
$$Br(t \to cH) < 3.4 \cdot 10^{-4}\ (2.4 \cdot 10^{-4})$$

$$Br(t \to uH) < 1.9 \cdot 10^{-4}\ (2.7 \cdot 10^{-4}),$$
$$Br(t \to cH) < 3.7 \cdot 10^{-4}\ (3.5 \cdot 10^{-4})$$

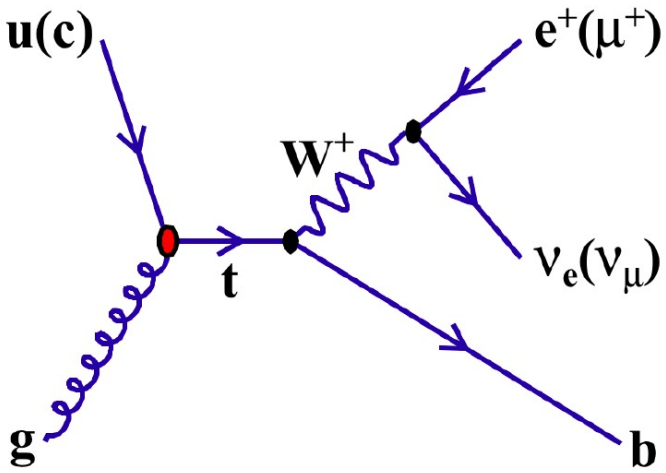




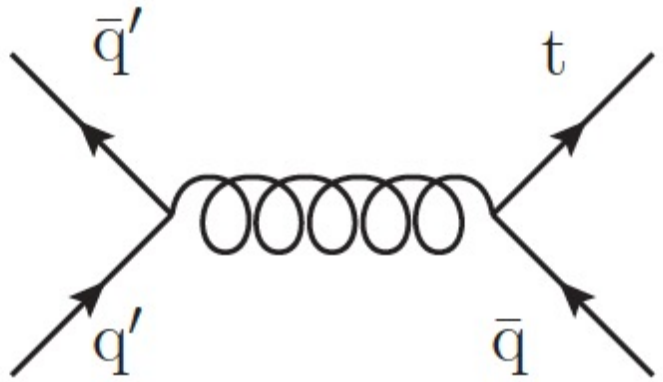


tg FCNC

Top+0 jet



Top+1 jet



tgq-FCNC

EPJC 82 (2022) 334

JHEP 02 (2017) 028

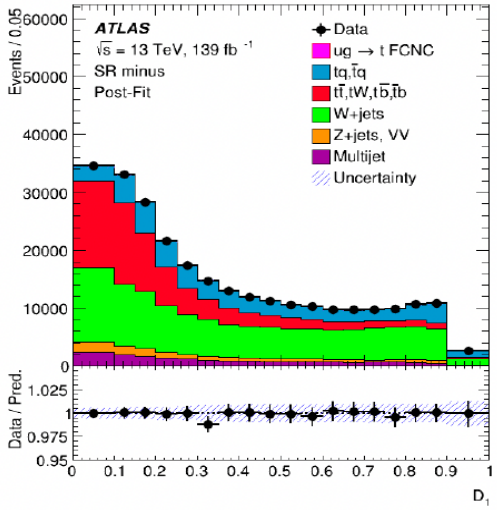
Run 1 !

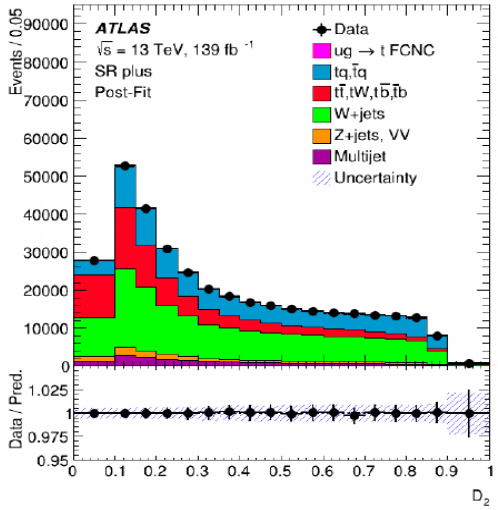
- **Top+0jet** : N_l=1, N_j=1, N_b=1, E_T-miss and $m_T(W)$ selections.
- Signal extracted from fit of NN discriminants, for ($g\bar{u} \to t$, $g\bar{c} \to t$, $gc \to t$) and $gu \to t$.
- VR regions (not part of the fit) for W+jets and $t\bar{t}$ backgrounds from (b)jets and NN discriminant selections.
- Non-prompt lepton from fit of E_T-miss (e) and $m_T(W)(\mu)$.

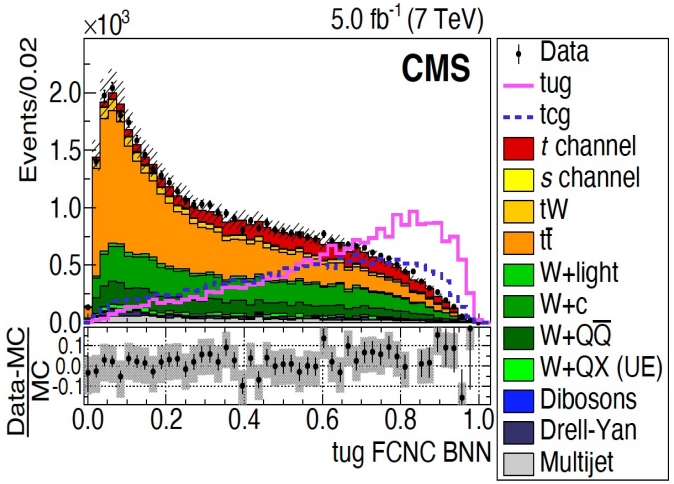
$$\boldsymbol{Br(t \to ug) < 0.6 \cdot 10^{-4}\ (0.5 \cdot 10^{-4})}$$
$$\boldsymbol{Br(t \to cg) < 3.7 \cdot 10^{-4}\ (2.0 \cdot 10^{-4})}$$

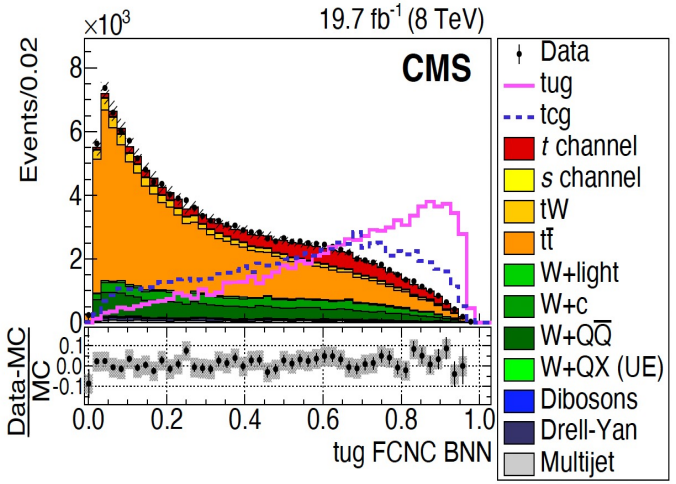
- **Top+1jet** : single top t-chan like analysis. N_μ=1, N_j= 2-3 jet, N_b=1.
- Multi-jet from data (lepton isolation inversion), $t\bar{t}$ (4j2b) and W+jets validated from data (0b).
- Signal extracted from fit of NN discriminants, for ($gg \to tu$, $gg \to tc$).

$$\boldsymbol{Br(t \to ug) < 2.0 \cdot 10^{-4}\ (2.8 \cdot 10^{-4})},$$
$$\boldsymbol{Br(t \to cg) < 4.1 \cdot 10^{-4}\ (2.8 \cdot 10^{-4})}$$





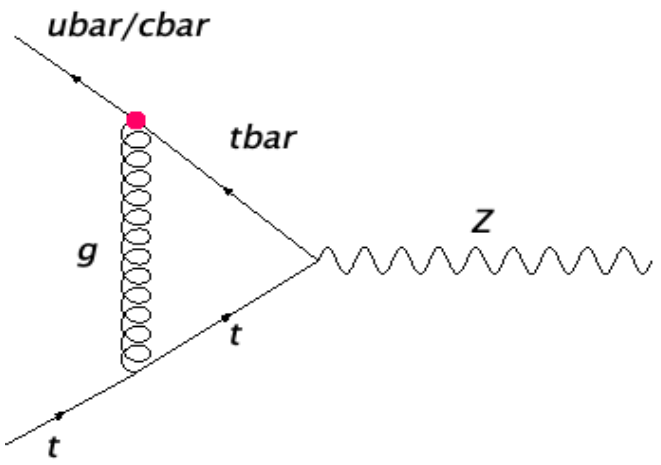


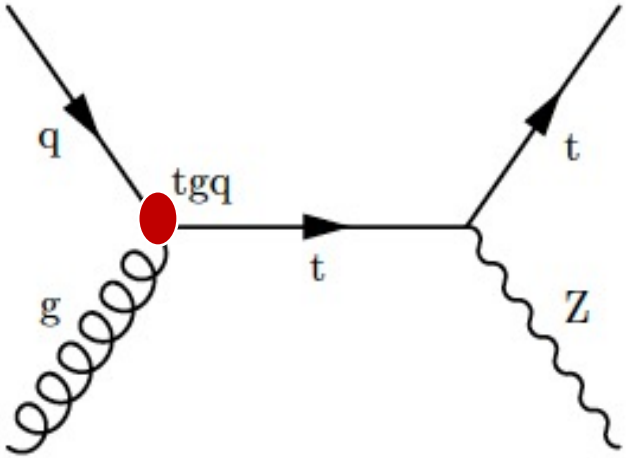


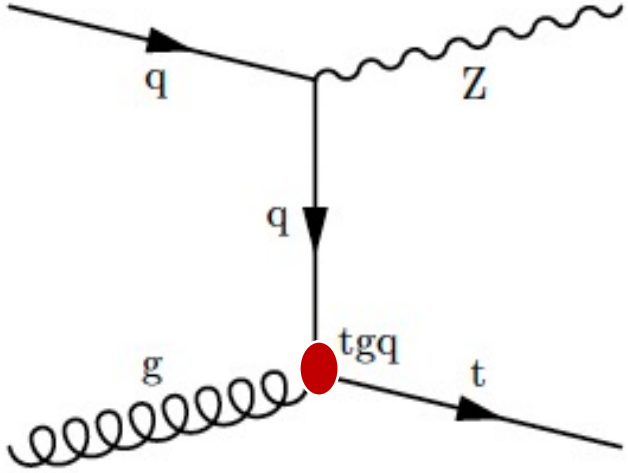
tgq combinations ?

- Top+0jet and top+1 jet tgq could be covered in a single analysis.

- tXq searches can be used to set limits on tgq,
  - At NLO-QCD, tgq at loop level of every tXq vertex, although it is a second order effect,
  - Single top FCNC tXq can be produced via a tgq => single top FCNC can all be re-interpreted as a search for tgq (true at LO).



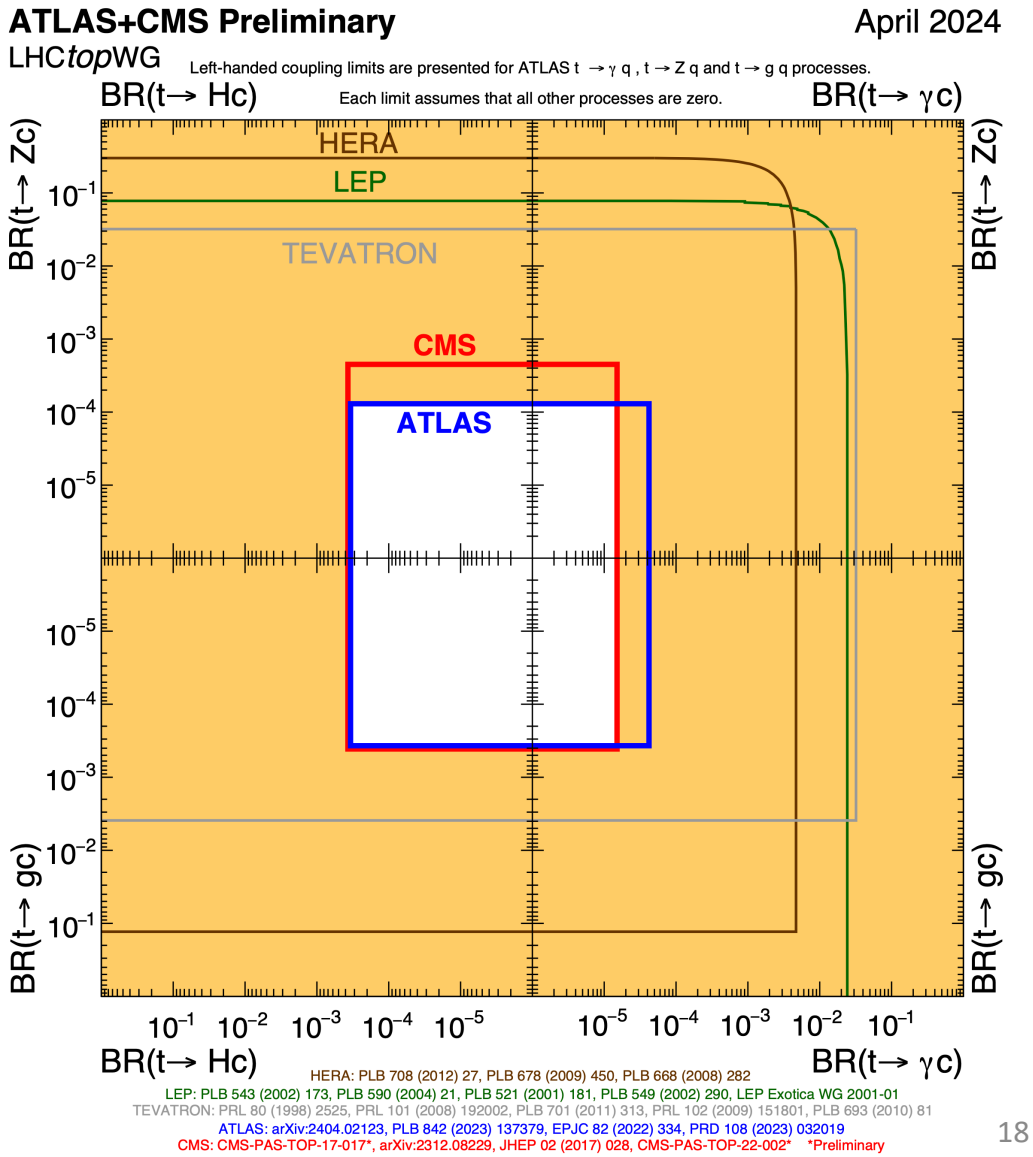




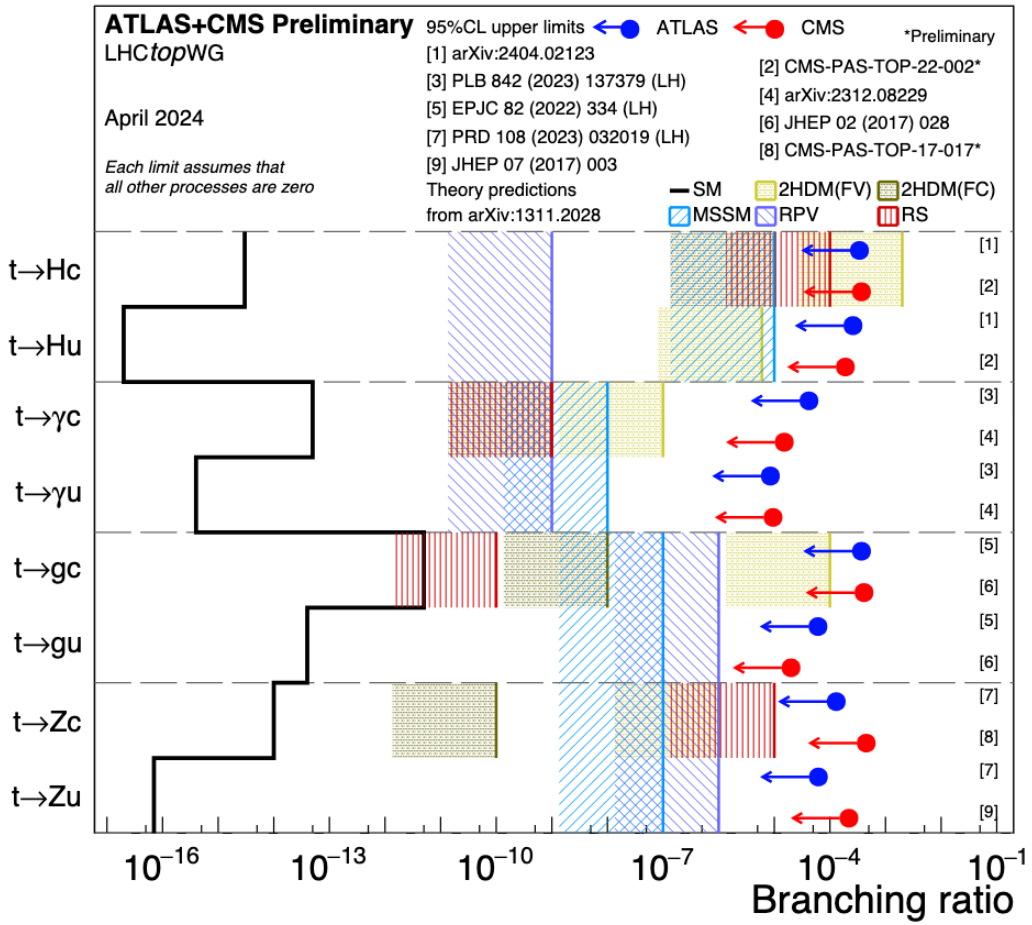
Conclusions/Remarks

- Since the LHC start-up, several top-FCNC searches were performed :
  - All top-boson couplings are covered, including the Higgs boson,
  - Single top-FCNC production modes combined with FCNC at decays,
  - tHq searches combined and lead to the best existing limits.

- Several progresses on the theory side :
  - Both collaborations could move to EFT interpretations => first step toward ATLAS-CMS “combinations” ?
  - Inclusion of $tqll$, from tHq and/or tZq (off Z-peak)
  - NLO QCD modelling is available, mixing has potentially limited contributions ?
  - Combinations of tZq and $t\gamma q$ signatures would increase the sensitivity?
  - Sensitivity to tgq could be increased by reinterpreting/combining tXq searches ?
  - Global fit implementation (also including 4-fermions operator) ?



Conclusions/Remarks



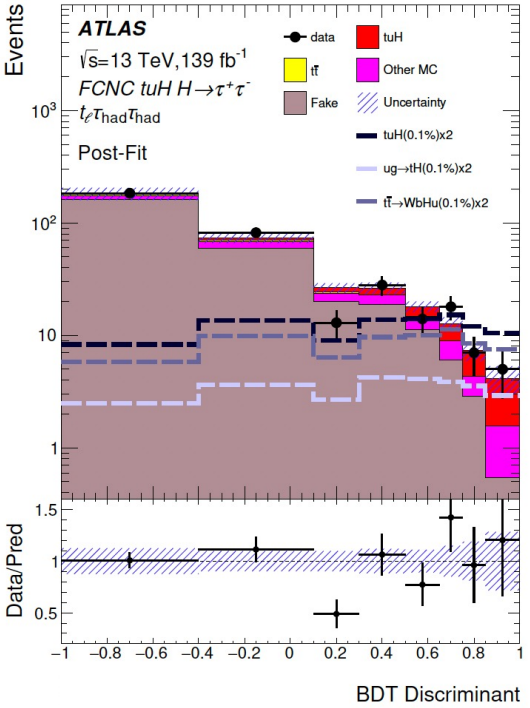
- Observations of experimental aspects :
  - Not all channels with the run2 data, some “old” results,
  - For similar luminosities, similar sensitivities usually reached,
  - Major use of multi-variate analyses, more elaborate techniques and higher regions “granularity” seems to give the best results.
  - Improvement from c-tagging seems moderate.
  - Different ATLAS-CMS treatments of non-prompt lepton backgrounds : fully data-driven vs partially MC –driven.
  - 2D contours sometimes provided, potentially with extrapolations.
- FCNC can also be searched for at FCC.
- Experimental combinations :
  - Within experiments, for different Higgs decay channels. Leads to the best sensitivities.
  - “Combinations” between ATLAS and CMS :
    - Require same theoretical framework,
    - Multi-variate shape analysis,
    - Need preparation and coordination *before* the analyses start.

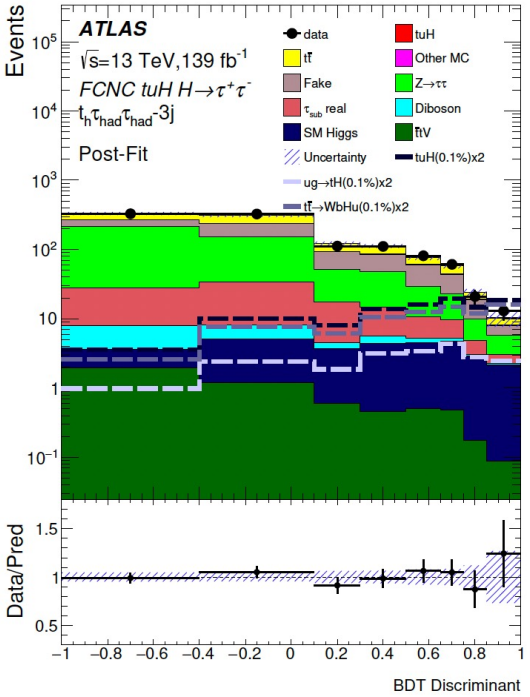
Backups

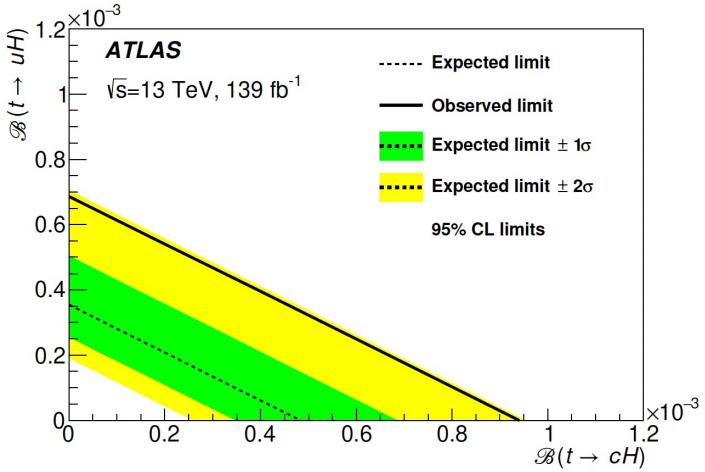
tH-FCNC, H→ $\tau\tau$

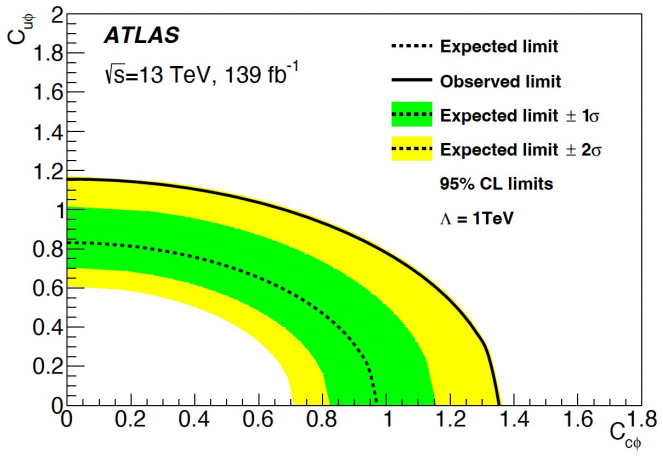
JHEP 06 (2023) 155

- Consider both hadronic and leptonic t_{SM} decays,
- Several events categories : number of a light leptons (e or μ), number of τ_{had} and number of light jets.
- Signal extraction from BDTs used in SR regions (FIXME def SR).
- Fake τ backgrounds ($t\bar{t}$, QCD multi-jet) => SF estimated from data in $t\bar{t}$-CR.







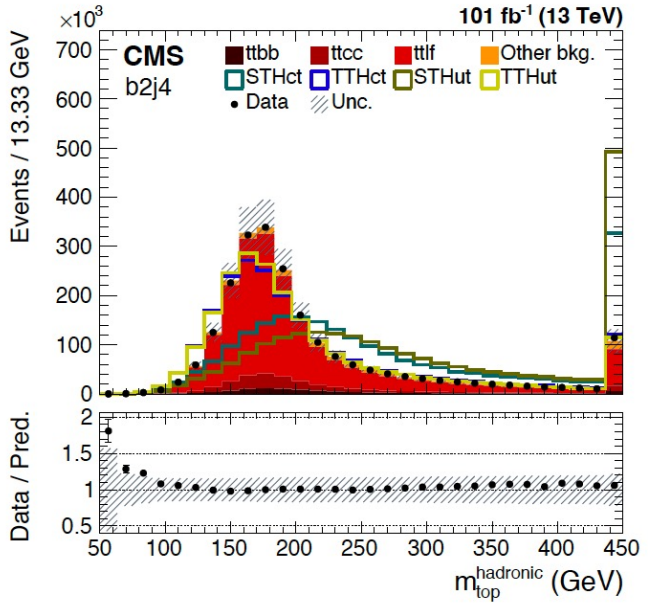


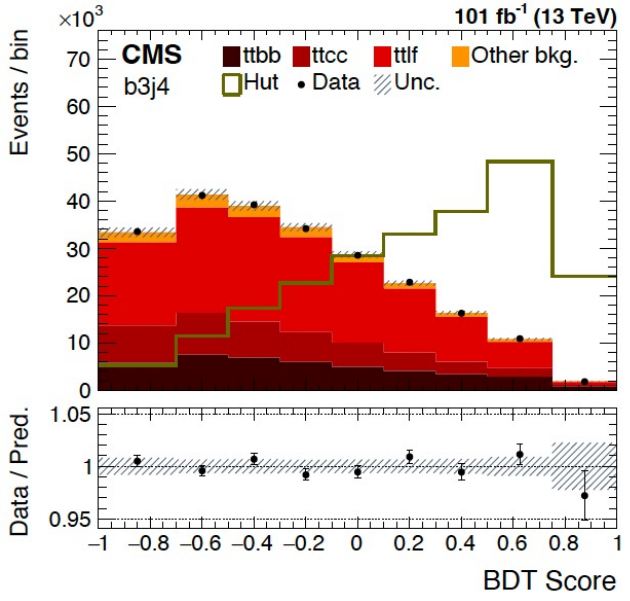
$Br(t \to uH) < 6.9 \cdot 10^{-4}$ $(3.5 \cdot 10^{-4})$;
$Br(t \to cH) < 9.4 \cdot 10^{-4}$ $(4.8 \cdot 10^{-4})$

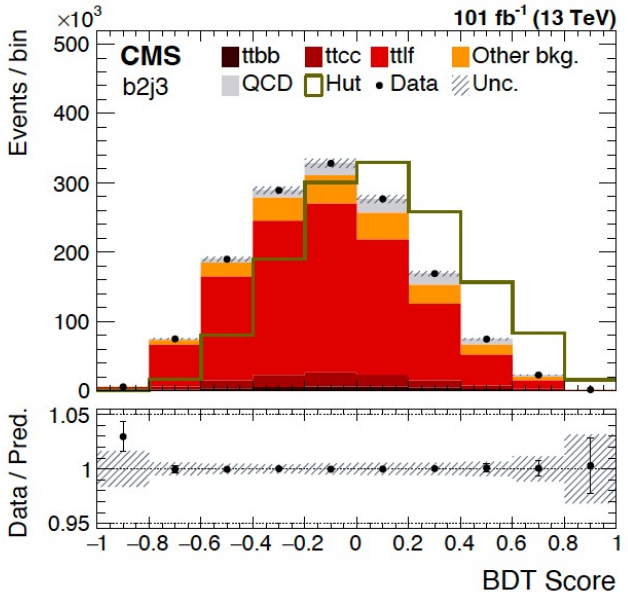
tH-FCNC, H→ $b\bar{b}$

JHEP 02 (2022) 169

- Single lepton channel (e or μ), events selection based on jets and b-tagged jets multiplicities (b-N,j-M), with N=2-4 and M=3,4.
- $t\bar{t}$ as the dominant background.
- DNN classifiers used for kinematic reconstruction (combinatorics) => leads to significant improvements in reconstruction efficiency : 5-15% in SR, up to 40% improvements for $t\bar{t}$ in CR (b4,j4),







- Signal extracted from fir of a BDT discriminant in all regions.

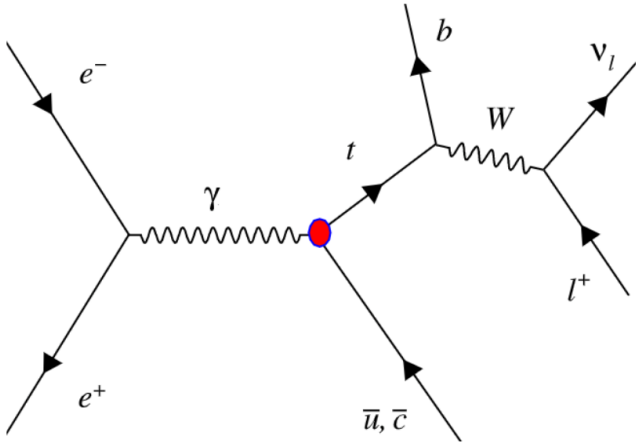
$$Br(t \to uH) < 7.9 \cdot 10^{-4}\ (11.0 \cdot 10^{-4});$$
$$Br(t \to cH) < 9.4 \cdot 10^{-4}\ (8.6 \cdot 10^{-4})$$

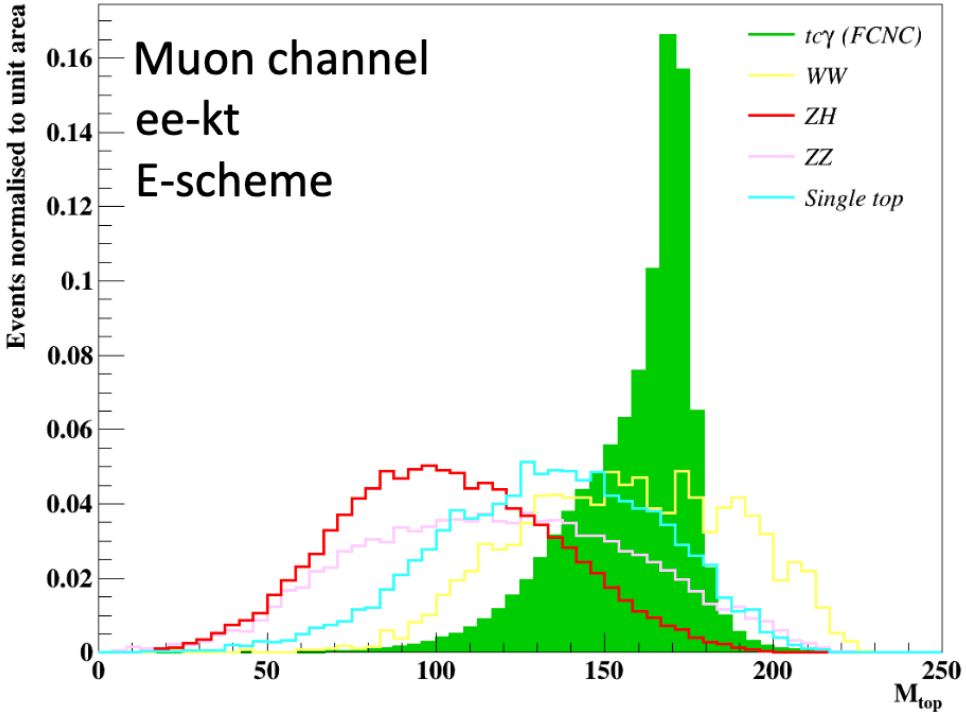
ATLAS results JHEP 05 (2019) 123

Sensitivity at FCCee

H.Khanpour&al. FCCee France-Italy workshop 2022

- Prospects of Top-FCNC search at FCCee.
- Single top production at $\sqrt{s}$=240 GeV.
- Simple cut&count analysis could already reach high sensitivity.

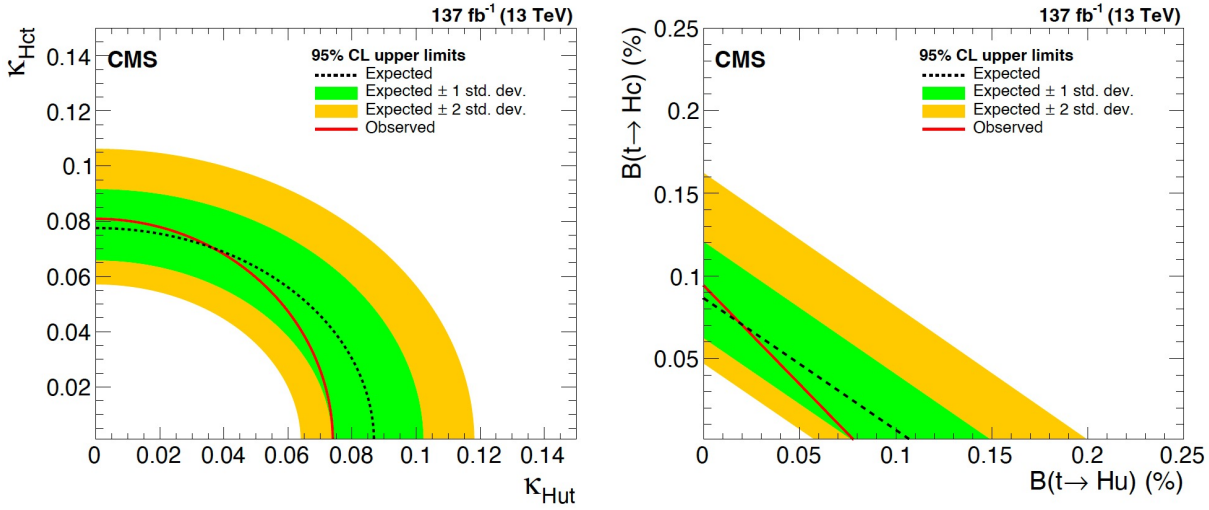




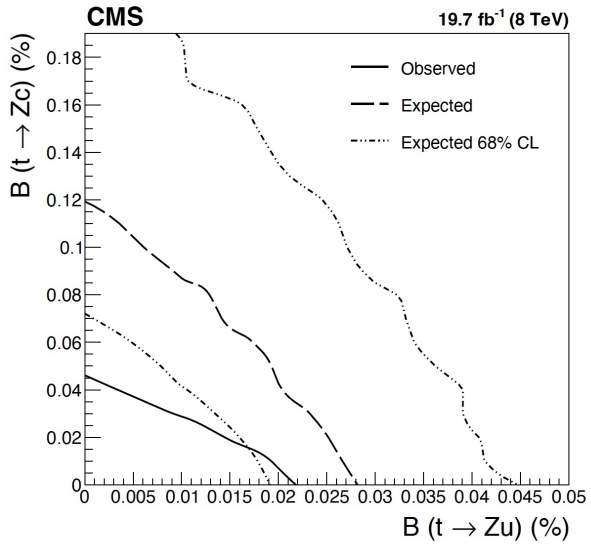
FCC-ee (240 GeV)	$Br(t \to c\gamma)$	$Br(t \to cZ)$
Electron Channel	6.19×10^{-5}	2.27×10^{-5}
Muon Channel	4.45×10^{-5}	1.63×10^{-5}

2D contours

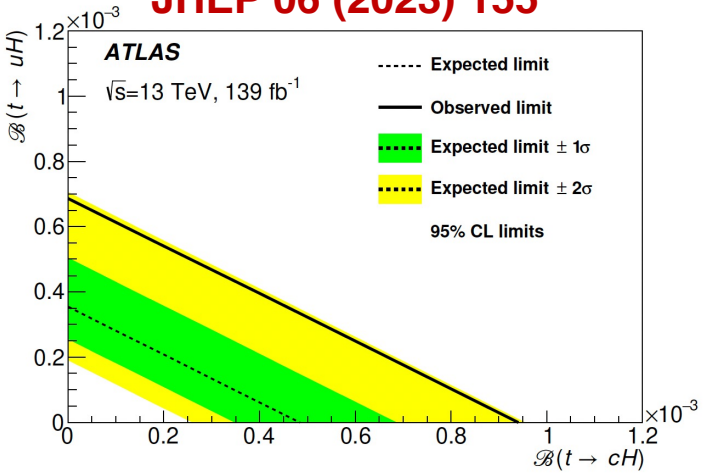
JHEP 02 (2022) 169

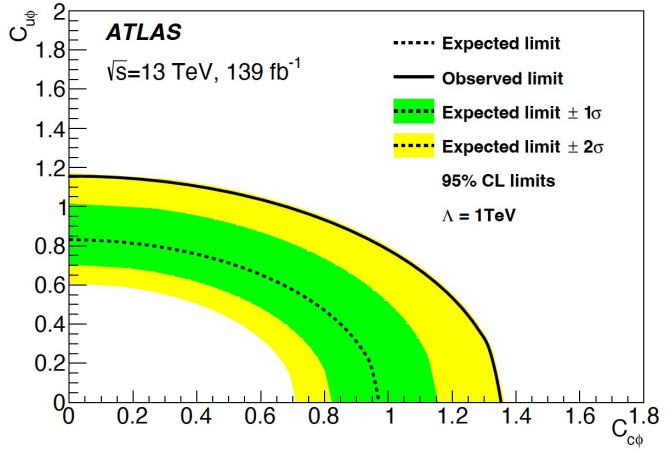


JHEP 07 (2017) 003



JHEP 06 (2023) 155



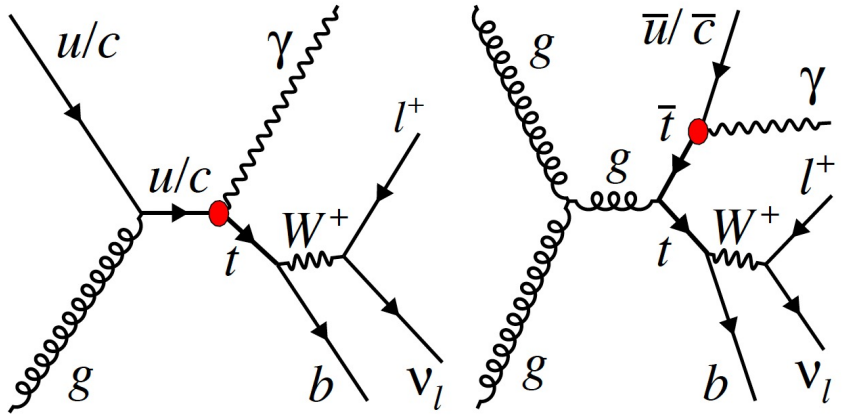


- 2D contours from extrapolations : Linear interpolation of limits on a single coupling (either tXu or tXc) ?

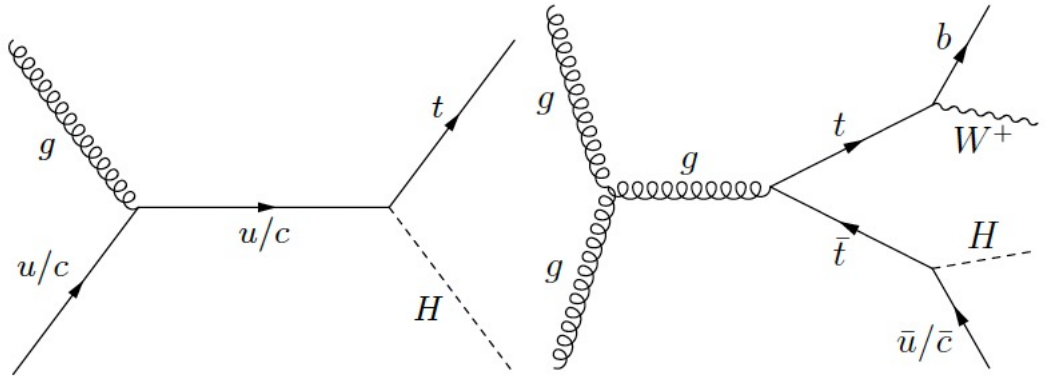
- Related assumptions :
  - Discriminating variable distributions for a mixture of tXu and tXc can be modelled by the sum of distributions from tXu-only and tXc-only,
  - Statistical fluctuations neglected. Should be correct for expected limits. Is it for observed ?
  - 1-2 sigma band extrapolations correct ?

Top-FCNC signatures

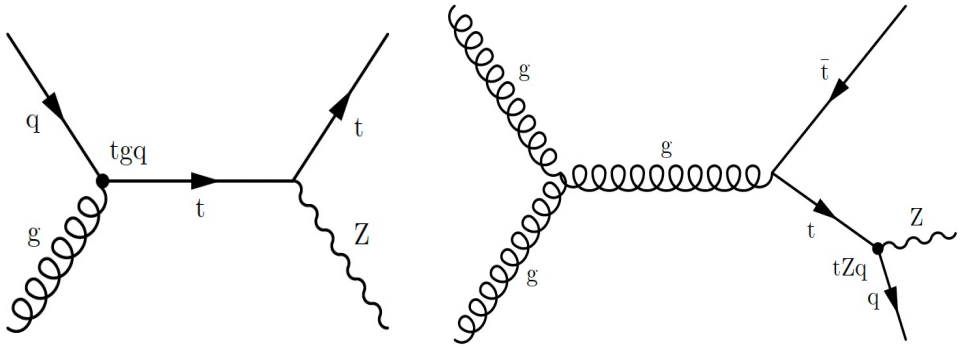
tγq-FCNC



tHq-FCNC : $H \to \gamma\gamma, \tau\tau, b\bar{b}, WW, ZZ$



tZq-FCNC



tgq-FCNC