Search for top FCNC

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on behalf of the ATLAS and CMS Collaborations

10th International Workshop on Top Quark Physics, Braga, Portugal

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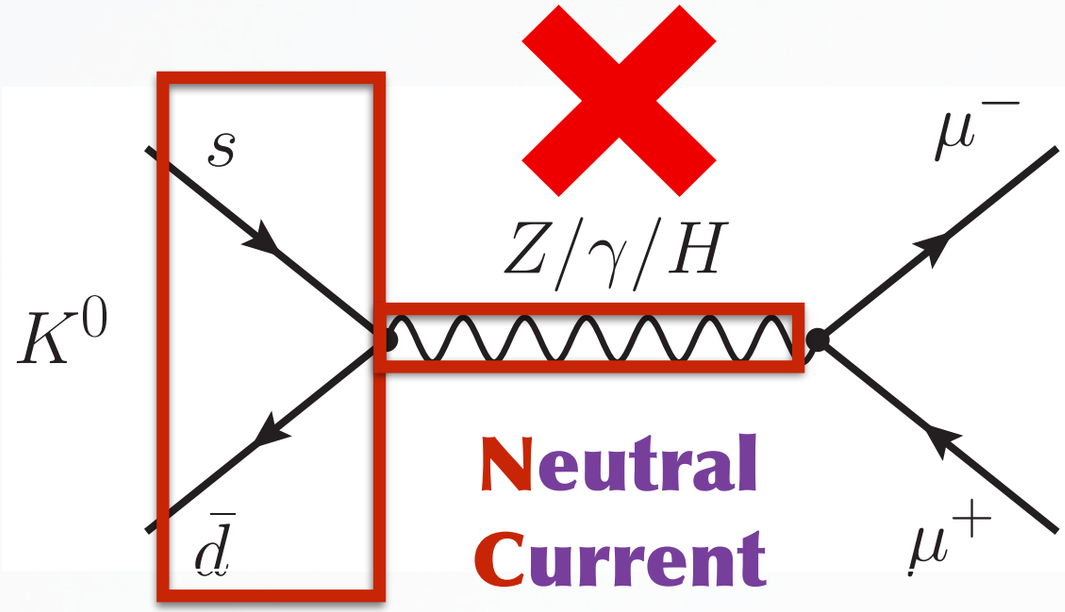
Research Foundation Flanders
Opening new horizons

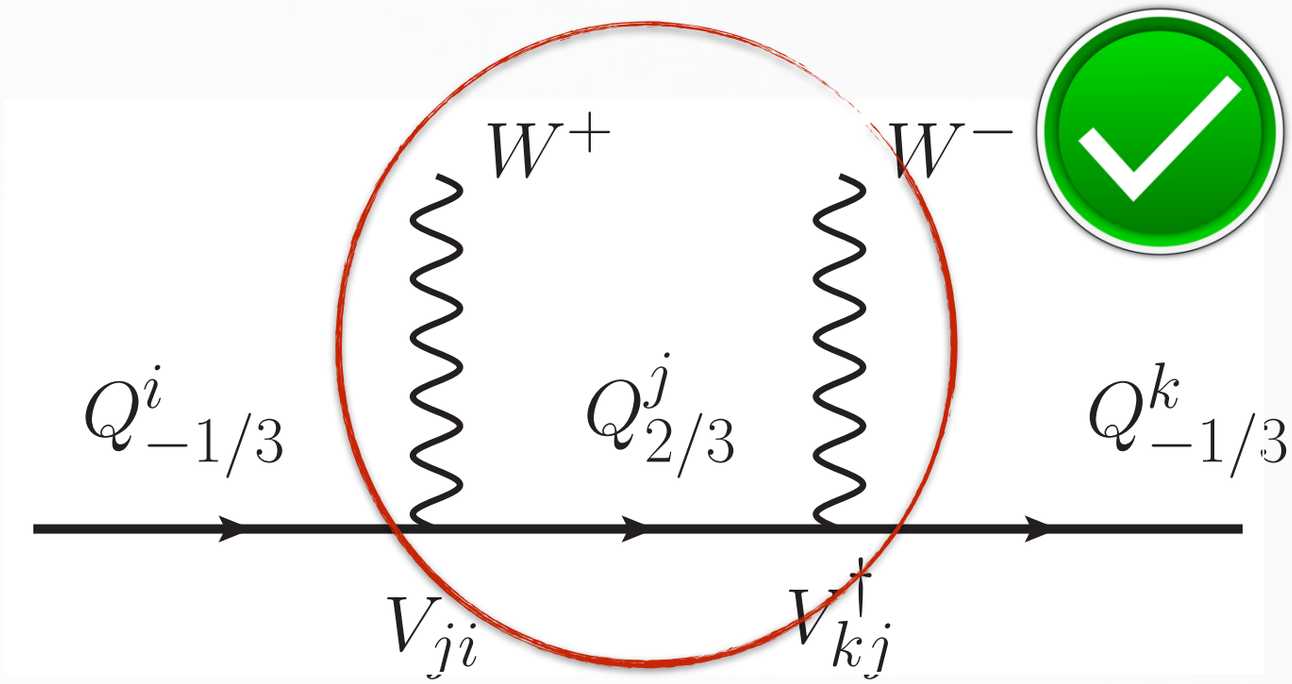
VRIJE UNIVERSITEIT BRUSSEL

Flavour changing neutral currents



Neutral Current

Flavour Changing



$$\parallel$$

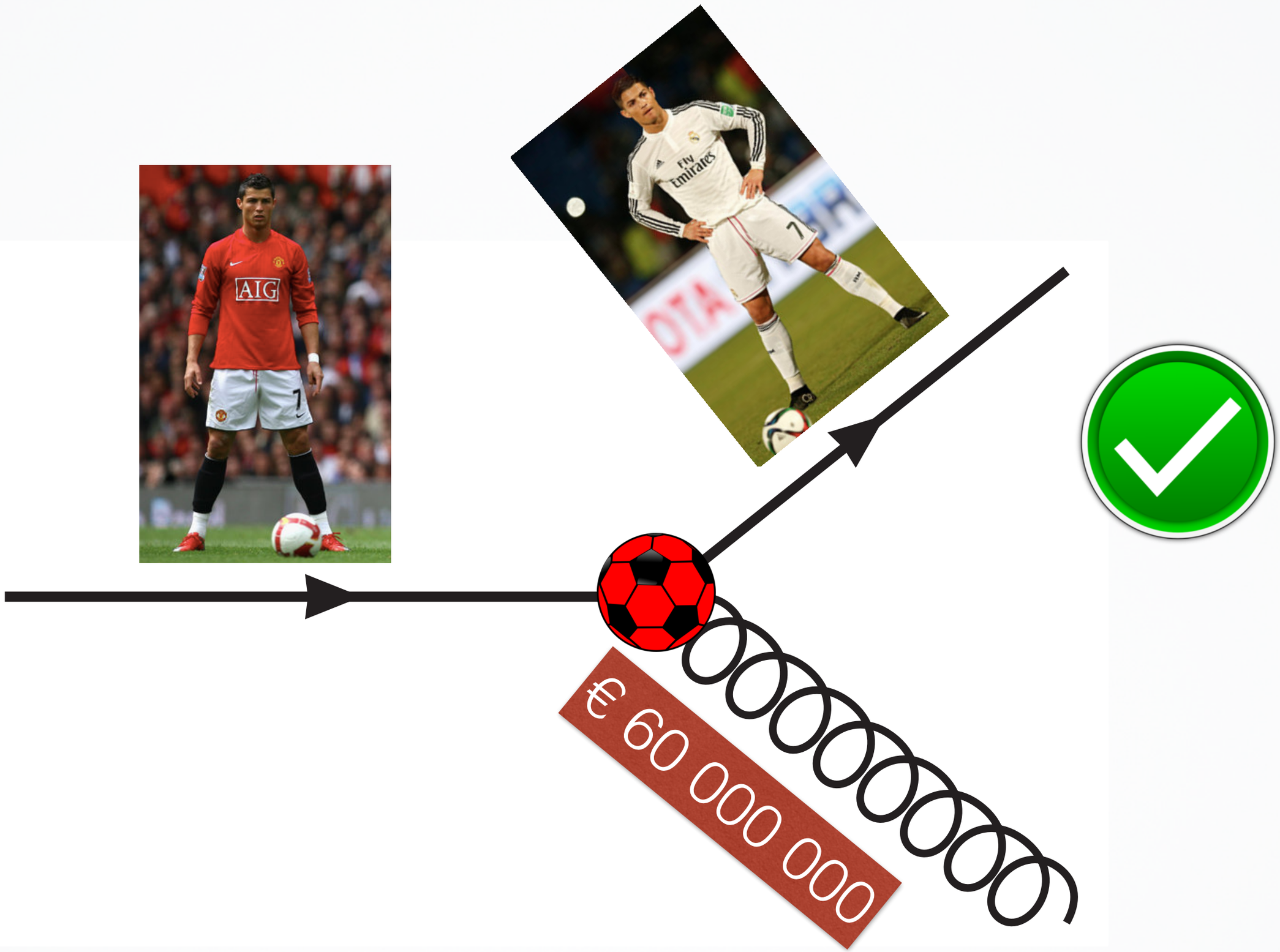
$$\sum_j V^\dagger_{kj} V_{ji} \frac{q}{q^2 - m_j^2} = \delta_{ki}$$

$m_j^2 \to m^2$

Quark mass degeneracy → no FCNC = Glashow-Iliopoulos-Maiani (GIM) mechanism (1970)

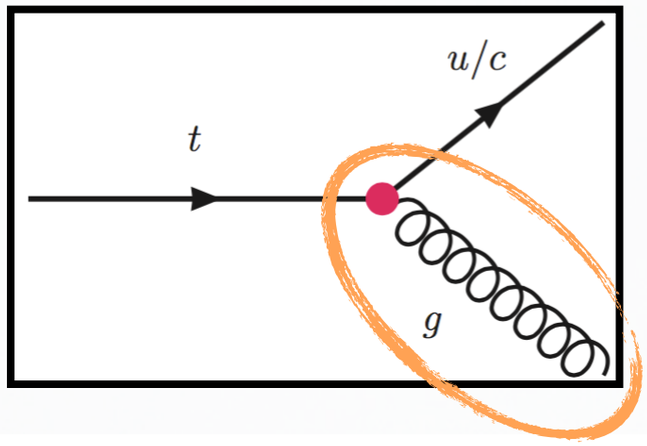
CKM matrix unitarity

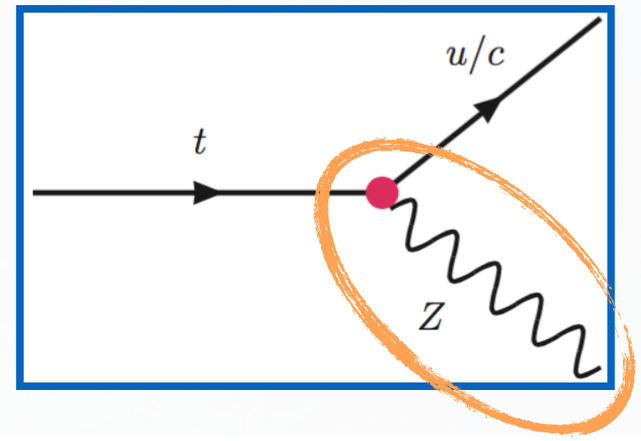
CR7 changing money current



FCNC with top quarks

Top + gluon





Top + Z

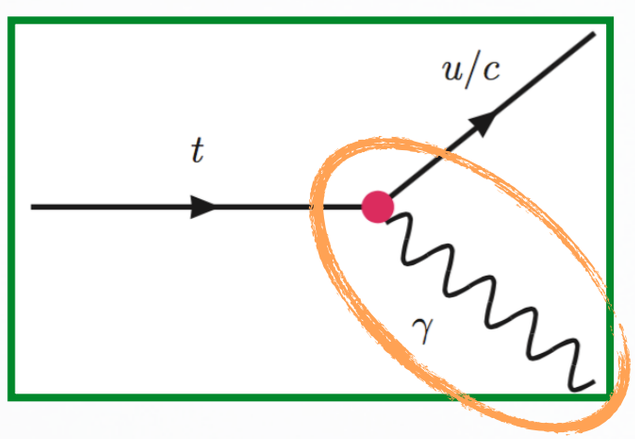
$$\mathcal{L} = \sum_{q=u,c} \Big[\sqrt{2} g_s \frac{\kappa_{gqt}}{\Lambda} \bar{t}\sigma^{\mu\nu} T_a (f^L_{Gq} P_L + f^R_{Gq} P_R) q G^a_{\mu\nu} +$$

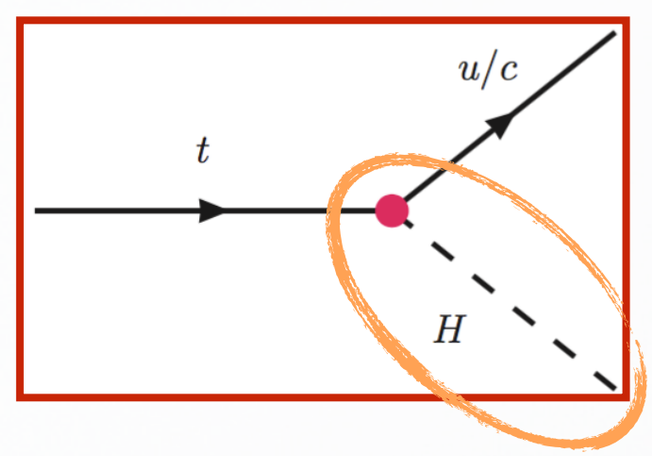
$$+ \frac{g}{\sqrt{2} c_W} \frac{\kappa_{zqt}}{\Lambda} \bar{t}\sigma^{\mu\nu} (f^L_{Zq} P_L + f^R_{Zq} P_R) q Z_{\mu\nu} + \frac{g}{4 c_W} \zeta_{zqt} \bar{t}\gamma^\mu (f^L_{Zq} P_L + f^R_{Zq} P_R) q Z_\mu -$$

$$- e \frac{\kappa_{\gamma qt}}{\Lambda} \bar{t}\sigma^{\mu\nu} (f^L_{\gamma q} P_L + f^R_{\gamma q} P_R) q A_{\mu\nu} +$$

$$+ \frac{g}{\sqrt{2}} \bar{t} \kappa_{Hqt} (f^L_{Hq} P_L + f^R_{Hq} P_R) q H \Big] + h.c.$$

Top + gamma





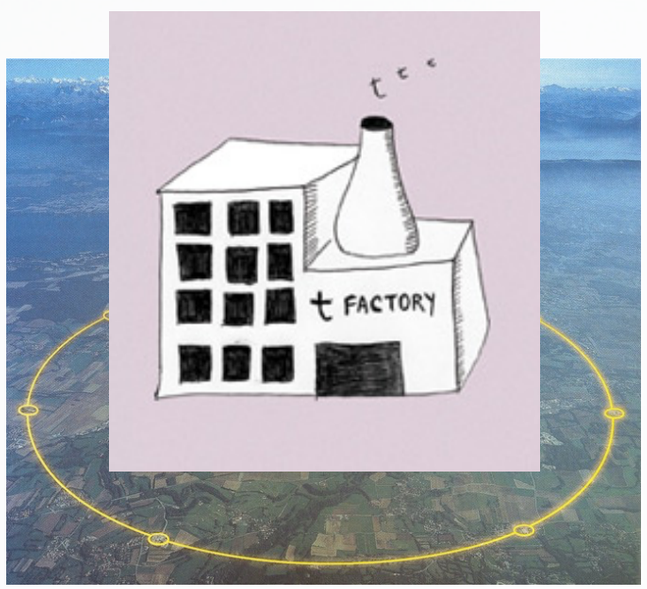
Top + Higgs

FCNC in SM and BSM

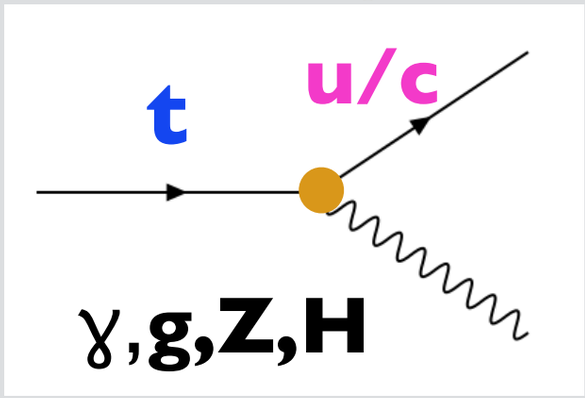
	SM	2HDM	MSSM	RS
BR(t→cg)	**10^{-12}**	10^{-8} - 10^{-4}	10^{-7} - 10^{-6}	10^{-10}
BR(t→cZ)	**10^{-14}**	10^{-10} - 10^{-6}	10^{-7} - 10^{-6}	10^{-5}
BR(t→cγ)	**10^{-14}**	10^{-9} - 10^{-7}	10^{-9} - 10^{-8}	10^{-9}
BR(t→cH)	**10^{-15}**	10^{-5} - 10^{-3}	10^{-9} - 10^{-5}	10^{-4}

K.Agashe et al., arXiv:1311.2028 (2013)

Other models that predict enhanced FCNC also exist, e.g. 1709.01690 (not included here)

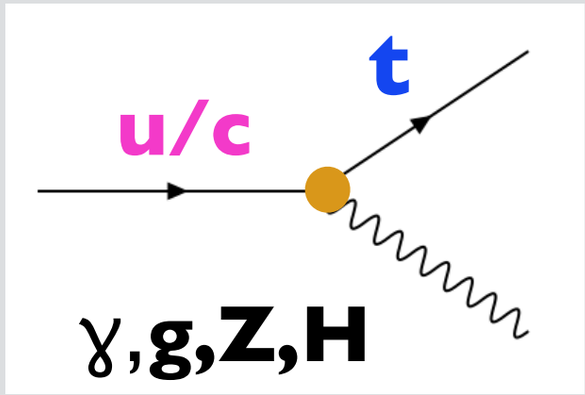


FCNC in decay



≈30M events

FCNC in production



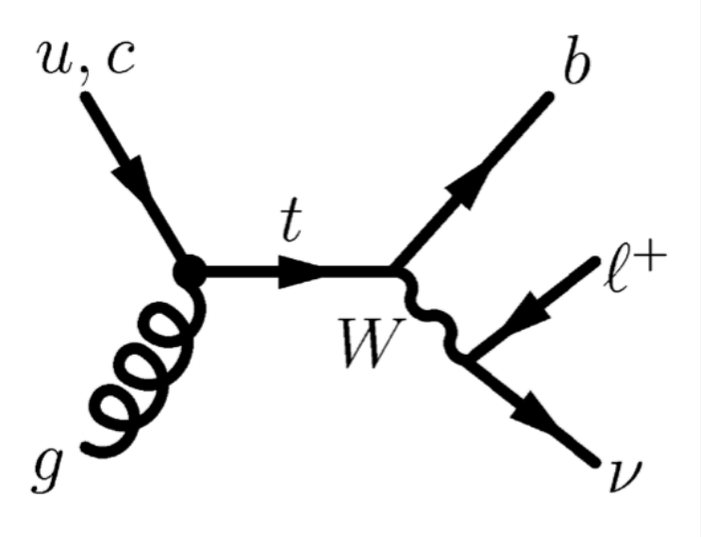
≈10M events

@13TeV, 40 fb^{-1}

Signal generation in Run 2
***ATLAS*: aMC@NLO+TopFCNC@NLO+Pythia8**
***CMS*: MadGraph(LO)+Pythia8**

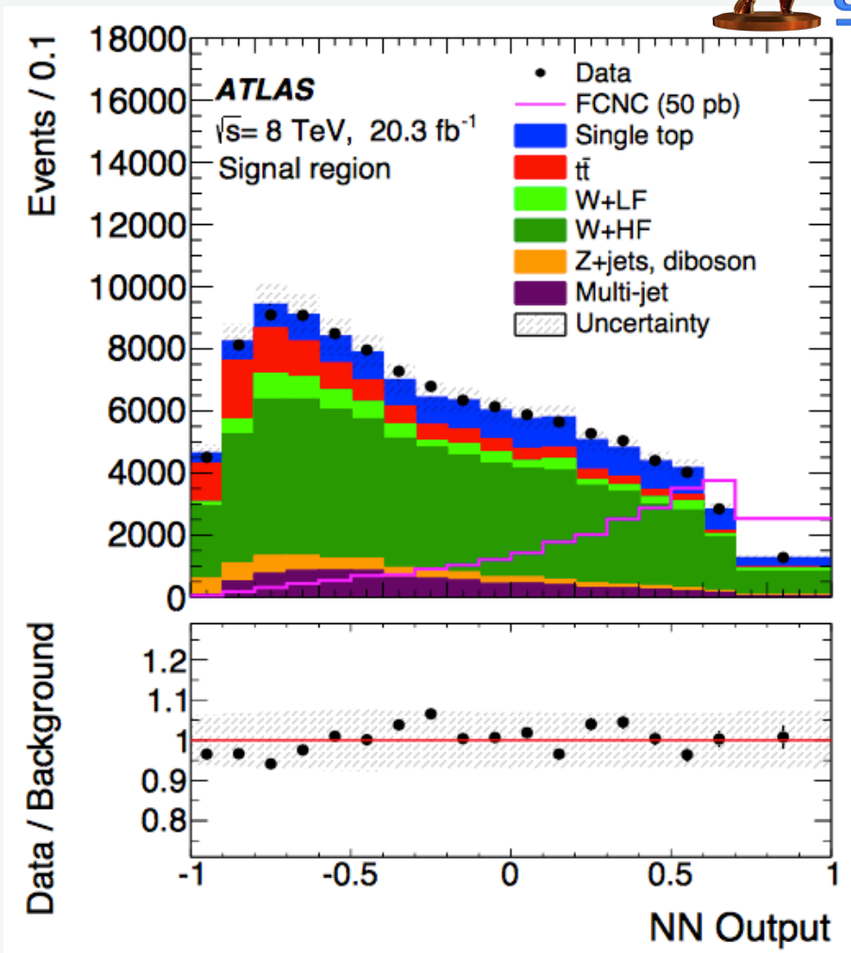
Search for top-gluon FCNC in single top

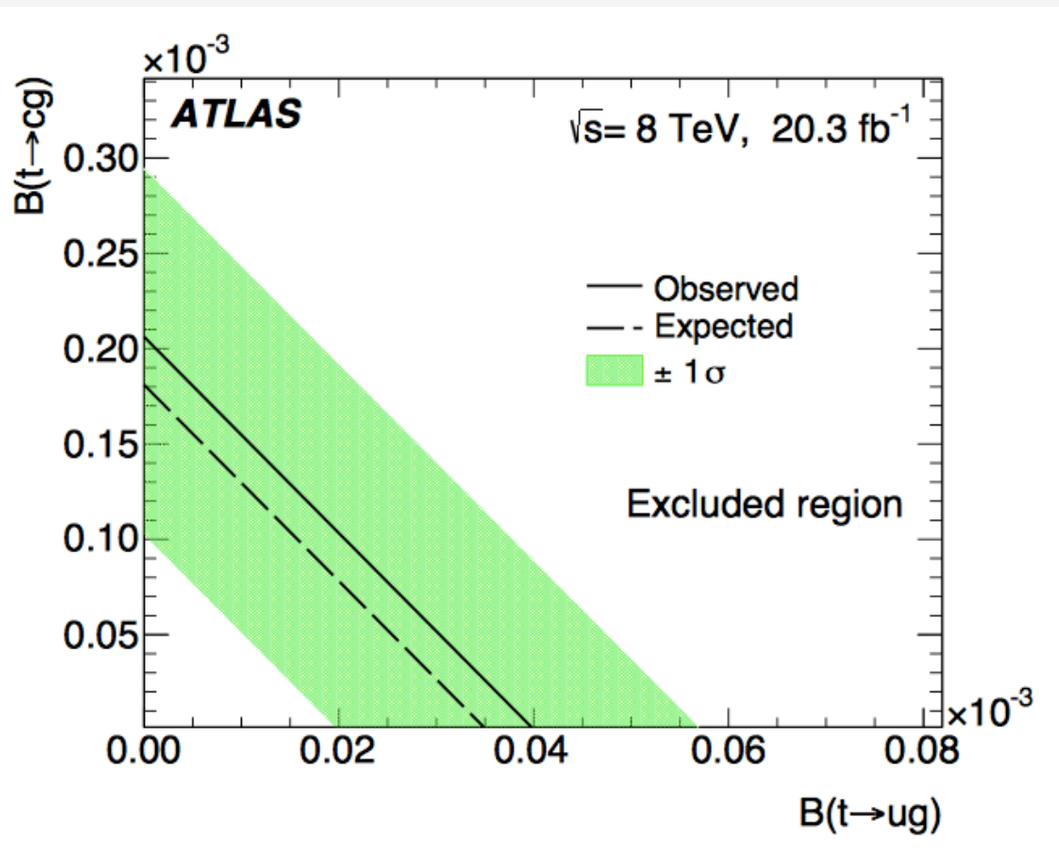
- Search for top-gluon FCNC in **single top** events
- Event topology is exclusive top leptonic decay: isolated lepton, missing E_T, = 1 b jet
- **W+jets** suppressed with NN
- **Best limits on B(t→gc)**



Eur. Phys. J. C (2016) 76:55

20 fb⁻¹, 8 TeV



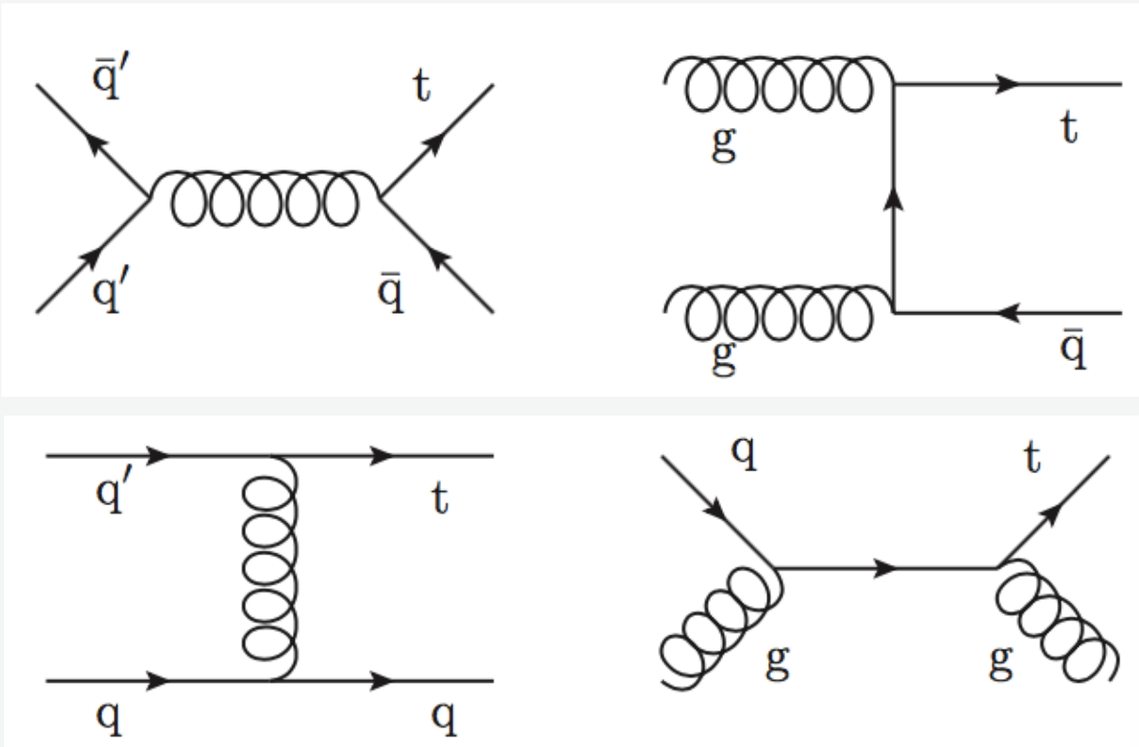


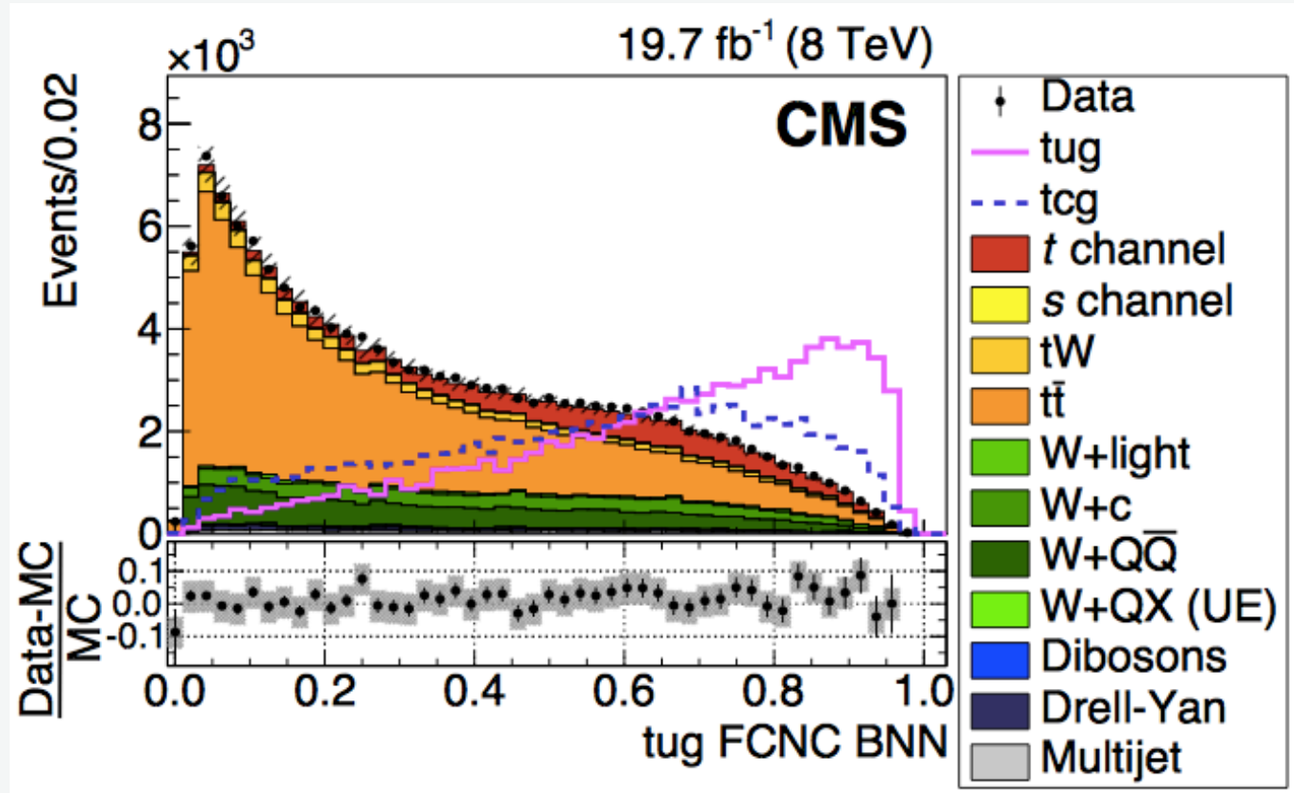
B(t→**g**u) < 0.0040 % (obs)
0.0035 % (exp)
B(t→**g**c) < 0.020 % (obs)
0.018 % (exp)

Search for top-gluon FCNC in single top

JHEP 02 (2017) 028

5+20 fb^{-1}, 7+8 TeV

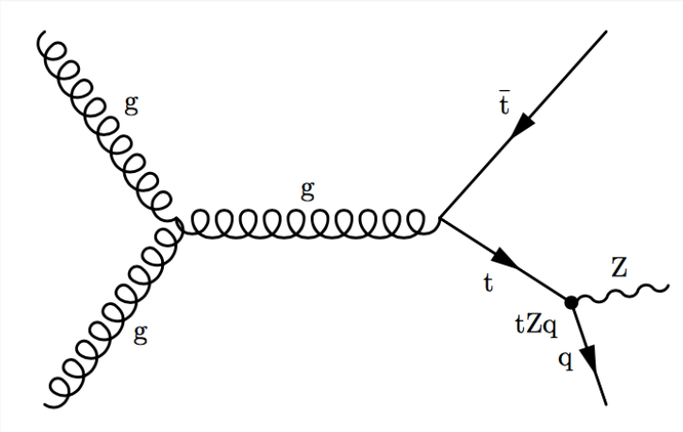


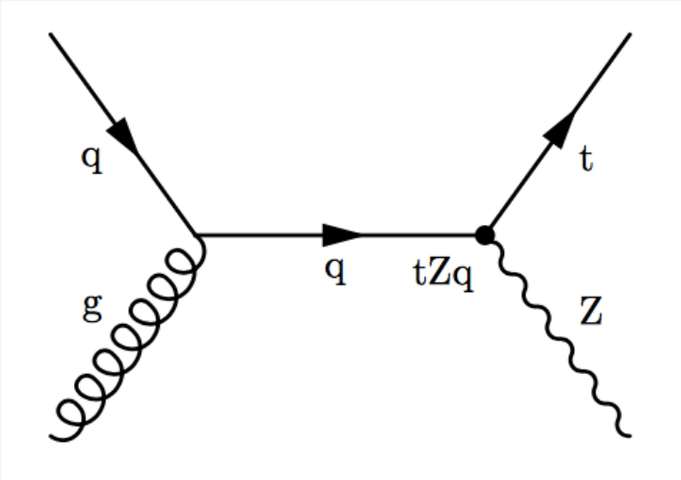


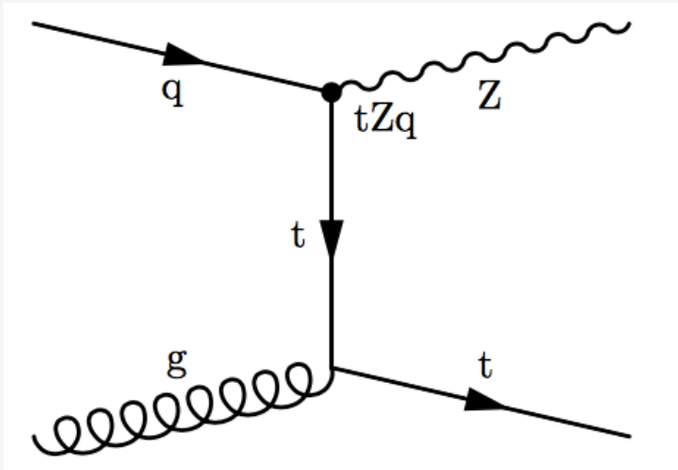
- Search for top-gluon FCNC in **single top + jet** events
- Event topology: isolated lepton, missing E_T, = 1 b jet, = 1 non-b jet
- **ttbar** suppressed with BNN
- **Best limits on B(t→gu)**

B(t→**g**u) < 0.0020 % (obs)
0.0028 % (exp)
B(t→**g**c) < 0.041 % (obs)
0.028 % (exp)

Search for top-Z FCNC in ttbar and single top



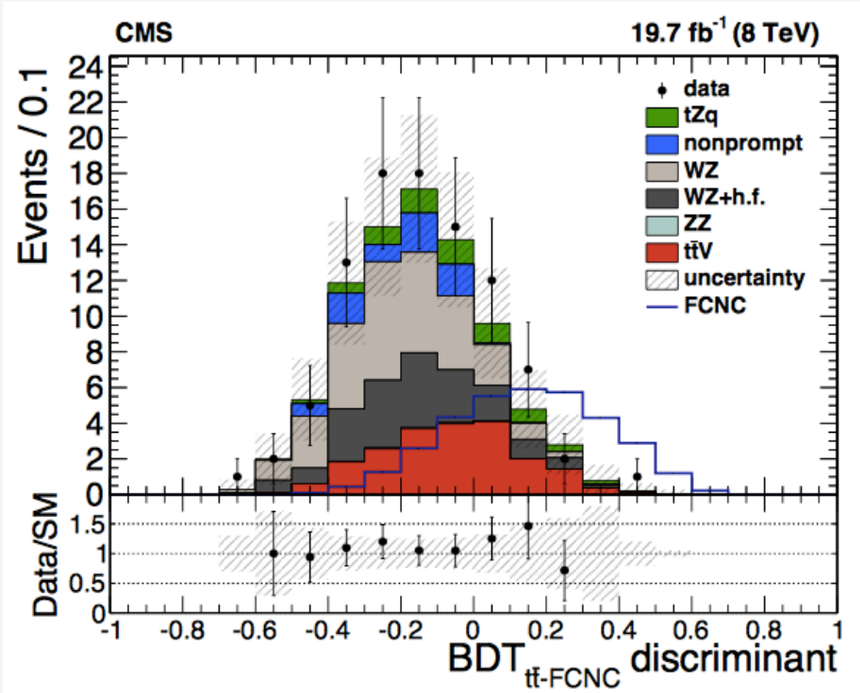


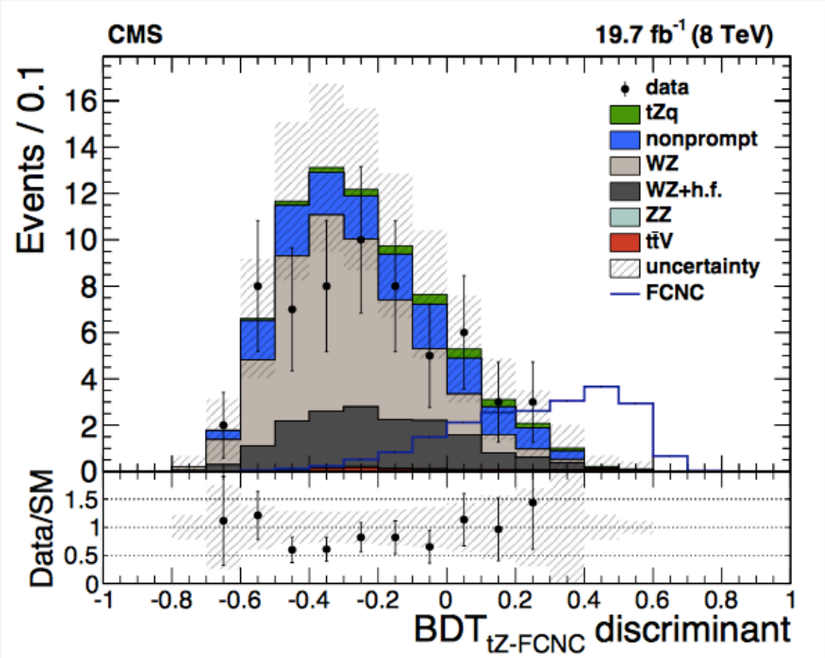


- Search for top-Z FCNC in **single top + ttbar** events
- Event topology: three isolated leptons, missing E_T, ≥ 1 b jet, ≥ 1 non-b jet (for ttbar)
- **WZ+jets, fake, ttbar+V** suppressed with BDT
- **First top-Z search to include single top**

JHEP 07 (2017) 003

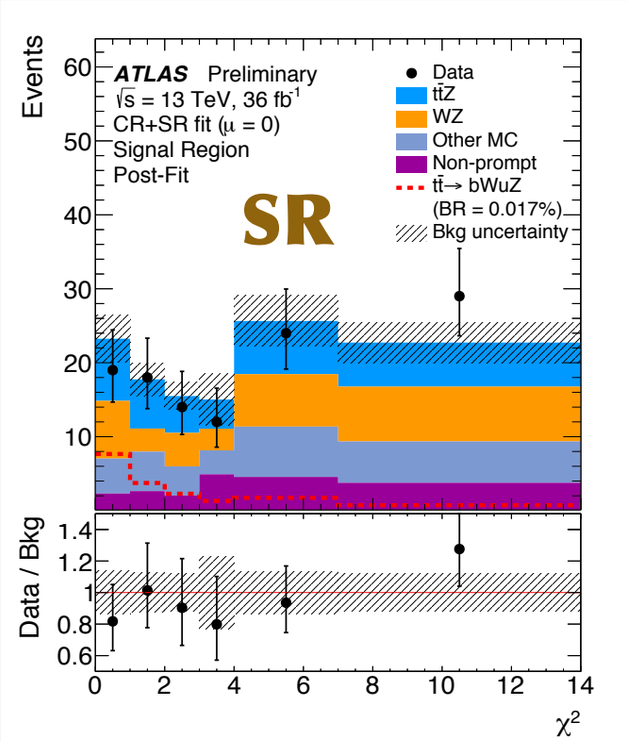
20 fb^{-1}, 8 TeV

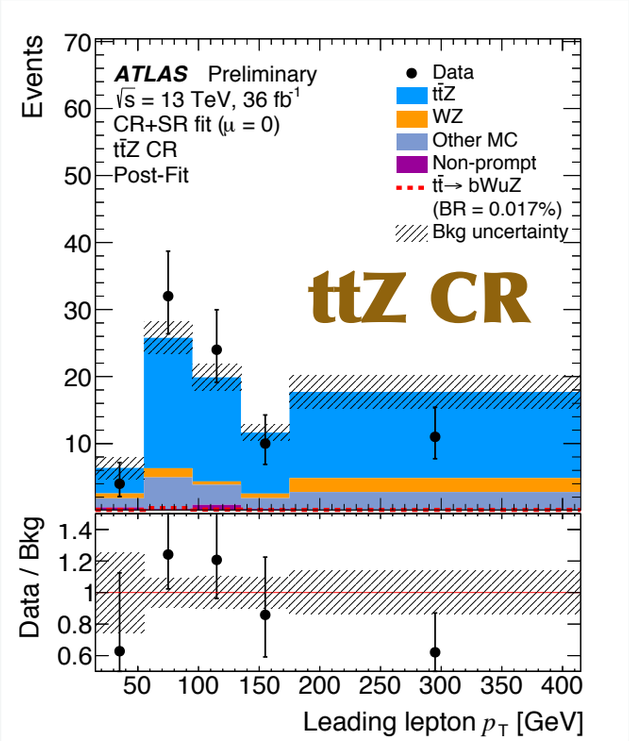




B(t→**Z**u) < 0.022 % (obs)
0.027 % (exp)
B(t→**Z**c) < 0.049 % (obs)
0.118 % (exp)

Search for top-Z FCNC in ttbar





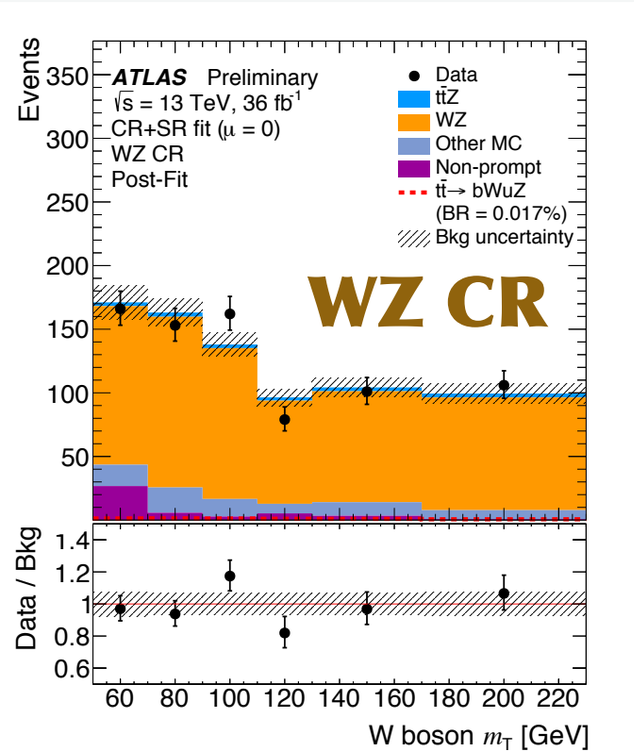
NEW

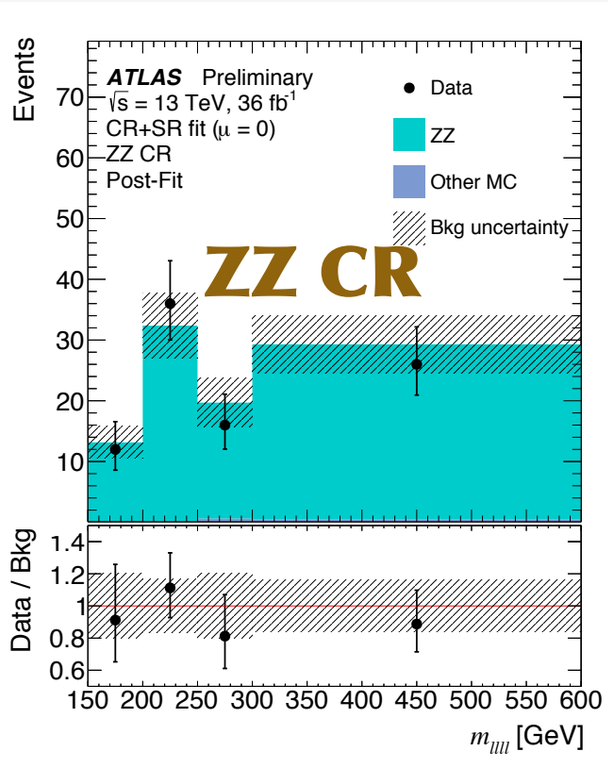
13 TeV

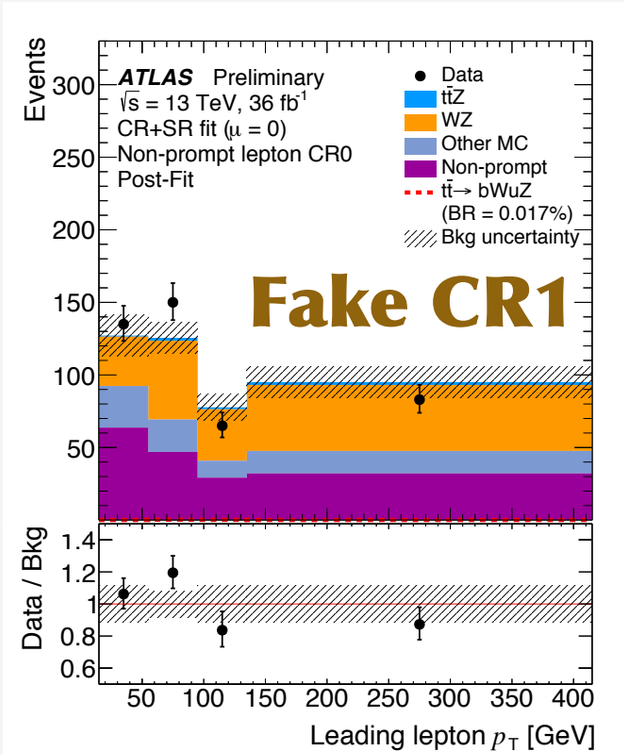
36 fb-1, 13 TeV

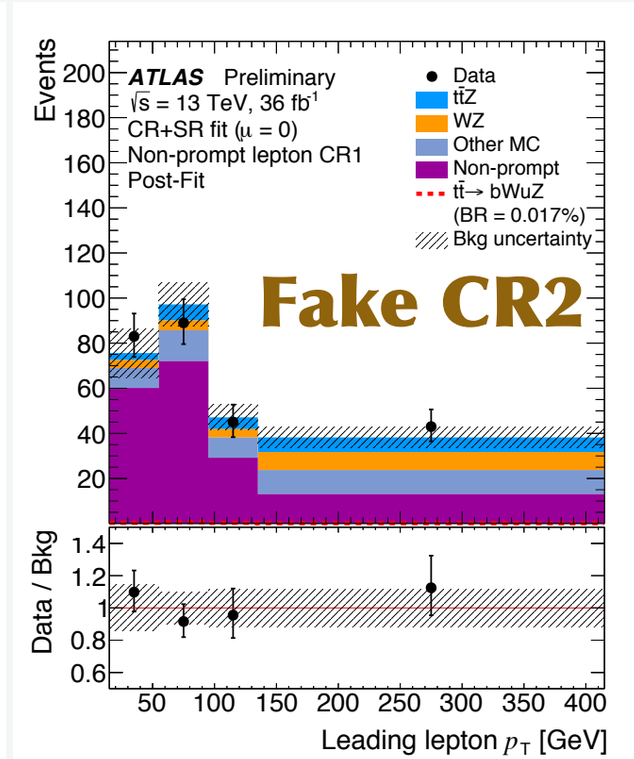
ATLAS

- Search for top-Z FCNC in **ttbar** events
- Event topology: three isolated leptons, missing E_T, = 1 b jet, ≥ 1 non-b jet
- Simultaneous fit in CRs (**WZ+jets, ZZ+jets, fake, ttbar+Z**) and SR
- **Best limits on B(t→Zq)**





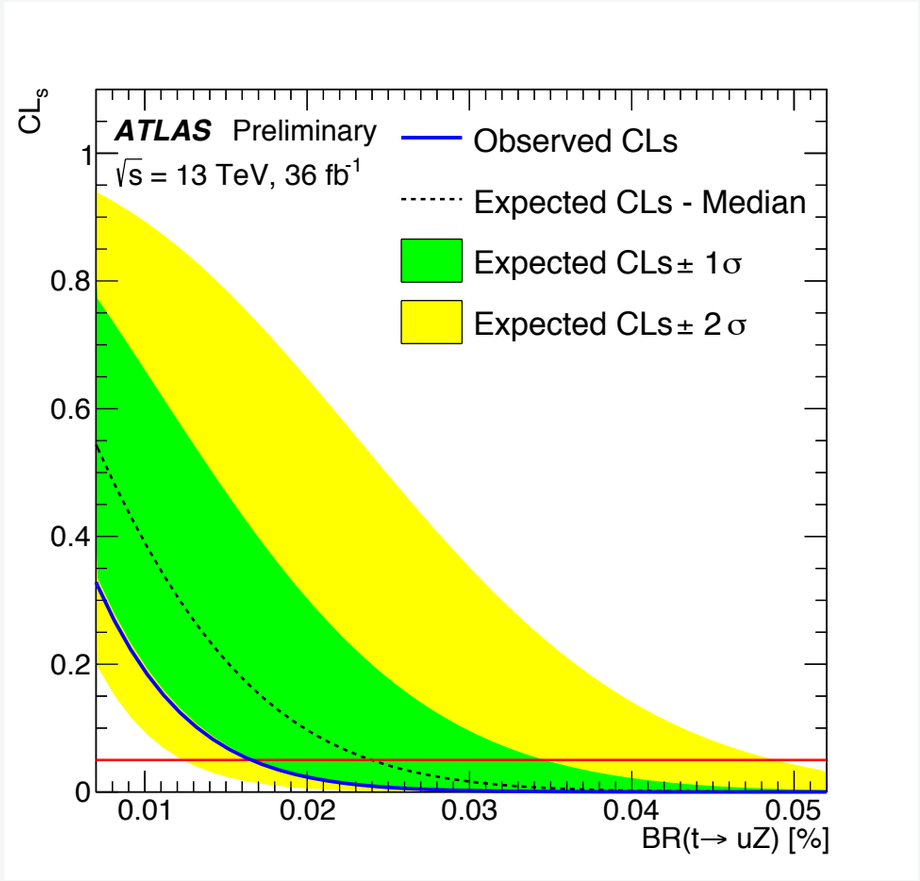


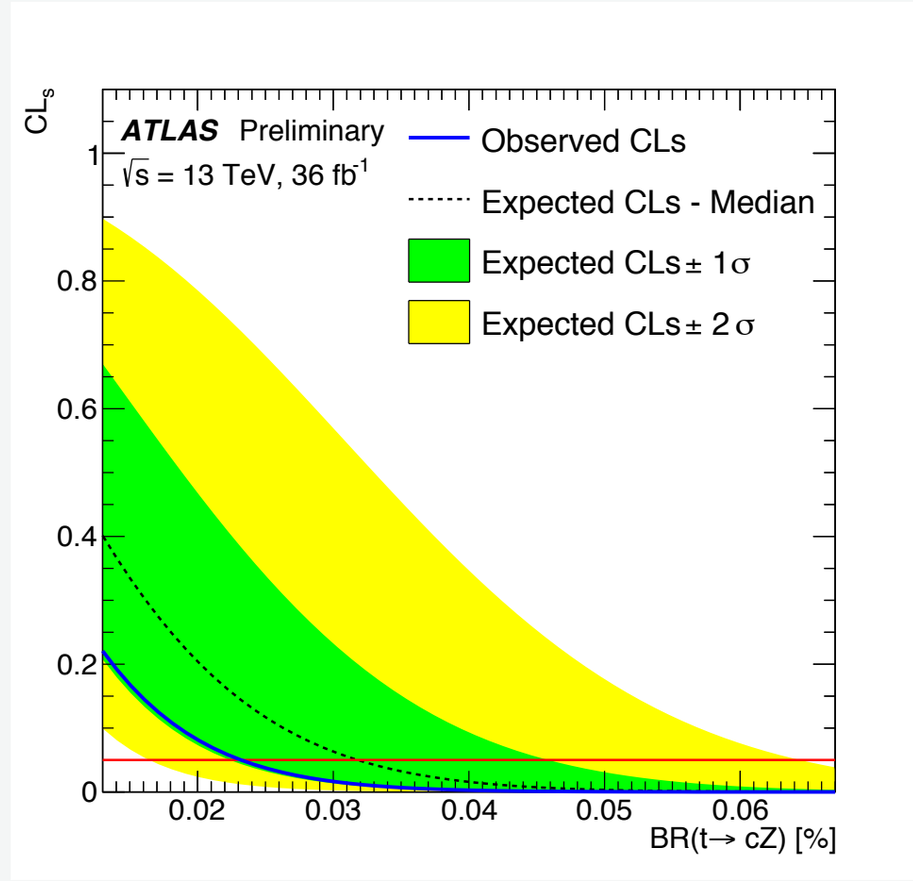


Search for top-Z FCNC in ttbar

Also presented in poster by Archil Durglishvili

36 fb^{-1}, 13 TeV



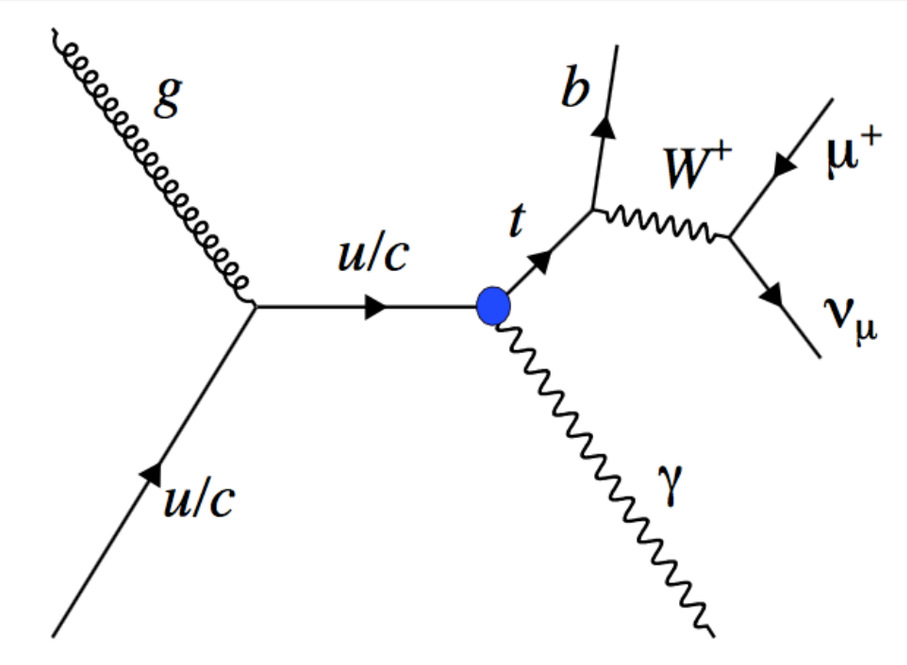


NEW

13 TeV

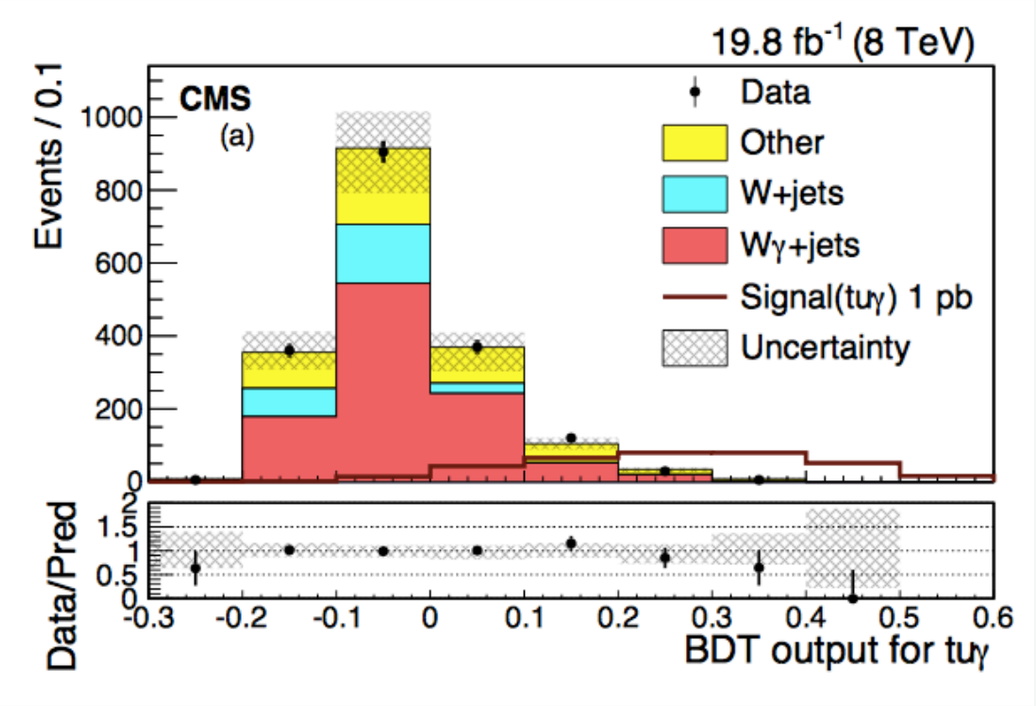
B(t→**Z**u) < 0.017 % (obs)
0.024 % (exp)
B(t→**Z**c) < 0.023 % (obs)
0.032 % (exp)

Search for top-γ FCNC in single top



JHEP 04 (2016) 035

20 fb^{-1}, 8 TeV



- Search for top-γ FCNC in **single top** events
- Event topology: isolated muon, isolated photon, missing E_T, ≤ 1 b jet
- **W(+γ)** suppressed with BDT
- **Best and only limits on B(t→γq)**

B(t→γu) < 0.013 % (obs)
0.019 % (exp)
B(t→γc) < 0.200 % (obs)
0.170 % (exp)

Fiducial region	Channel	N_{obs}	N_{SM}	ϵ	$\sigma_{fid}^{95\%}$ (fb)
Basic selection (Table 3)	tuγ	1794	1805 ± 215	0.16	122
	tcγ			0.19	103
Basic selection and $N_{b\,jet} = 1$	tuγ	275	258 ± 49	0.11	47
	tcγ			0.14	39

Search for top-H FCNC in ttbar

- Search for top-H FCNC in **ttbar** events
- Event topology: = 2 isolated photons
  leptonic: isolated lepton, missing E_T, = 1 b jets, ≥ 2 jets
  hadronic: no isolated leptons, ≥ 1 b jets, ≥ 4 jets
- Discrimination against **non-resonant γγ+jets, ttbar+γ, Wγγ** with m(γγ)
- **Best limits on B(t→Hq)**

NEW 13 TeV

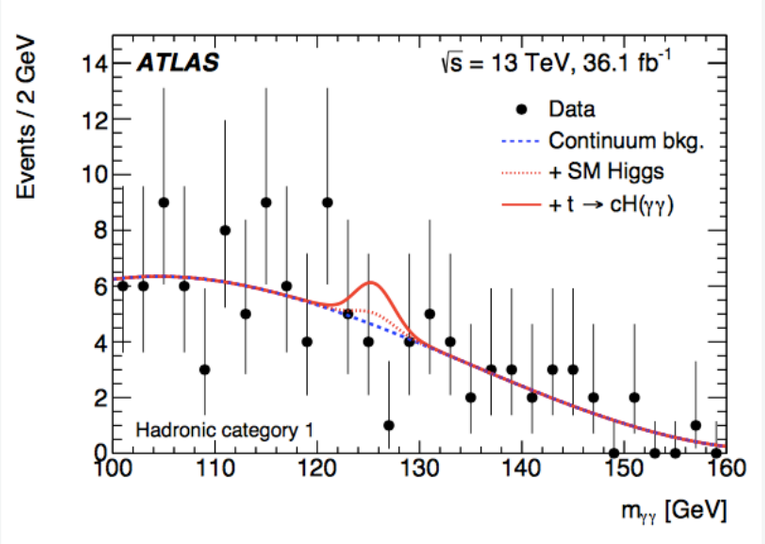
H→γγ

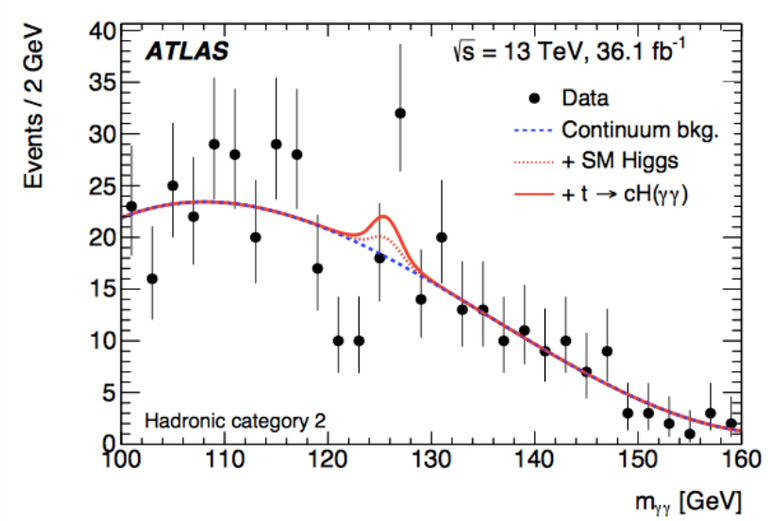
arXiv:1707.01404

36 fb^{-1}, 13 TeV

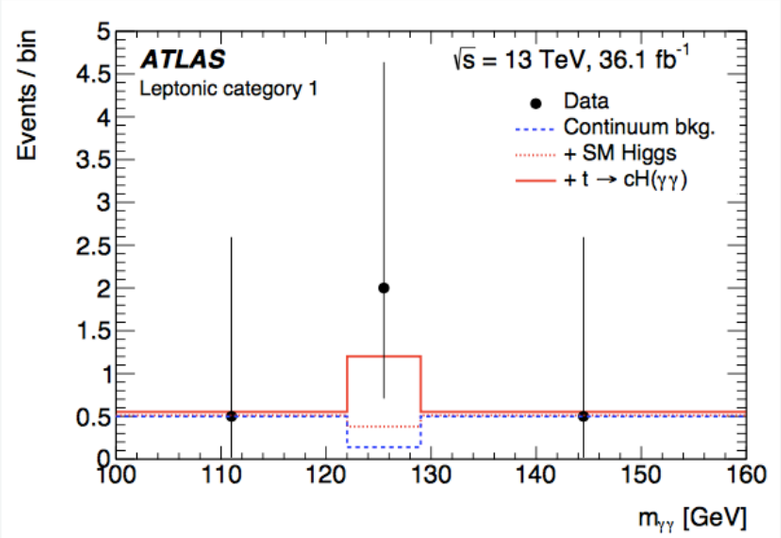
$M_t \in$ [120,200] GeV | **$M_t \notin$ [120,200] GeV**

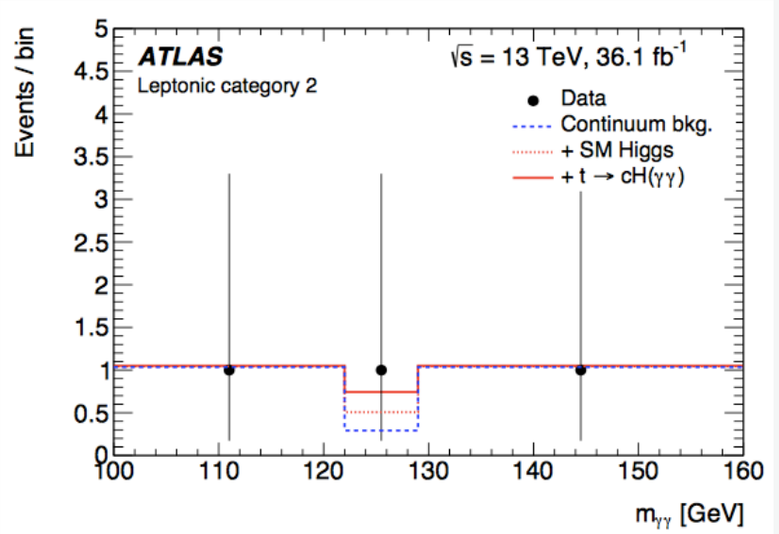
hadronic





leptonic





Search for top-H FCNC in ttbar

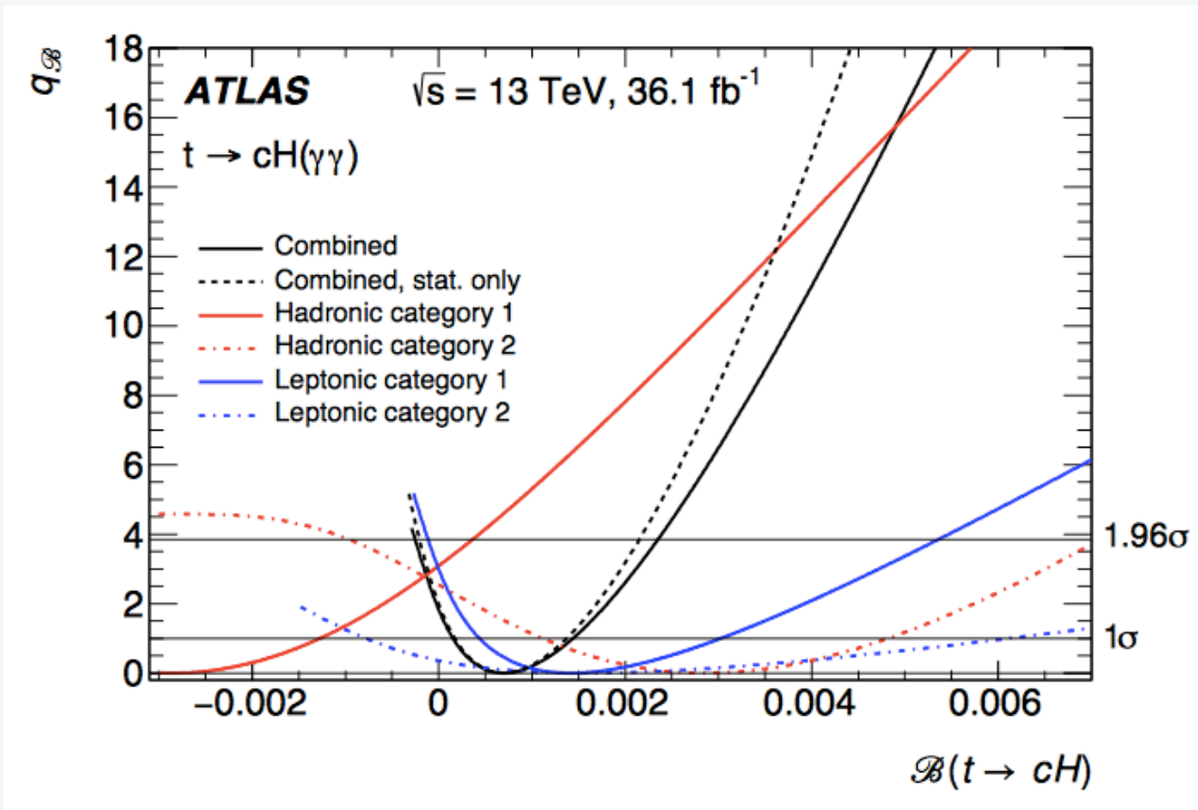
NEW

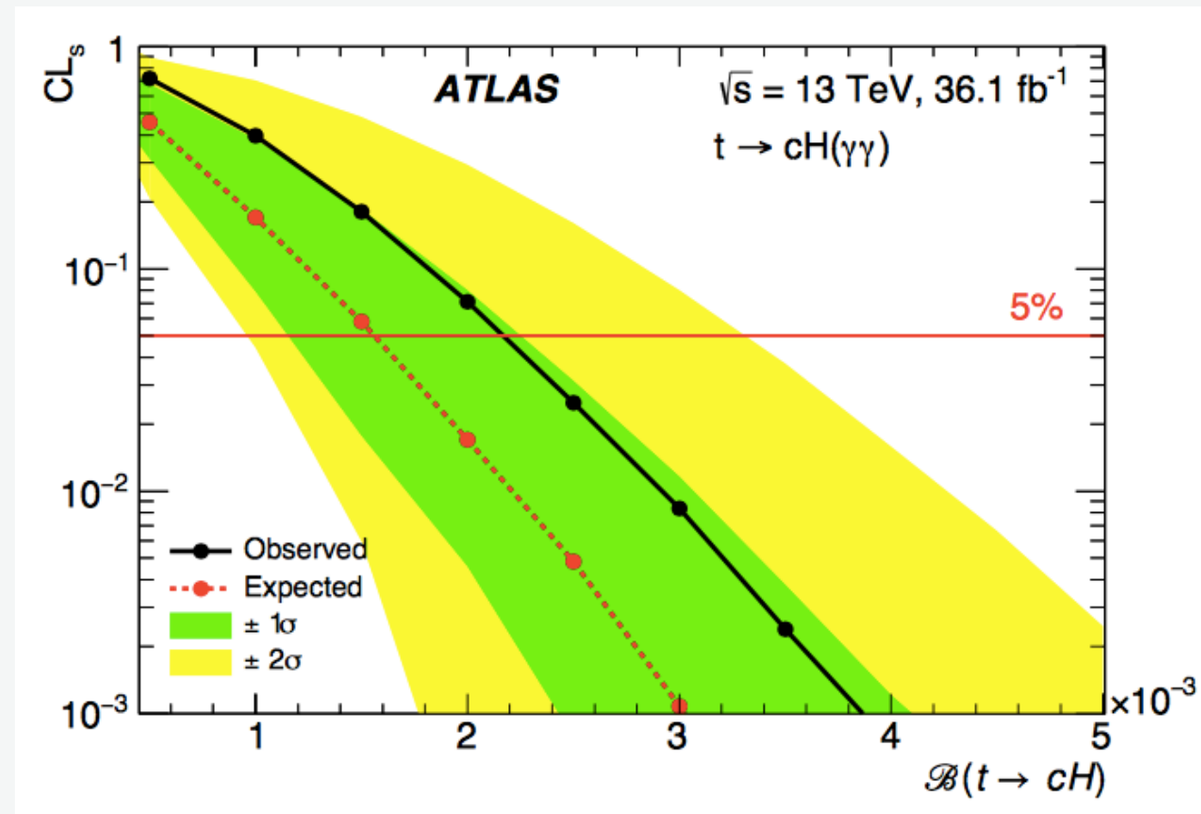
13 TeV

$H \rightarrow \gamma\gamma$

arXiv:1707.01404

36 fb^{-1}, 13 TeV





B(t→**H**u) < 0.24 % (obs)
0.17 % (exp)
B(t→**H**c) < 0.22 % (obs)
0.16 % (exp)

Search for top-H FCNC in ttbar and single top

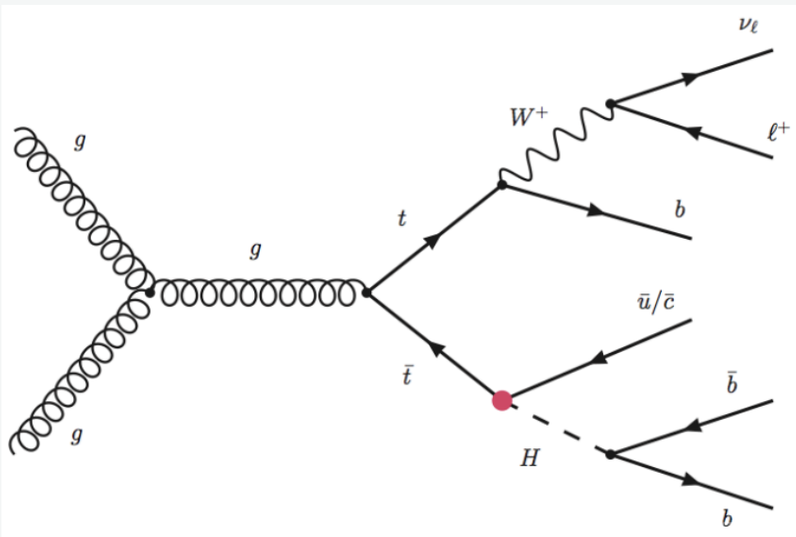
- Search for top-H FCNC in **single top + ttbar** events
- Event topology: isolated lepton, missing E_T, ≥ 2 b jets, ≥ 1 non-b jet
- **ttbar+jets** suppressed with BDT
- **First top-H search to include single top**

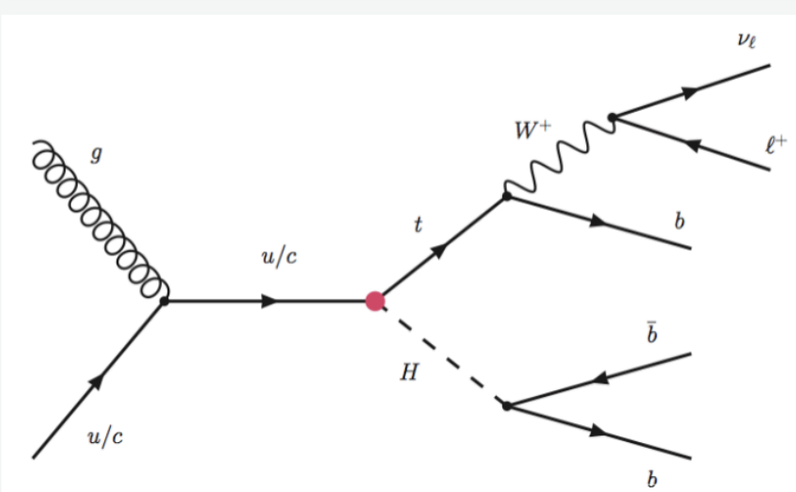
NEW 13 TeV

H→bb

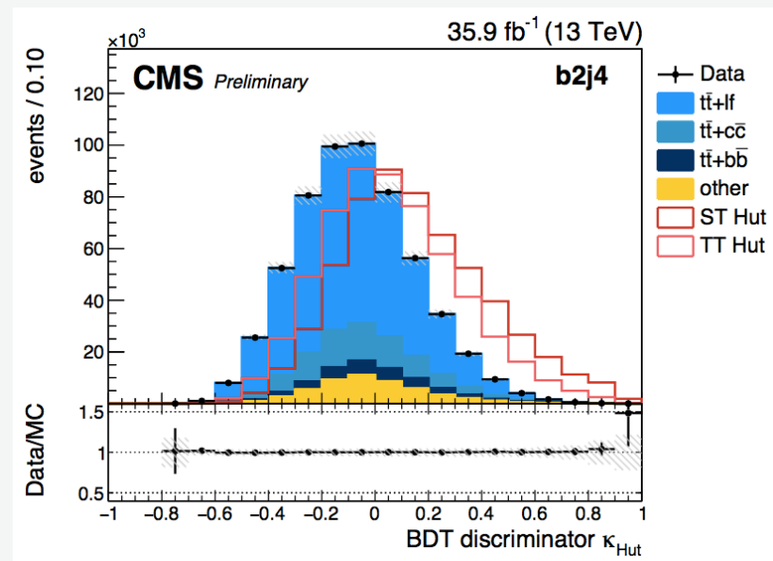
TOP-17-003

36 fb^{-1}, 13 TeV

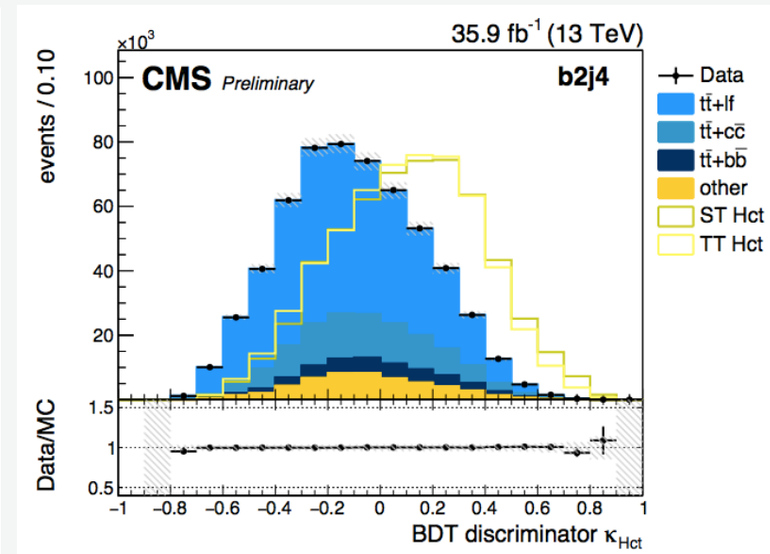


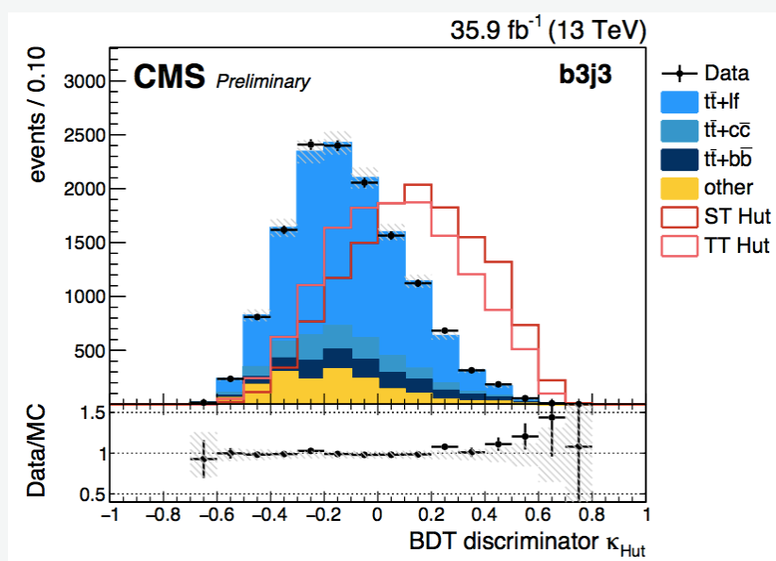


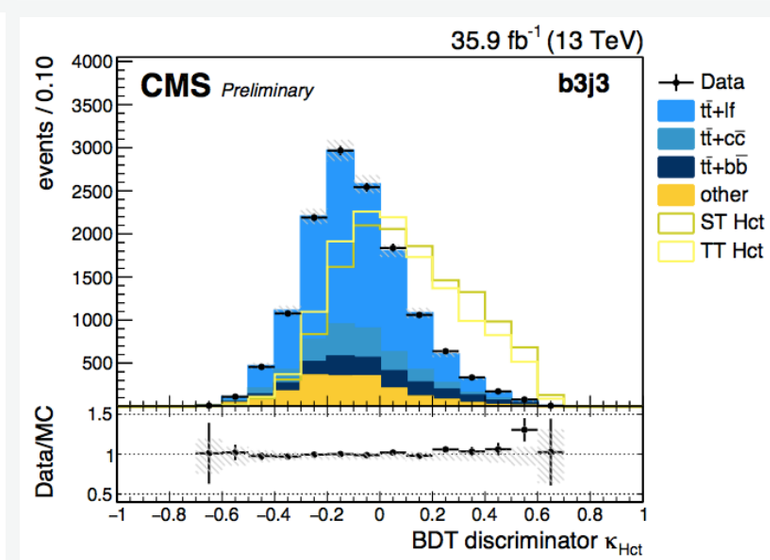
Hut



Hct







Search for top-H FCNC in ttbar and single top

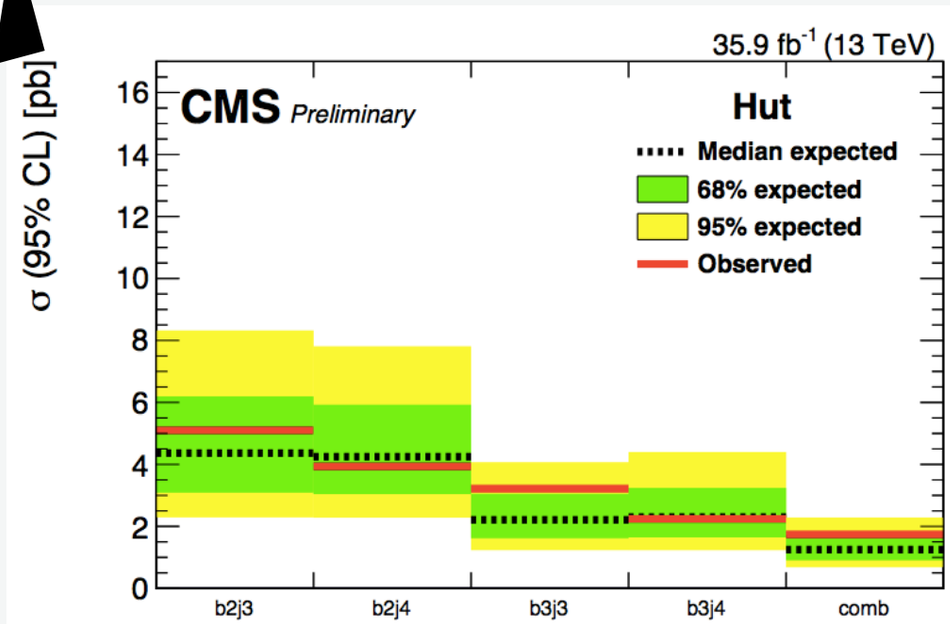
NEW

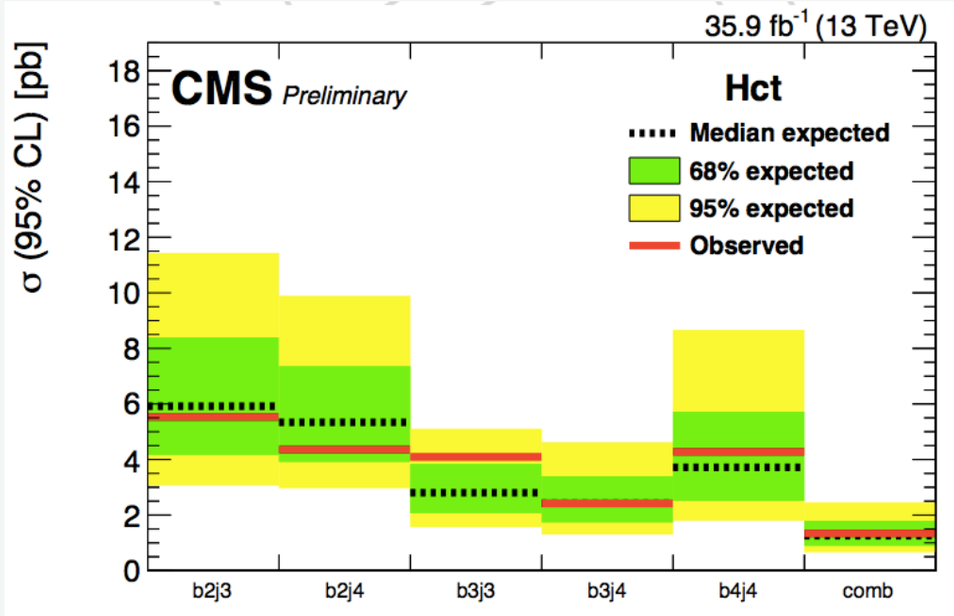
13 TeV

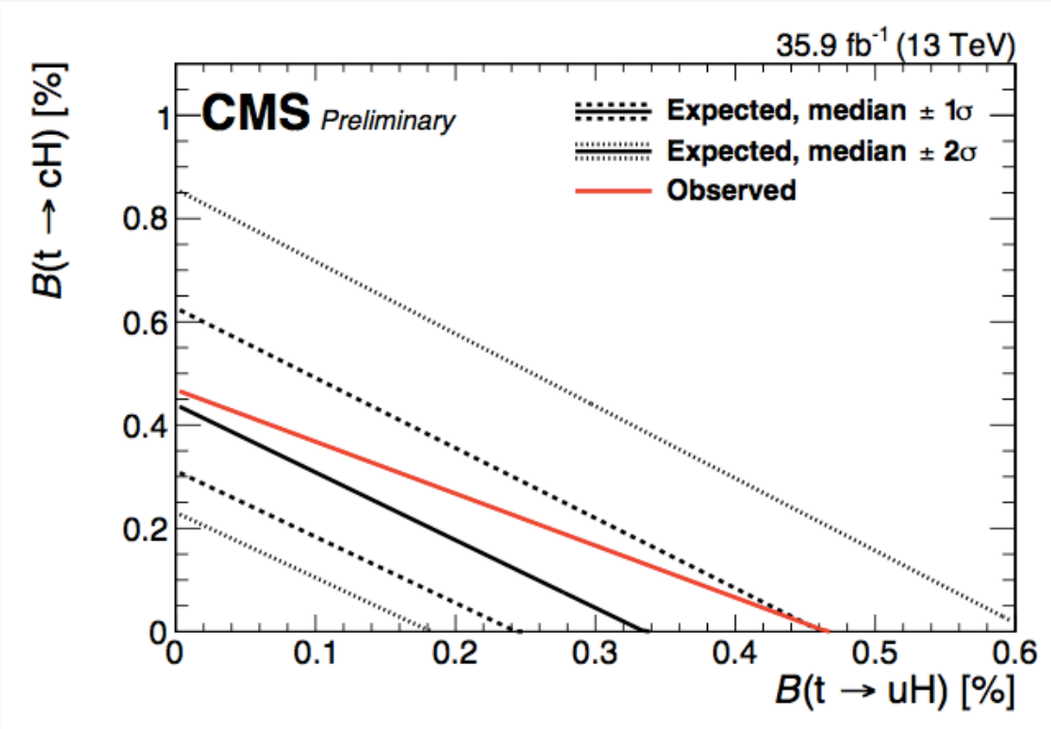
H→bb

TOP-17-003

36 fb^{-1}, 13 TeV





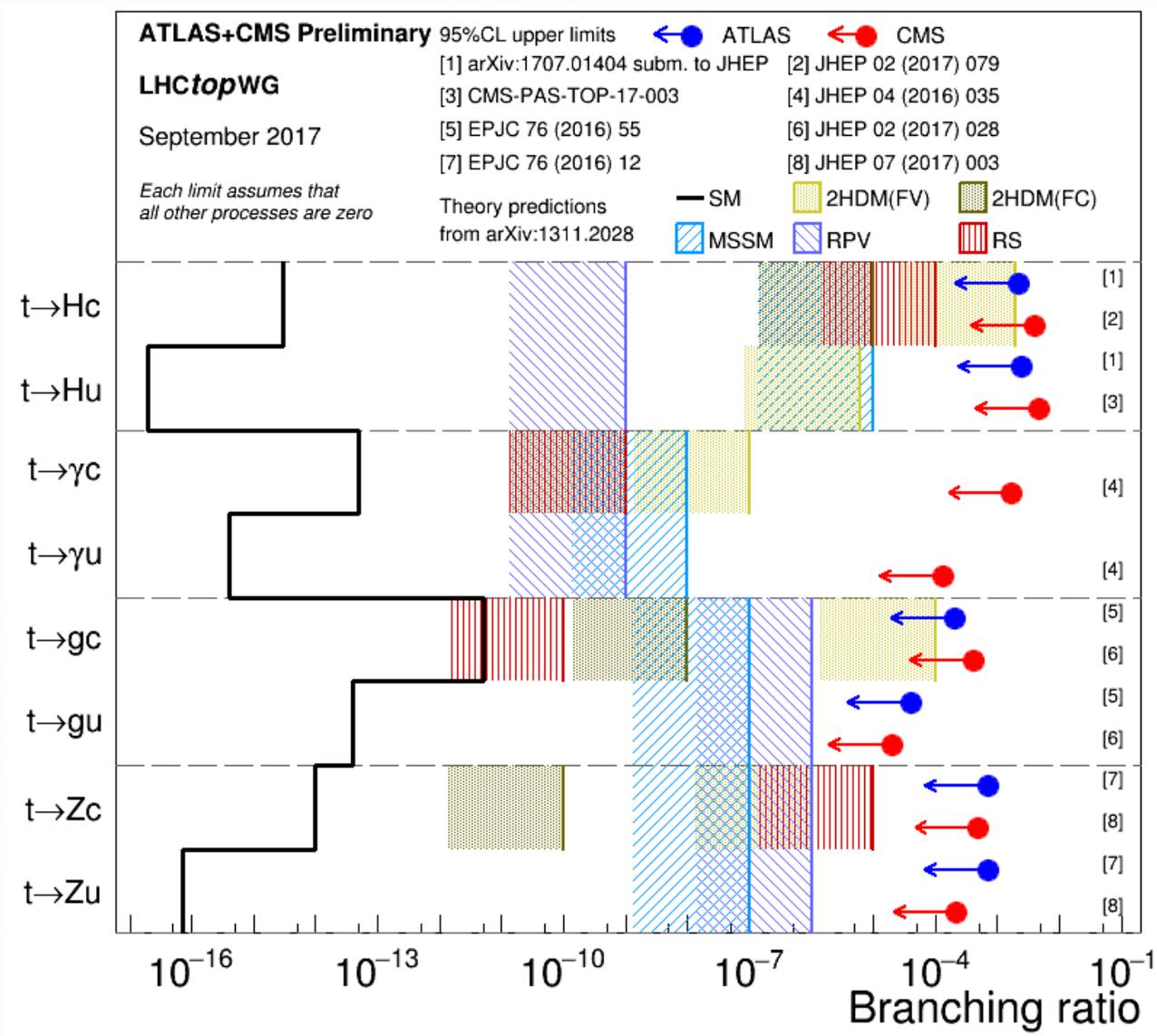


B(t→**H**u) < 0.47 % (obs)
0.34 % (exp)
B(t→**H**c) < 0.47 % (obs)
0.44 % (exp)

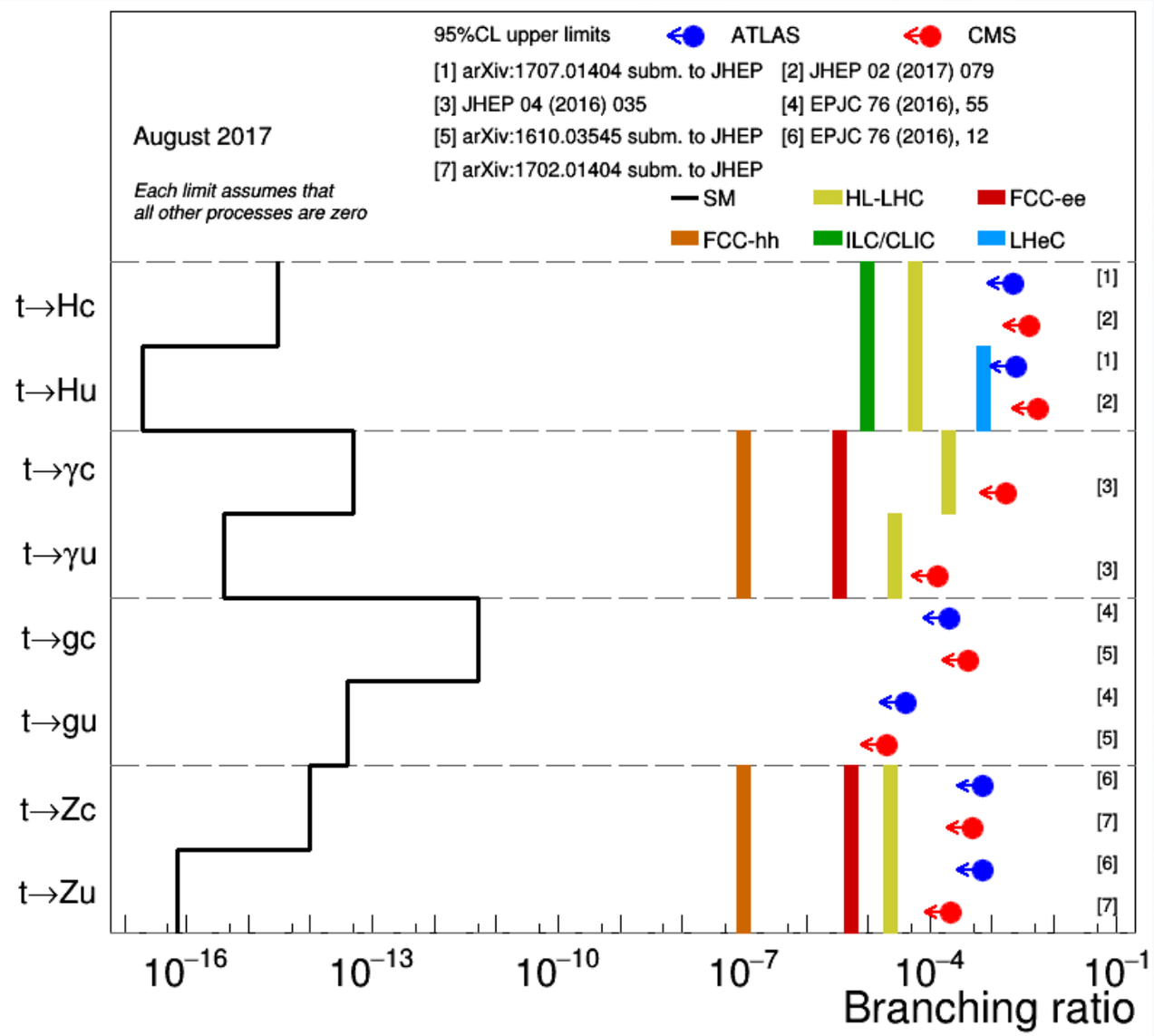
Also presented in poster by Predrag Cirkovic

Summary of top FCNC limits

BSM predictions



Future projections



Conclusion

- FCNC → unique playground for precise tests of the SM and to search for BSM physics
- 13 TeV data → significantly improve 8 TeV FCNC limits
- LHC is a top factory → a lot of opportunities for FCNC searches with top quarks

FCNC !
FCNC !
FCNC !

Search for top-H FCNC in ttbar and single top

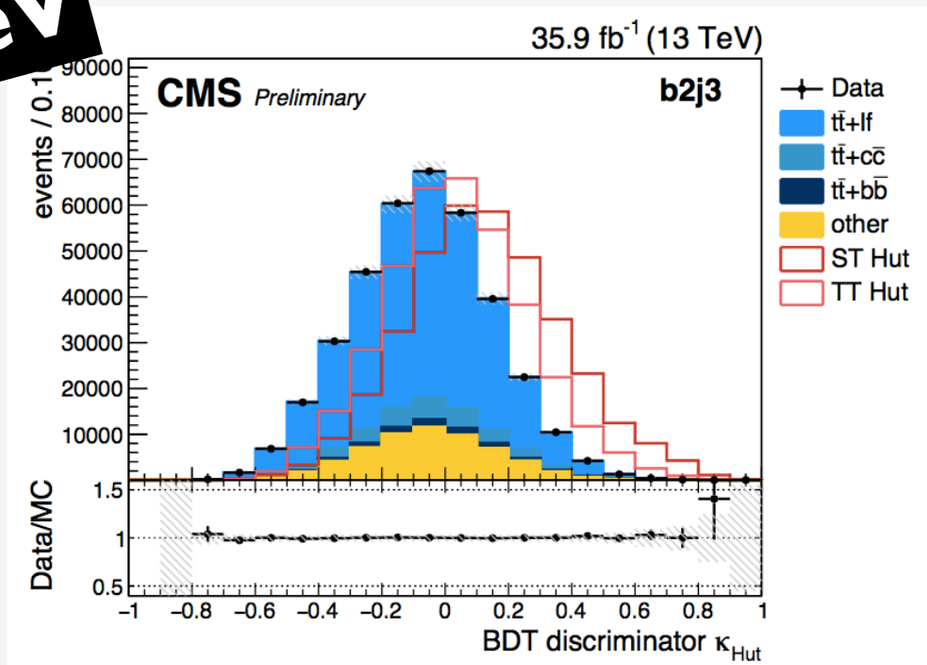
NEW

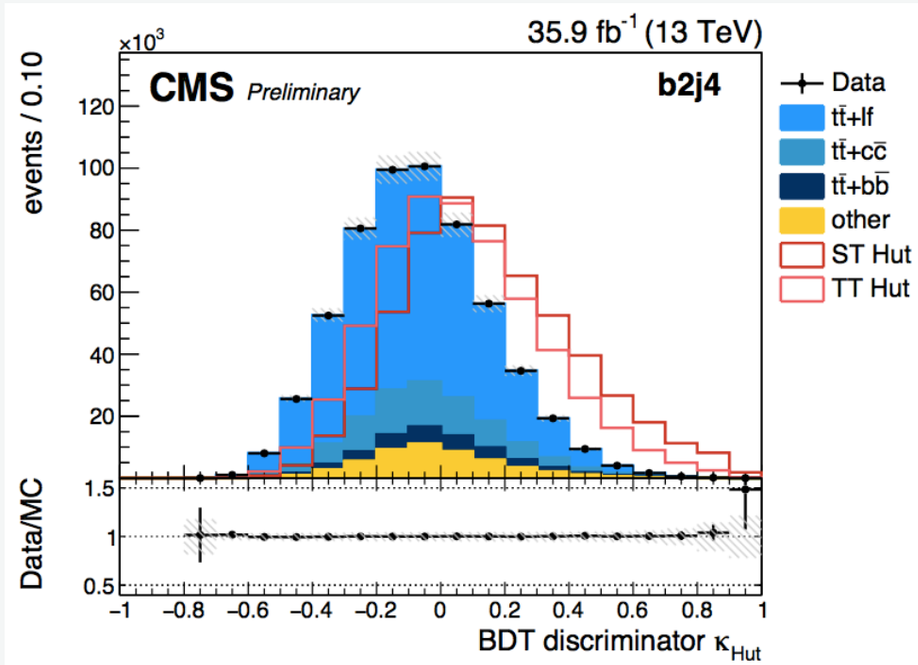
13 TeV

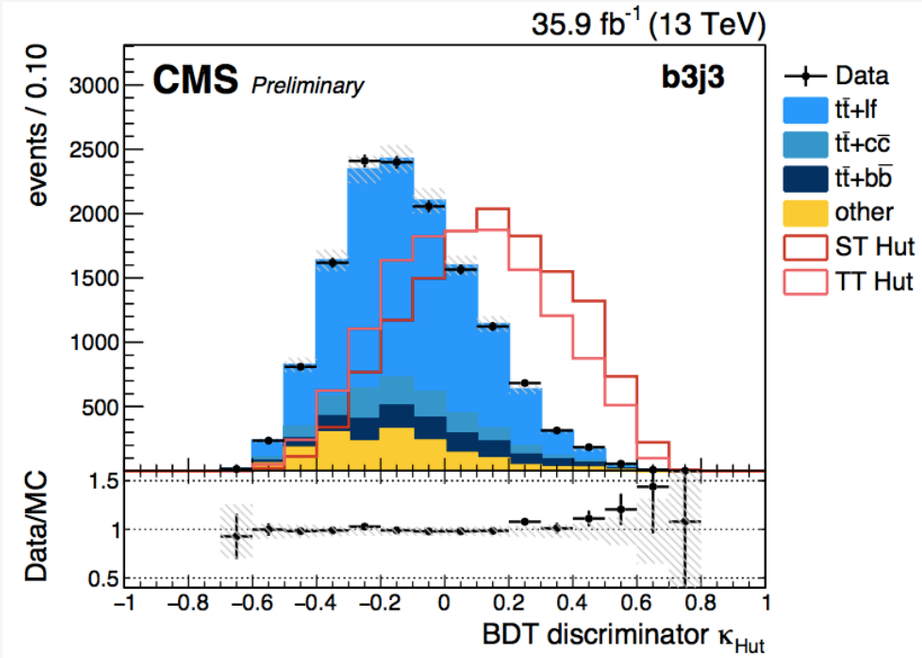
H→bb

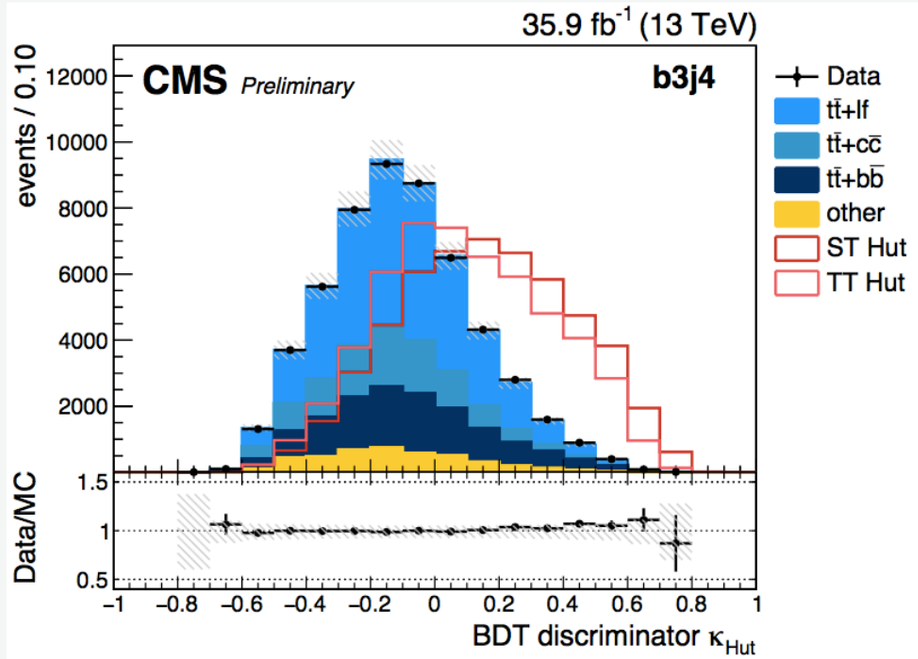
TOP-17-003

36 fb^{-1}, 13 TeV









Search for top-H FCNC in ttbar and single top

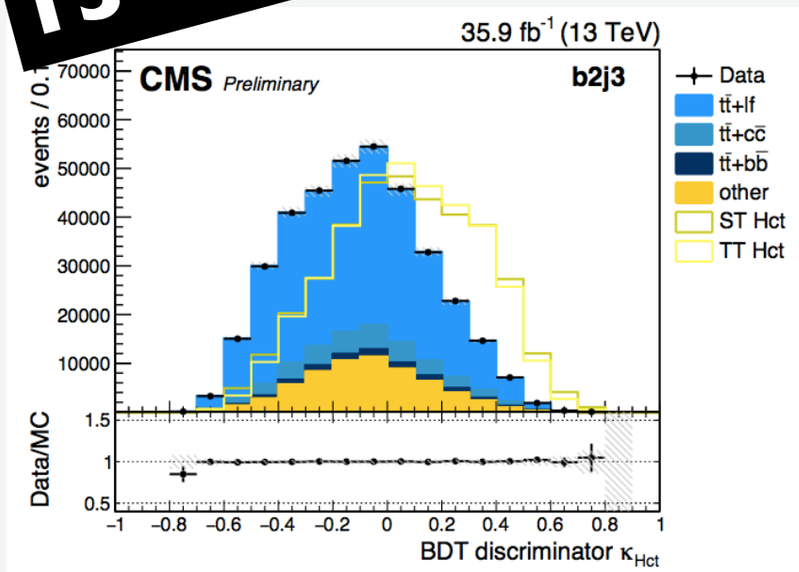
NEW

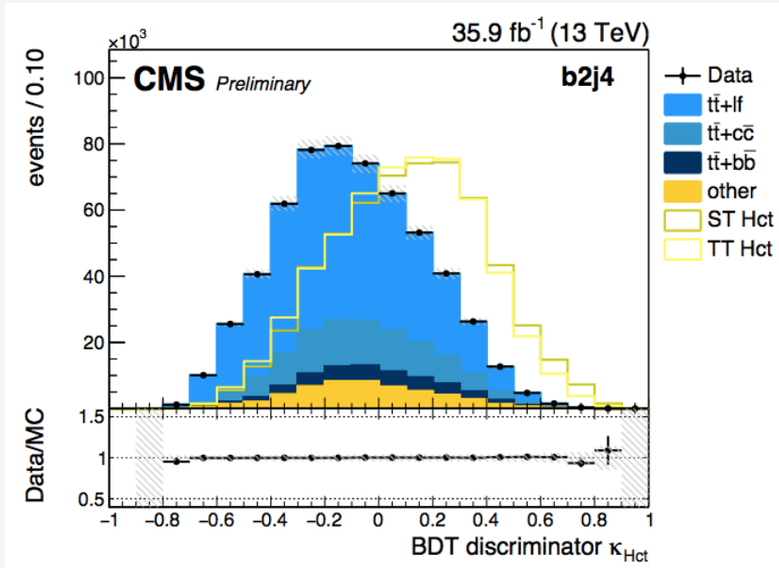
13 TeV

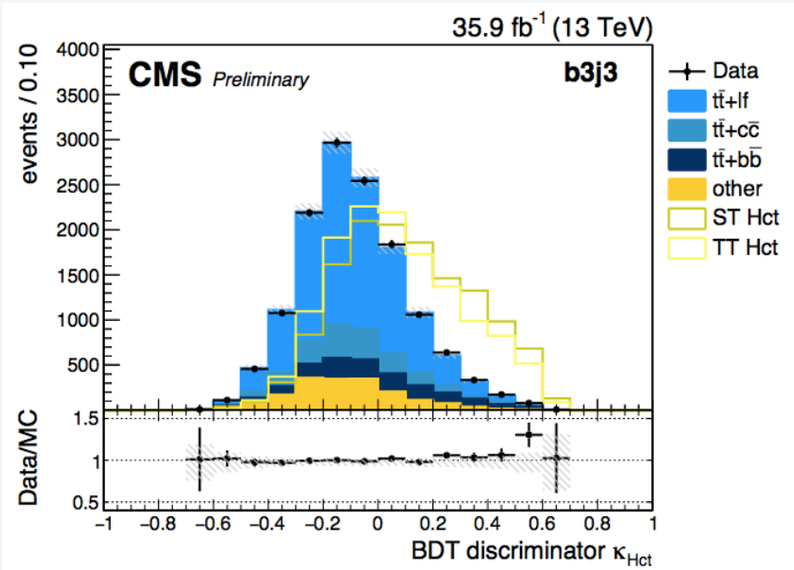
H→bb

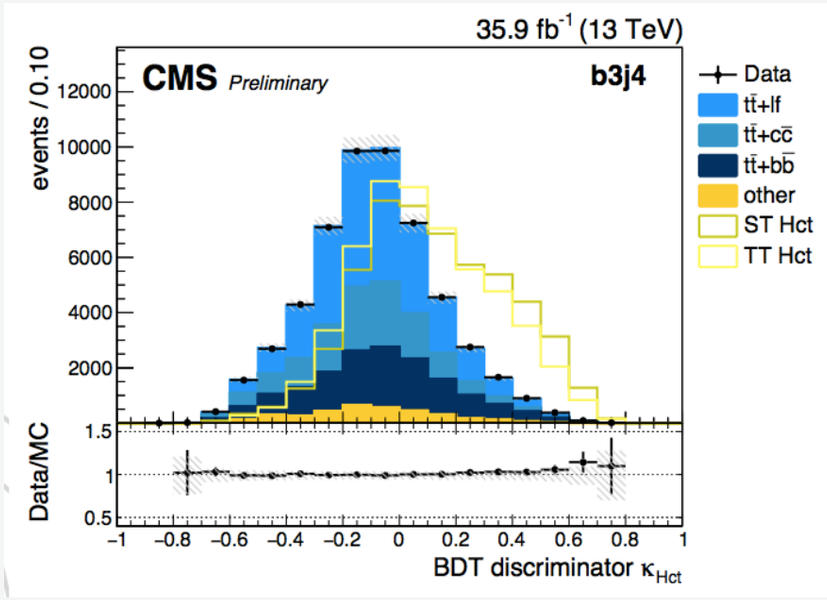
TOP-17-003

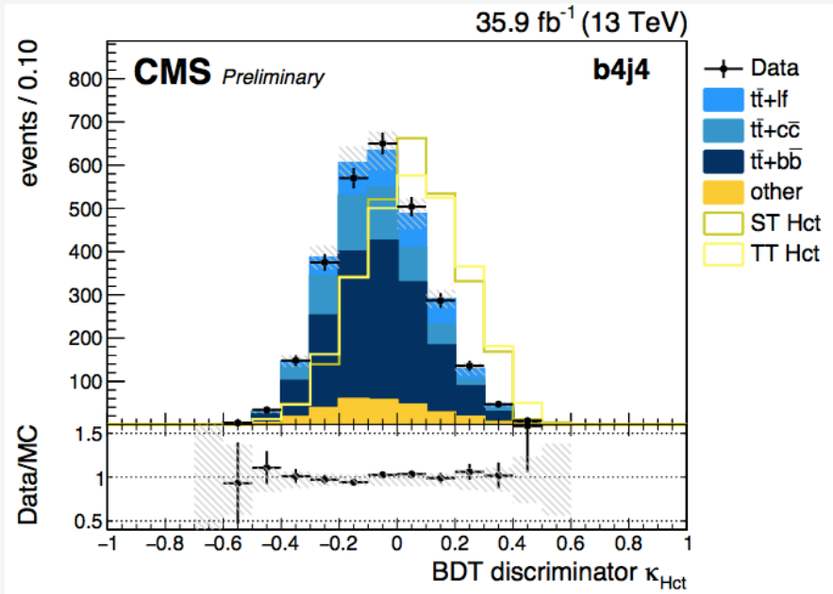
36 fb^{-1}, 13 TeV











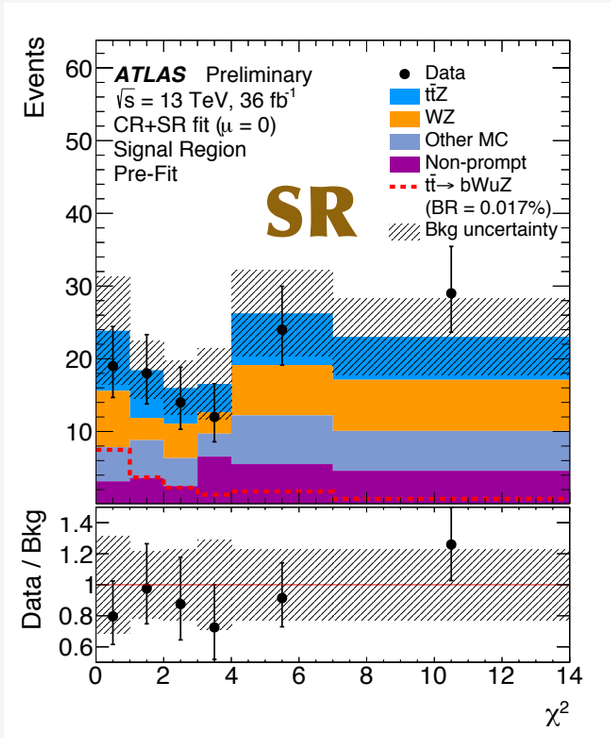
Search for top-Z FCNC in ttbar

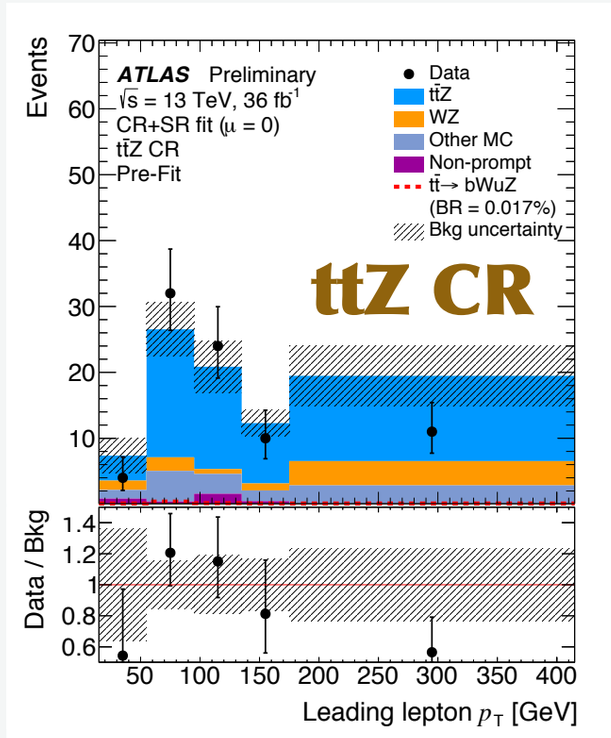
NEW

13 TeV

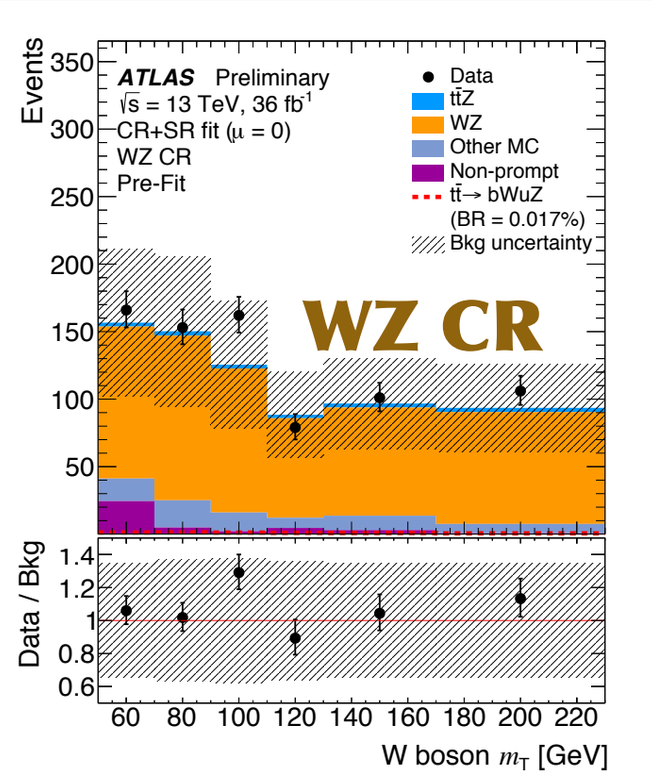
TOPQ-2017-06

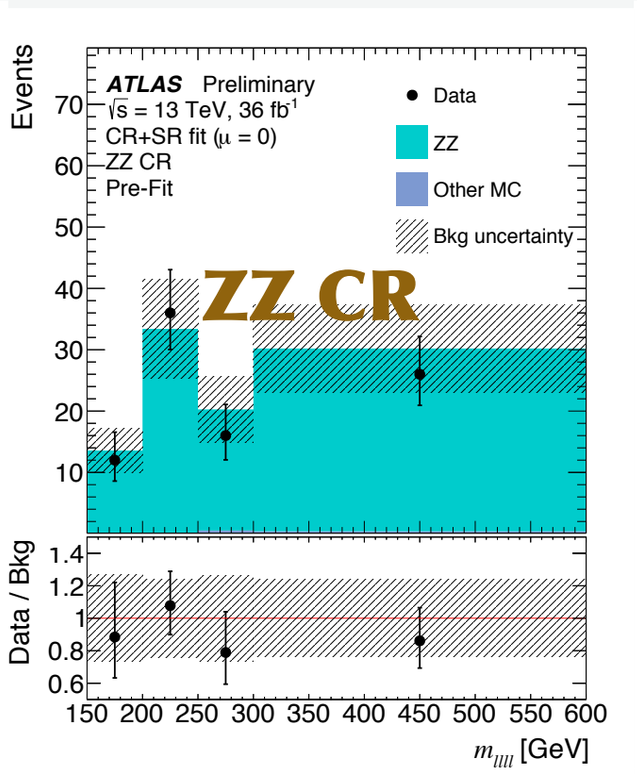
36 fb^{-1}, 13 TeV

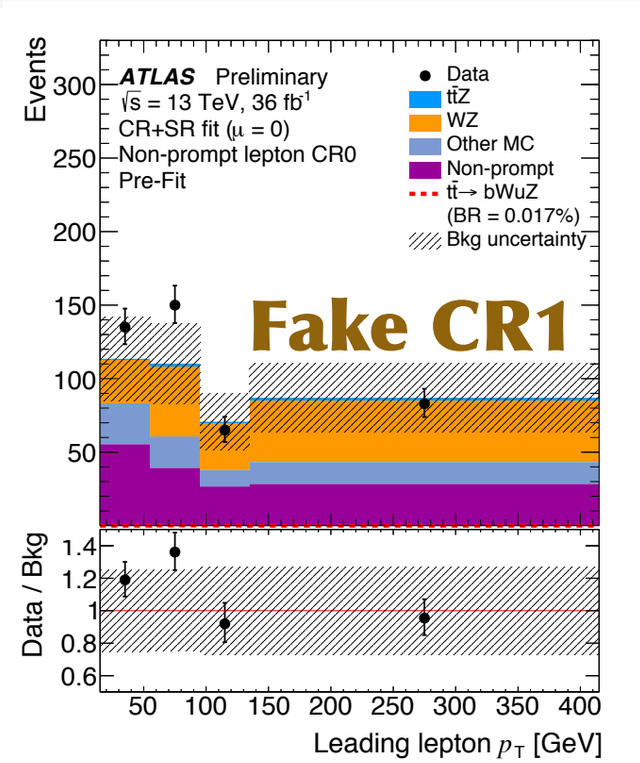


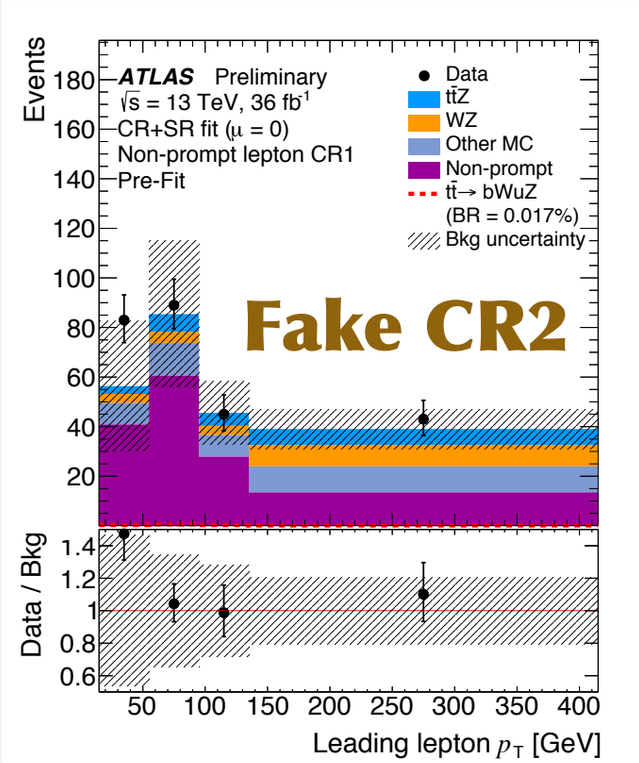


pre-fit





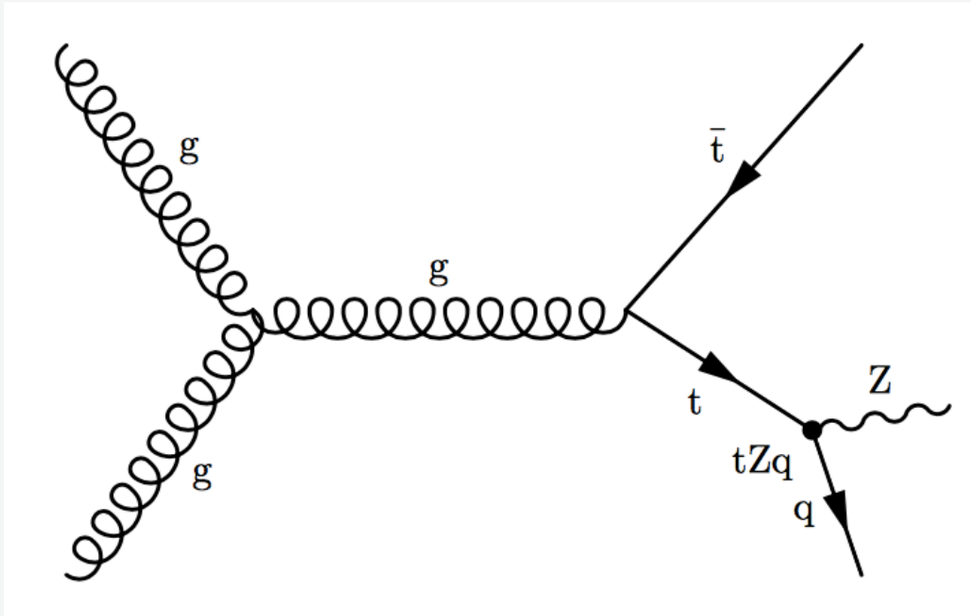




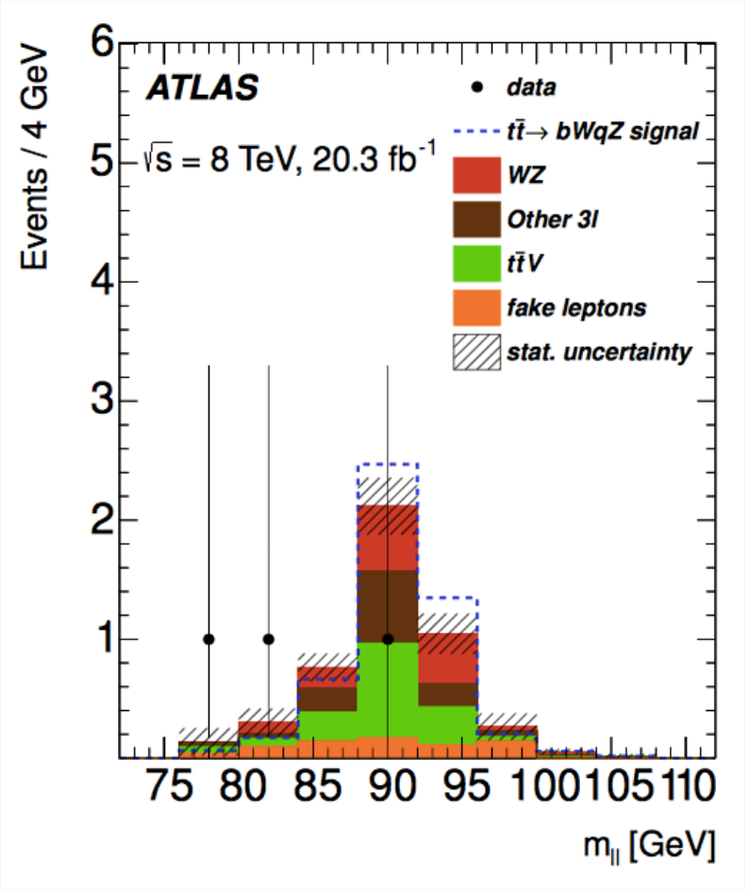
Search for top-Z FCNC in ttbar

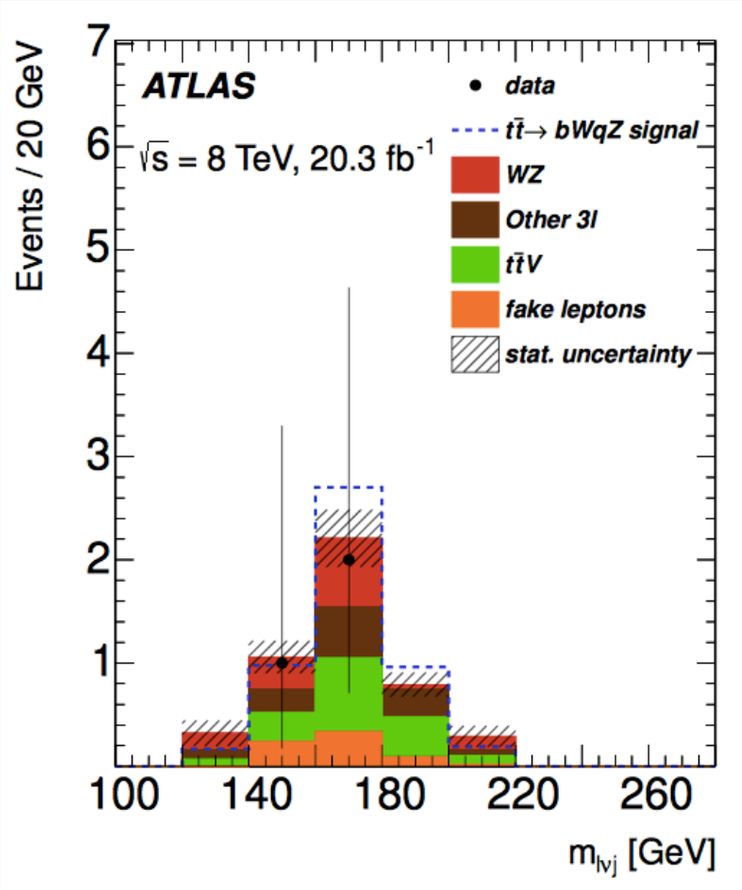
Eur.Phys.J. C76 (2016) 12

20 fb^{-1}, 8 TeV



- Search for top-Z FCNC in **ttbar** events
- Event topology: three isolated leptons, missing E_T, ≤ 3 jets in total, ≤ 2 b jets
- **WZ+jets, fake, ttbar+V** suppressed by χ^2 top reconstruction selection





B(t→**Z**q) < 0.07 % (obs)
0.08 % (exp)

Search for top-H FCNC in ttbar

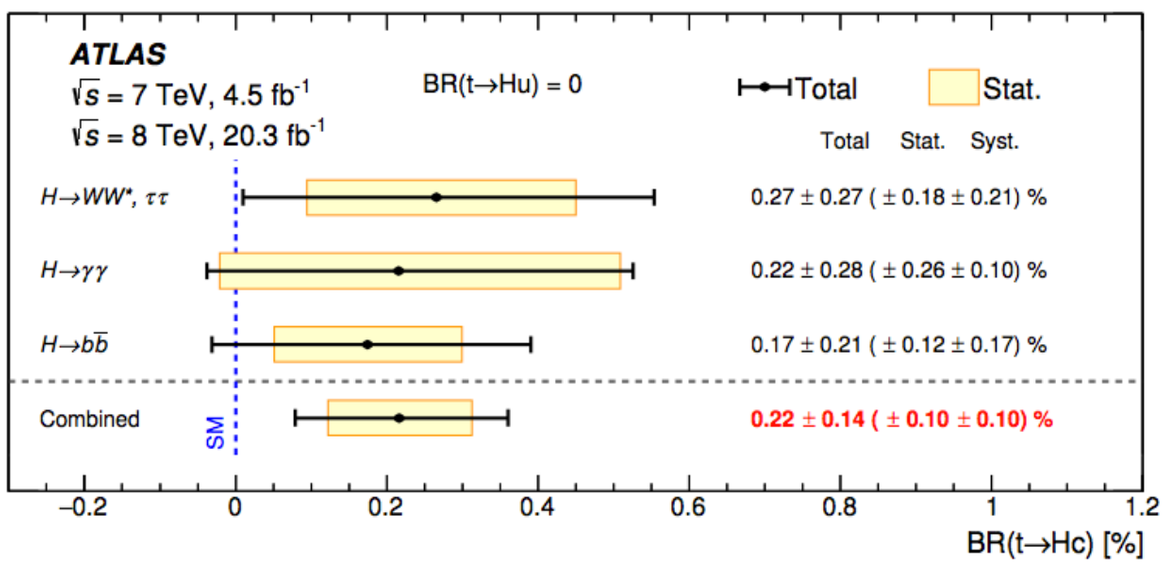
JHEP 12 (2015) 061

20 fb^{-1}, 8 TeV

8 TeV combination: H→γγ, bb, WW/ττ

JHEP 02 (2017) 079

20 fb^{-1}, 8 TeV



	$\mathcal{B}_{obs}(t \to Hc)$	$\mathcal{B}_{exp}(t \to Hc)$	$\mathcal{B}_{exp}+\sigma$	$\mathcal{B}_{exp}-\sigma$
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	1.26	1.33	1.87	0.95
Diphoton leptonic	0.99	0.93	1.26	0.68
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

B(t→**H**u) < 0.45 % (obs)
0.29 % (exp)
B(t→**H**c) < 0.46 % (obs)
0.25 % (exp)

B(t→**H**u) < 0.55 % (obs)
0.40 % (exp)
B(t→**H**c) < 0.40 % (obs)
0.43 % (exp)

Next step: ATLAS+CMS combination?

Search for top-H FCNC in ttbar

JHEP 06 (2014) 008

20 fb^{-1}, 8 TeV

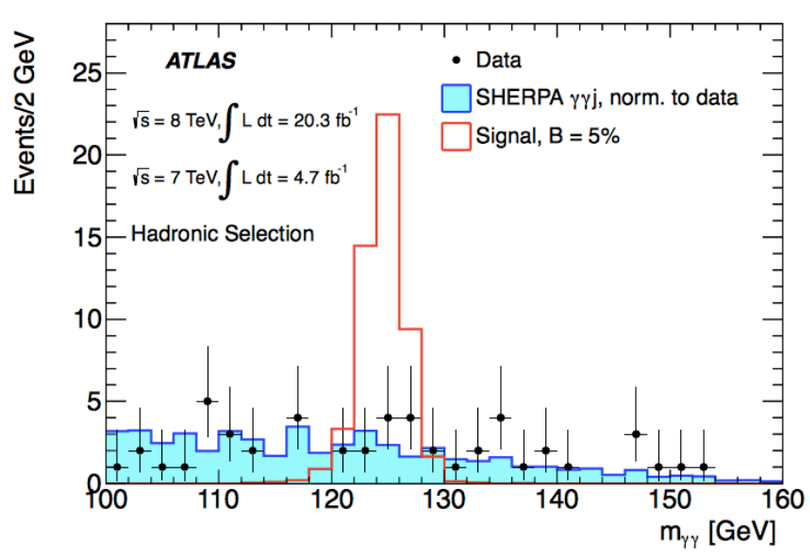
H→γγ

JHEP 02 (2017) 079

20 fb^{-1}, 8 TeV

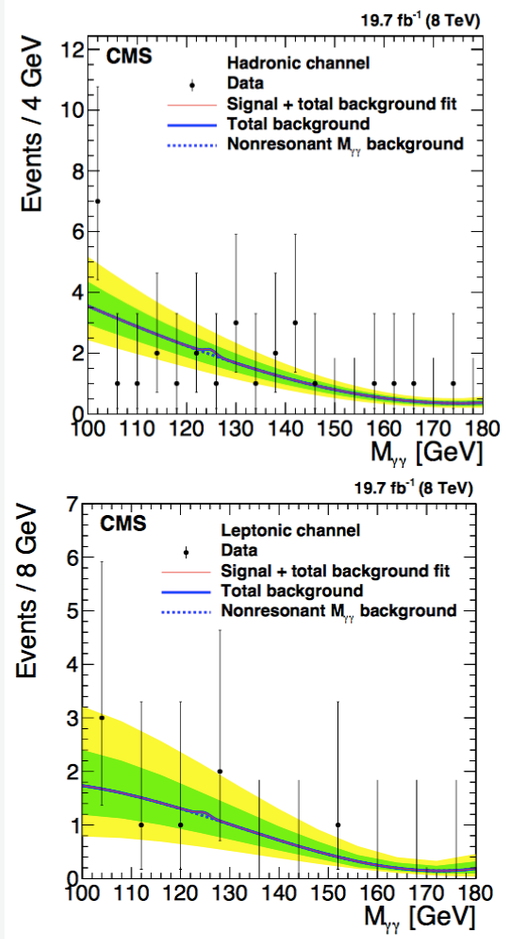
- Search for top-H FCNC in **ttbar** events
- Event topology: = 2 isolated photons
  leptonic: isolated lepton, missing E_T, ≥ 1 b jets, ≥ 2 jets
  hadronic: no isolated leptons, ≥ 1 b jets, ≥ 4 jets
- Discrimination against non-resonant **γγ+jets** with m(γγ) (hadronic)

hadronic



leptonic

	$t \to cH$	$t\bar{t}$ &$W(\gamma)$	$S_{\gamma\gamma j \to \ell}$	Data
	(%)	Events		
$\gamma\gamma$ selection	34.9	313.7		118500
1 lepton	6.0	21.8	188.2	210
$N_{jets} \geq 2$, $m_T > 30$ GeV	3.8	3.4	18.8	30
Mass requirements	1.9	1.2	3.5	4
At least 1 b-tag	1.3±0.1	0.9±0.5	0.5±0.2	1



ATLAS

B(t→**H**u) < 0.61 % (obs)
0.64 % (exp)
B(t→**H**c) < 0.56 % (obs)
0.42 % (exp)

B(t→**H**u) < 0.42 % (obs)
0.60 % (exp)
B(t→**H**c) < 0.47 % (obs)
0.67 % (exp)

CMS

Search for top-H FCNC in ttbar

JHEP 12 (2015) 061

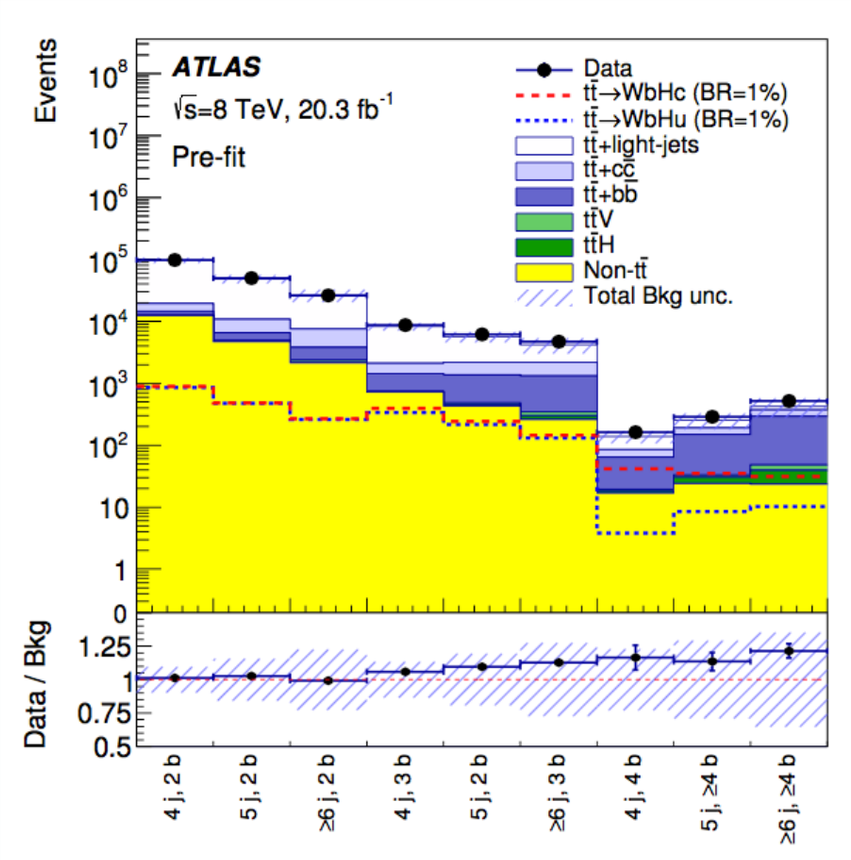
20 fb^{-1}, 8 TeV

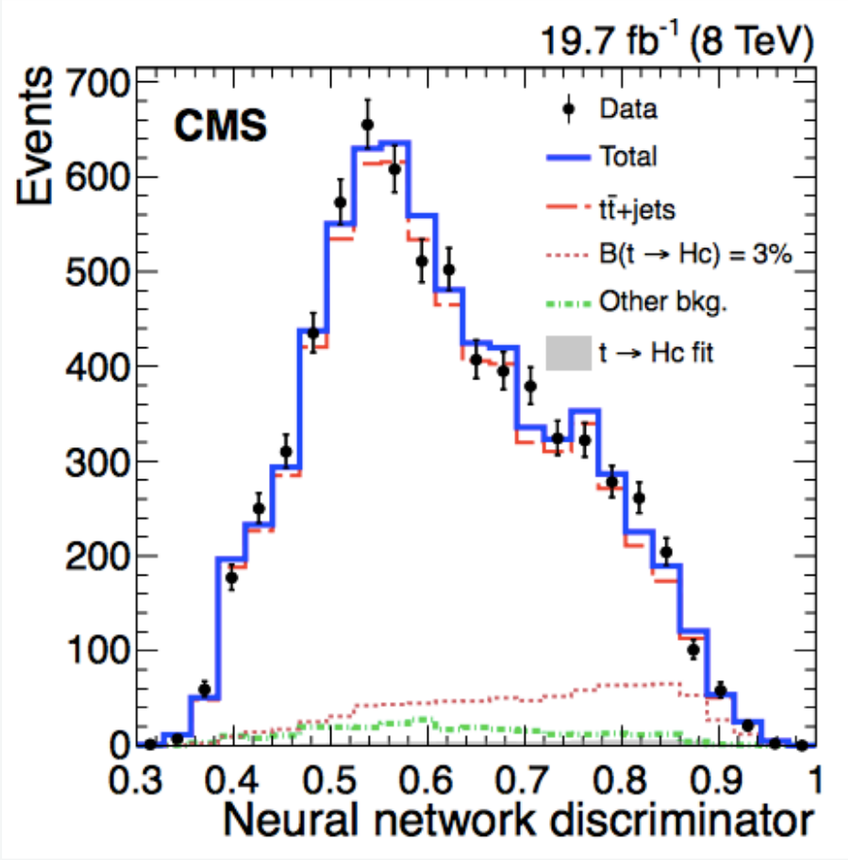
H→bb

JHEP 02 (2017) 079

20 fb^{-1}, 8 TeV

- Search for top-H FCNC in **ttbar** events
- Event topology: isolated lepton, missing E_T, $\geq$ 2 b jets, $\geq$ 6 jets (ATLAS), $\geq$ 3 b jets, $\geq$ 4 jets (CMS)
- **Ttbar+jets** suppressed with likelihood discriminant (ATLAS) and ANN (CMS)





ATLAS

B(t→**H**u) < 0.61 % (obs)
0.64 % (exp)
B(t→**H**c) < 0.56 % (obs)
0.42 % (exp)

B(t→**H**u) < 1.92 % (obs)
0.84 % (exp)
B(t→**H**c) < 1.16 % (obs)
0.89 % (exp)

CMS

Search for top-H FCNC in ttbar

JHEP 12 (2015) 061

20 fb^{-1}, 8 TeV

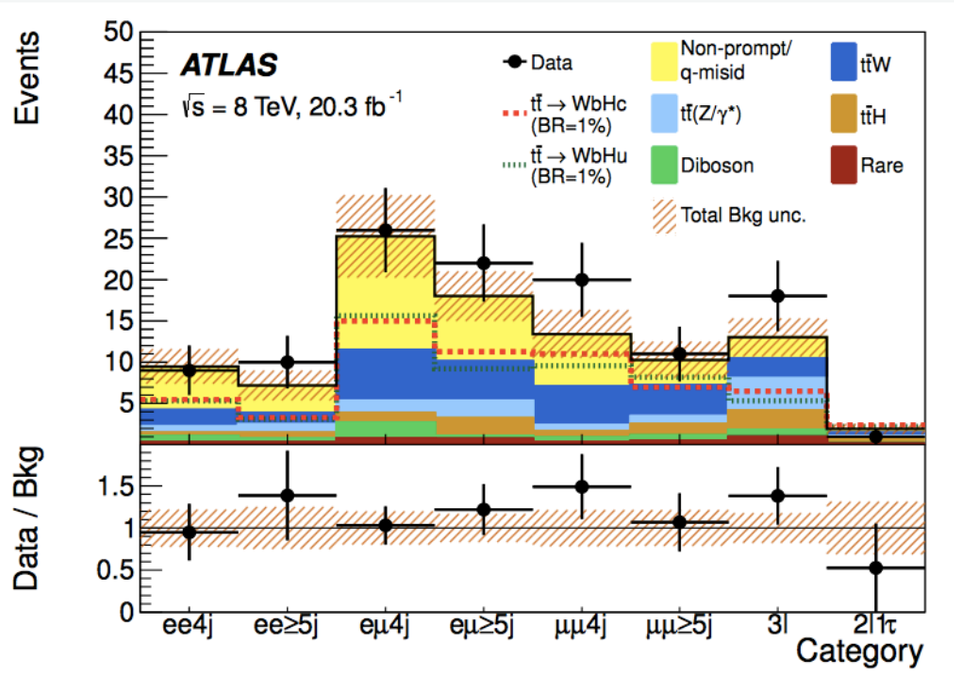
H→WW/(ττ)

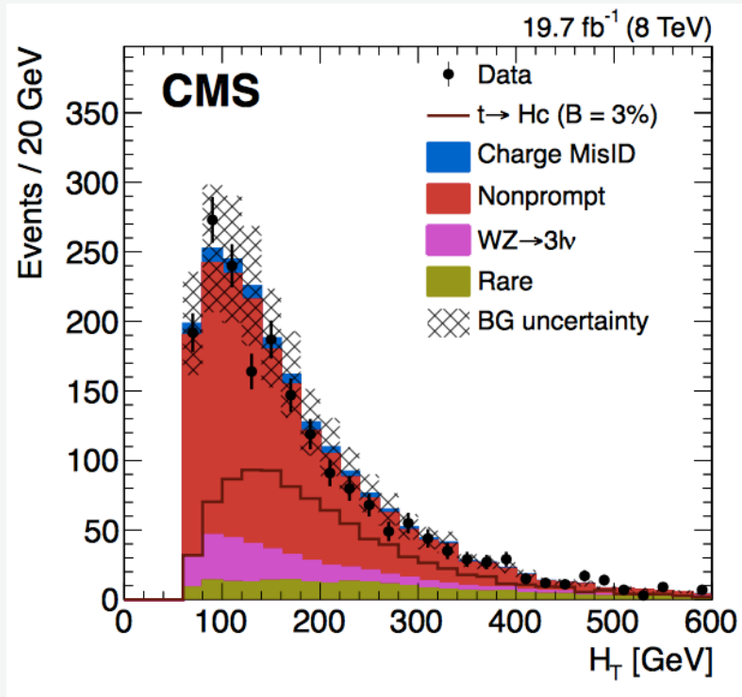
JHEP 02 (2017) 079

20 fb^{-1}, 8 TeV

- Search for top-H FCNC in **ttbar** events
- Event topology: =2 (SS-only for CMS), =3 isolated leptons, missing E_T, ≥ 1 b jets, ≥ 3 jets (ATLAS), ≥ 2 jets (CMS)
- **Ttbar(V)+jets (non-prompt, charge mis-id)** background and signal fitted across the event categories

ATLAS





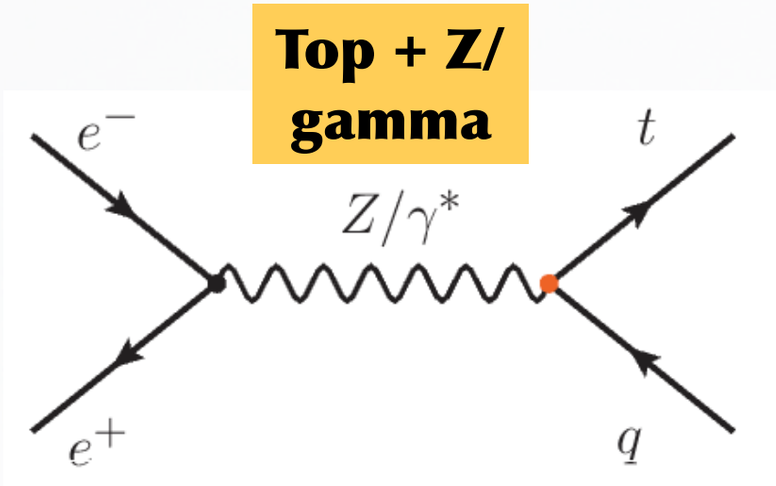
B(t→**H**u) < 0.78 % (obs)
0.57 % (exp)
B(t→**H**c) < 0.79 % (obs)
0.54 % (exp)

B(t→**H**u) < 0.86 % (obs)
0.82 % (exp)
B(t→**H**c) < 0.93 % (obs)
0.89 % (exp)

CMS

FCNC at LEP and HERA

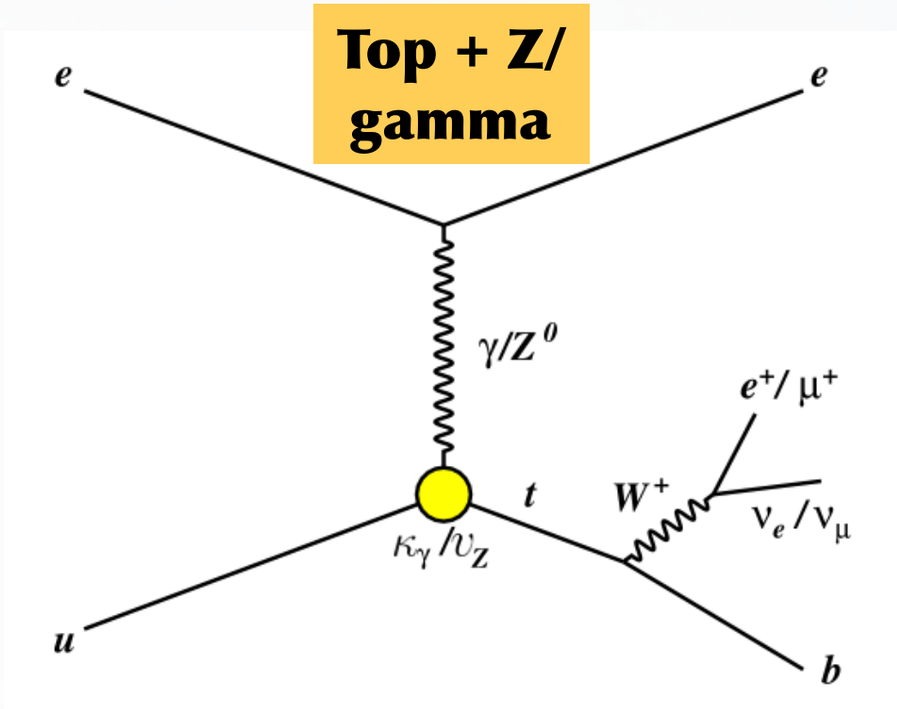
Search for **$e^+e^- \to t\ u/c$** at
LEP2



L3 *Phys. Lett. B549 (2002) 290-300*
OPAL *Phys. Lett. B521 (2001) 181-194*
ALEPH *Phys. Lett. B494 (2000) 33*
DELPHI *Phys. Lett. B590 (2004) 21-34*

$B(t \to \gamma q) \lesssim 4\ \%$
$B(t \to Zq) \lesssim 10\ \%$

Search for **$ep \to t\ e\ X$** at
HERA

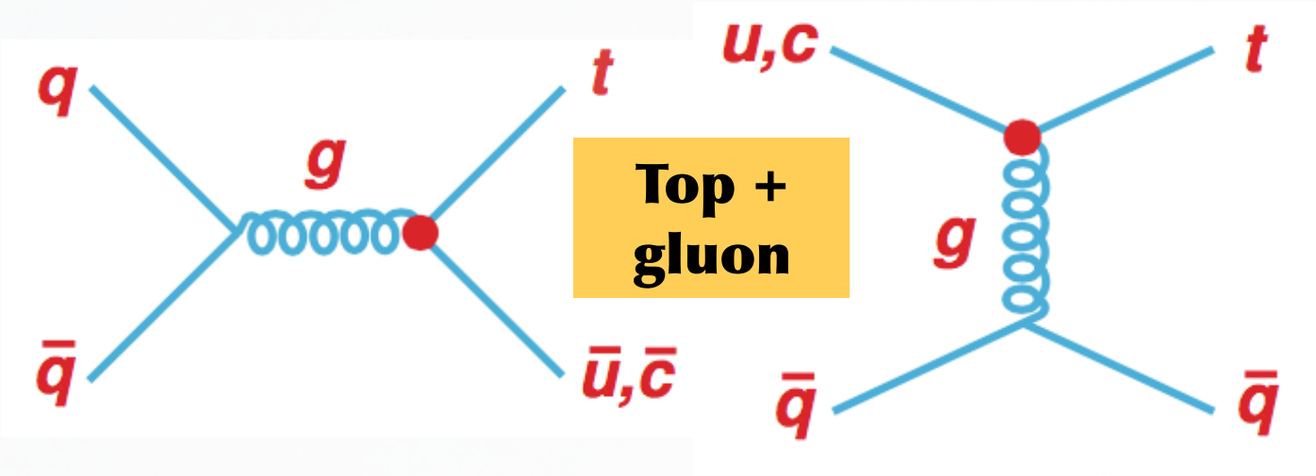


ZEUS *Phys. Lett. B708 (2012) 27-36*
H1 *Phys. Lett. B678 (2009) 450*

$B(t \to \gamma q) \lesssim 0.5\ \%$
$B(t \to Zq) \lesssim 4\ \%$

FCNC at Tevatron

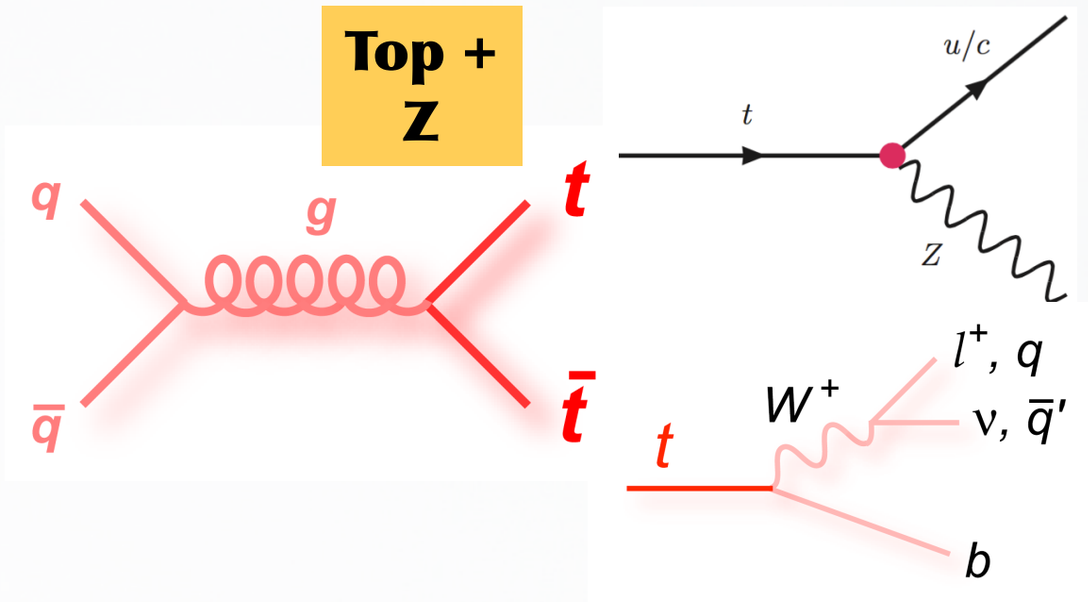
Search for t → g q at DØ



$B(t \to gu) \lesssim 0.02\ \%$
$B(t \to gc) \lesssim 0.4\ \%$

Phys. Lett. B693 (2010) 81-87

Search for t → Z q at CDF



$B(t \to Zq) \lesssim 3.7\ \%$

Phys. Rev. Lett. 101 (2008) 192002

Global fit for FCNC couplings

- **Parametrize top FCNC interactions with EFT approach at NLO**
- **Set bounds on top quark effective operators via χ^2-based global fit**

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2} O_i$$

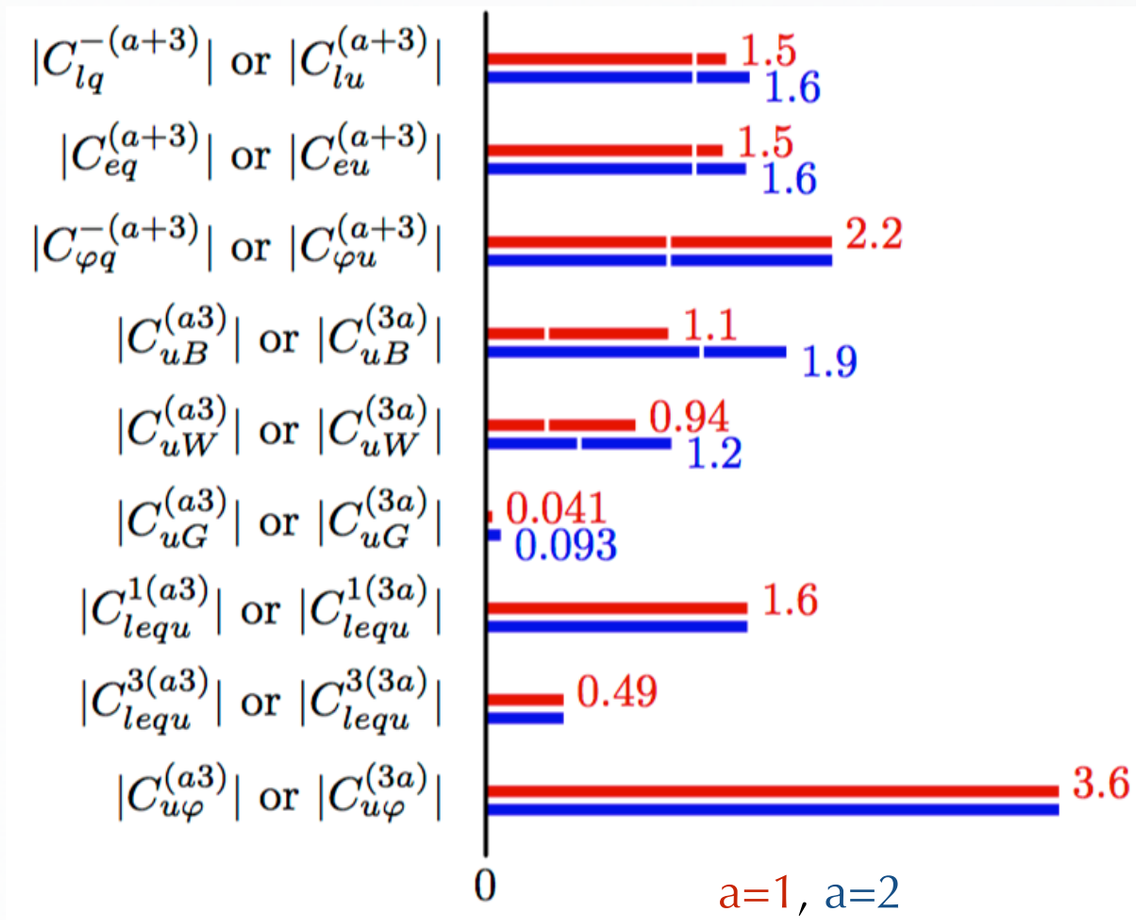
$$-\frac{g_W}{2c_W}\begin{cases} v_{tq}^Z \\ -a_{tq}^Z \end{cases} = \frac{-e}{2s_W c_W}\frac{m_t^2}{\Lambda^2}\left[C_{\varphi u}^{(a+3)*} \pm C_{\varphi q}^{-(a+3)*}\right],$$

$$-\frac{g_W}{2\sqrt{2}} g_{qt}\begin{cases} g_{qt}^v \\ g_{qt}^a \end{cases} = \frac{-2m_t}{v}\frac{m_t^2}{\Lambda^2}\left[C_{u\varphi}^{(a3)} \pm C_{u\varphi}^{(3a)*}\right],$$

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

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

$$-g_s\frac{\kappa_{tq}^g}{\Lambda}\begin{cases} f_{tq}^g \\ ih_{tq}^g \end{cases} = g_s\frac{m_t}{\Lambda}\left[C_{uG}^{(3a)} \pm C_{uG}^{(a3)*}\right].$$

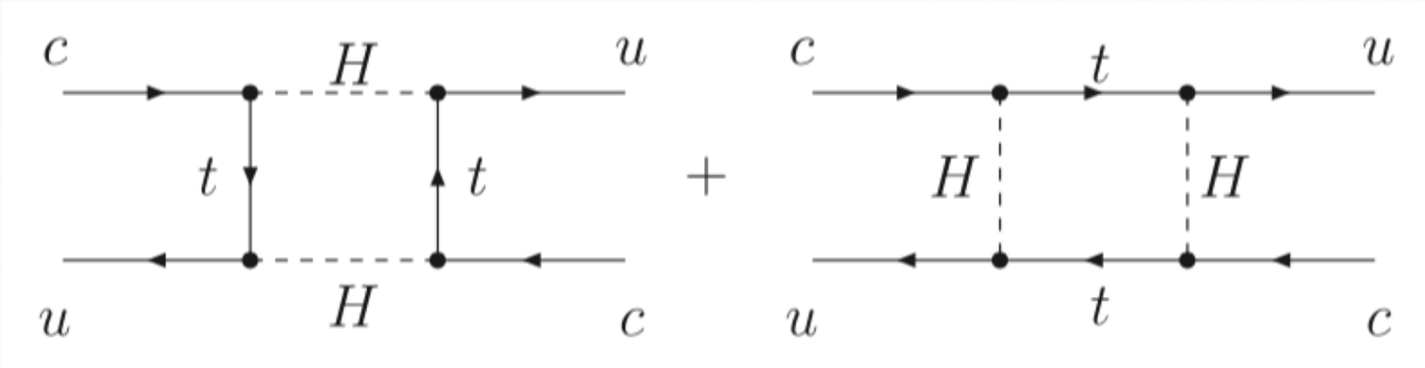


white mark - single non-vanishing coefficient

G. Durieux et al., arXiv:1412.7166

Indirect probe of FCNH

$D^0 - \overline{D^0}$ mixing



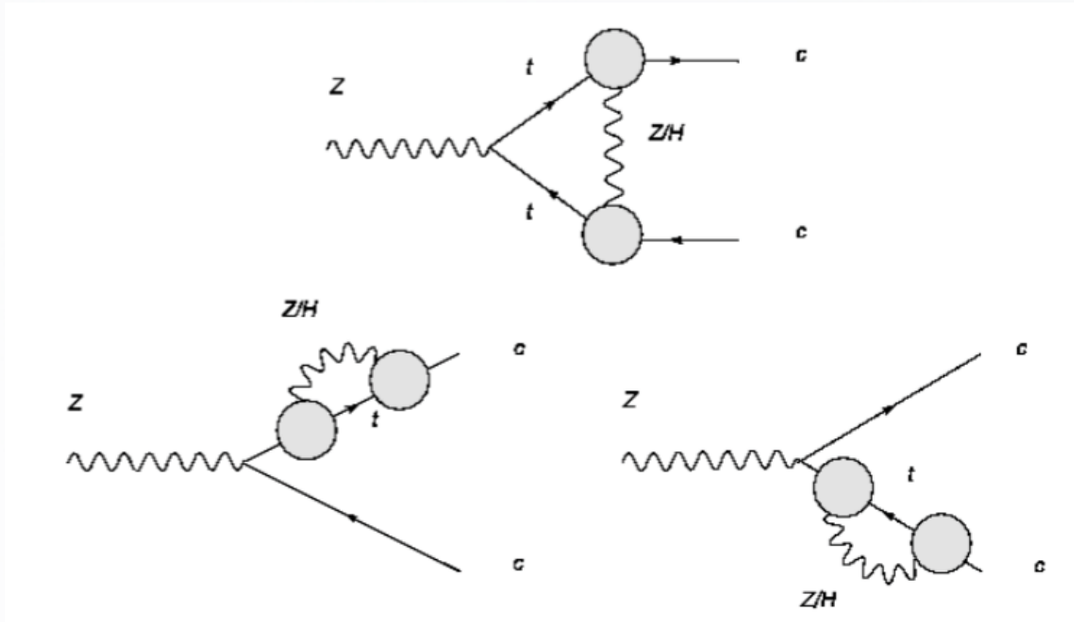
$\Delta M_D = (1.4 \pm 0.5) \times 10^{-15}$ GeV/c^2 **BaBar, Belle**

$$\mathrm{Br}(\mathrm{t} \to \mathrm{qh}) < 5 \times 10^{-3}$$

A. Fernandez et al., J.Phys.G37:085007,2010

XiaoJuan Wang et al., arxiv:1703.02691

$Z \to c\bar{c}$



$$\mathrm{Br}\ (\mathrm{t} \to \mathrm{qh}) < 0.21\ \%$$

F. Larios et al., Phys.Rev. D72 (2005) 057504