



Review on FCNC experimental searches



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on behalf of the ATLAS and the CMS collaborations

Top LHC France
2015-05-18

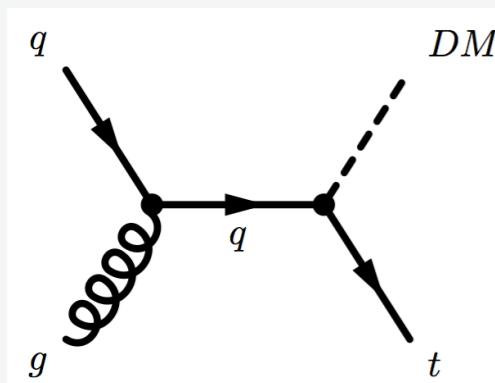
Outline

- Introduction to FCNC interaction processes
- Experimental searches for FCNC
- Latest experimental results from ATLAS and CMS
- Conclusion

FCNC interactions

- Flavour-changing neutral current (FCNC) transition is an interaction process where a fermion undergoes the change of flavour without alternation of its charge
- FCNC amplitudes at tree level are forbidden by the Glashow-Iliopoulos-Maiani (GIM) mechanism in the Standard Model (SM)
- However, highly GIM-suppressed FCNC transitions are possible in the SM in the higher orders via loop induced processes
- Some extensions of the SM could introduce FCNC decays at tree level including new particles:

- Fourth-generation models
- Extended technicolor models
- Leptoquark models
- Extra dimensions
- Extra quark models
- Supersymmetry
- Two-Higgs-Doublet models



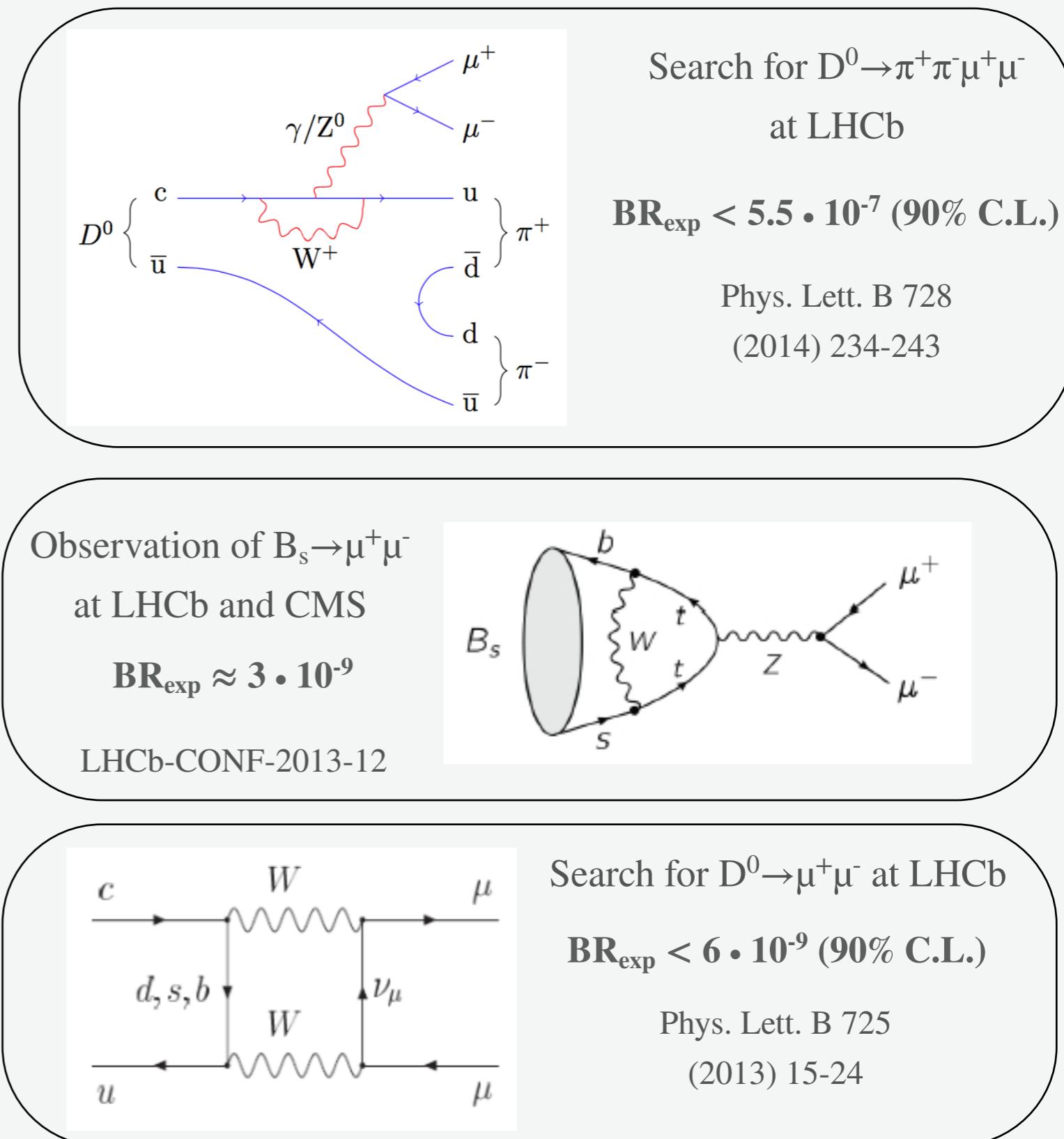
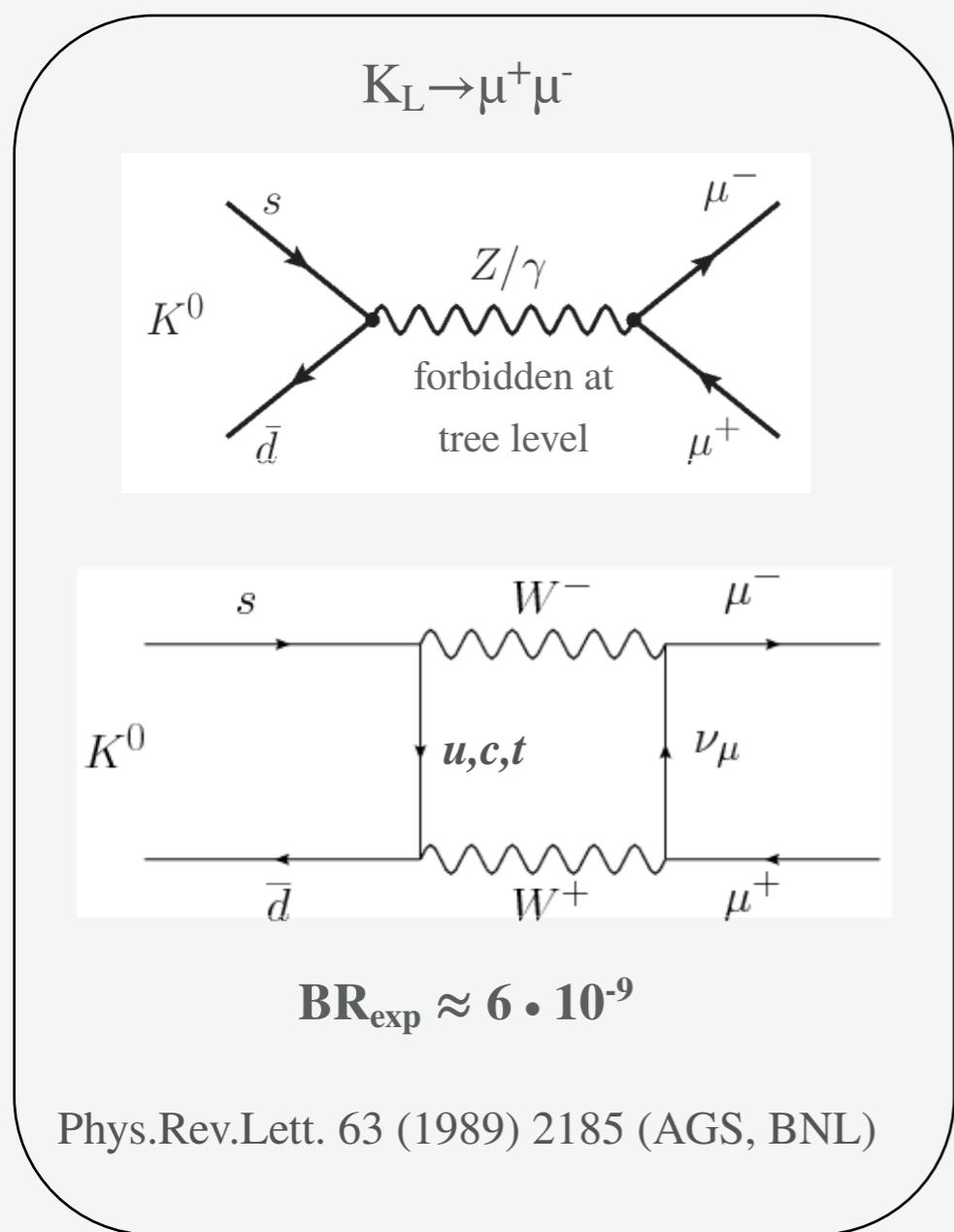
Model	$\text{Br} (t \rightarrow Z/\gamma q)$
SM	$\sim 10^{-12}$
SUSY	$\sim 10^{-6}$
2HDM	$\sim 10^{-7}$

**Observation of FCNC
process = new physics**

GIM mechanism: S. L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. D 2 (1970) 1285

Examples of FCNC non-top-quark related searches

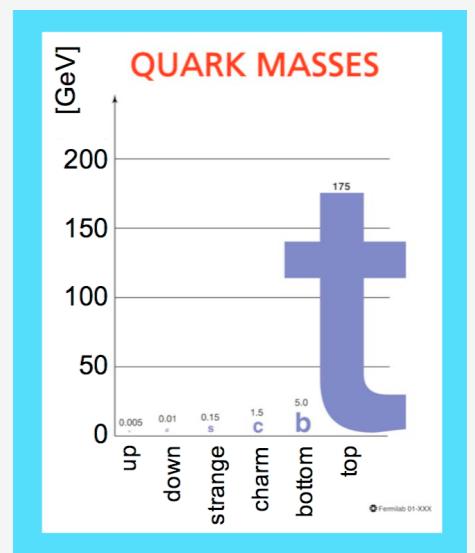
FCNC can be studied in the decays of D, B, K-mesons - FCNC decays are highly suppressed



Why top ?

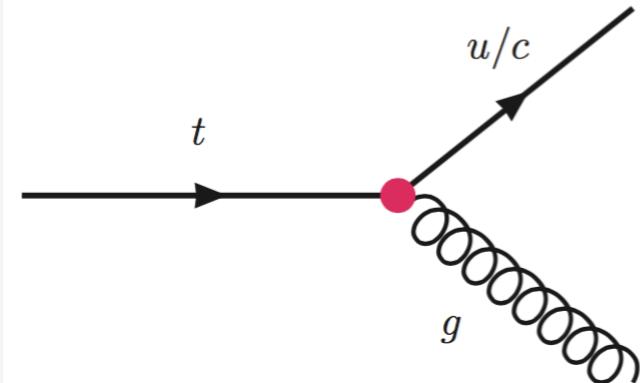
Search for FCN(C/H) in events with top-quark is promising because of the several important properties of a top-quark:

- The formation of strong bound states occurs much slower than the decay of top-quark which results in a clean event signature
- Yukawa coupling for top-quark is close to unity which makes it an interesting candidate to study EW symmetry breaking mechanism
- Top-quark is the heaviest elementary particle ever discovered - sensitivity to new physics searches
- Almost exclusively decays to b-quark and W-boson - distinctive event signature

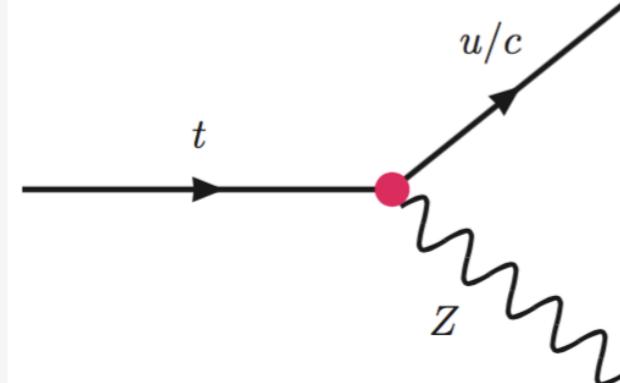


FCNC searches with a top-quark

gqt

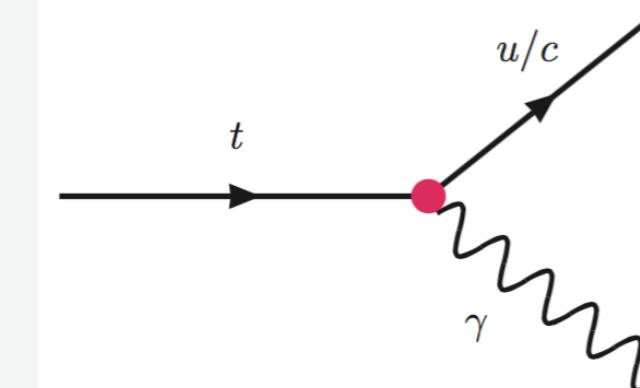


Zqt

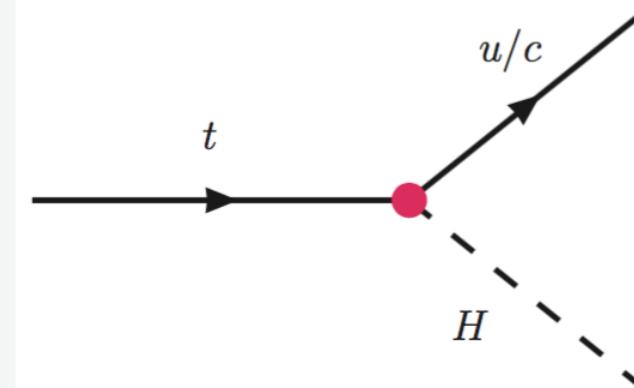


$$\begin{aligned} \mathcal{L} = & \sum_{q=u,c} \left[\sqrt{2} g_s \frac{\kappa_{gqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} T_a (f_{Gq}^L P_L + f_{Gq}^R P_R) q G_{\mu\nu}^a \right. \\ & + \frac{g}{\sqrt{2} c_W} \frac{\kappa_{zqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} (f_{Zq}^L P_L + f_{Zq}^R P_R) q Z_{\mu\nu} \\ & - e \frac{\kappa_{\gamma qt}}{\Lambda} \bar{t} \sigma^{\mu\nu} (f_{\gamma q}^L P_L + f_{\gamma q}^R P_R) q A_{\mu\nu} \\ & \left. + \frac{g}{\sqrt{2}} \bar{t} \kappa_{Hqt} (f_{Hq}^L P_L + f_{Hq}^R P_R) q H \right] + \text{h.c.} \end{aligned}$$

γqt

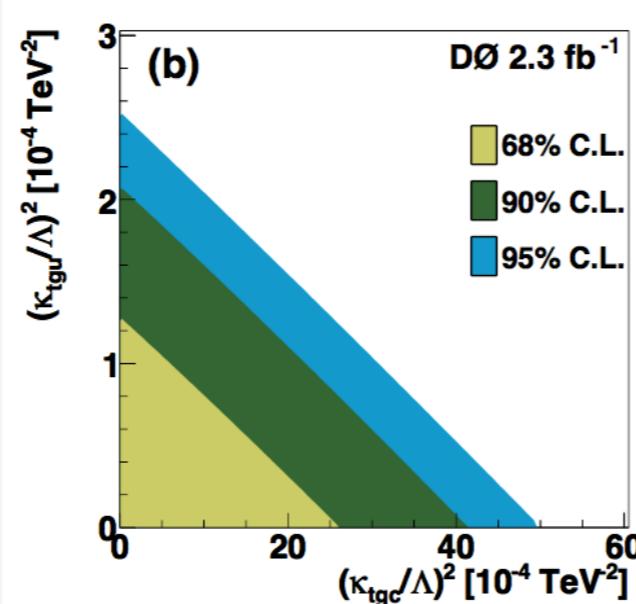
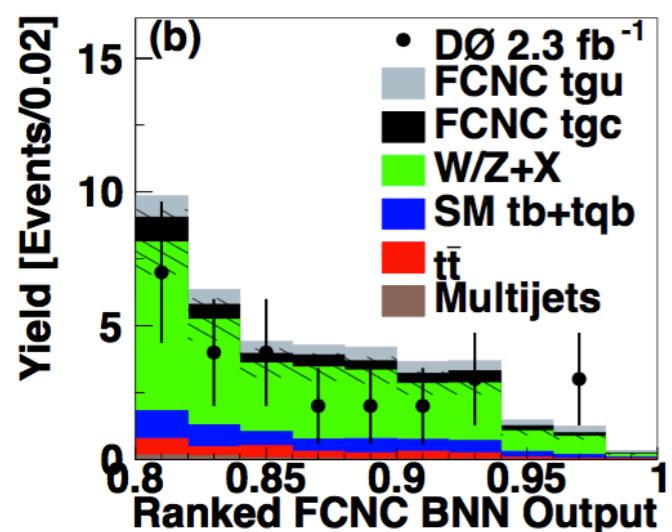
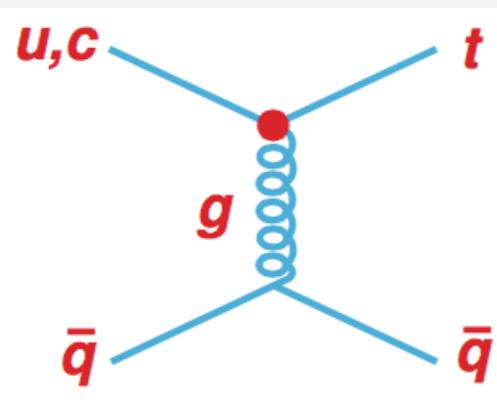
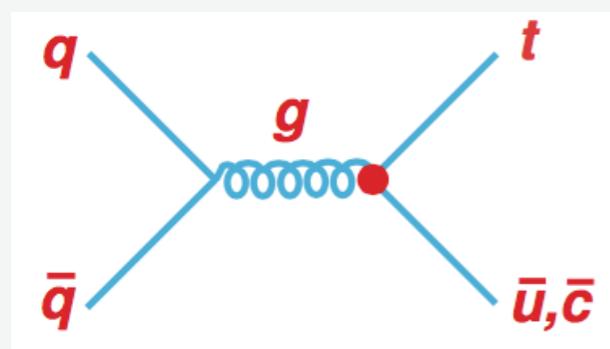


Hqt



FCNC searches at Tevatron

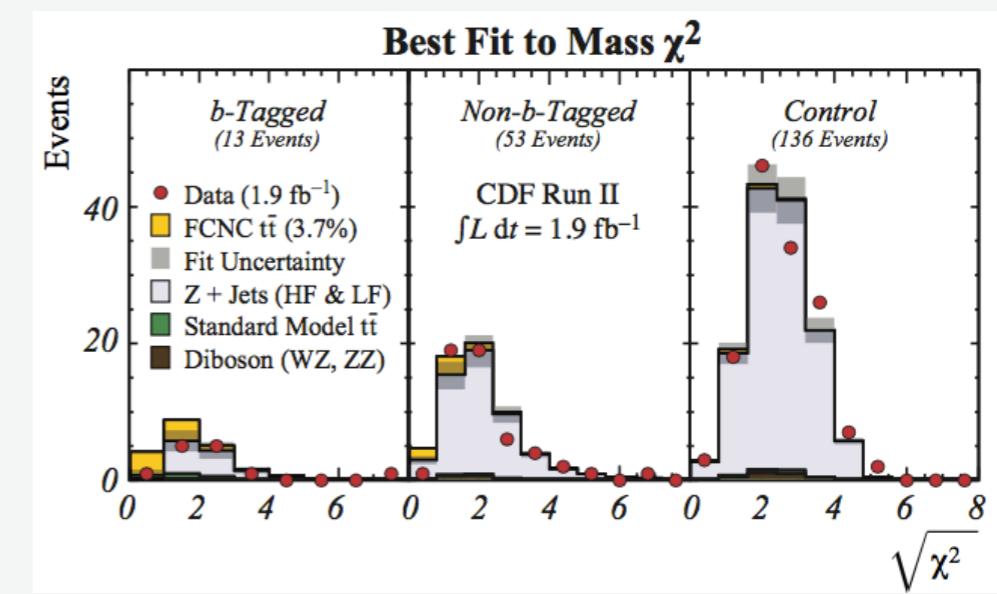
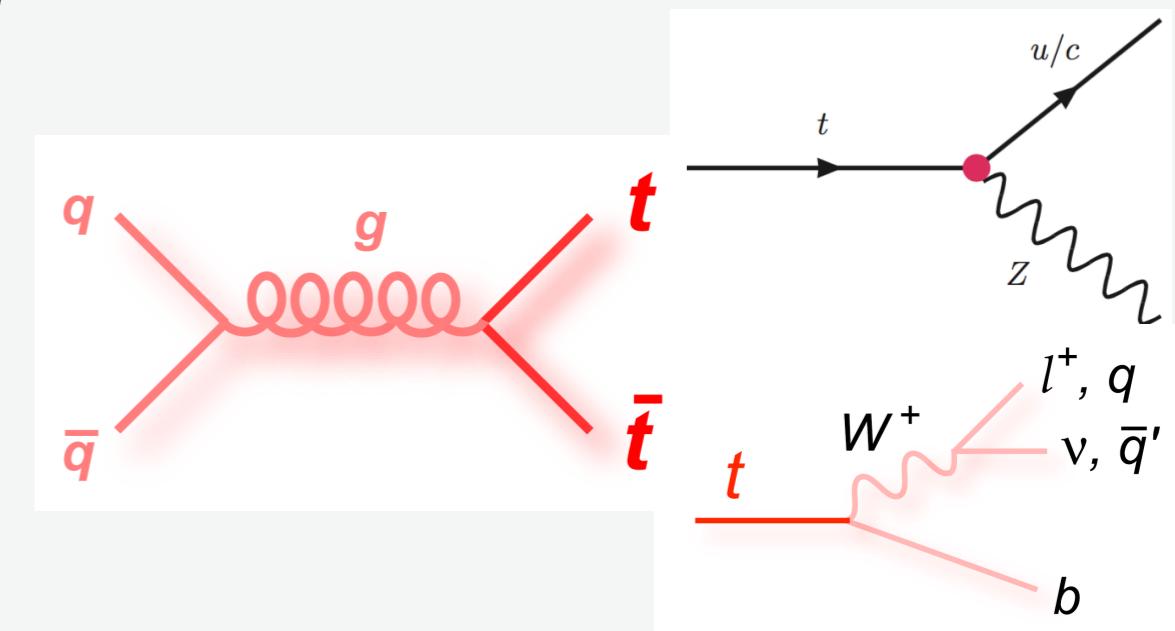
Search for $t \rightarrow gq$ FCNC events at DØ



	tgu	tgc
Cross section	0.20 pb	0.27 pb
κ_{tgc}/Λ	0.013 TeV^{-1}	0.057 TeV^{-1}
$\mathcal{B}(t \rightarrow fg)$	2.0×10^{-4}	3.9×10^{-3}

Phys.Lett.B693:81-87,2010

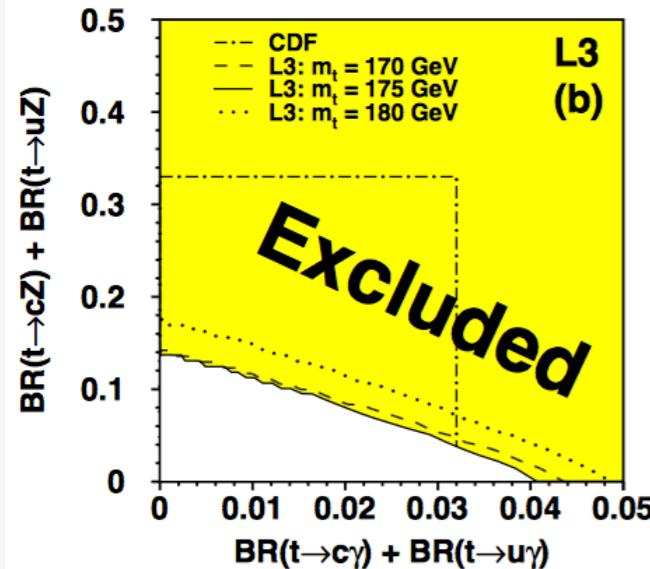
Search for $t \rightarrow Zq$ FCNC events at CDF



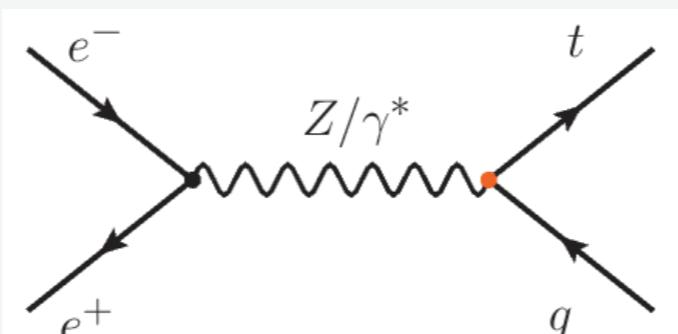
$$\text{BR}(t \rightarrow qZ) < 3.7 \cdot 10^{-2}$$

Phys.Rev.Lett.101:192002,2008

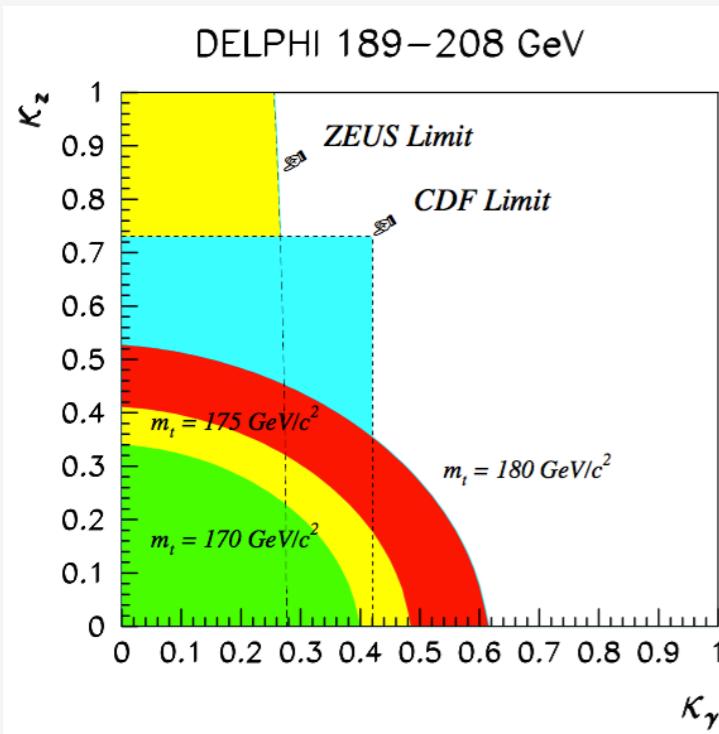
FCNC searches at LEP2 and HERA



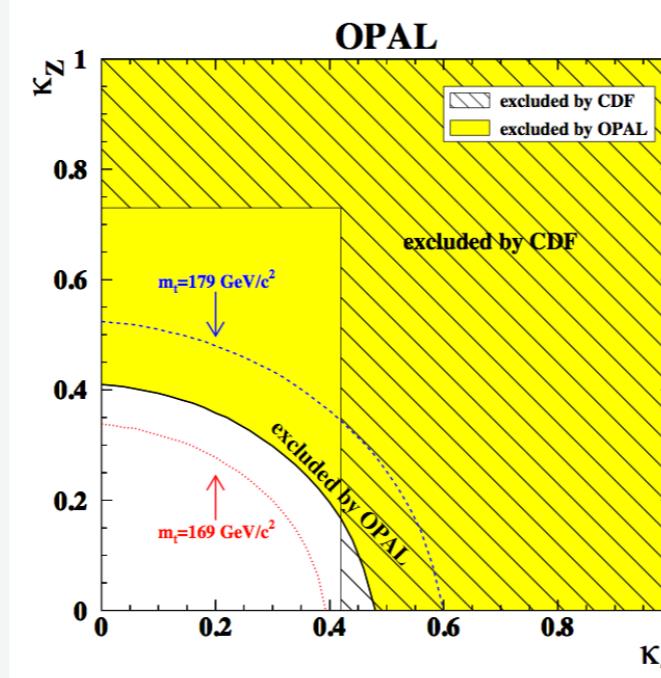
FCNC searches in
 $e^+e^- \rightarrow tq\bar{q}$ at LEP2



Phys.Lett.B549:290-300,2002

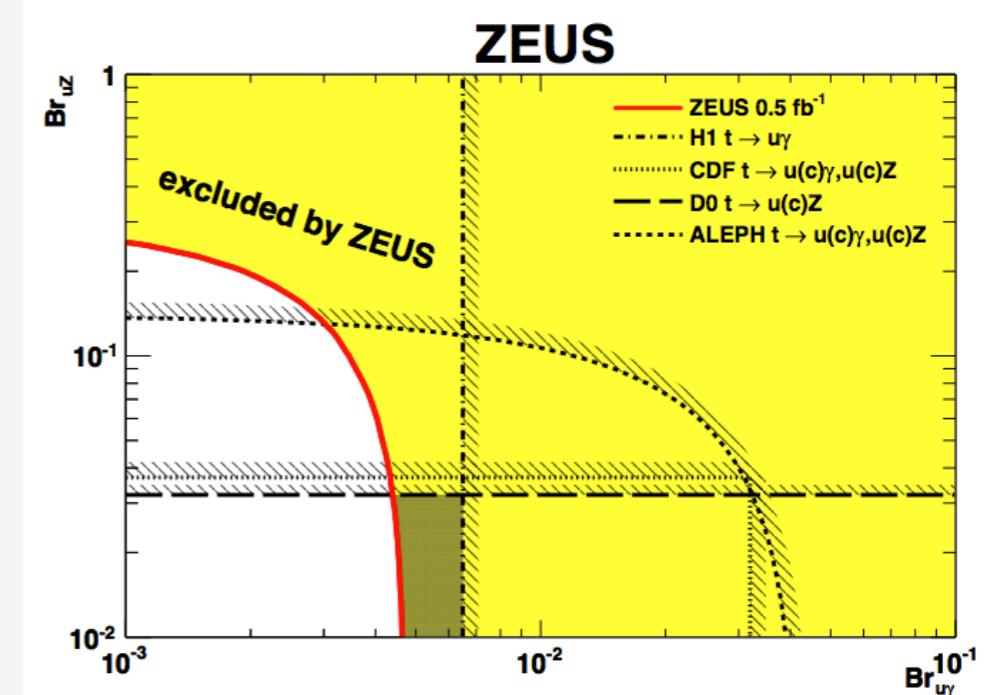
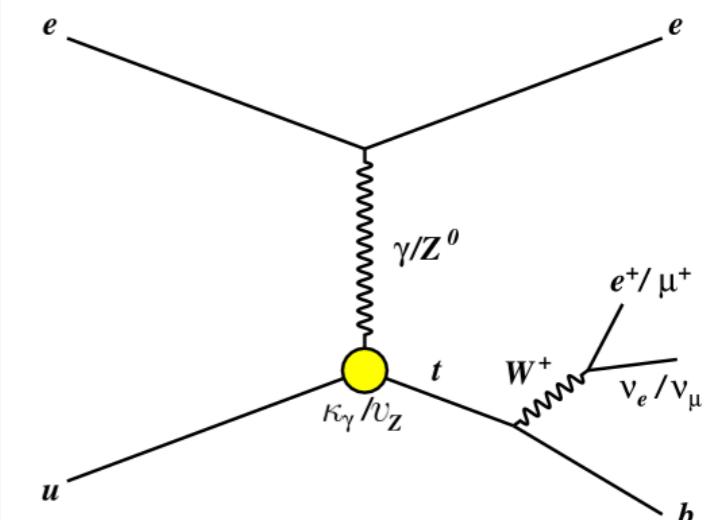


Phys.Lett. B590 (2004) 21-34



Phys.Lett.B521:181-194,2001

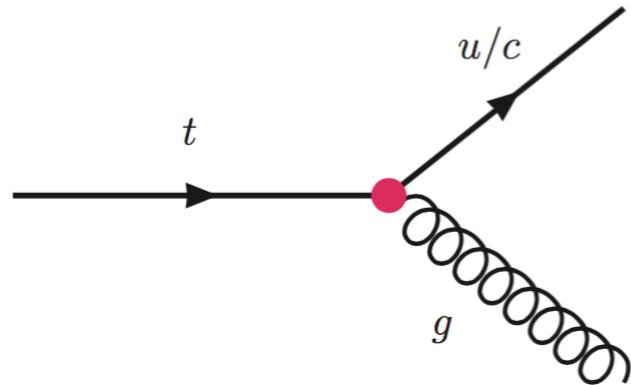
FCNC searches at HERA in $ep \rightarrow etX$



Phys.Lett.B708:27-36,2012

FCNC searches at the LHC

gqt

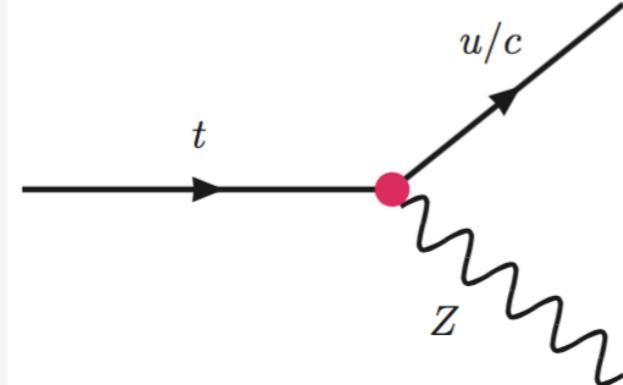


[ATLAS-CONF-2013-063](#)

[Phys. Lett. B712 \(2012\) 351-369](#)

[CMS-PAS-TOP-14-007](#)

Zqt



[JHEP 1209 \(2012\) 139](#)

[Phys. Rev. Lett. 112 \(2014\) 171802](#)

[CMS-PAS-TOP-12-021](#)

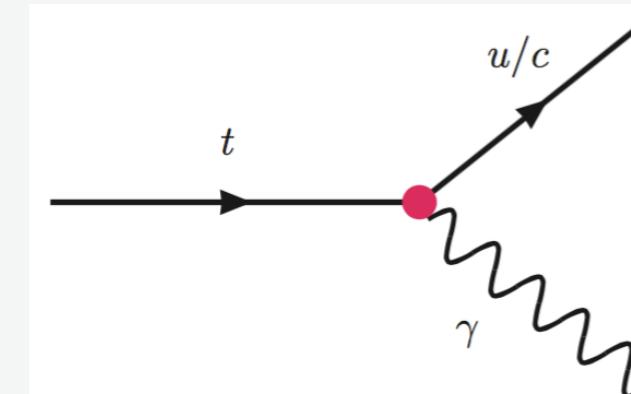
[CMS-PAS-TOP-14-003](#)

[JHEP 06 \(2014\) 008](#)

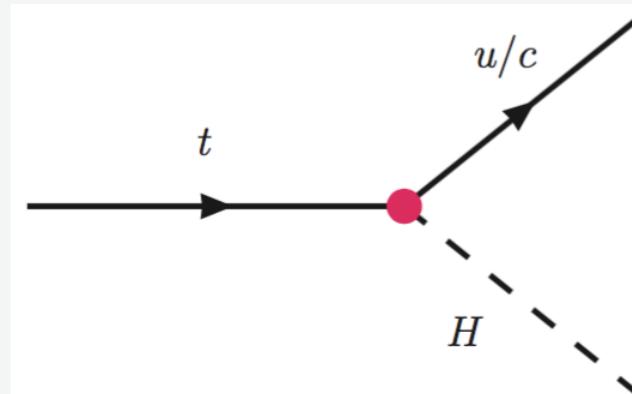
[CMS-PAS-HIG-13-034](#)

[CMS-PAS-TOP-13-017](#)

γ qt

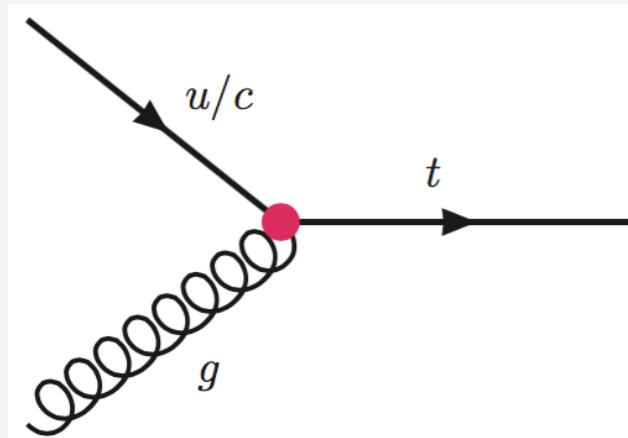


Hqt



Search for single top production at ATLAS

ATLAS-CONF-2013-063
ATLAS, 14 fb⁻¹, 8 TeV



MEtop @NLO (approx.)

W+jets is validated with looser b-jet selection (but veto events with tight b-tagged jets)

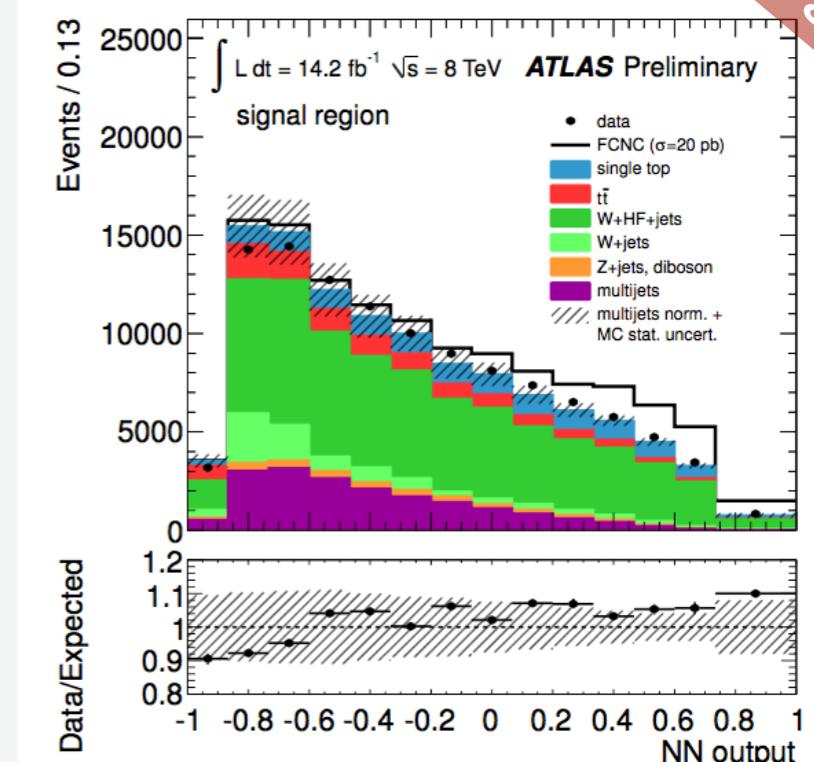
QCD multijet events are estimated with electron-jet approach with template fit in missing E_T (electrons), and fake matrix method (muons)

$$\begin{aligned}\kappa_{ugt}/\Lambda &< 5.1 \cdot 10^{-3} \text{ TeV}^{-1} \\ \kappa_{cgt}/\Lambda &< 1.1 \cdot 10^{-2} \text{ TeV}^{-1} \\ \text{BR}(t \rightarrow ug) &< 3.1 \cdot 10^{-5} \\ \text{BR}(t \rightarrow cg) &< 1.6 \cdot 10^{-4}\end{aligned}$$

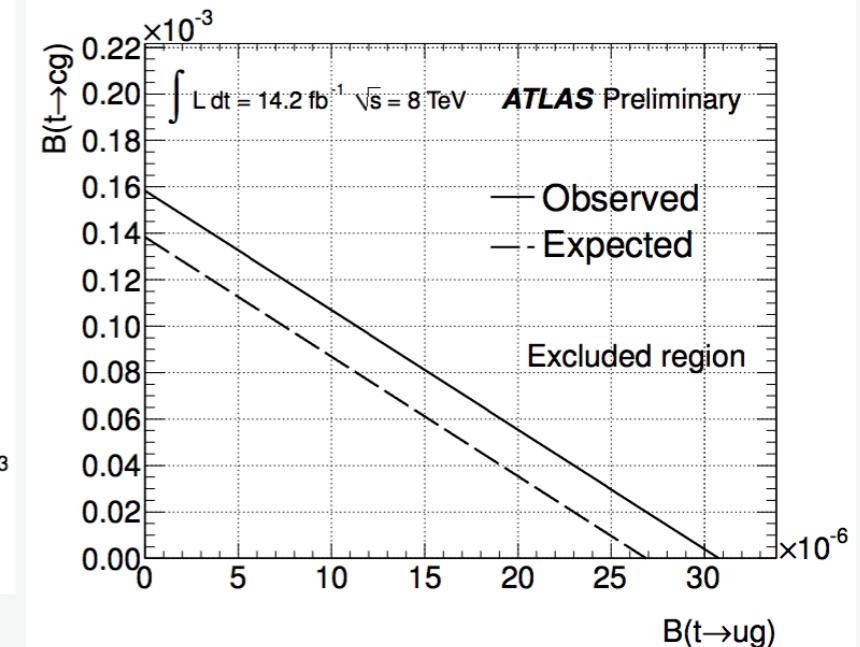
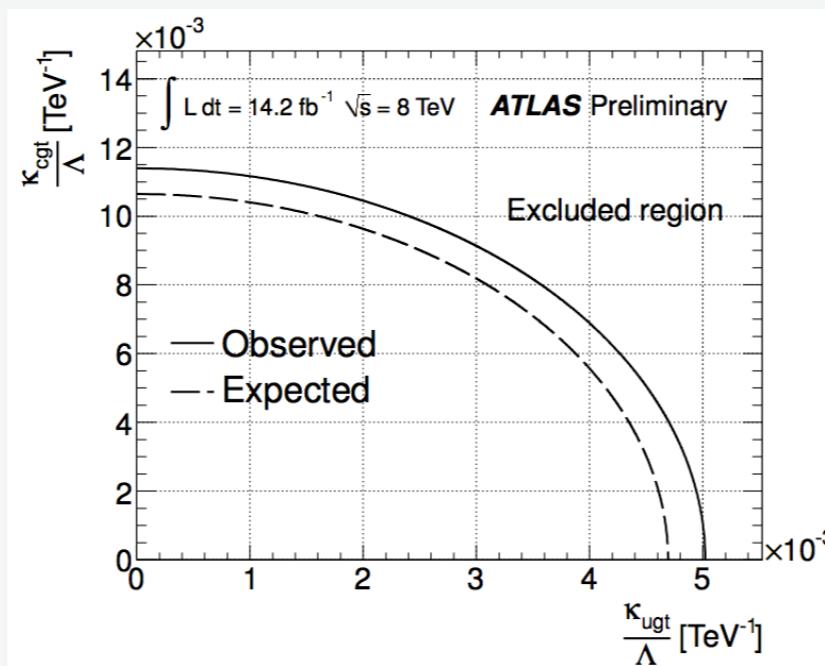
Event signature is the top-quark decay: exactly one isolated lepton, missing E_T and one b-tagged jet

Main background: W+jets, QCD multijet, single top, ttbar, Z+jets

MVA approach is used to discriminate signal and background events based on: $p_T(b)$, $p_T(W)$, $\Delta\phi(W,\nu)$ in the top-quark rest frame, charge of the lepton, $\eta(\ell)$, $\Delta\phi(\ell,b)$, $\eta(\ell\nu b)$, ...

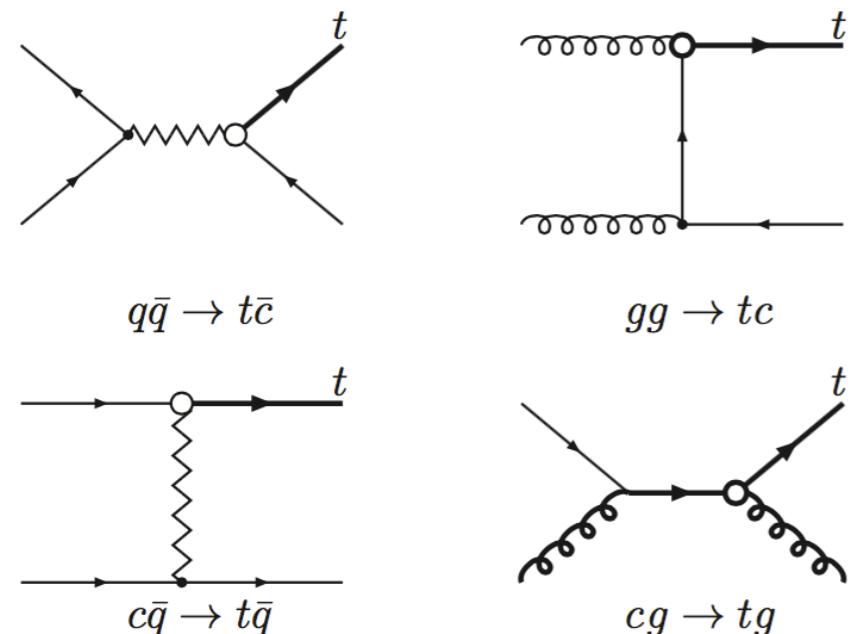


Limits extracted from MVA discriminator binned likelihood fit with Bayesian approach



Search in t-channel single top at CMS

CMS-PAS-TOP-14-007
CMS, 5 fb⁻¹, 7 TeV



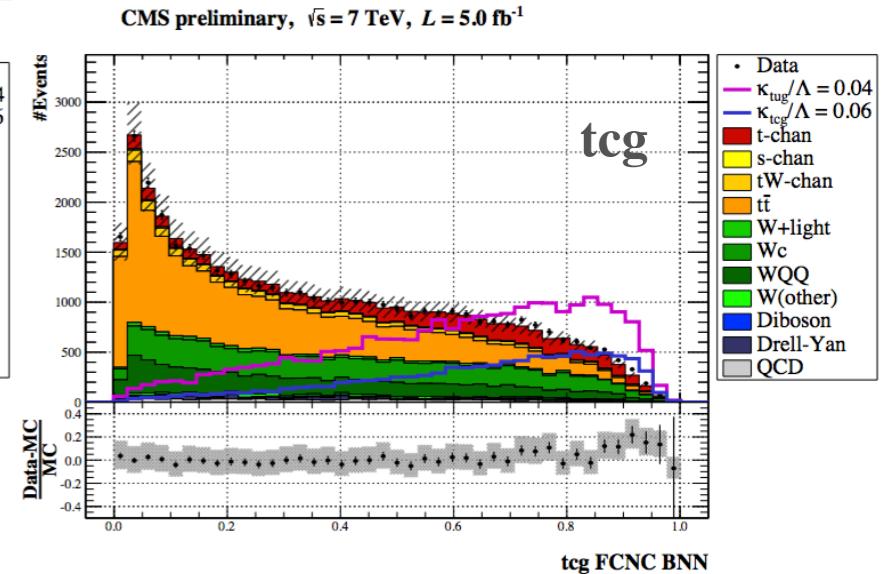
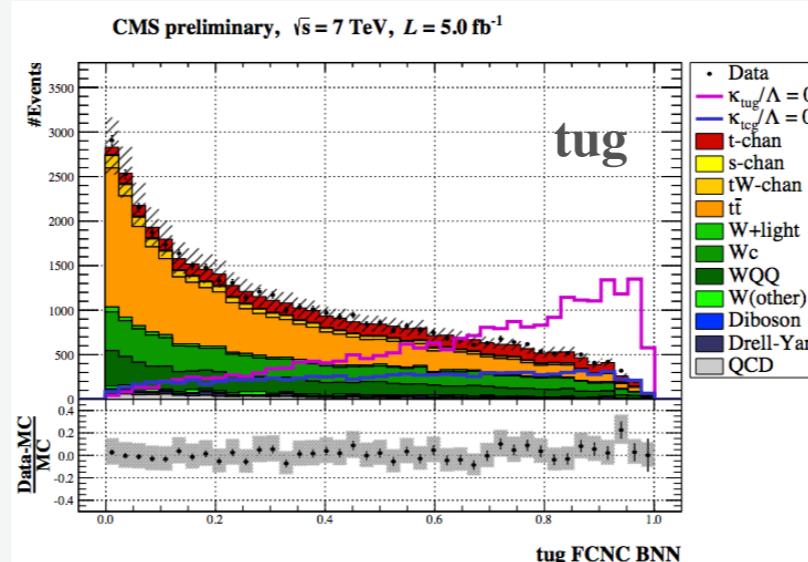
CompHEP @NLO (approx.)

QCD multijet background is estimated from a template fit using a dedicated BNN (QCD template is taken from control region with reversed lepton isolation)

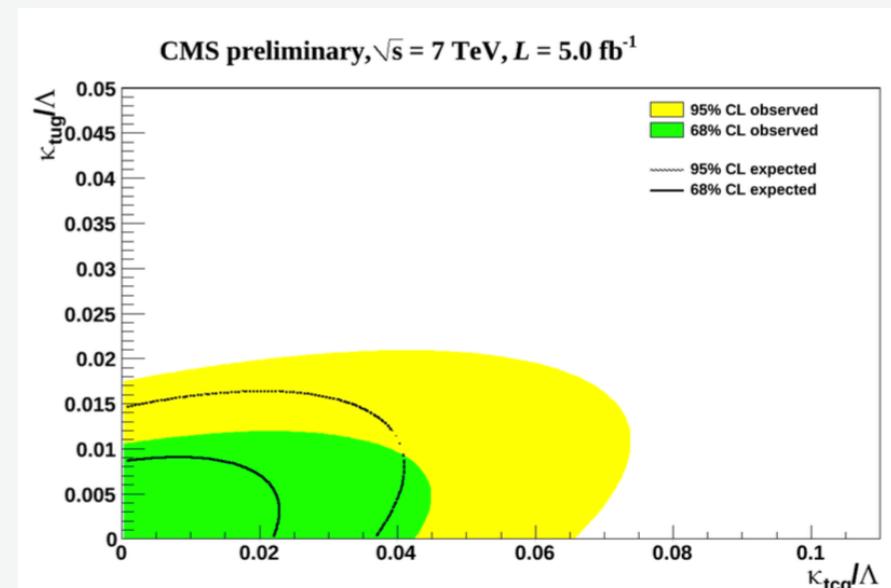
Control regions of 4-jet 1-tag (**ttbar**) and 0-tag (**W+jets**) are used to validate background MC predictions

Event signature: exactly one isolated muon, missing E_T , at least one b-tagged jet and one non-b-tagged jet (same as for SM t-channel single top)

Bayesian Neural Network (BNN) is used to discriminate signal and background using: $p_T(b)$, $p_T(j_1j_2)$, $p_T(\mu)$, $p_T(W)$, $\Delta\phi(\mu, \nu)$, $\cos\theta(\mu, W)$ in the W-boson rest frame, ...

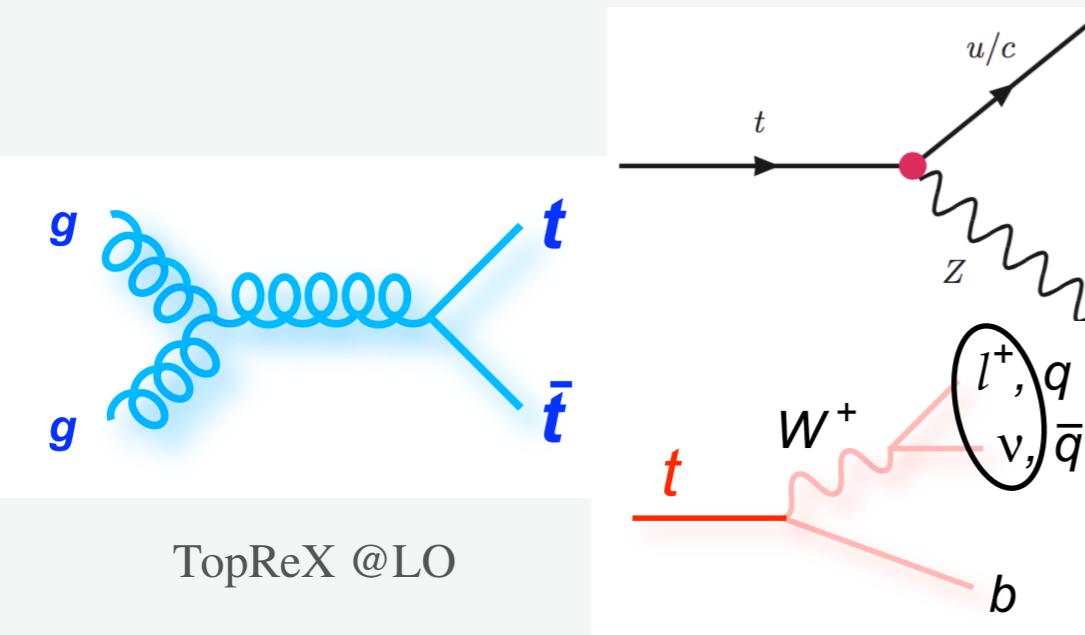


$$\begin{aligned} \kappa_{\text{ugt}}/\Lambda &< 1.8 \cdot 10^{-2} \text{ TeV}^{-1} \\ \kappa_{\text{cgt}}/\Lambda &< 5.6 \cdot 10^{-2} \text{ TeV}^{-1} \\ \text{BR}(t \rightarrow ug) &< 3.6 \cdot 10^{-4} \\ \text{BR}(t \rightarrow cg) &< 3.4 \cdot 10^{-5} \end{aligned}$$



Search for $t \rightarrow Zq$ in $t\bar{t}$ events at ATLAS

JHEP 1209 (2012) 139
ATLAS, 2 fb^{-1} , 7 TeV



Event signature: exactly three isolated leptons, missing E_T , at least two jets

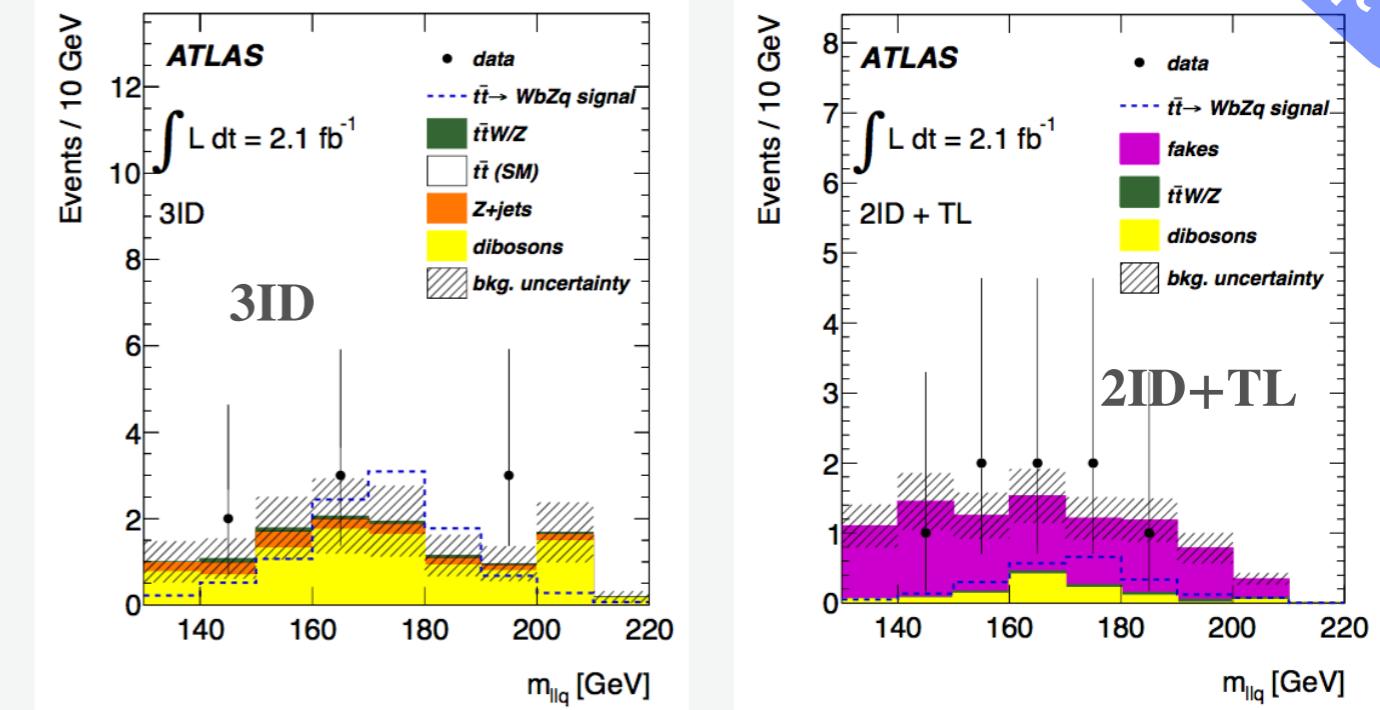
Analysis is performed in the channels with 3 tight lepton (**3ID**) and 2 tight leptons + 1 track-lepton (**2ID+TL**)

Fake lepton background is evaluated with a data-driven method: scale factor in **3ID** and fake matrix method in **2ID+TL**

Main background: $WZ/ZZ+jets$, fakes, $Z+jets$

Additional requirement of a presence of b-jet for **2ID+TL** channel

Events are **tested** for consistency with $t\bar{t}\rightarrow WbZq$ process by χ^2 minimisation



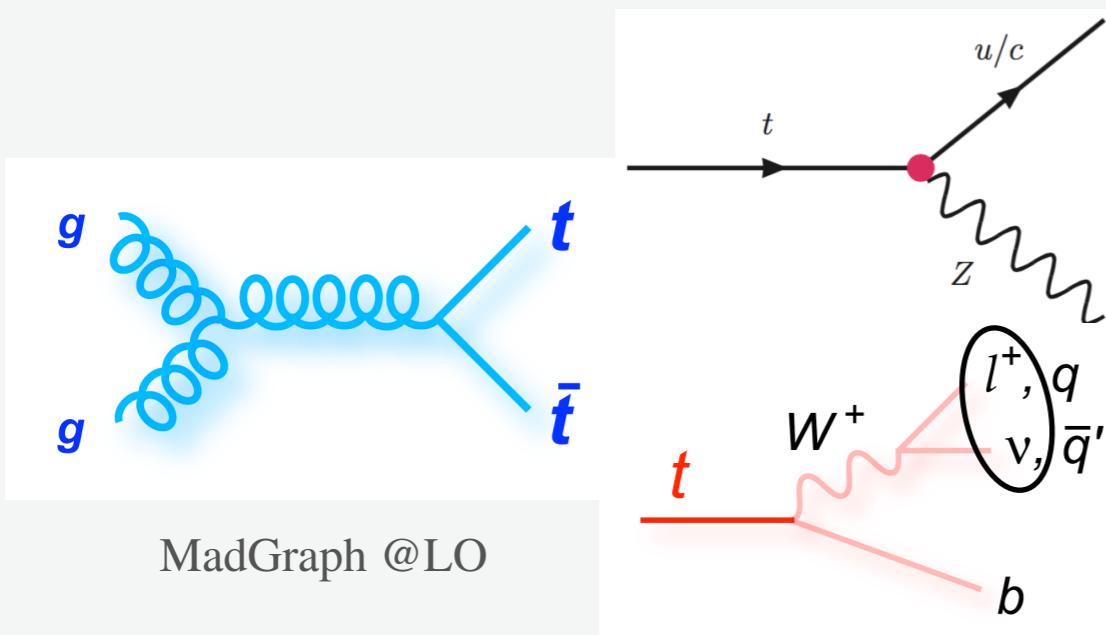
Limits extracted using binned likelihood fit with modified Frequentist (CLs) likelihood method

channel	observed	(-1σ)	expected	($+1\sigma$)
3ID	0.81%	0.63%	0.95%	1.4%
2ID+TL	3.2%	2.15%	3.31%	4.9%
Combination	0.73%	0.61%	0.93%	1.4%

$$\text{BR}(t \rightarrow Zq) < 0.73 \cdot 10^{-2}$$

Zq_t

Search for $t \rightarrow Zq$ in ttbar events at CMS

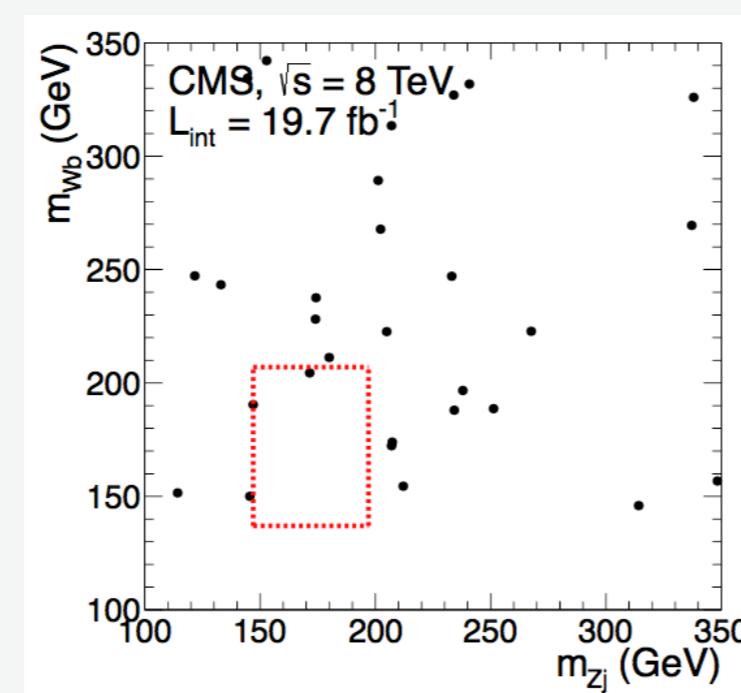
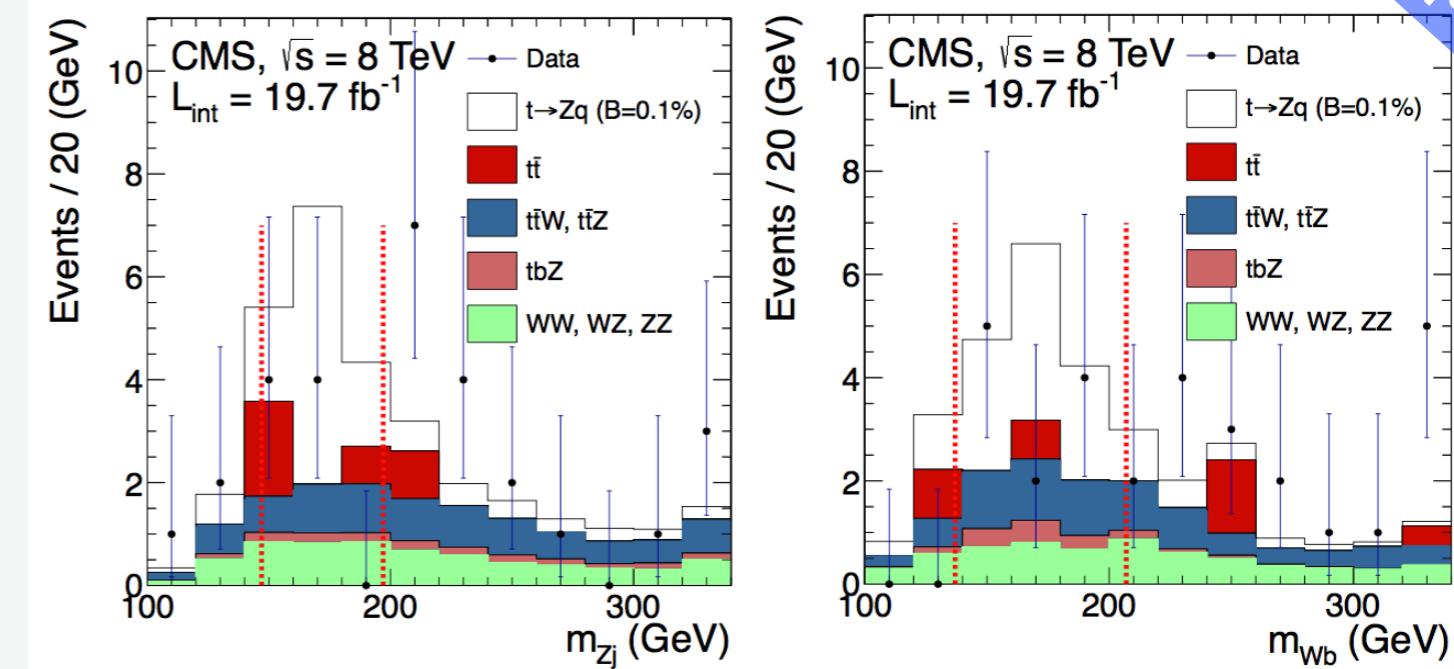


Event signature: exactly three isolated leptons, missing E_T , at least two jets of which exactly one jet is b-tagged

Combinatorics is resolved by the best top quark mass reconstruction

WZ/ZZ predictions are validated in control regions in data

Drell-Yan and ttbar backgrounds are estimated from data



Limits extracted using binned likelihood fit with modified Frequentist (CLs) likelihood method

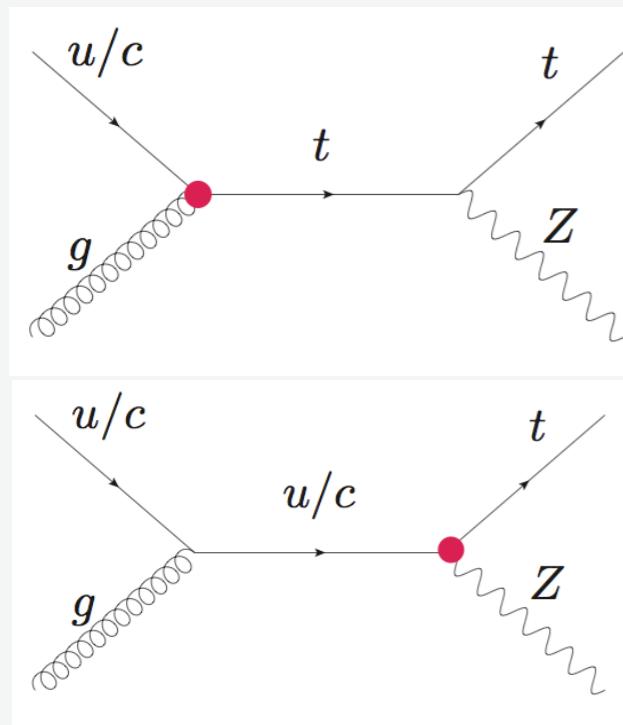
$\mathcal{B}(t \rightarrow Zq)$	8 TeV	7 TeV + 8 TeV
Expected upper limit	<0.10%	<0.09%
Observed upper limit	<0.06%	<0.05%
1 σ boundary	0.06–0.13%	0.06–0.13%
2 σ boundary	0.05–0.20%	0.05–0.18%

$\text{BR}(t \rightarrow Zq) < 0.05 \cdot 10^{-2}$

Search for tZ events in single top at CMS

CMS-PAS-TOP-12-021
CMS, 5 fb^{-1} , 7 TeV

$Z_{q\bar{t}}$



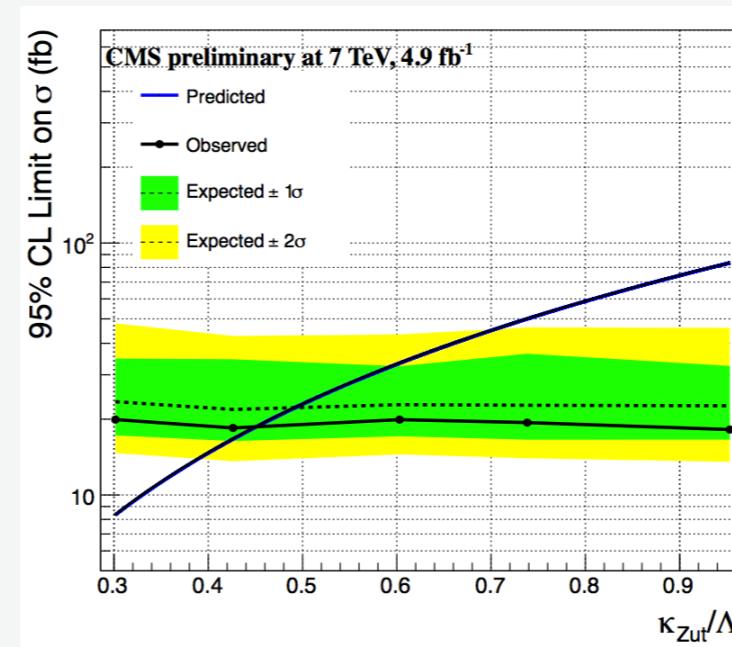
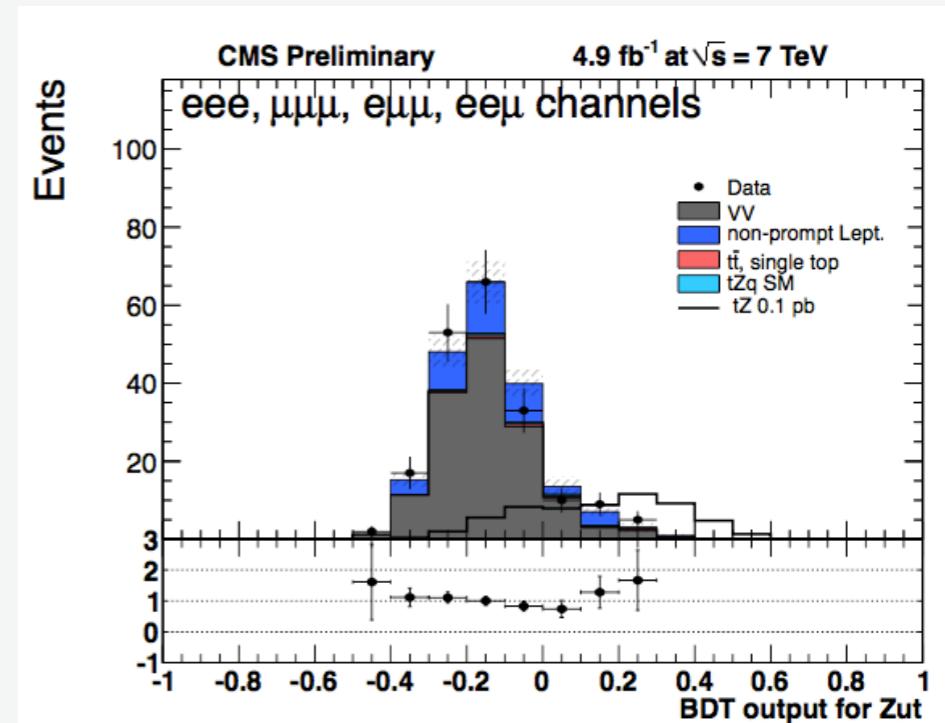
MadGraph @LO

Event signature: exactly three isolated leptons, missing E_T , one b-tagged jet

WZ+jets and Z+jets (fake)
backgrounds are estimated from template fit in data using $m_T(W)$:
WZ+jets template from MC, Z+jets template from data with reversed lepton isolation

BDT is used to discriminate signal and background using: $p_T(Z)$, $\eta(Z)$, number of jets, number of b-jets, $\Delta\phi(l_W, b)$, reconstructed top quark mass, b-tag discriminator, ...

Limits extracted using profile likelihood ratio (PLR) method in modified Frequentist approach (CLs)

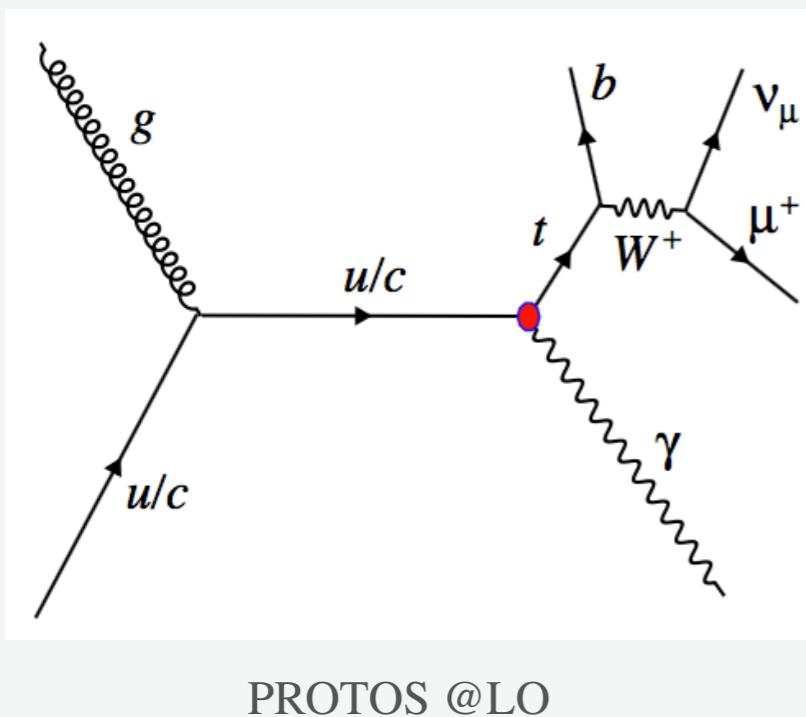


$\kappa_{Zut}/\Lambda < 0.45 \text{ TeV}^{-1}$
 $\kappa_{Zct}/\Lambda < 2.27 \text{ TeV}^{-1}$
 $\kappa_{ugt}/\Lambda < 0.10 \text{ TeV}^{-1}$
 $\kappa_{cgt}/\Lambda < 0.35 \text{ TeV}^{-1}$
 $\text{BR}(t \rightarrow Zu) < 0.51 \cdot 10^{-2}$
 $\text{BR}(t \rightarrow Zc) < 11.4 \cdot 10^{-2}$
 $\text{BR}(t \rightarrow ug) < 0.56 \cdot 10^{-2}$
 $\text{BR}(t \rightarrow cg) < 7.12 \cdot 10^{-2}$

Search for $t\gamma$ events in single top at CMS

CMS-PAS-TOP-14-003
CMS, 19 fb^{-1} , 8 TeV

$\chi_{q\bar{t}}$



PROTOS @LO

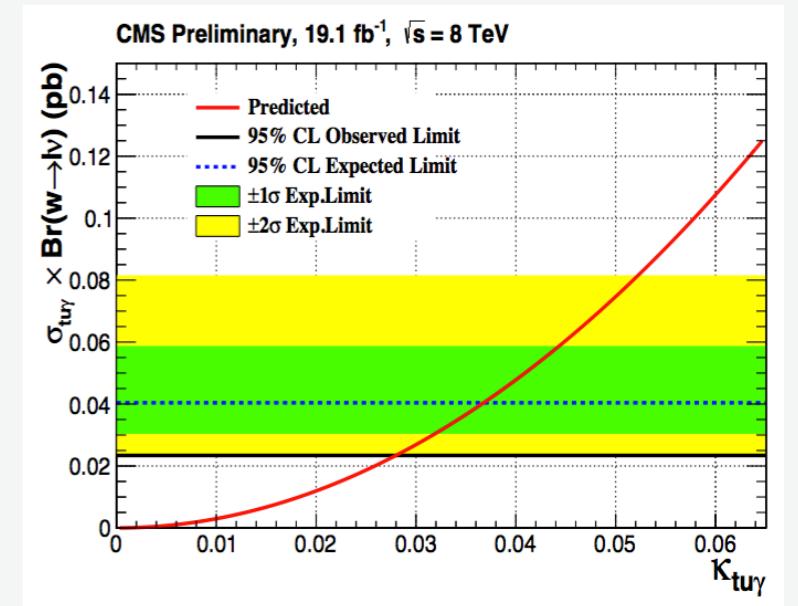
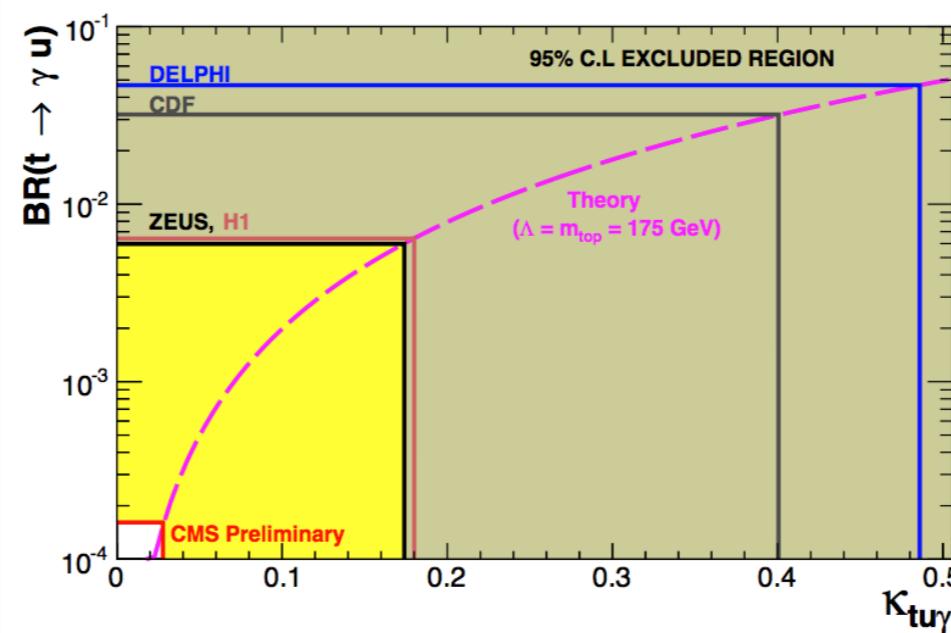
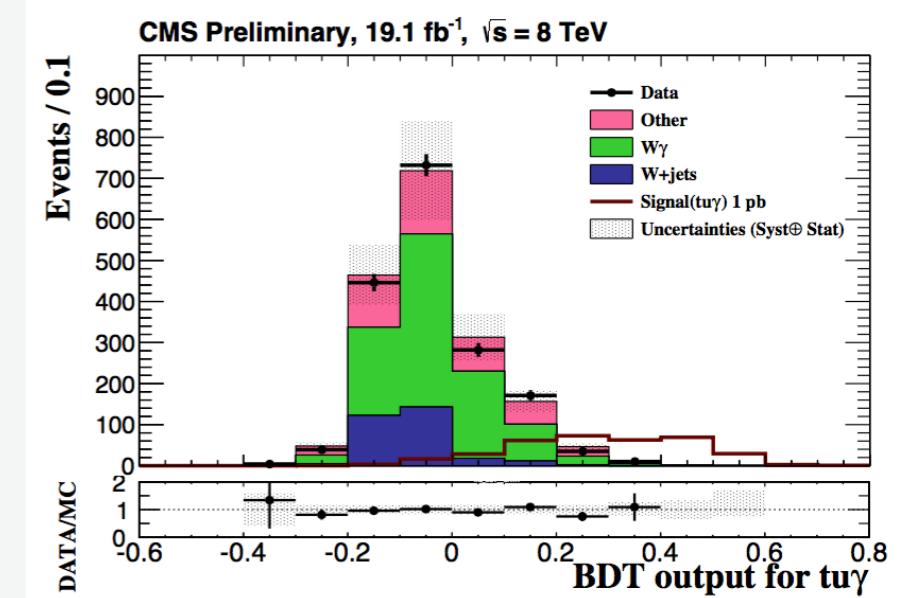
BDT is used to discriminate signal and background using:
 $p_T(\gamma)$, $p_T(b)$, $p_T(\mu)$, $\Delta R(\mu, \gamma)$,
 $\Delta R(b, \gamma)$, number of jets, b-tag discriminator, ...

$$\begin{aligned}\kappa_{u\gamma t}/\Lambda &< 0.028 \text{ TeV}^{-1} \\ \kappa_{c\gamma t}/\Lambda &< 0.094 \text{ TeV}^{-1} \\ \text{BR}(t \rightarrow u\gamma) &< 0.016 \cdot 10^{-2} \\ \text{BR}(t \rightarrow c\gamma) &< 0.182 \cdot 10^{-2}\end{aligned}$$

Event signature: exactly one isolated muon, one photon, missing E_T , one b-tagged jet

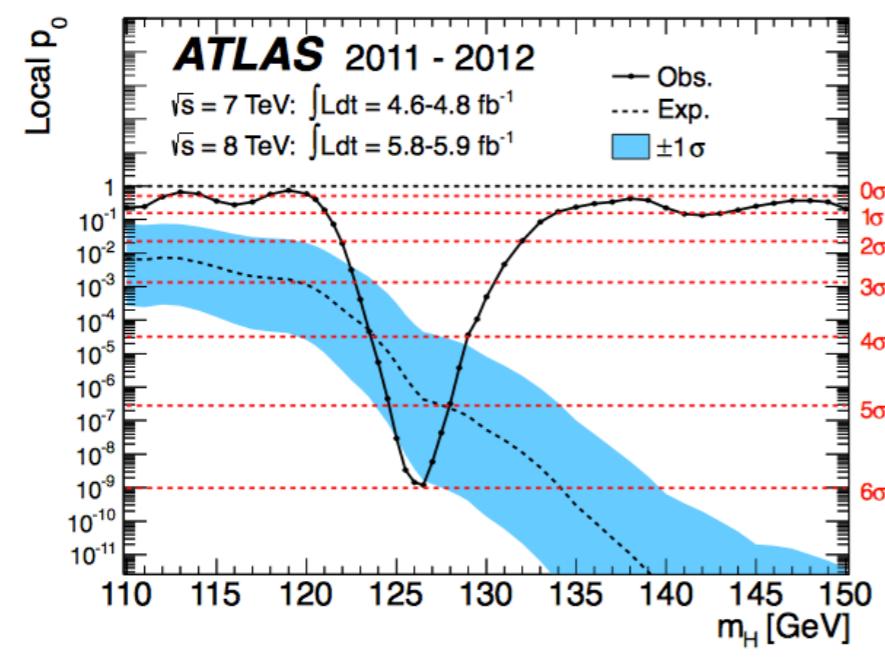
Main background: $W\gamma + \text{jets}$, $W + \text{jets}$, $t\bar{t}$, $Z\gamma + \text{jets}$

$W\gamma + \text{jets}$ and $W + \text{jets}$ backgrounds
are estimated from data with a template fit method using $\cos\theta(W, \gamma)$:
 $W + \text{jets}$ template taken from data with no b-jet requirement



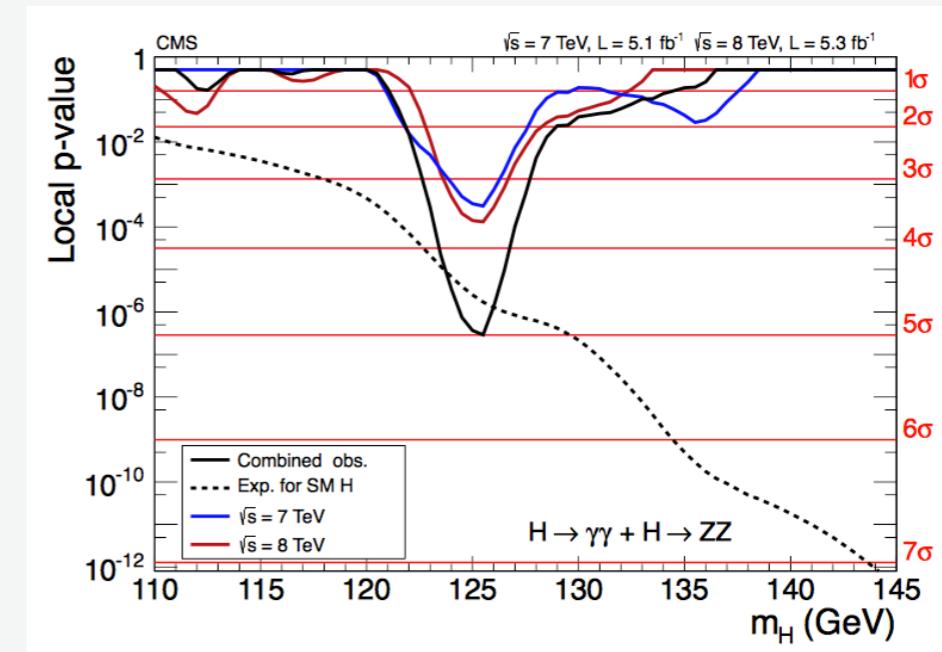
Limits extracted using profile likelihood ratio (PLR) method in modified Frequentist approach (CLs)

Higgs + FCNC = ❤ ?



Phys. Lett. B 716 (2012) 1-29

A new
particle
is born

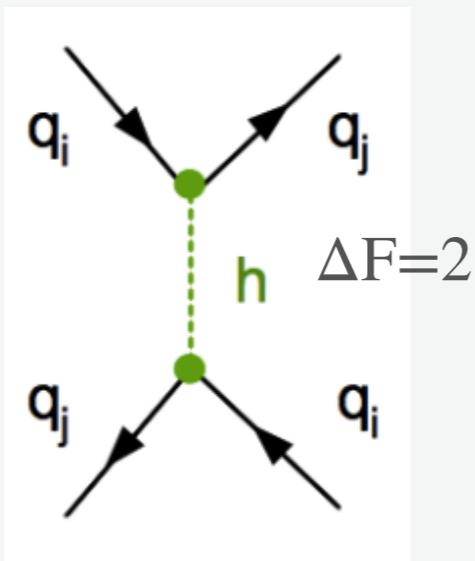


Phys. Lett. B 716 (2012) 30

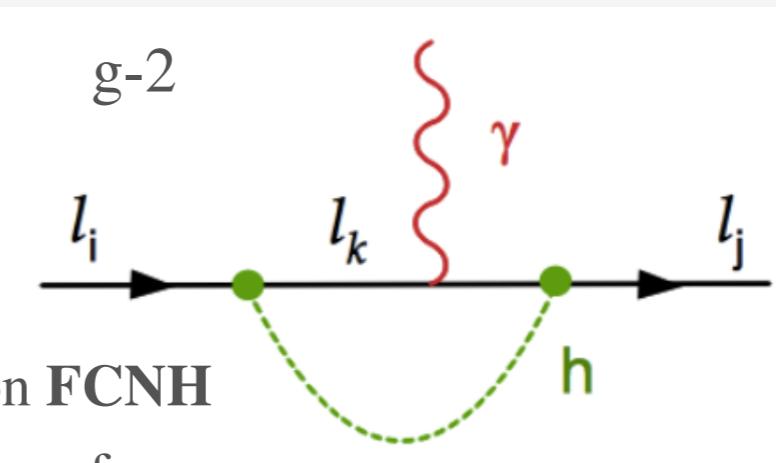
but we don't know it very well
yet ...

Higgs + FCNC = ❤ ?

**Tight constraints on
FCNH couplings to
light quarks from
neutral meson
oscillations**



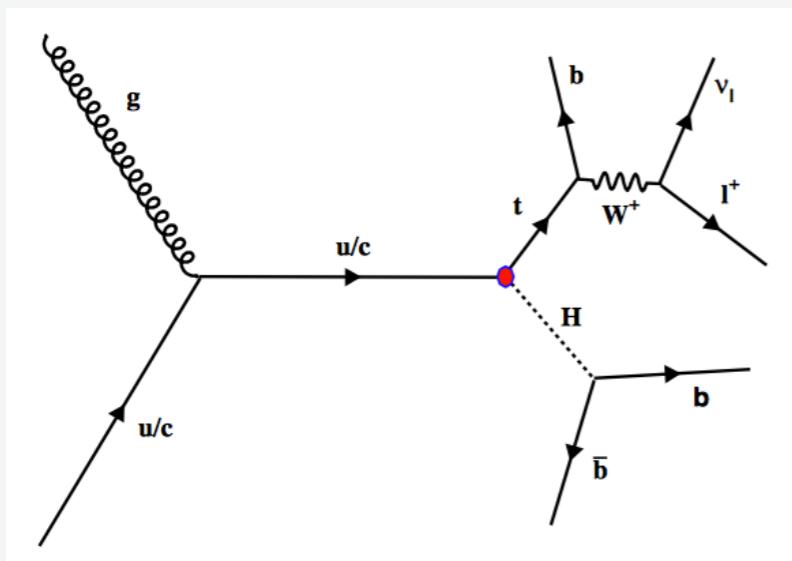
**Stringent limits on FCNH
couplings to leptons from
LFV searches**



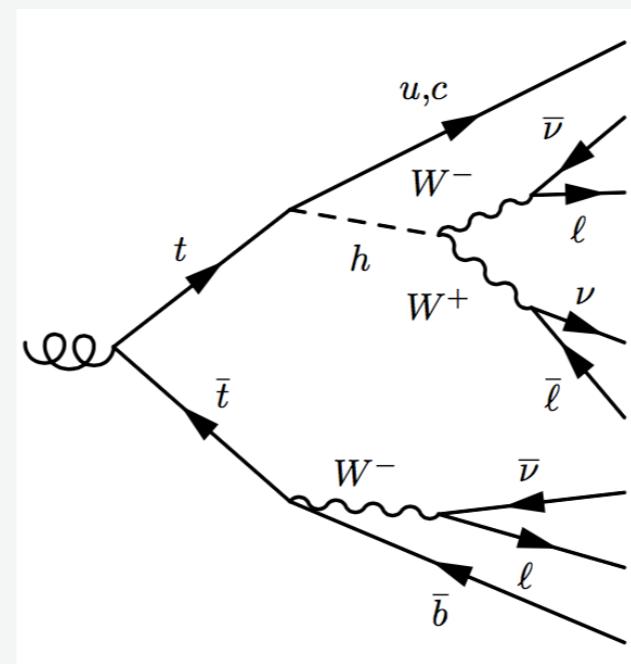
<http://arxiv.org/abs/1202.5704>

Is there a place for FCNH with a top quark ?

FCNH in single top



FCNH in ttbar

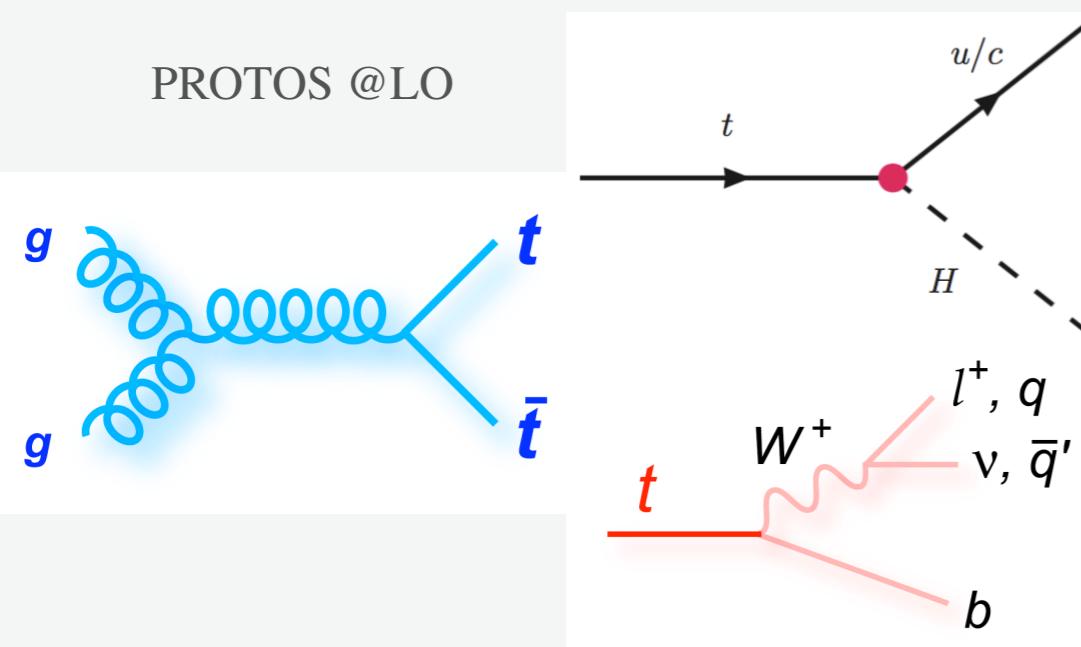


Should we expect a large FCNH coupling strength with a top quark as in case of Yukawa interactions ?

H \bar{q}

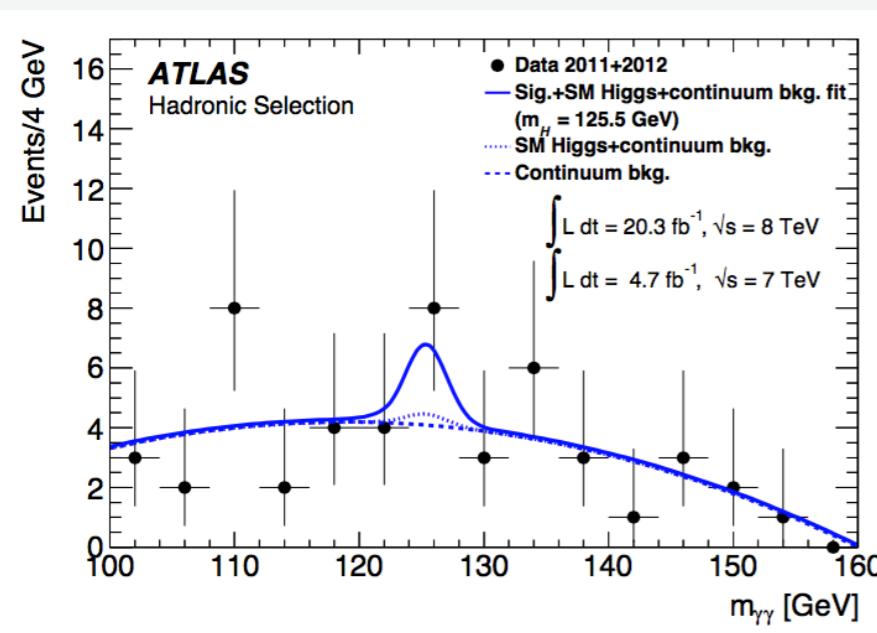
Search for $t \rightarrow Hq$ in $t\bar{t}$ bar events at ATLAS

PROTOS @LO



In **hadronic channel** background is estimated from the data fit using non-resonant $\gamma\gamma + \text{jets}$ shape.

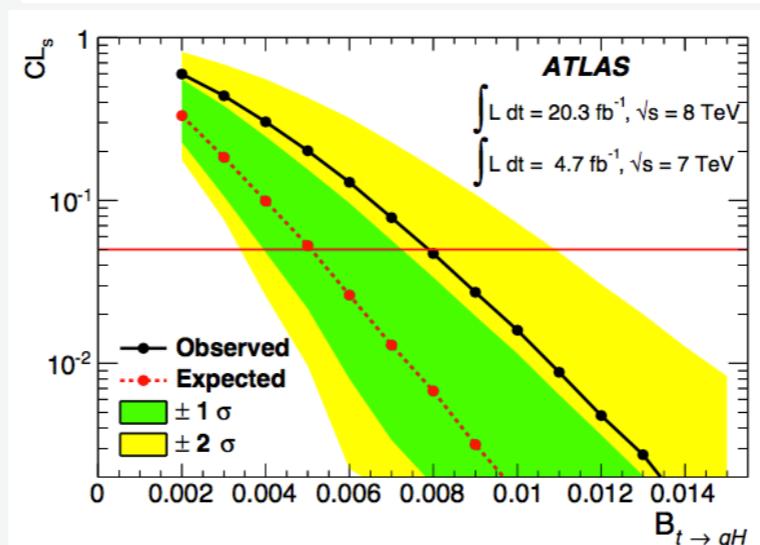
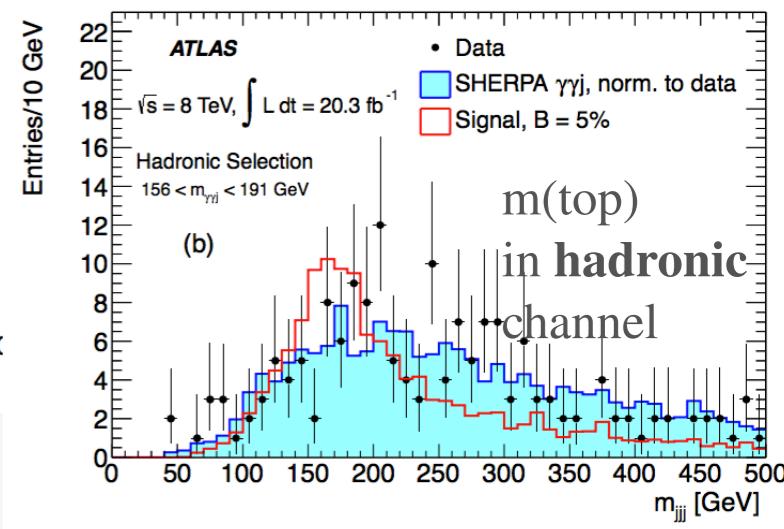
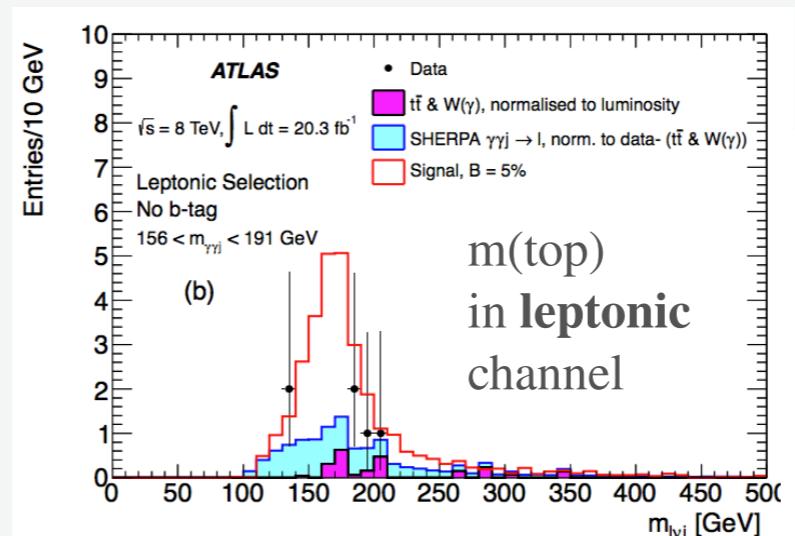
Leptonic channel uses transfer factor (SR/CR) with the central value measured in hadronic channel.



Analysis is done in $H \rightarrow \gamma\gamma$ channel

Event signature: two photons, one b-tagged jet, 3 jets (W-boson **hadronic** decays) or one isolated lepton, missing E_T and one jet (W-boson **leptonic** decays)

Main background: $\gamma\gamma + \text{jets}$, $W + \text{jets}$, $t\bar{t}$ bar



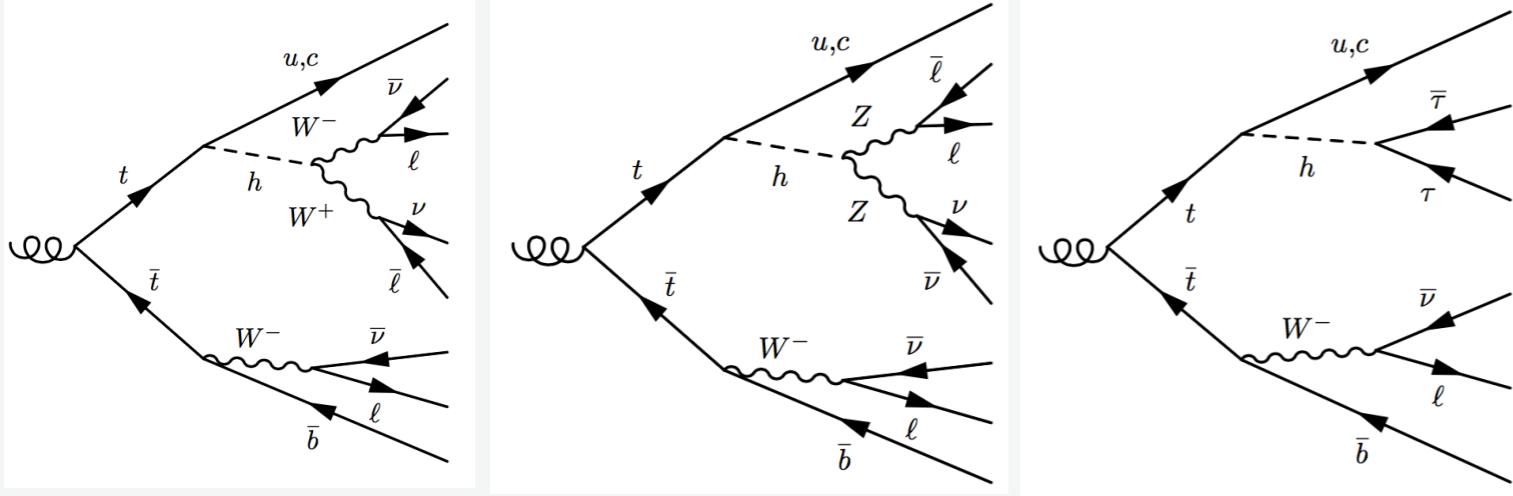
Limits extracted using CLs method

$K_{qHt} < 0.17$
 $\text{BR}(t \rightarrow qH) < 0.79 \cdot 10^{-2}$

Search for $t \rightarrow Hq$ in $t\bar{t}$ bar events at CMS

CMS-PAS-TOP-13-017
CMS, 20 fb^{-1} , 8 TeV

H \bar{q}



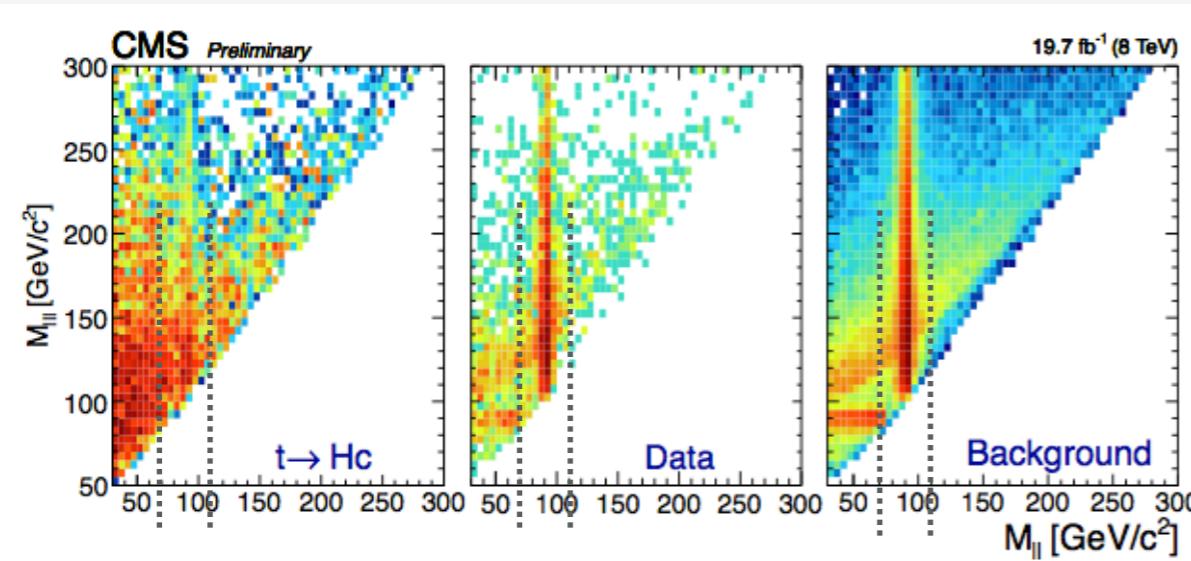
Analysis is done in multilepton
($H \rightarrow WW/ZZ/\tau\tau$) channel

Event signature: three or two same-sign leptons, one b-tagged jet (used for background validation in CRs), missing E_T , at least two jets

PYTHIA6 @LO

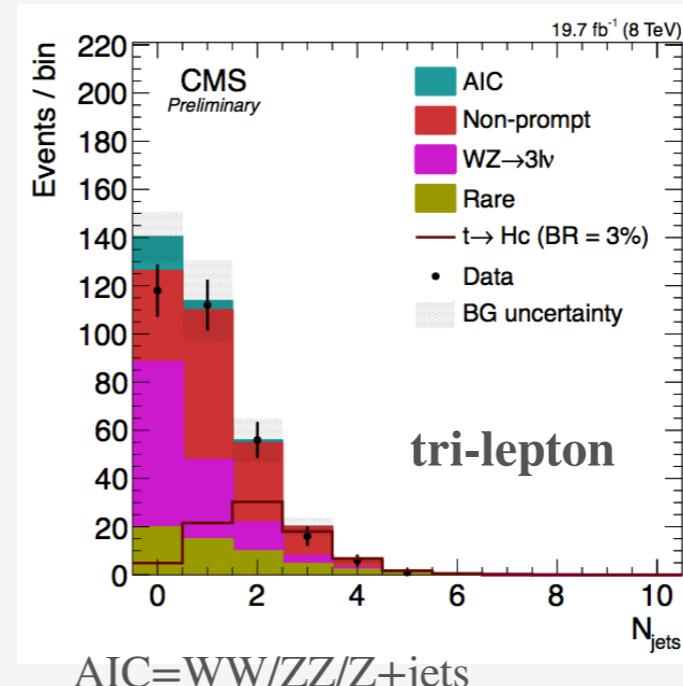
Additional selection in **tri-lepton** channel:

Main background: $WZ + \text{jets}$, $t\bar{t} + V$ (**tri-lepton**), fake leptons, charge mis-ID (**same-sign dilepton**)



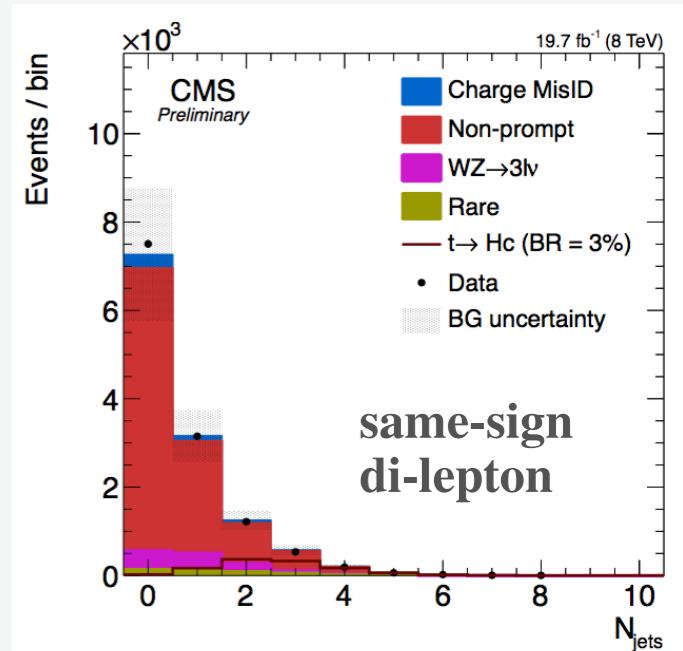
Additional selection in **di-lepton**

channel includes cuts on missing E_T and H_T



AIC= $WW/ZZ/Z + \text{jets}$

Fake lepton and charge mis-ID background are estimated from data



$\kappa_{qHt} < 0.18$
 $\text{BR}(t \rightarrow qH) < 0.93 \cdot 10^{-2}$

Search for $t \rightarrow Hq$ in $t\bar{t}$ bar events at CMS

CMS-PAS-HIG-13-034
CMS, 20 fb^{-1} , 8 TeV

Based on a combination of two analyses performed in multilepton ($H \rightarrow WW/ZZ/\tau\tau$) and $H \rightarrow \gamma\gamma$ channels

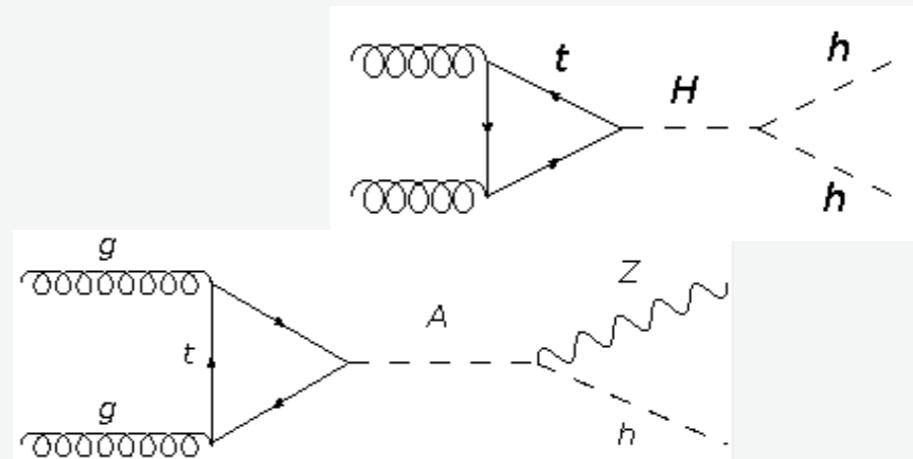
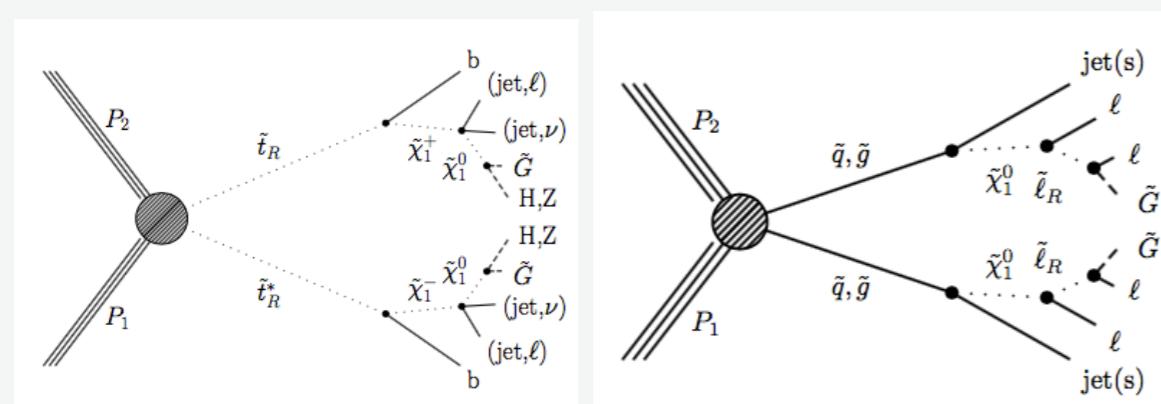
Phys. Rev. D 90
032006 (2014)
CMS, 20 fb^{-1} , 8 TeV

CMS-PAS-
HIG-13-025
CMS, 20 fb^{-1} , 8 TeV

$H_{\tilde{q}}$

Multi-lepton analysis is done in the framework of the SUSY search for natural Higgsino, slepton, etc.

Di-photon analysis developed for the search for 2HDM $H \rightarrow H_{\text{SM}}H_{\text{SM}}$ and $A \rightarrow ZH_{\text{SM}}$



Several SUSY scenarios are probed, also possible to set limits on FCNH in this inclusive search:

Higgs boson decay mode	Upper limits on $\mathcal{B}(t \rightarrow cH)$		
	Obs.	Exp.	1σ range
$\mathcal{B}(H \rightarrow WW^*) = 23.1\%$	1.6 %	1.6 %	(1.0–2.2)%
$\mathcal{B}(H \rightarrow \tau\tau) = 6.2\%$	7.01%	5.0 %	(3.5–7.7)%
$\mathcal{B}(H \rightarrow ZZ^*) = 2.9\%$	5.3%	4.11%	(2.9–6.5)%
Combined	1.3%	1.2%	(0.9–1.7)%

$\kappa_{qHt} < 0.21$
 $\text{BR}(t \rightarrow qH) < 1.28 \cdot 10^{-2}$

MadGraph @LO is used for FCNH generation

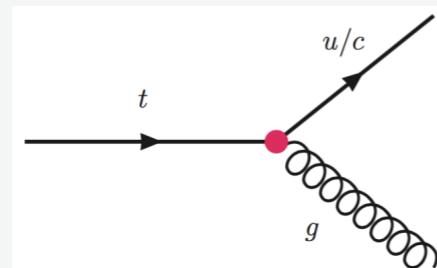
Higgs Decay Mode	observed	expected	1σ range
$H \rightarrow WW^*$ ($\mathcal{B} = 23.1\%$)	1.58 %	1.57 %	(1.02–2.22) %
$H \rightarrow \tau\tau$ ($\mathcal{B} = 6.15\%$)	7.01 %	4.99 %	(3.53–7.74) %
$H \rightarrow ZZ^*$ ($\mathcal{B} = 2.89\%$)	5.31 %	4.11 %	(2.85–6.45) %
combined multileptons ($WW^*, \tau\tau, ZZ^*$)	1.28 %	1.17 %	(0.85–1.73) %
$H \rightarrow \gamma\gamma$ ($\mathcal{B} = 0.23\%$)	0.69 %	0.81 %	(0.60–1.17) %
combined multileptons + diphotons	0.56 %	0.65 %	(0.46–0.94) %

Combination of results

$\kappa_{qHt} < 0.14$
 $\text{BR}(t \rightarrow qH) < 0.56 \cdot 10^{-2}$

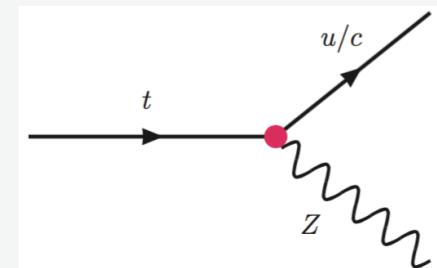
Summary on FCNC searches at the LHC

gqt



Experiment	BR($t \rightarrow ug$)	BR($t \rightarrow cg$)	Reference
ATLAS	$3.1 \cdot 10^{-5}$	$1.6 \cdot 10^{-4}$	ATLAS-CONF-2013-063
CMS	$3.6 \cdot 10^{-4}$	$3.4 \cdot 10^{-3}$	CMS-PAS-TOP-14-007

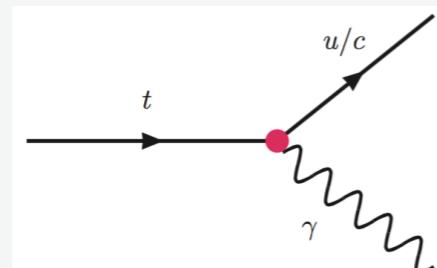
Zqt



Experiment	BR($t \rightarrow uZ$)	BR($t \rightarrow cZ$)	Reference
ATLAS	$0.73 \cdot 10^{-2}$		JHEP 1209 (2012) 139
CMS	$0.05 \cdot 10^{-2}$		Phys. Rev. Lett. 112 (2014) 171802
CMS	$0.51 \cdot 10^{-2}$	$11.4 \cdot 10^{-2}$	CMS-PAS-TOP-12-021

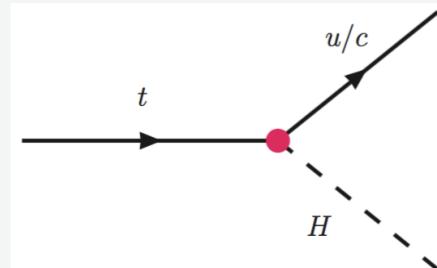
Experiment	BR($t \rightarrow u\gamma$)	BR($t \rightarrow c\gamma$)	Reference
CMS	$0.02 \cdot 10^{-2}$	$0.18 \cdot 10^{-2}$	CMS-PAS-TOP-14-003

γqt



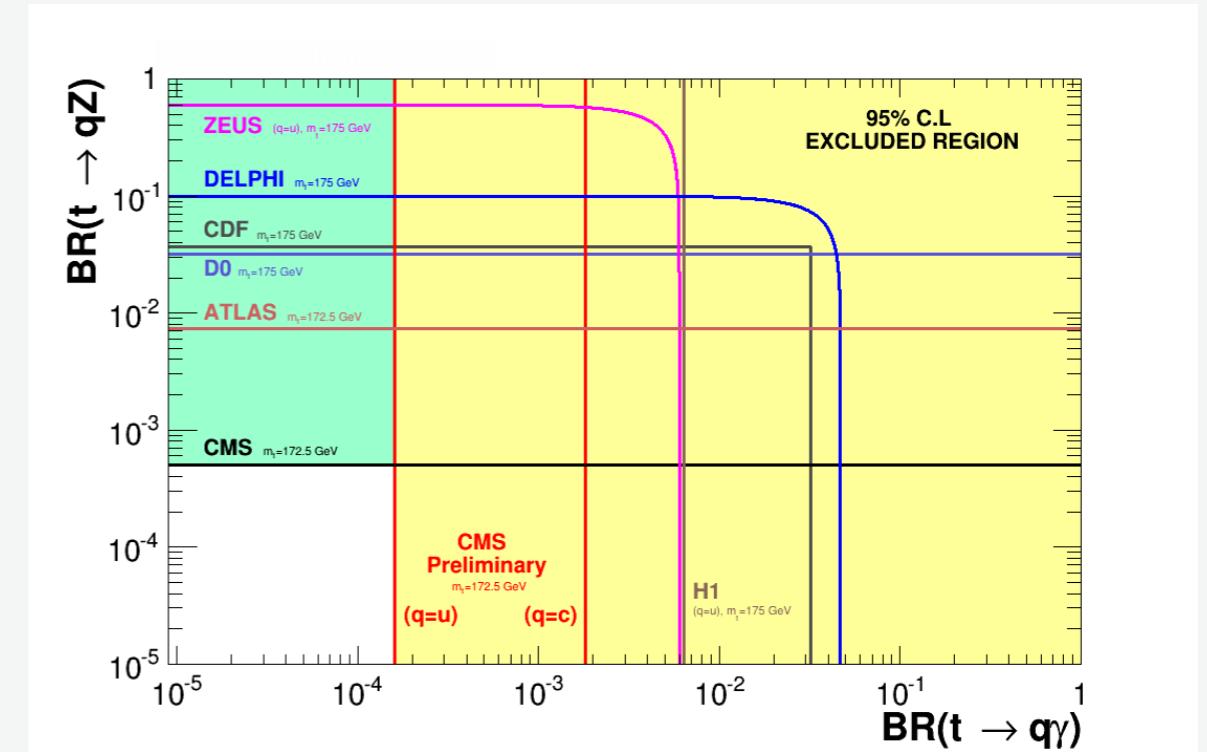
Experiment	BR($t \rightarrow uH$)	BR($t \rightarrow cH$)	Reference
ATLAS	$0.79 \cdot 10^{-2}$		JHEP 06 (2014) 008
CMS	$0.56 \cdot 10^{-2}$		CMS-PAS-HIG-13-034

Hqt



Conclusion

- An experimental review on FCNC searches was presented
- All known types of FCNC couplings are considered in the searches including various final states
- No evidence of new physics **yet**
- The ATLAS and the CMS experiments have **significantly improved the exclusion limits** for FCNC couplings with Run I data
- Looking forward to Run II analyses results from the LHC



Best limits on FCNC top quark decays from the LHC :

$\text{BR}(t \rightarrow ug)$	$3.1 \cdot 10^{-5}$	ATLAS-CONF-2013-063
$\text{BR}(t \rightarrow cg)$	$1.6 \cdot 10^{-4}$	ATLAS-CONF-2013-063
$\text{BR}(t \rightarrow qZ)$	$0.05 \cdot 10^{-2}$	Phys. Rev. Lett. 112 (2014) 171802
$\text{BR}(t \rightarrow ug)$	$0.02 \cdot 10^{-2}$	CMS-PAS-TOP-14-003
$\text{BR}(t \rightarrow cg)$	$0.18 \cdot 10^{-2}$	CMS-PAS-TOP-14-003
$\text{BR}(t \rightarrow qH)$	$0.56 \cdot 10^{-2}$	CMS-PAS-HIG-13-034