EFTs from Top FCNC searches (results, issues, strategy for FCNC)

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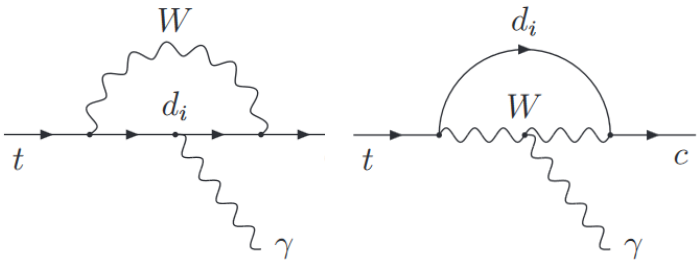
LHC Top Working Group
21-23 November 2016 @ CERN

Introduction

- Flavor-Changing Neutral Current (FCNC) for top-quark



- These interactions are highly suppressed in the Standard Model due to GIM (Glashow-Iliopoulos-Maiani) mechanism: no tree diagram

Standard Model (branching ratio)			
$t \to uZ$	8×10^{-17}	$t \to cZ$	1×10^{-14}
$t \to u\gamma$	3.7×10^{-16}	$t \to c\gamma$	4.6×10^{-14}
$t \to ug$	3.7×10^{-14}	$t \to cg$	4.6×10^{-12}
$t \to uH$	2×10^{-17}	$t \to cH$	3×10^{-15}

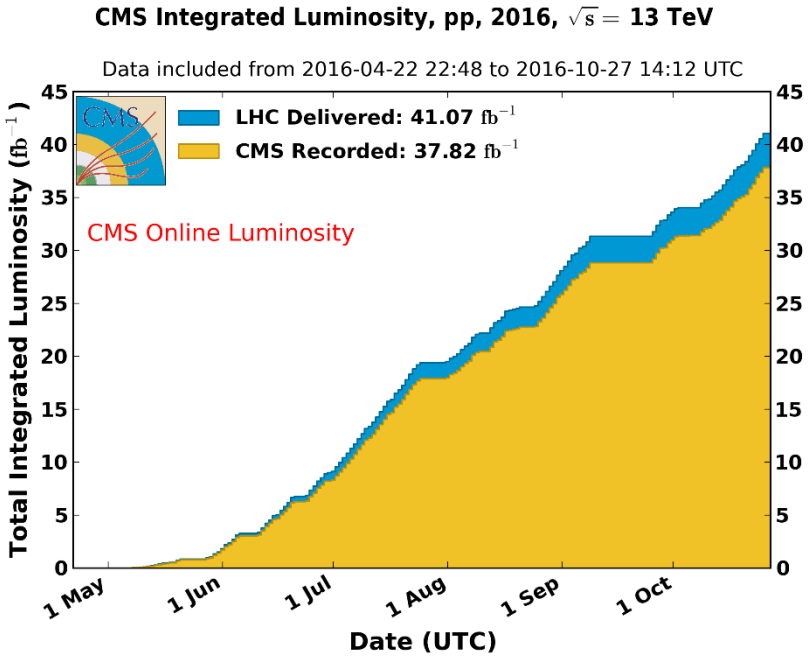
[arXiv:0409342]

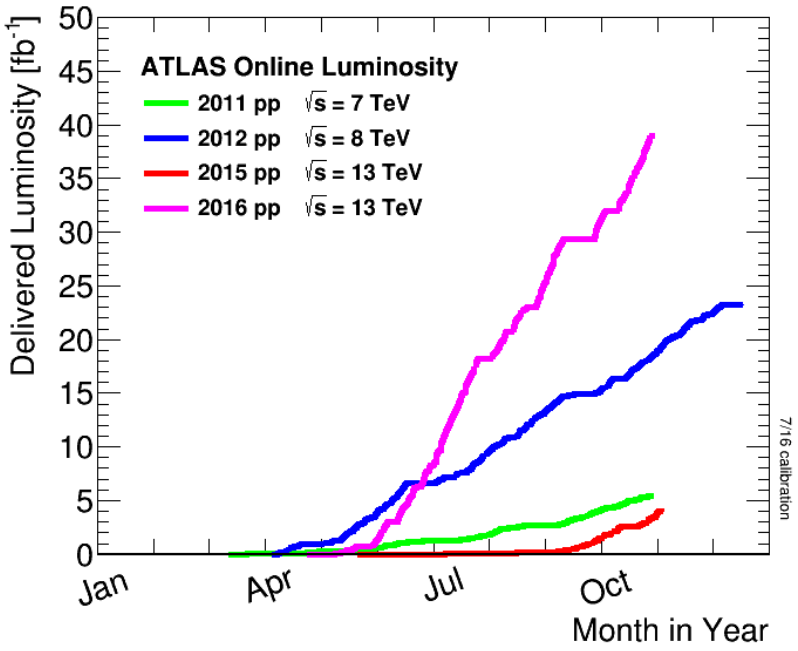
- In some Beyond Standard Models, these processes could be enhanced.

→FCNC = promising signatures of New Physics

Introduction

Available integrated luminosity





- FCNC searches with the Run II data: ongoing
- Public results are based on Run I data: $(\sqrt{s} = 7 \text{ or } 8 \text{ TeV})$

Part 1:

Context & strategy of the Top FCNC searches

Effective Field Theory (EFT) approach

Effective model for anomalous couplings between top & boson

Wilson coefficients (complex number)

Higher order are neglected (LO EW accuracy)

$$\mathcal{L}_{\text{eff}} = \sum \frac{C_x}{\Lambda^2}\mathcal{O}_{6,x} + \sum \frac{C_x}{\Lambda^4}\mathcal{O}_{8,x} + \sum \frac{C_x}{\Lambda^6}\mathcal{O}_{10,x} + \dots + \text{h.c.}$$

Energy scale of new physics

Dimension-6 gauge invariant operators

List of 56 dimension-6 operators

Description in term of anomalous couplings

The current LHC results are expressed in the framework of anomalous couplings (AC)

[arXiv:0803.3810, 0811.3842, 0904.2387]

$$
\begin{aligned}
\mathcal{L}_{FCNC} = \sum_{q=u,c} \Bigg[& \frac{\sqrt{2}}{2} g_s \frac{\kappa_{gqt}}{\Lambda} \cdot \bar{t}\sigma^{\mu\nu} \left(f_{gq}^{L} P_L + f_{gq}^{R} P_R\right) q G_{\mu\nu}^{a} \\
+ & \frac{\sqrt{2}}{2} e \frac{\kappa_{\gamma qt}}{\Lambda} \cdot \bar{t}\sigma^{\mu\nu} \left(f_{\gamma q}^{L} P_L + f_{\gamma q}^{R} P_R\right) q A_{\mu\nu} \\
+ & \frac{1}{\sqrt{2}} \eta_{hqt} \cdot \bar{t} \left(f_{hq}^{L} P_L + f_{hq}^{R} P_R\right) q H \\
+ & \frac{\sqrt{2}}{4} \frac{g}{\cos\theta_W} \frac{\kappa_{zqt}}{\Lambda} \cdot \bar{t}\sigma^{\mu\nu} \left(f_{zq}^{L} P_L + f_{zq}^{R} P_R\right) q Z_{\mu\nu} \\
+ & \frac{1}{4} \frac{g}{\cos\theta_W} \zeta_{zqt} \cdot \bar{t}\gamma^{\mu} \left(\tilde{f}_{zq}^{L} P_L + \tilde{f}_{zq}^{R} P_R\right) q Z_{\mu} \Bigg] + h.c
\end{aligned}
$$

$$
\text{with } \sigma^{\mu\nu} = \frac{i}{2}[\gamma^{\mu}, \gamma^{\nu}]
$$

Assumptions & comments

- No 4-fermions contacts are considered.

- Several conventions are possible for the parameters.
  → limit should be put on the anomalous BR top decay (independent-convention way)

Example of conventions

$$\sqrt{\left|f^L_{xq}\right|^2 + \left|f^R_{xq}\right|^2} = 1 \qquad \frac{\kappa_{xqt}}{\Lambda},\ \zeta_{xqt},\ \text{and}\ \eta_{xqt} > 0$$

$$\sqrt{\left|\tilde{f}^L_{xq}\right|^2 + \left|\tilde{f}^R_{xq}\right|^2} = 1$$

- Simplifying assumption on f^L_{xq} f^R_{xq} $\tilde{f}^R_{xq}$ $\tilde{f}^L_{xq}$

  - Kinematics seems to be not sensible to the choice of theses parameters **[to quantify]**
  - In the analysis, these parameters are usually fixed to a given value :

    - f^R_{xq} =0 & f^L_{xq}=1
    - f^R_{xq} =1 & f^L_{xq}=0

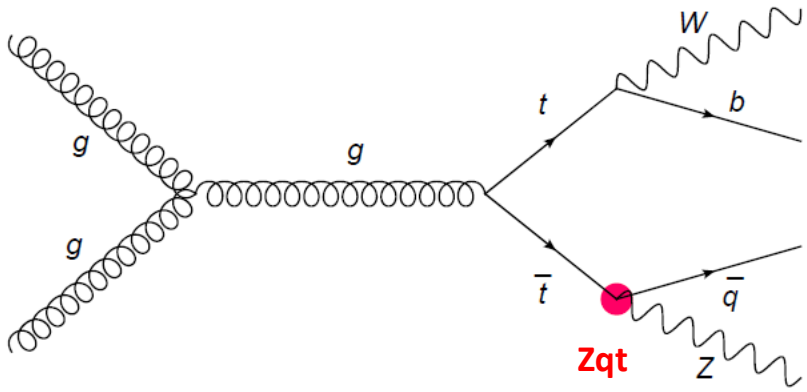
    (example)

Searches for FCNC

2 ways to look for FCNC:

1. In the top decay of tt processes: t → X q

Ex: κ_{Zqt}/Λ coupling



No c-tagger used in the analyses.
Sensibility to u and to c should be similar.

A search only based on this kind of processes is not interested for X = g or γ
(almost indistinguishable from background)

Searches for FCNC

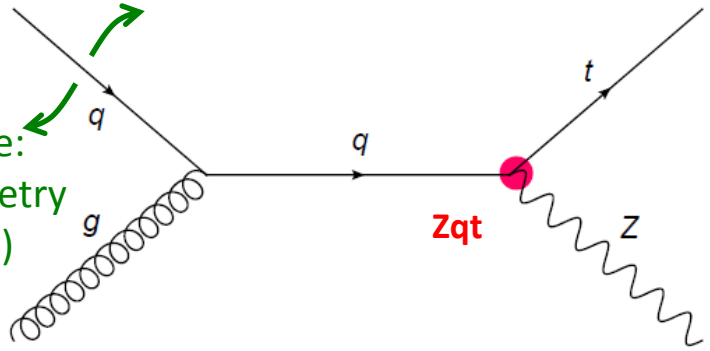
2 ways to look for FCNC:

1. In the top decay of tt processes: t → X q
2. In the associated single top production: pp → tX

Ex: κ_{Zqt}/Λ coupling

Less sensitive when the process is c-initiated

Interesting variable: the charge asymmetry (defined as q $|\eta_W|$)



\+ taking into account an irreducible SM background source: pp → tXq (b-initiated process)

Searches for FCNC

2 ways to look for FCNC:

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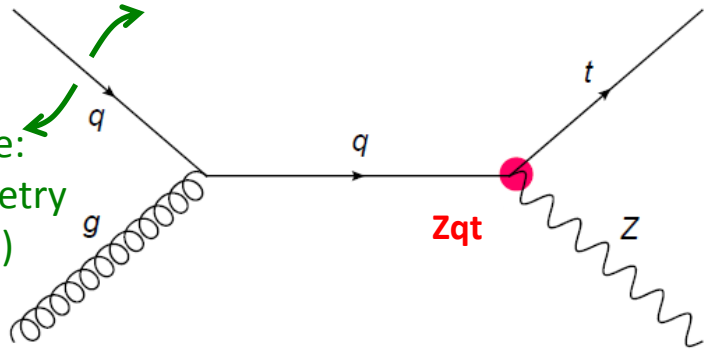


\+ taking into account an irreducible SM background source: pp → tXq (b-initiated process)

Tricky part for the generation

Overlap between pp → tX + 1 extra jet and pp → tt with t→Xq

Issues to apply the ME/PS merging technique → Diagram removal, diagram subtraction

Searches for FCNC @ LO QCD

Top decay	κ_{gqt}/Λ	$\kappa_{\gamma qt}/\Lambda$	κ_{zqt}/Λ	ζ_{zqt}	η_{hqt}
t→g q	X				
t→γ q		X			
t→Z q			X	X	
t→h q					X

Single top	κ_{gqt}/Λ	$\kappa_{\gamma qt}/\Lambda$	κ_{zqt}/Λ	ζ_{zqt}	η_{hqt}
p p → t (g)	X				
p p → t γ	X	X			
p p → t Z	X		X	X	
p p → t h	X				X

X: considered
X: usually neglected

Searches for FCNC @ LO QCD

Top decay	κ_{gqt}/Λ	$\kappa_{\gamma qt}/\Lambda$	κ_{zqt}/Λ	ζ_{zqt}	η_{hqt}
t→g q	X				
t→γ q		X			
t→Z q			X	X	
t→h q					X

Single top	κ_{gqt}/Λ	$\kappa_{\gamma qt}/\Lambda$	κ_{zqt}/Λ	ζ_{zqt}	η_{hqt}
p p → t (g)	X				
p p → t γ	X	X			
p p → t $l^+ l^-$	X	X	X	X	
p p → t b $\bar{b}$	X	X	X	X	X

X: considered
X: usually neglected

Part 2:

LHC results on Top FCNC searches

FCNC coupling: tgq

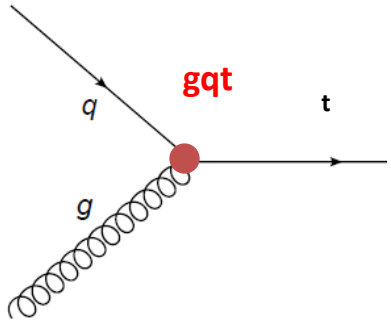
Signature = leptonic decay of a top quark

TOPQ-2011-18

7 TeV, L^{int}= 2.05 fb^{-1}

TOPQ-2014-13

8 TeV, L^{int}=20.3 fb^{-1}



Selection:

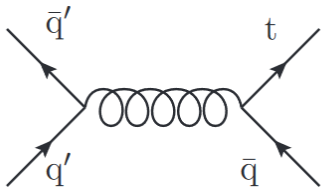
- 1 isolated lepton
- 1 b-tagged jet
- MET

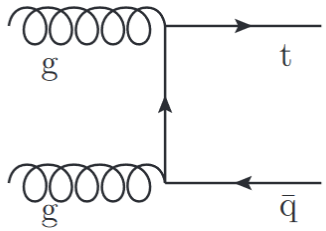
- A neural network is used in order to discriminate signal from background

TOP-14-007

7 TeV, L^{int}=5.0 fb^{-1} +

8 TeV, L^{int}=19.7 fb^{-1}





Selection devoted to both FCNC & Wtb:

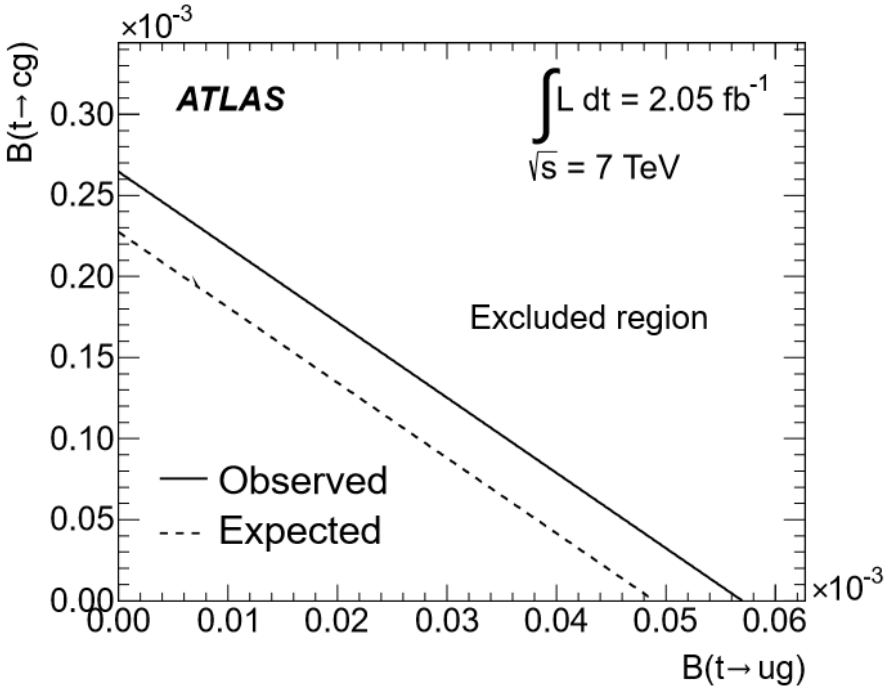
- 1 isolated muon
- 2 or 3 jets
- At least 1 b-tagged jet

- A neural network is used in order to discriminate signal from background

FCNC coupling: tgq

TOPQ-2011-18

7 TeV, L^{int}= 2.05 fb^{-1}



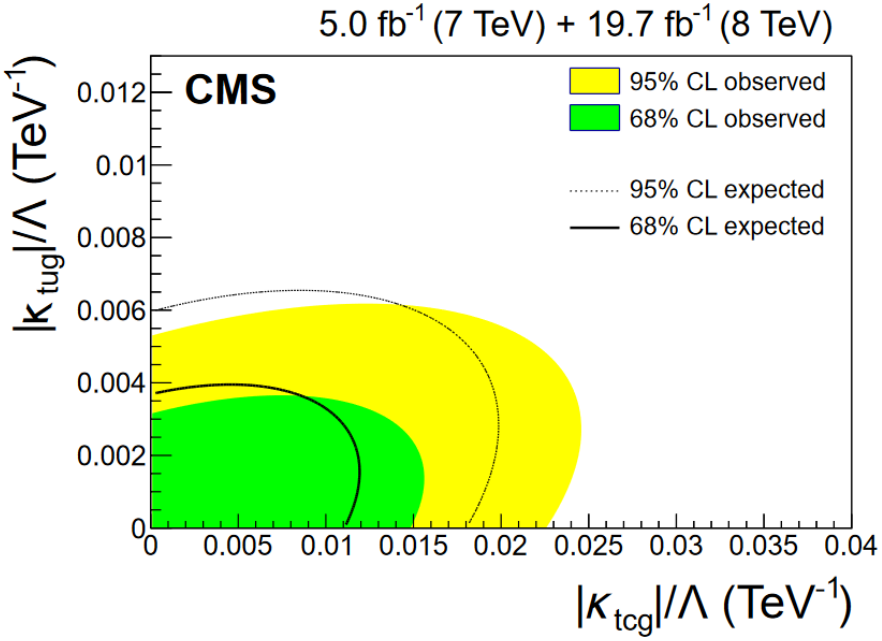
Upper limits @ CL= 95%:

$$BR(t \to gu) < 0.57 \times 10^{-4}$$
$$BR(t \to gc) < 2.7 \times 10^{-4}$$

TOP-14-007

7 TeV, L^{int}=5.0 fb^{-1} +

8 TeV, L^{int}=19.7 fb^{-1}



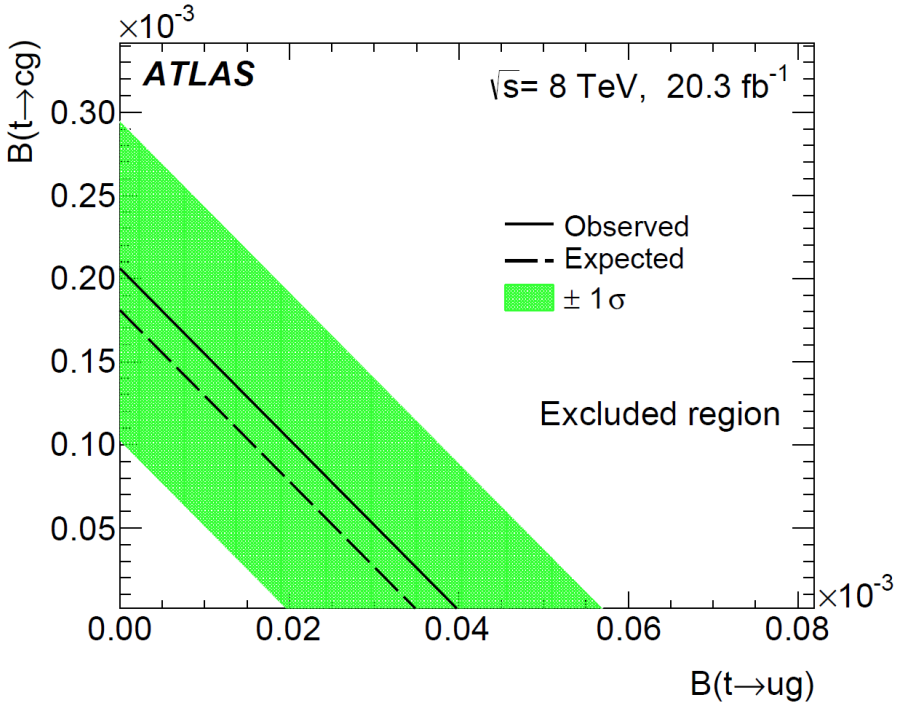
Upper limits @ CL= 95%:

$$BR(t \to gu) < 0.2 \times 10^{-4}$$
$$BR(t \to gc) < 4.1 \times 10^{-4}$$

FCNC coupling: tgq

TOPQ-2014-13

8 TeV, L^{int}=20.3 fb^{-1}

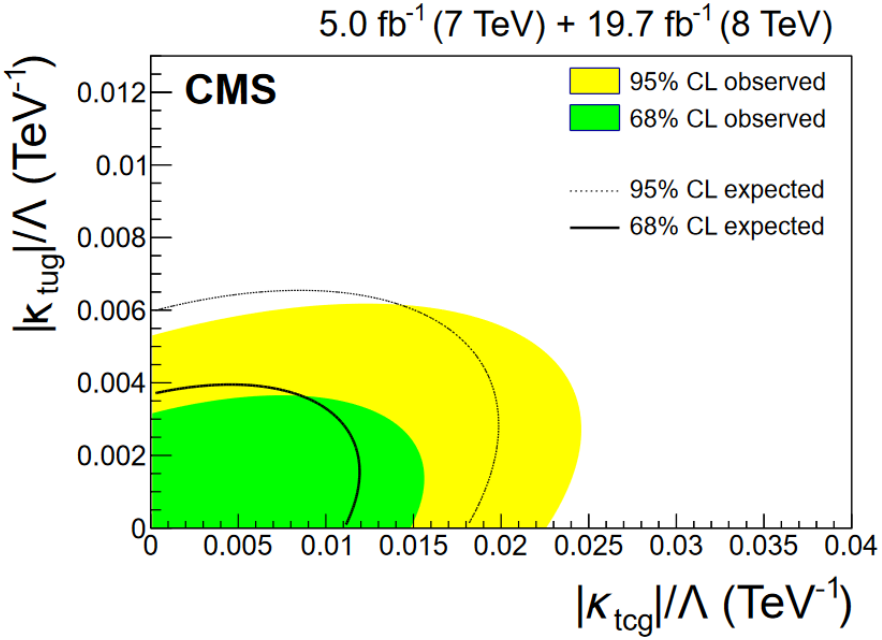


Upper limits @ CL= 95%:

$$BR(t \to gu) < 0.4 \times 10^{-4}$$
$$BR(t \to gc) < 2 \times 10^{-4}$$

TOP-14-007

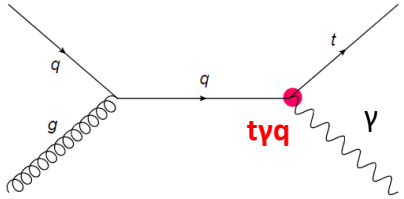
7 TeV, L^{int}=5.0 fb^{-1} +
8 TeV, L^{int}=19.7 fb^{-1}



Upper limits @ CL= 95%:

$$BR(t \to gu) < 0.2 \times 10^{-4}$$
$$BR(t \to gc) < 4.1 \times 10^{-4}$$

FCNC coupling: tγq

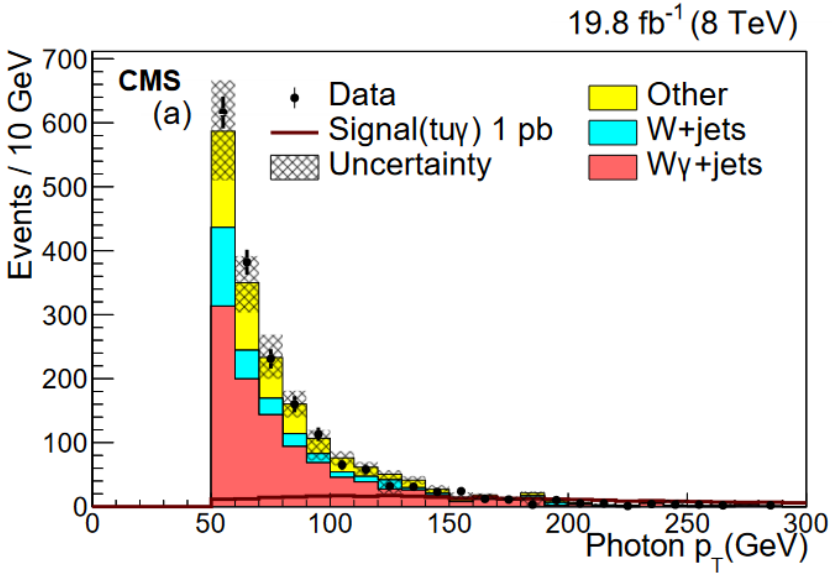


Signature =
- leptonic decay of a top quark (only the muonic channel)
- hard photon

TOP-14-007

7 TeV, L^{int}=5 fb^{-1}

Selection:
- 1 isolated muon. No isolated electron.
- 1 isolated photon with high pT.
- At least 1 jet.
- 0 or 1 b-tagged jet.
- MET > 30 GeV.
- Rec top invariant mass within 30 to 220 GeV .

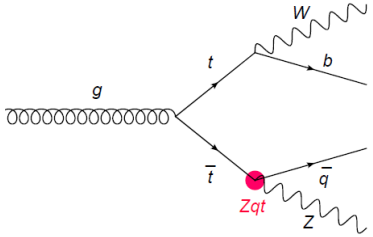


Upper limits @ CL= 95%:

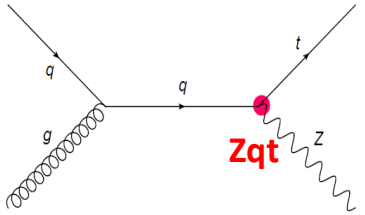
$$BR(t \to \gamma u) < 1.3 \times 10^{-4}$$
$$BR(t \to \gamma c) < 17 \times 10^{-4}$$

- A neural network is used to describe Wγ+jets and W+jets background from data.
- A BDT is used to discriminate signal from background (one for each coupling).

FCNC coupling: tzq



Signature = trileptonic final state (leptonic decay for one top + Z>ll)



TOPQ-2014-13

8 TeV, L^{int}=20.3 fb^{-1}

Only ttbar processes

Selection:

- 3 isolated leptons
- One pair compatible with a Z boson decay
- At least 2 jets
- 1 or 2 b-tagged jets
- MET > 20 GeV

Reconstruction of the top-antitop system through a χ^2 minimisation

$$\chi^2 = \frac{\left(m^{\text{reco}}_{j_a\ell_a\ell_b} - m_{t_{\text{FCNC}}}\right)^2}{\sigma^2_{t_{\text{FCNC}}}} + \frac{\left(m^{\text{reco}}_{j_b\ell_c\nu} - m_{t_{\text{SM}}}\right)^2}{\sigma^2_{t_{\text{SM}}}} + \frac{\left(m^{\text{reco}}_{\ell_c\nu} - m_W\right)^2}{\sigma^2_W}$$

TOP-12-039

8 TeV, L^{int}=19.7 fb^{-1}

Both ttbar + single top processes

Selection:

- 3 isolated leptons
- One pair compatible with a Z boson decay
- MET > 40 GeV
- M_T^W > 10 GeV

single-top process	tt process
Exactly 1 b-jet	At least 2 jets At least 1 b-jet

A BDT is used to discriminate the signal from the Standard Model processes.

FCNC coupling: tzq

Signature = trileptonic final state (leptonic decay for one top + Z>ll)

TOPQ-2014-13

8 TeV, L^{int}=20.3 fb^{-1}

Only ttbar processes

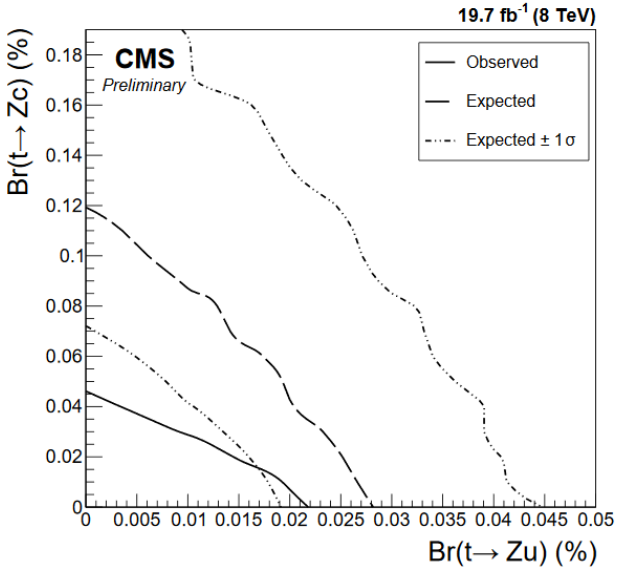
Observed and expected 95% CL limits on $\boldsymbol{BR(t \to Zq)}$.

Observed	7×10^{-4}
(-1σ)	6×10^{-4}
Expected	8×10^{-4}
$(+1\sigma)$	12×10^{-4}

TOP-12-039

8 TeV, L^{int}=19.7 fb^{-1}

Both ttbar + single top processes

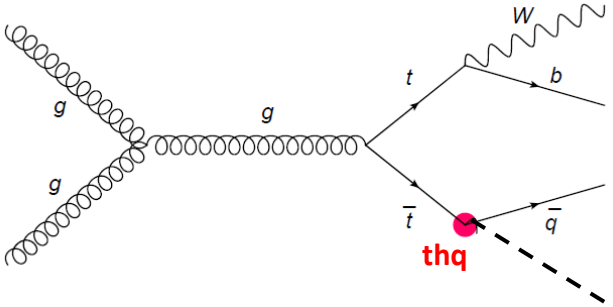


$\boldsymbol{BR(t \to Zu) < 2.2 \times 10^{-4}}$

$\boldsymbol{BR(t \to Zc) < 4.9 \times 10^{-4}}$

FCNC coupling: thq

Only the ttbar process is taken into account in the searches.



3 different analyses according to the Higgs decay:

H→γγ
BR=0.23%

Clean signature but small BR
CMS/ATLAS consider both leptonic & hadronic decay of the top quark.

H→bb
BR=58.1%

High statistics but mutijet background
CMS: BDT for top quark reco, then neural network for extracting data
ATLAS: selection based on high multiplicity of b-tagged jets + a likelihood discriminant combining information from invariant mass distributions and the flavour of the jets

H→WW/ττ/ZZ
BR=21.5%/6.3%/2.6%

Multileptonic signature
CMS: trileptonic & SS dileptonic signatures
ATLAS: id CMS & SS dileptonic +1 hadronic τ

Most recent results:

TOPQ-2014-14
7 TeV, L^{int}=4.5 fb^{-1}
8 TeV, L^{int}=20.3 fb^{-1}

TOP-13-017
8 TeV, L^{int}=19.7 fb^{-1}

TOP-14-019
8 TeV, L^{int}=19.7 fb^{-1}

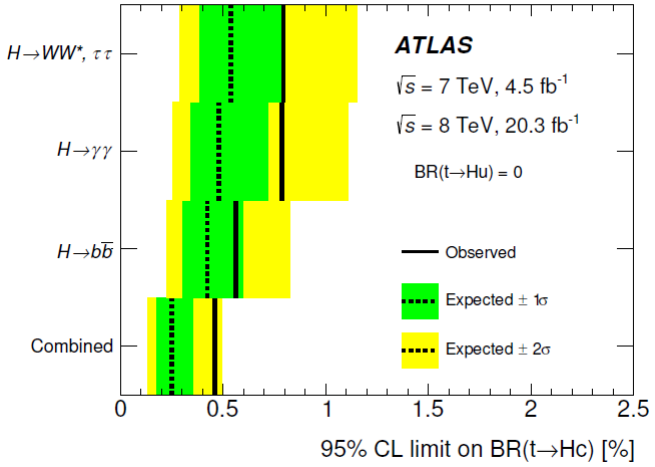
TOP-14-020
8 TeV, L^{int}=19.8 fb^{-1}

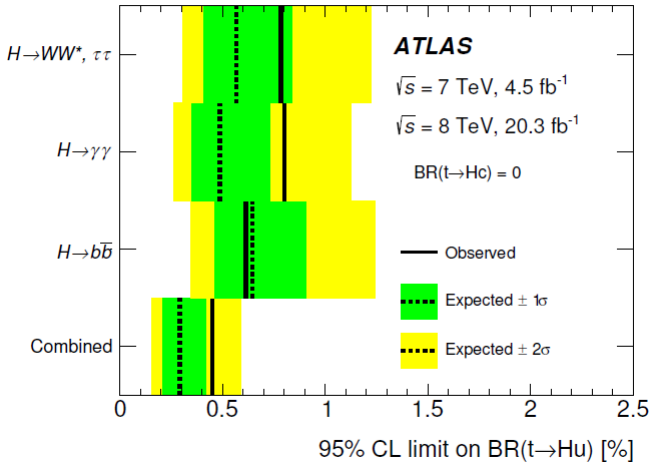
FCNC coupling: thq

TOPQ-2014-14

7 TeV, L^{int}=4.5 fb^{-1}

8 TeV, L^{int}=20.3 fb^{-1}





Upper limits @ CL= 95%

H→bb	TOP-14-020 8 TeV, L^{int}=19.8 fb^{-1} $\boldsymbol{BR(t \to Hu) < 192\times10^{-4}}$ $\boldsymbol{BR(t \to Hc) < 116\times10^{-4}}$
H→WW/ττ/ZZ	TOP-13-017 8 TeV, L^{int}=19.7 fb^{-1} $\boldsymbol{BR(t \to Hc) < 93 \times 10^{-4}}$
H→γγ	TOP-14-019 8 TeV, L^{int}=19.7 fb^{-1} $\boldsymbol{BR(t \to Hu) < 42\times10^{-4}}$ $\boldsymbol{BR(t \to Hc) < 47\times10^{-4}}$

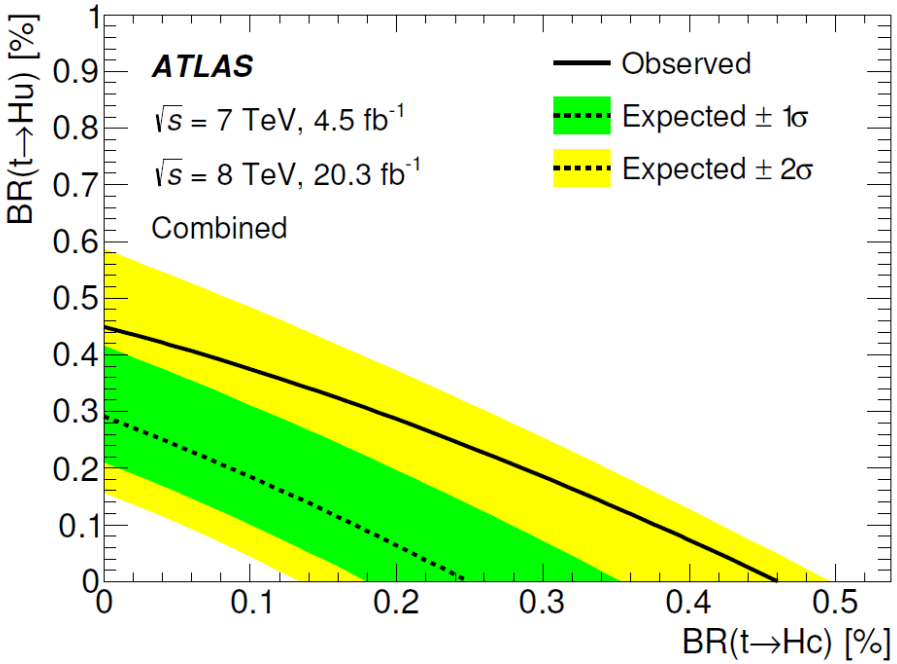
FCNC coupling: thq

TOPQ-2014-14

7 TeV, L^{int}=4.5 fb^{-1}

8 TeV, L^{int}=20.3 fb^{-1}

combination



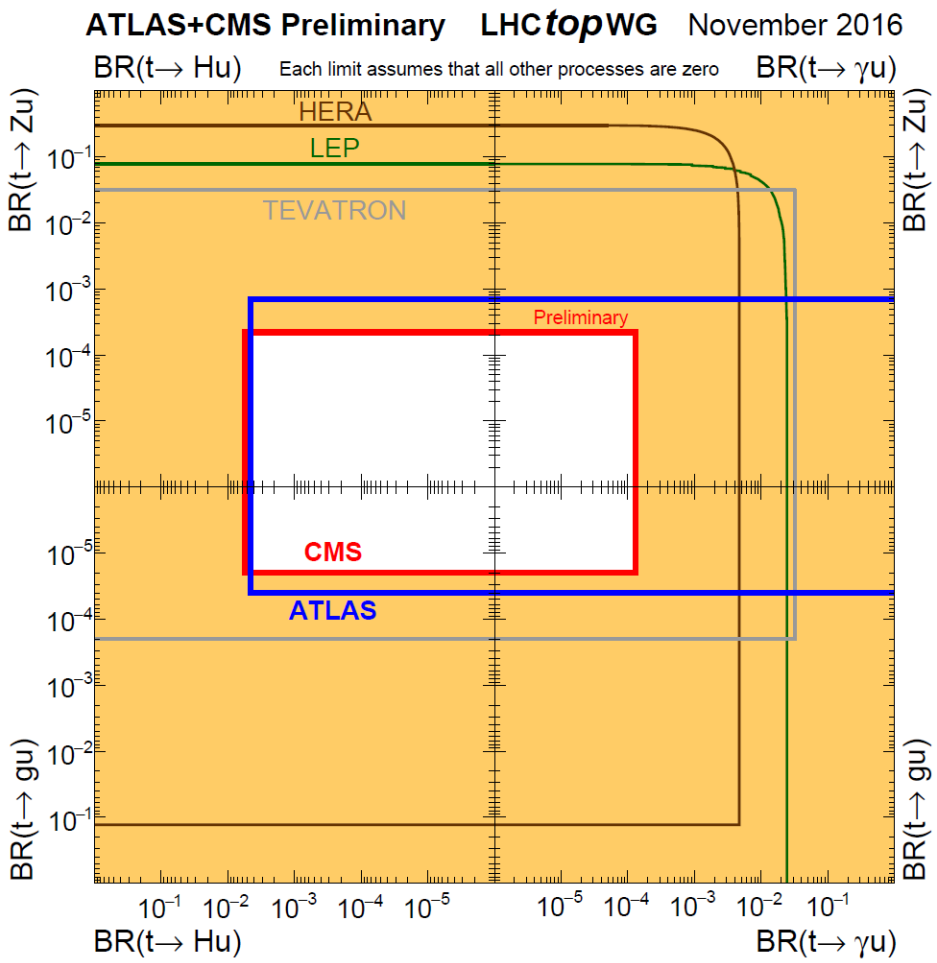
Upper limits @ CL= 95%:

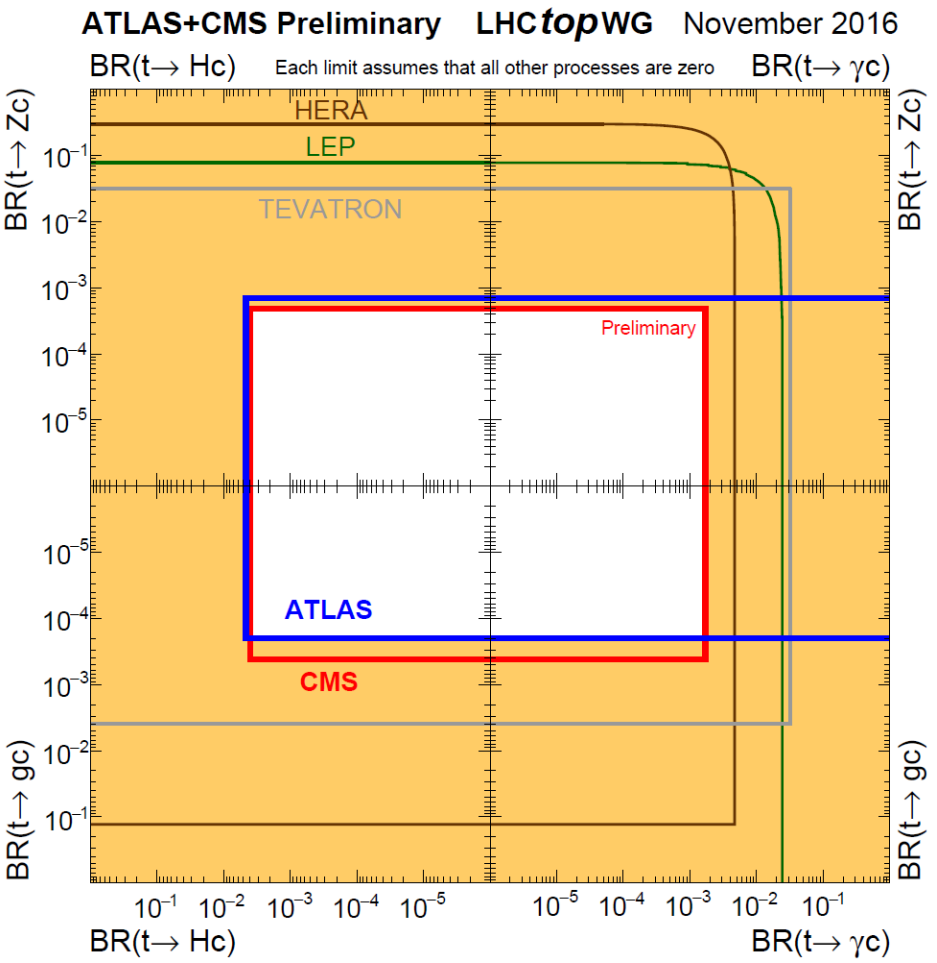
$$\mathbf{BR(t \rightarrow Hu) < 45{\times}10^{-4}}$$
$$\mathbf{BR(t \rightarrow Hc) < 46{\times}10^{-4}}$$

Upper limits @ CL= 95%

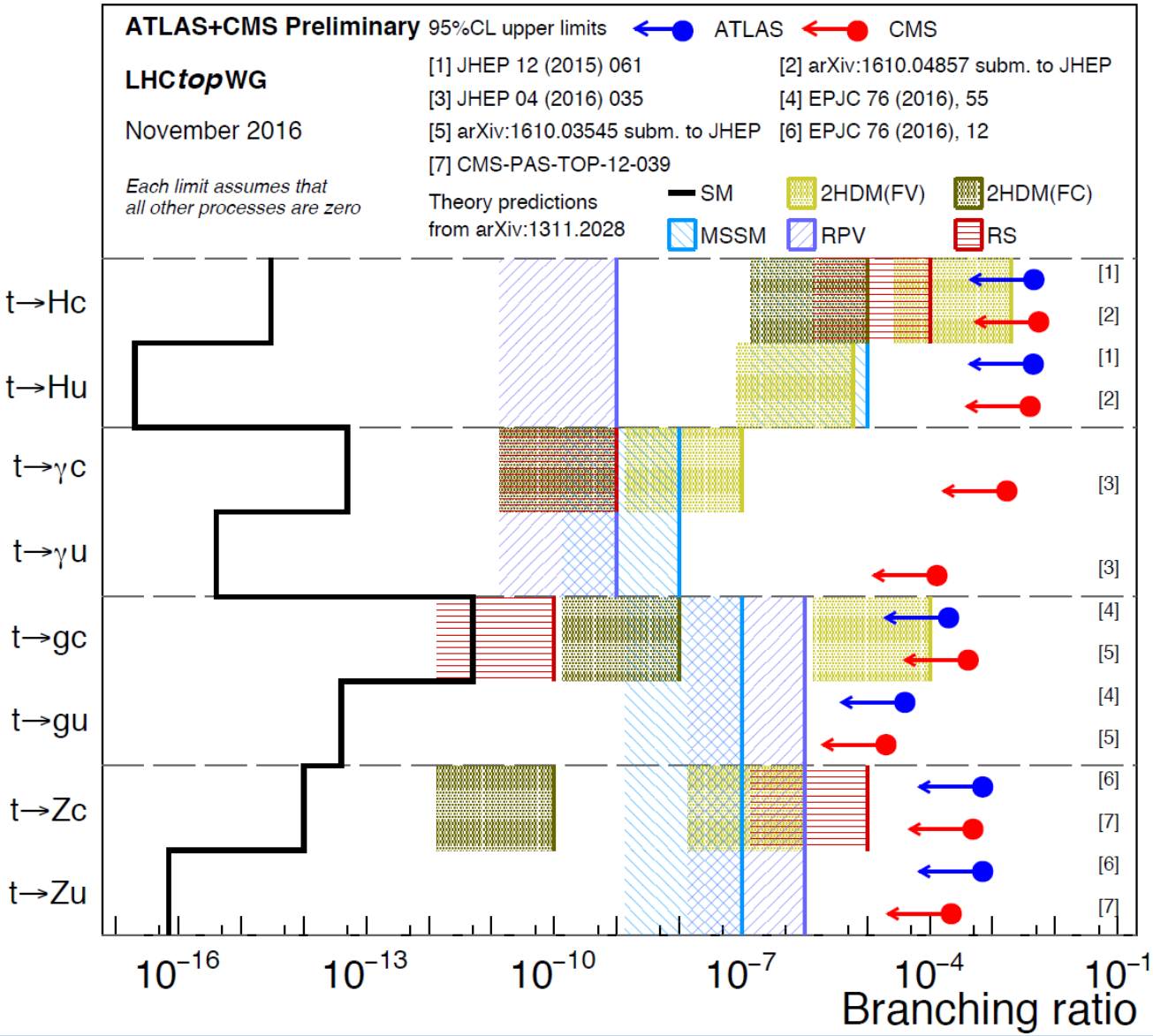
H→bb	TOP-14-020 8 TeV, L^{int}=19.8 fb^{-1} $\boldsymbol{BR(t \rightarrow Hu) < 192{\times}10^{-4}}$ $\boldsymbol{BR(t \rightarrow Hc) < 116{\times}10^{-4}}$
H→WW/ττ/ZZ	TOP-13-017 8 TeV, L^{int}=19.7 fb^{-1} $\boldsymbol{BR(t \rightarrow Hc) < 93 \times 10^{-4}}$
H→γγ	TOP-14-019 8 TeV, L^{int}=19.7 fb^{-1} $\boldsymbol{BR(t \rightarrow Hu) < 42{\times}10^{-4}}$ $\boldsymbol{BR(t \rightarrow Hc) < 47{\times}10^{-4}}$

Summary of the top FCNC searches





Summary of the top FCNC searches



Part 3:

To go further ….

ATLAS-CMS-theorists combined strategy

In the framework of anomalous couplings (AC)

- **Using the data the best we can.**

  → Covering all the channels : single top & ttbar

- **The results must be comparable between collaborations and must be combinable.**

  →Homogenization: the model conventions, the generator choice, …
  →Combination

- **The experimental results must be usable by theorists**

  →Providing required public materials for recasting & reinterpretation
  →Discussion: pros or cons of multivariate analysis?

Moving to EFT @ LO QCD

Considering the available TopFCNC model from the FeynRules (FR) database:
http://feynrules.irmp.ucl.ac.be/wiki/TopFCNC

[Phys.Rev. D91 (2015) 034024, Phys.Rev. D91 (2015) 074017]

Model description: - before EWSB, gauge-eigenstate, no 4-fermions contact, CKM=1, m_b=0
- 1 scale Λ + 11 complex coefficients for u-quark + 11 for c-quark

	"ζ_{zut}"			"$\kappa_{\gamma ut}/\Lambda, \kappa_{zut}/\Lambda$" L	R	L	R	"κ_{gut}/Λ" L	R	"η_{hut}" L	R
Th name	$C^{(3,1+3)}_{\phi q}$	$C^{(1,1+3)}_{\phi q}$	$C^{(1+3)}_{\phi u}$	$C^{(13)}_{uW}$	$C^{(31)}_{uW}$	$C^{(13)}_{uB}$	$C^{(31)}_{uB}$	$C^{(13)}_{uG}$	$C^{(31)}_{uG}$	$C^{(13)}_{u\phi}$	$C^{(31)}_{u\phi}$
FR name	C3phiq	C1phiq	C1phiu	Ctw	Cuw	Ctb	Cub	Ctg	Cug	Ctphi	Cuphi
t→gq								X	X		
t→γq				X	X	X	X				
t→Zq	X	X	X	X	X	X	X				
t→hq										X	X
p p → t (g)								X	X		
p p → t γ				X	X	X	X	X	X		
p p → t Z	X	X	X	X	X	X	X	X	X		
p p → t h								X	X	X	X

Moving to EFT @ NLO QCD

Considering the available TopFCNC model from the FeynRules (FR) database: [Phys.Rev. D91 (2015) 034024, Phys.Rev. D91 (2015) 074017]

http://feynrules.irmp.ucl.ac.be/wiki/TopFCNC

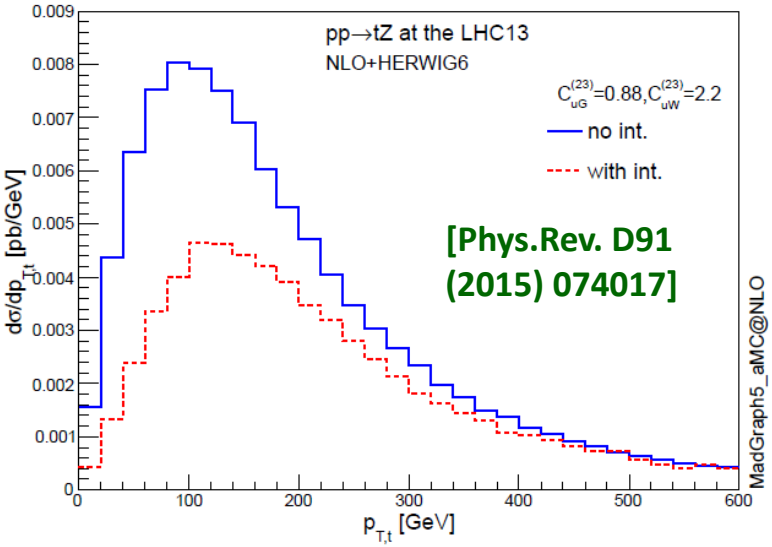
Model description: - before EWSB, gauge-eigenstate, no 4-fermions contact, CKM=1, m_b=0

- 1 scale Λ + 11 complex coefficients for u-quark + 11 for c-quark

	"ζ_{zut}"			"$\kappa_{\gamma ut}/\Lambda, \kappa_{zut}/\Lambda$"				"κ_{gut}/Λ"		"η_{hut}"	
				L	R	L	R	L	R	L	R
Th name	$C^{(3,1+3)}_{\phi q}$	$C^{(1,1+3)}_{\phi q}$	$C^{(1+3)}_{\phi u}$	$C^{(13)}_{uW}$	$C^{(31)}_{uW}$	$C^{(13)}_{uB}$	$C^{(31)}_{uB}$	$C^{(13)}_{uG}$	$C^{(31)}_{uG}$	$C^{(13)}_{u\phi}$	$C^{(31)}_{u\phi}$
FR name	C3phiq	C1phiq	C1phiu	Ctw	Cuw	Ctb	Cub	Ctg	Cug	Ctphi	Cuphi
t→gq								X	X		
t→γq				X	X	X	X	X	X		
t→Zq	X	X	X	X	X	X	X	X	X		
t→hq								X	X	X	X
p p → t (g)								X	X		
p p → t γ				X	X	X	X	X	X		
p p → t Z	X	X	X	X	X	X	X	X	X		
p p → t h								X	X	X	X

Moving to EFT @ NLO QCD

Several coefficients contribute to the same experimental signature.



- At NLO QCD with EFT, producing one sample by activating one coefficient at a time is not enough.
  → Dealing with interferences
- Could we make simplifying assumptions?
  For instance: $C^{(13)}{}_{u\phi} = C^{(31)}{}_{u\phi}$

- **How to deal with the Monte-Carlo production?**
- **How to deal with a multivariate analysis with interferences?**
- **A global fit of several analysis results is needed for constraining all the couplings.**

  How to do it?

Back-up slides

Summary of the top FCNC searches

Coupling	CMS Results	ATLAS Results
κ_{gqt}/Λ [GeV^{-2}]	TOP-14-007 7 TeV, L^{int}=5.0 fb^{-1} + 8 TeV, L^{int}=19.7 fb^{-1} $\boldsymbol{BR(t \to gu) < 0.2\times10^{-4}}$ $\boldsymbol{BR(t \to gc) < 4.1\times10^{-4}}$	TOPQ-2014-13 8 TeV, L^{int}=20.3 fb^{-1} $\boldsymbol{BR(t \to gu) < 0.4\times10^{-4}}$ $\boldsymbol{BR(t \to gc) < 2\times10^{-4}}$
$\kappa_{\gamma qt}/\Lambda$ [GeV^{-2}]	TOP-14-003 8 TeV, L^{int}=19.8 fb^{-1} $\boldsymbol{BR(t \to \gamma u) < 1.3 \times 10^{-4}}$ $\boldsymbol{BR(t \to \gamma c) < 17 \times 10^{-4}}$	
κ_{Zqt}/Λ [GeV^{-2}]	TOP-12-039 8 TeV, L^{int}=19.7 fb^{-1} Both ttbar + single top processes $\boldsymbol{BR(t \to Zu) < 2.2\times10^{-4}}$ $\boldsymbol{BR(t \to Zc) < 4.9\times10^{-4}}$	TOPQ-2014-08 8 TeV, L^{int}=20.3 fb^{-1} Only ttbar processes $\boldsymbol{BR(t \to Zq) < 7\times10^{-4}}$

observed 95% CL upper limits

Summary of the top FCNC searches

Coupling	Channel	CMS Results	ATLAS Results TOPQ-2014-14 7 TeV, L^{int}=4.5 fb^{-1} 8 TeV, L^{int}=20.3 fb^{-1}
η_{hqt} [no unit]	H→bb	TOP-14-020 8 TeV, L^{int}=19.8 fb^{-1} Only ttbar processes $BR(t \to Hu) < 192\times10^{-4}$ $BR(t \to Hc) < 116\times10^{-4}$	Only ttbar processes $BR(t \to Hu) < 61\times10^{-4}$ $BR(t \to Hc) < 56\times10^{-4}$
	H→WW/ττ/ZZ	TOP-13-017 8 TeV, L^{int}=19.7 fb^{-1} Only ttbar processes $BR(t \to Hc) < 93\times10^{-4}$	Only ttbar processes $BR(t \to Hu) < 78\times10^{-4}$ $BR(t \to Hc) < 79\times10^{-4}$
	H→γγ	TOP-14-019 8 TeV, L^{int}=19.7 fb^{-1} Only ttbar processes $BR(t \to Hu) < 42\times10^{-4}$ $BR(t \to Hc) < 47\times10^{-4}$	Only ttbar processes $BR(t \to Hq) < 79\times10^{-4}$
	Combination		$BR(t \to Hu) < 45\times10^{-4}$ $BR(t \to Hc) < 46\times10^{-4}$

Description in term of anomalous couplings

Links between couplings and Wilson coefficients

$$\kappa_{gqt} f^L_{gq} = \frac{v}{g_s \Lambda} \left[\bar{c}_{uG}\right]^*_{i3} \,, \qquad \kappa_{gqt} f^R_{gq} = \frac{v}{g_s \Lambda} \left[\bar{c}_{uG}\right]_{3i} \,,$$

$$\kappa_{\gamma qt} f^L_{\gamma q} = \frac{v}{e \Lambda} \left[c_W \bar{c}_{uB} - s_W \bar{c}_{uW}\right]^*_{i3} \,, \qquad \kappa_{\gamma qt} f^R_{\gamma q} = \frac{v}{e \Lambda} \left[s_W \bar{c}_{uB} - c_W \bar{c}_{uW}\right]_{3i} \,,$$

$$\kappa_{zqt} f^L_{zq} = -\frac{2 c_W v}{g \Lambda} \left[s_W \bar{c}_{uB} + c_W \bar{c}_{uW}\right]^*_{i3} \,, \qquad \kappa_{zqt} f^R_{zq} = -\frac{2 c_W v}{g \Lambda} \left[c_W \bar{c}_{uB} + s_W \bar{c}_{uW}\right]_{3i}$$

$$\zeta_{zqt} \tilde{f}^L_{zq} = -\frac{2v^2}{\Lambda^2} \left[\left(\bar{c}^{(1)}_{hq} - \bar{c}^{(3)}_{hq}\right)_{i3} + \left(\bar{c}^{(1)}_{hq} - \bar{c}^{(3)}_{hq}\right)^*_{3i}\right] \,, \qquad \zeta_{zqt} \tilde{f}^R_{zq} = -\frac{2v^2}{\Lambda^2} \left[\left(\bar{c}_{hu}\right)_{i3} + \left(\bar{c}_{hu}\right)^*_{3i}\right] \,,$$

$$\eta_{hqt} \hat{f}^L_{hq} = \frac{3v^2}{2\Lambda^2} \left[\bar{c}_{uh}\right]^*_{3i} \,, \qquad \eta_{hqt} \hat{f}^R_{hq} = \frac{3v^2}{2\Lambda^2} \left[\bar{c}_{uh}\right]_{i3} \,,$$

Conventions

$$\sqrt{\left|f^L_{xq}\right|^2 + \left|f^R_{xq}\right|^2} = 1$$

$$\sqrt{\left|\tilde{f}^L_{xq}\right|^2 + \left|\tilde{f}^R_{xq}\right|^2} = 1$$

$\frac{\kappa_{xqt}}{\Lambda}$, ζ_{xqt}, and η_{xqt} are real and positive

EFT @ NLO QCD [charm quark]

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	"ζ_{zct}"			"$\kappa_{\gamma ct}/\Lambda, \kappa_{zct}/\Lambda$"				"κ_{gct}/Λ"		"η_{hct}"	
				L	R	L	R	L	R	L	R
Th name	$C^{(3,2+3)}_{\phi q}$	$C^{(2,2+3)}_{\phi q}$	$C^{(2+3)}_{\phi u}$	$C^{(23)}_{uW}$	$C^{(32)}_{uW}$	$C^{(23)}_{uB}$	$C^{(32)}_{uB}$	$C^{(23)}_{uG}$	$C^{(32)}_{uG}$	$C^{(23)}_{u\phi}$	$C^{(32)}_{u\phi}$
FR name	C3phiq	C1phiq	C1phiu	Ctcw	Cctw	Ctcb	Cctb	Ctcg	Cctg	Ctcphi	Cctphi
t→gq								X	X		
t→γq				X	X	X	X	X	X		
t→Zq	X	X	X	X	X	X	X	X	X		
t→hq								X	X	X	X
p p → t (g)								X	X		
p p → t γ				X	X	X	X	X	X		
p p → t Z	X	X	X	X	X	X	X	X	X		
p p → t h								X	X	X	X