Searches for FCNC with top quarks

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on behalf of the ATLAS and the CMS collaborations

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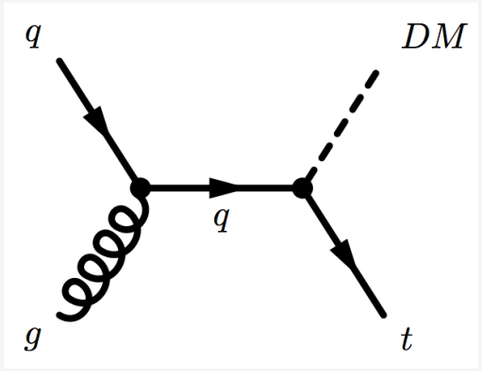
FCNC interactions

- **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:



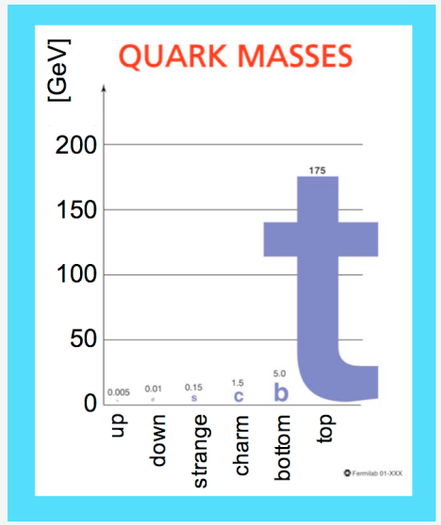
- Fourth-generation models
- Extended technicolor models
- Leptoquark models
- Extra dimensions
- Extra quark models
- Supersymmetry
- Two-Higgs-Doublet models

Model	Br ($t \to Z/\gamma\, q$)
SM	**~ 10^{-12}**
SUSY	~ 10^{-6}
2HDM	~ 10^{-7}

Observation of FCNC process = new physics

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

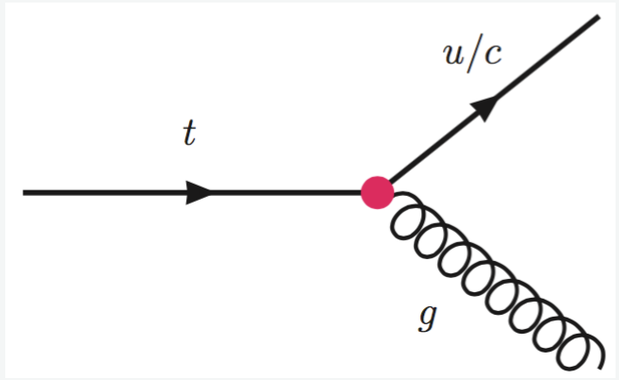
Why to look for FCNC with a top quark ?



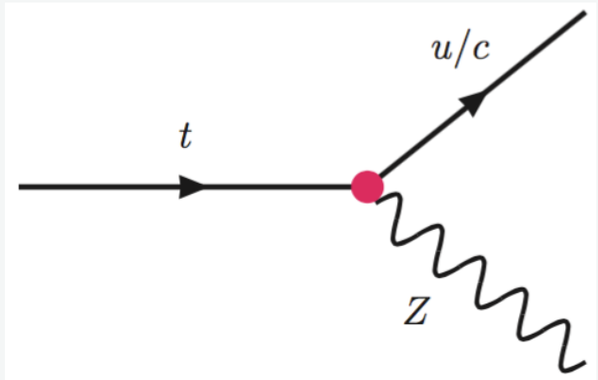
- Distinctive event signature of top quark decay
- Several models predict a large coupling of the new particles to the top quark = enhanced sensitivity to FCNC in the top quark sector
- FCNC in single top production is particularly interesting due to enhanced production associated with an up quark

FCNC searches with top quark

gqt

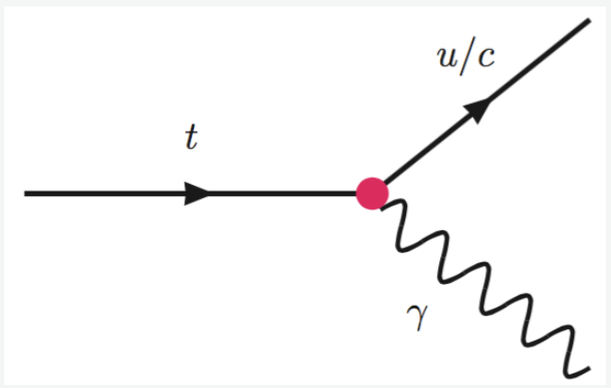


Zqt

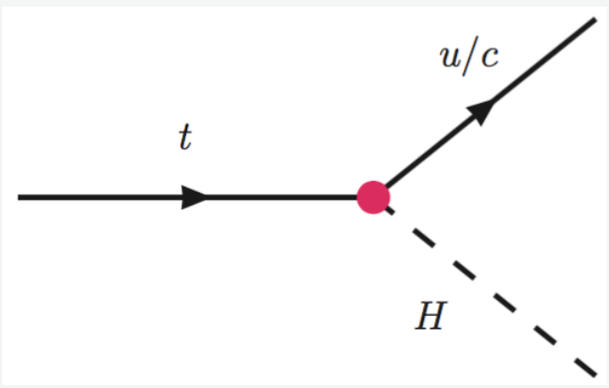


$$
\begin{aligned}
\mathcal{L} \;=\; & \sum_{q=u,c} \Big[\sqrt{2}\, g_s \frac{\kappa_{gqt}}{\Lambda} \bar{t}\, \sigma^{\mu\nu}\, T_a (f^L_{Gq} P_L + f^R_{Gq} P_R)\, q\, G^a_{\mu\nu} \\
& + \frac{g}{\sqrt{2} c_W} \frac{\kappa_{zqt}}{\Lambda} \bar{t} \sigma^{\mu\nu}\, (f^L_{Zq} P_L + f^R_{Zq} P_R)\, q\,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

γqt

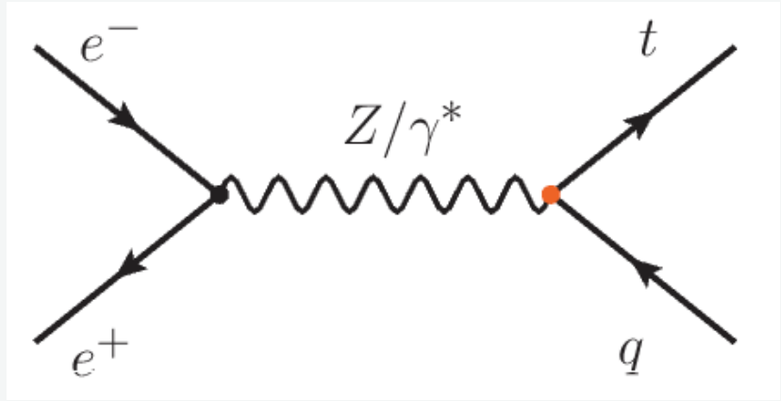


Hqt



FCNC searches at LEP2 and HERA

FCNC searches in $e^+e^- \rightarrow tqbar$ at LEP2



$\kappa_{q\gamma t} \lesssim 0.4$

$\kappa_{qZt} \lesssim 0.4$

$BR(t \rightarrow q\gamma) \lesssim 4\ \%$

$BR(t \rightarrow qZ) \lesssim 10\ \%$

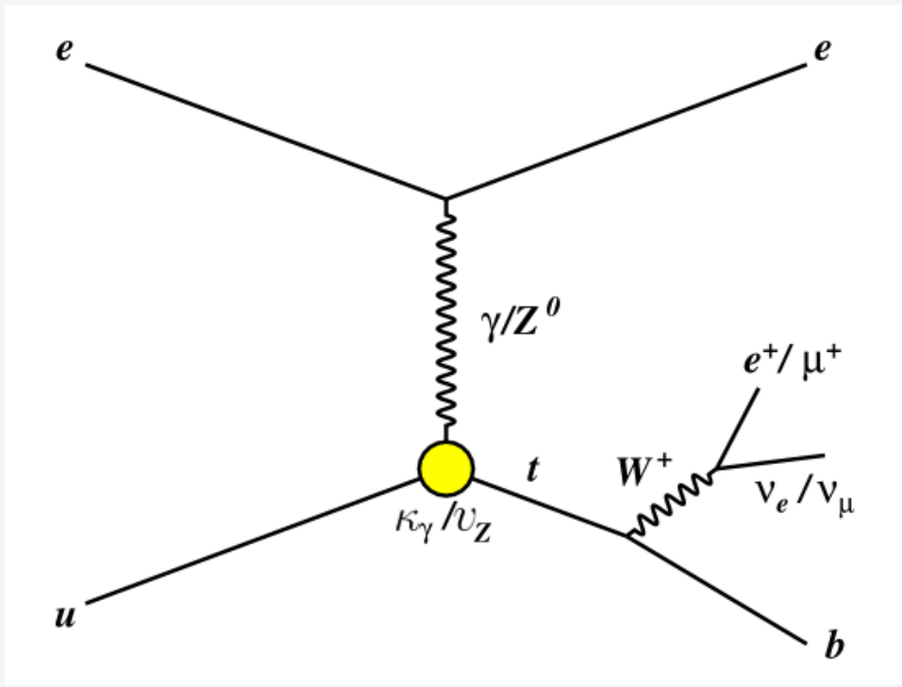
L3: Phys. Lett. B549 (2002) 290-300

OPAL: Phys. Lett. B521 (2001) 181-194

ALEPH: Phys. Lett. B494 (2000) 33

DELPHI: Phys. Lett. B590 (2004) 21-34

FCNC searches at HERA in $ep \rightarrow etX$



$BR(t \rightarrow q\gamma) \lesssim 0.5\ \%$

$BR(t \rightarrow qZ) \lesssim 4\ \%$

ZEUS: Phys. Lett. B708 (2012) 27-36

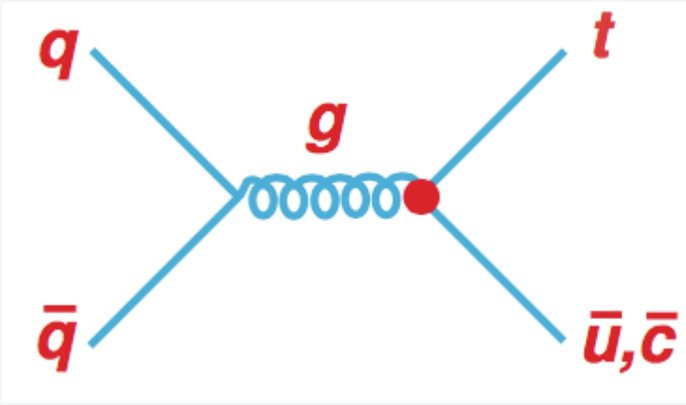
H1: Phys. Lett. B678 (2009) 450

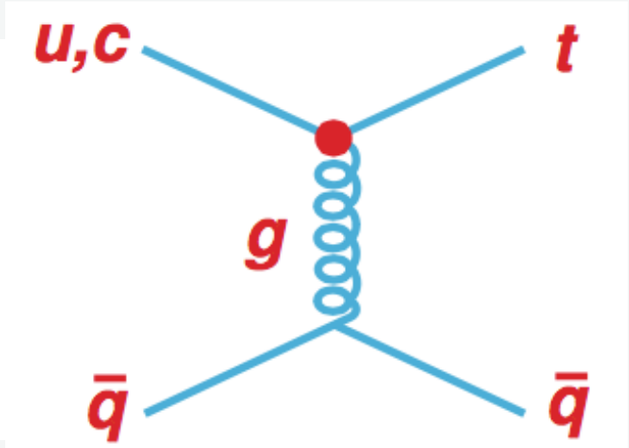
$$\Delta\mathcal{L}_{\text{eff}} = e\, e_t\, \bar{t} \frac{i\sigma_{\mu\nu} p^\nu}{\Lambda}\, \kappa_\gamma\, u\, A^\mu + \frac{g}{2\cos\theta_W}\, \bar{t}\gamma_\mu\, v_Z\, u Z^\mu + \text{h.c.}$$

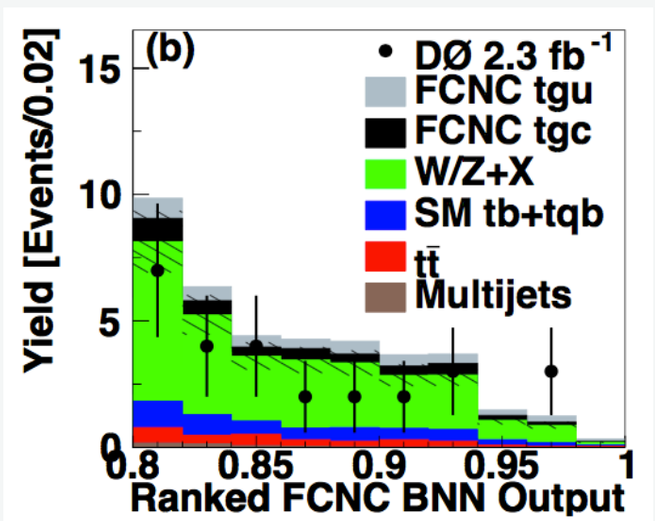
Λ=175 GeV

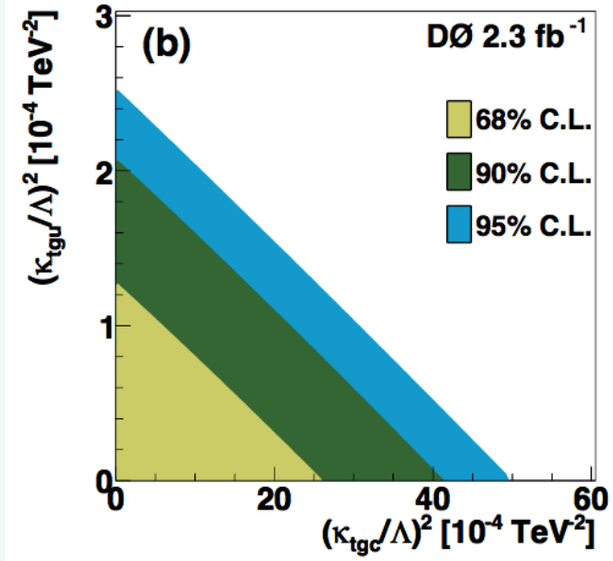
FCNC searches at TEVATRON

gqt — Search for $t \to gq$ at DØ





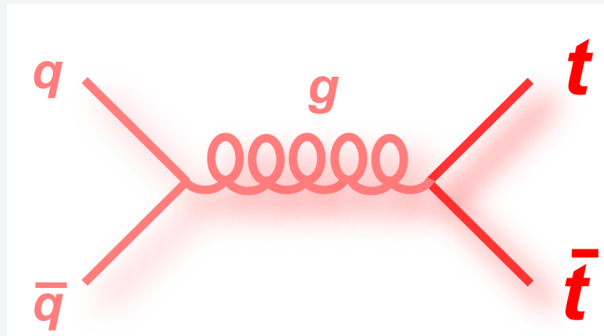


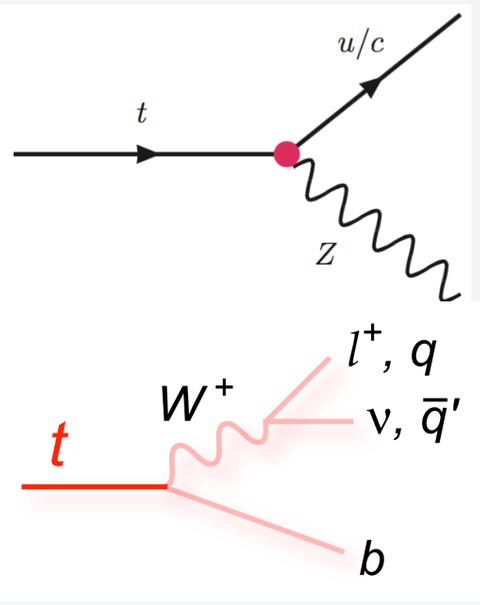


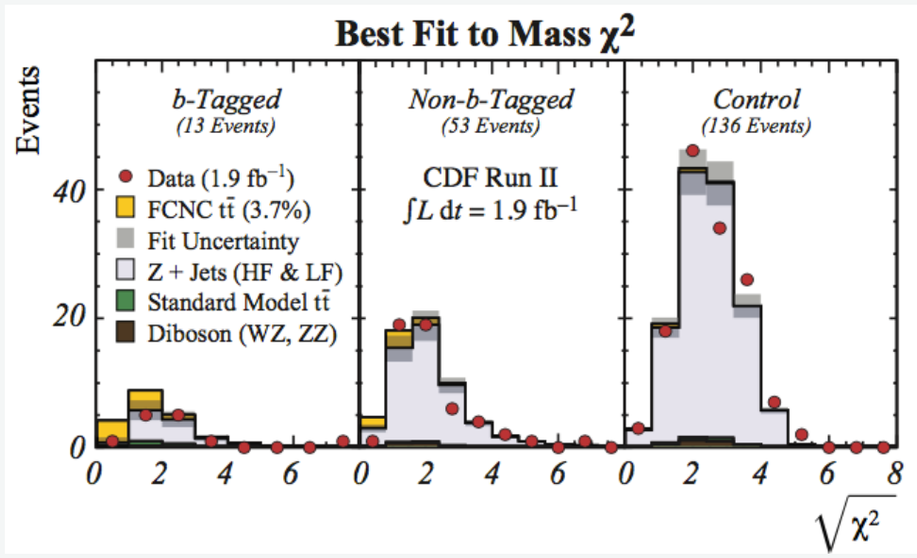
	tgu	tgc
Cross section	0.20 pb	0.27 pb
κ_{tgf}/Λ	0.013 TeV^{-1}	0.057 TeV^{-1}
$\mathcal{B}(t \to fg)$	2.0×10^{-4}	3.9×10^{-3}

Phys. Lett. B693 (2010) 81-87

Zqt — Search for $t \to Zq$ at CDF





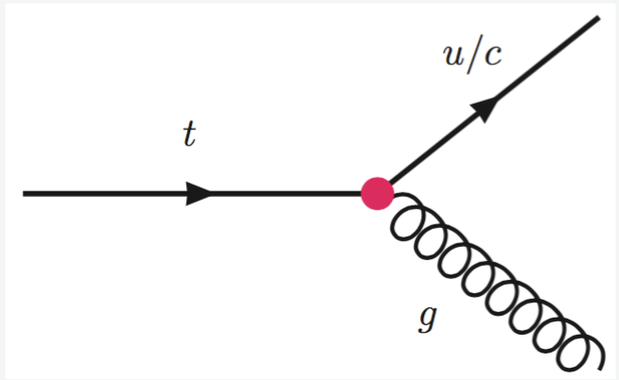


BR($t \to qZ$) < 3.7 %

Phys. Rev. Lett. 101 (2008) 192002

FCNC searches at the LHC

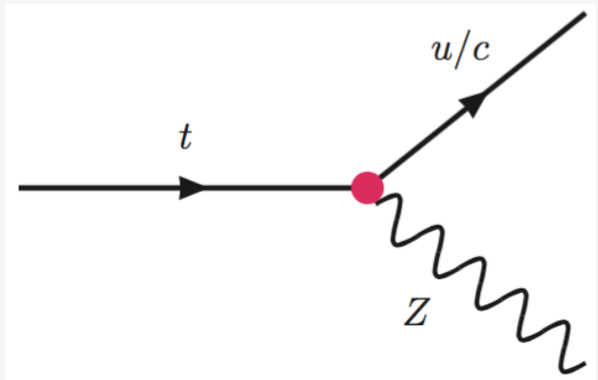
gqt



ATLAS: arXiv:1509.00294v1

CMS: CMS-PAS-TOP-14-007

Zqt

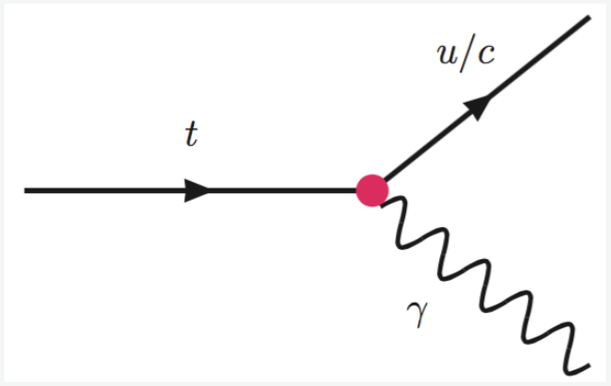


ATLAS: arXiv:1508.05796v1

CMS: Phys. Rev. Lett. 112 (2014) 171802

CMS: CMS-PAS-TOP-12-021

CMS: CMS-PAS-TOP-14-003



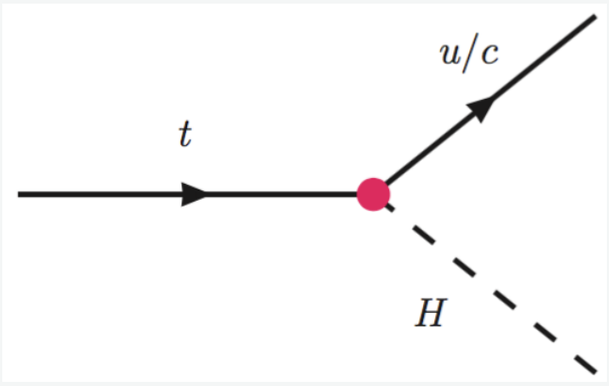
γqt

ATLAS: JHEP 06 (2014) 008

ATLAS: PAPER SOON !

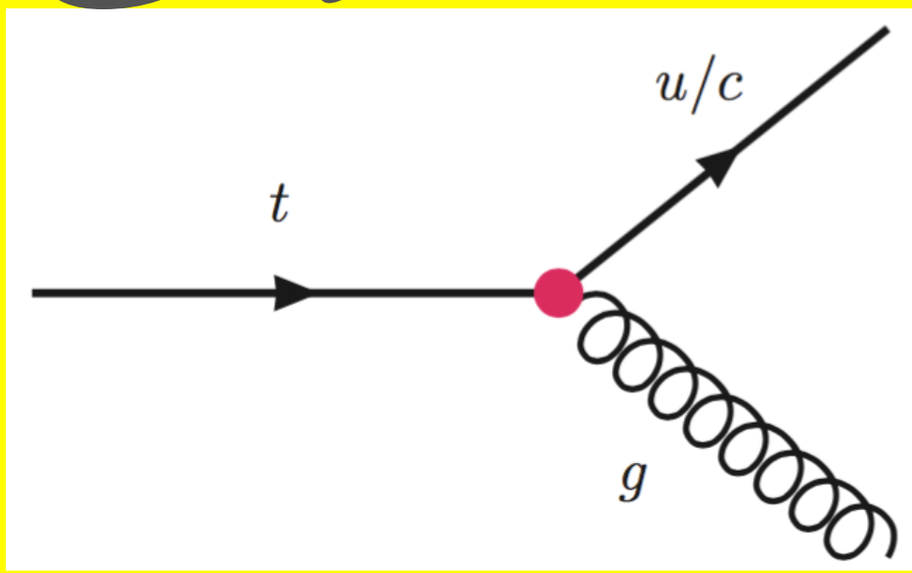
CMS: CMS-PAS-TOP-14-019

CMS: CMS-PAS-TOP-13-017



Hqt

gqt

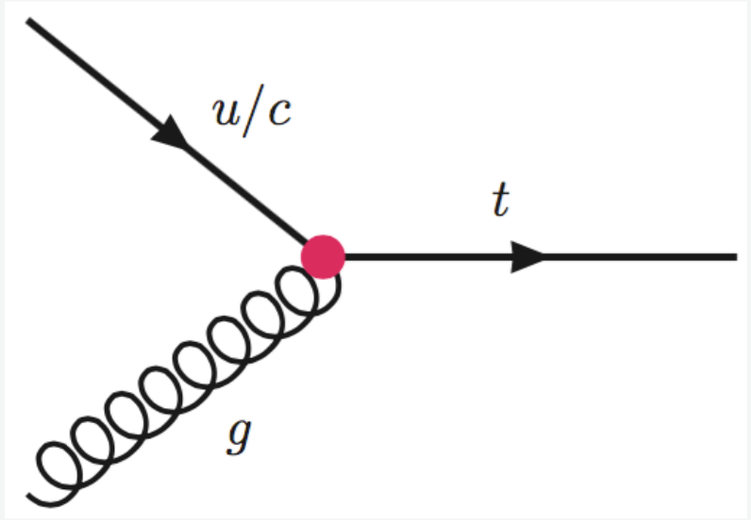


Search for single top production at ATLAS

arXiv:1509.00294v1
ATLAS, 20 fb^{-1}, 8 TeV

NEW

gqt



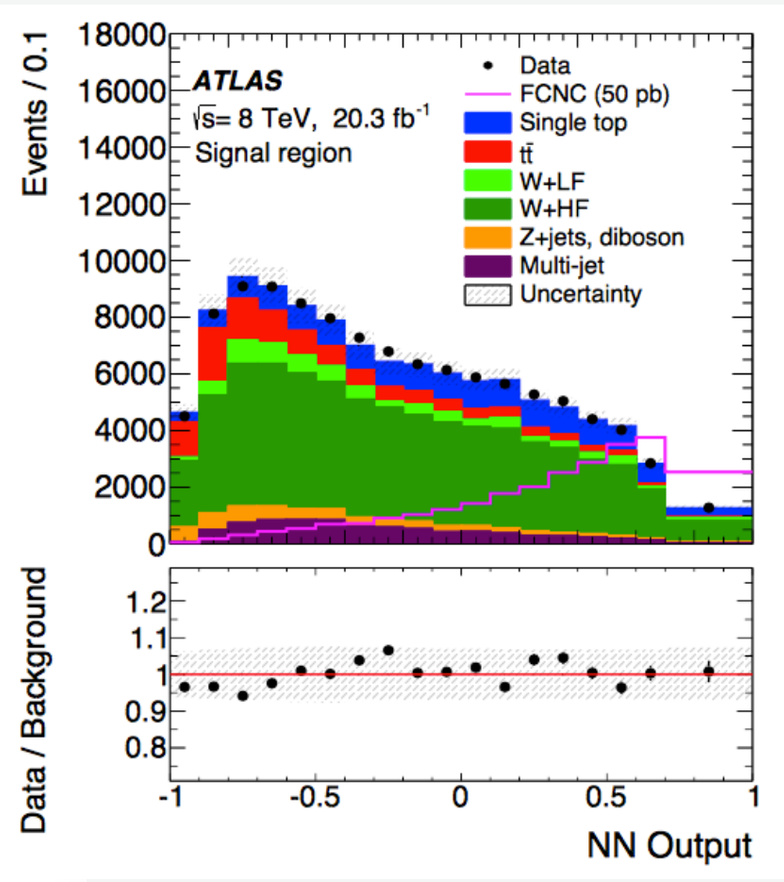
MEtop @NLO (approx.)

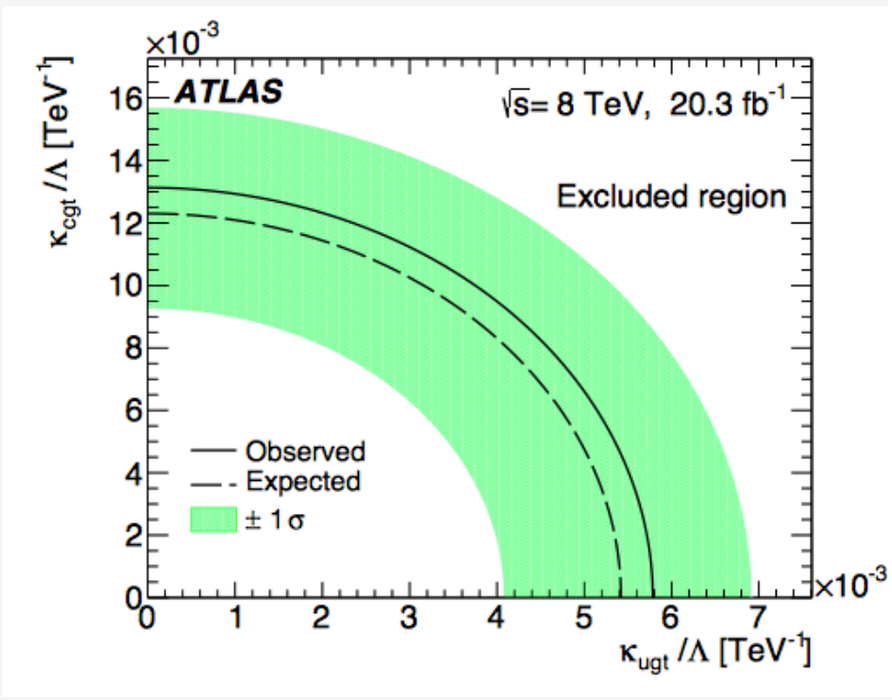
Main background: W+jets, QCD multijet, single top, ttbar, Z+jets

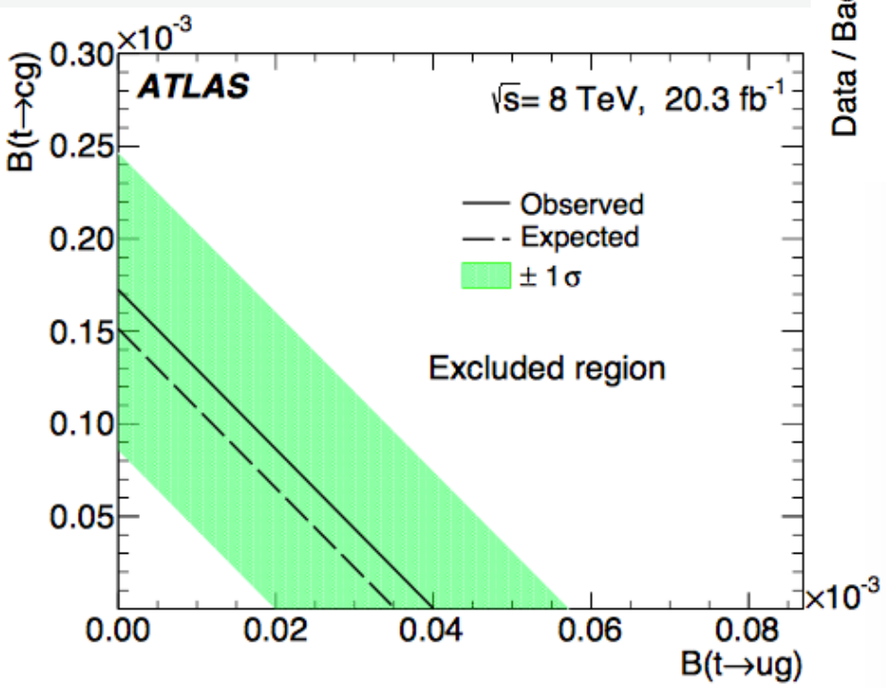
Event signature is the top quark decay: exactly one isolated lepton, missing E_T and one b-tagged jet

MVA approach to discriminate signal and background events

QCD Multi-jet is measured in data from the missing E_T template fit







$\kappa_{ugt}/\Lambda < 0.58 \cdot 10^{-2}$ TeV^{-1}

$\kappa_{cgt}/\Lambda < 1.3 \cdot 10^{-2}$ TeV^{-1}

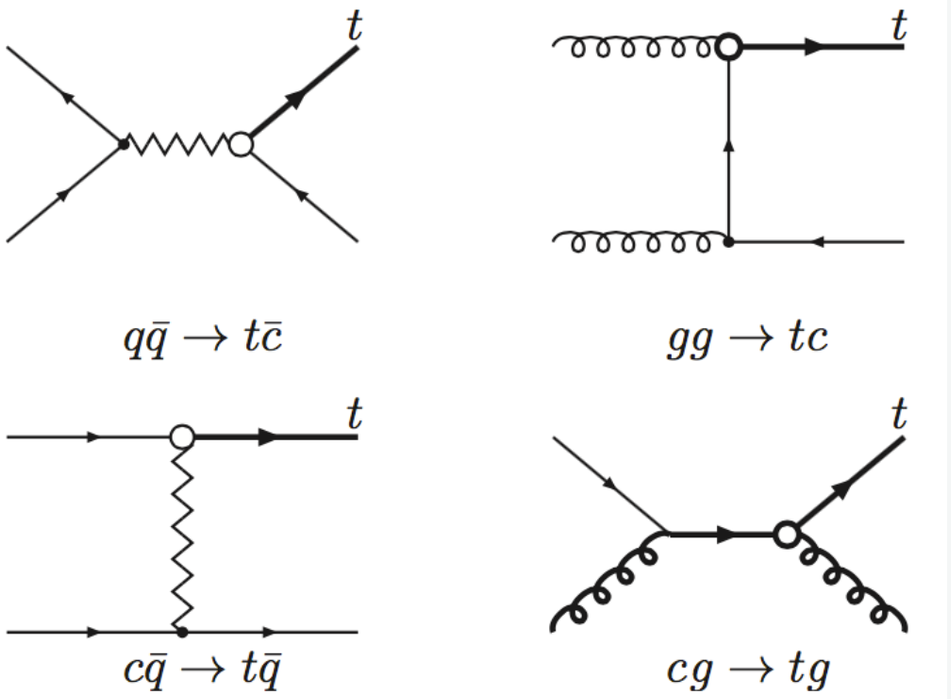
BR(t→u**g**) < 0.0040 % (obs)
0.0035 % (exp)

BR(t→c**g**) < 0.017 % (obs)
0.015 % (exp)

Search in t-channel single top at CMS

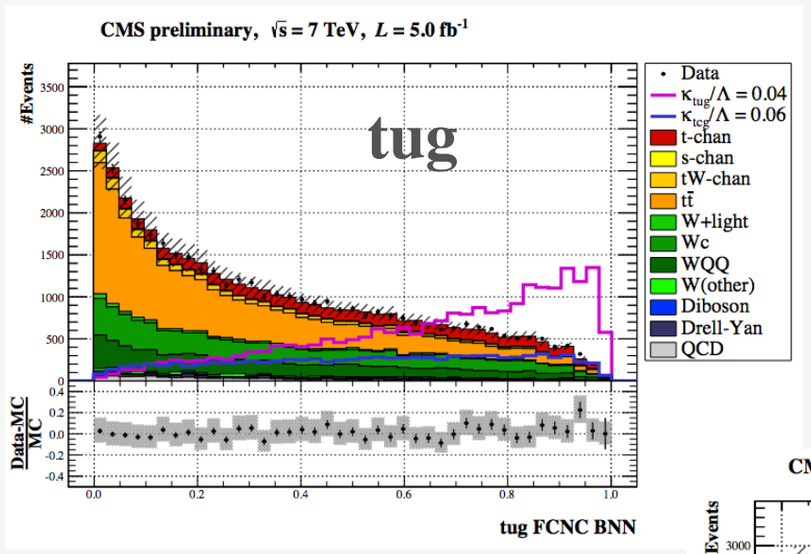
CMS-PAS-TOP-14-007
CMS, 5 fb^{-1}, 7 TeV

gqt



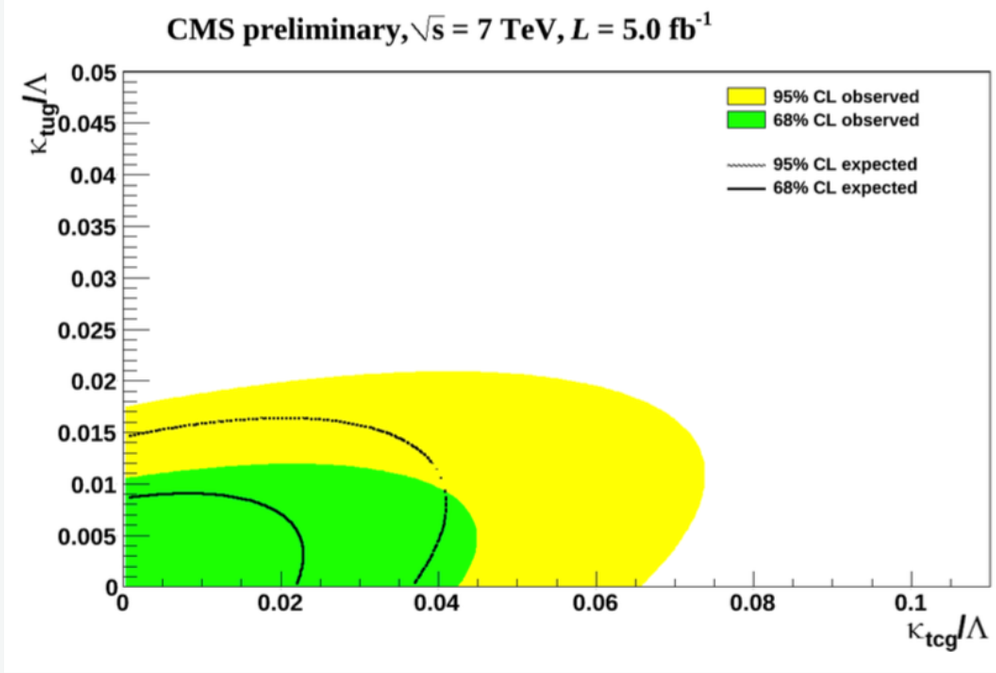
CompHEP @NLO (approx.)

Event signature: one isolated muon, missing E_T, $\geq$ 1 b-jet, $\geq$ 1 non-b-jet



Bayesian Neural Network (BNN) is used to discriminate signal and background

QCD Multi-jet is measured in data from the QCD BNN template fit

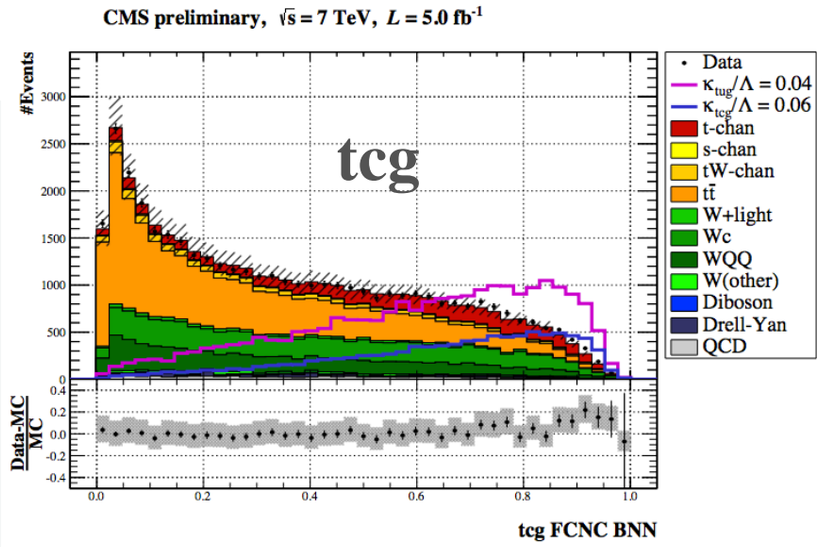


$\kappa_{ugt}/\Lambda < 1.8 \cdot 10^{-2}$ TeV^{-1}

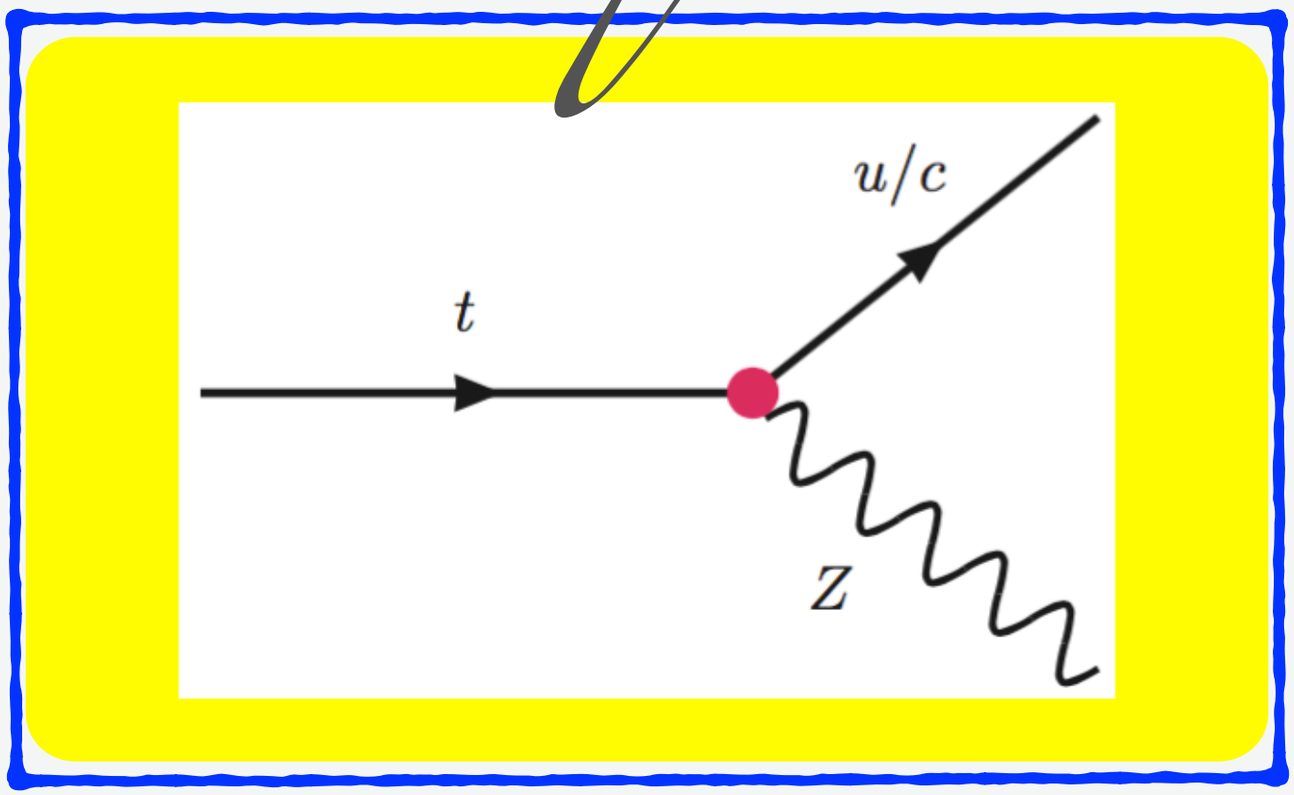
$\kappa_{cgt}/\Lambda < 5.6 \cdot 10^{-2}$ TeV^{-1}

BR(t→ug) < 0.036 % (obs)
0.016 % (exp)

BR(t→cg) < 0.34 % (obs)
0.11 % (exp)



Zgt

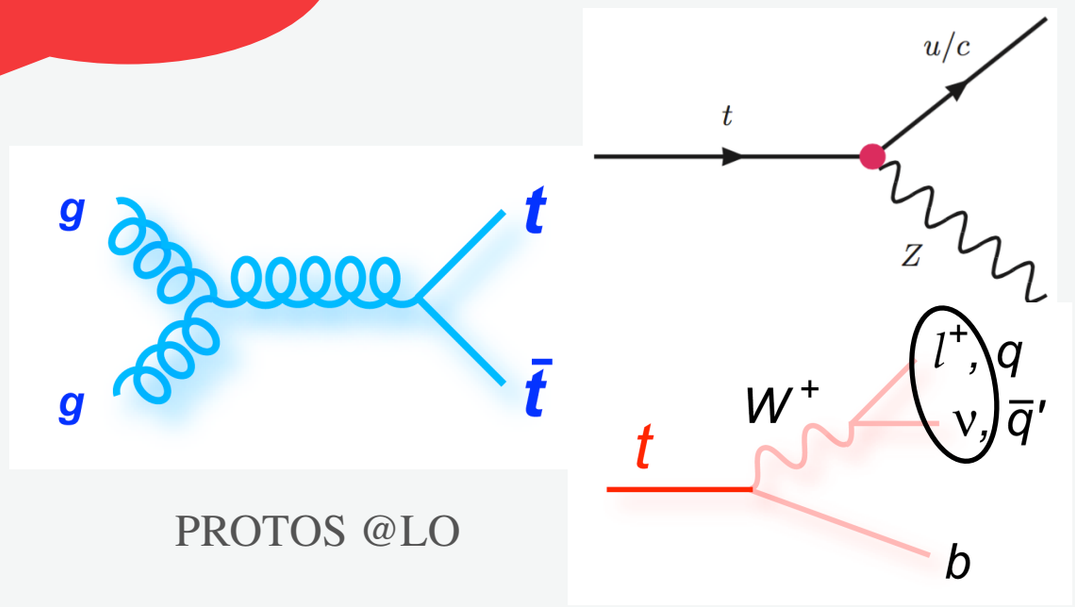


Search for t→Zq in ttbar events at ATLAS

arXiv:1508.05796
ATLAS, 20 fb^{-1}, 8 TeV

NEW

Zqt

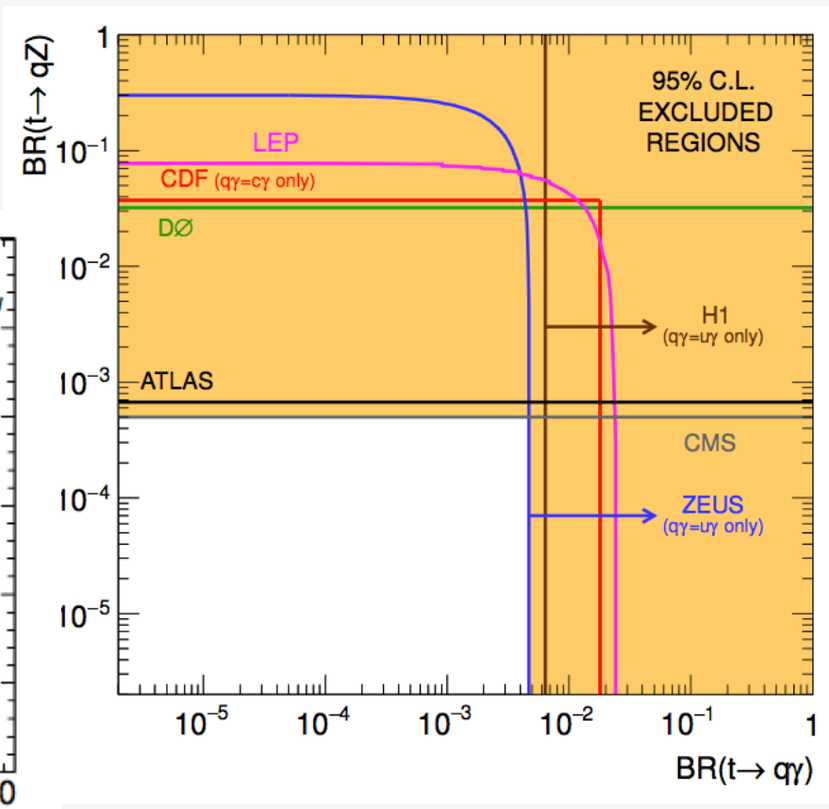


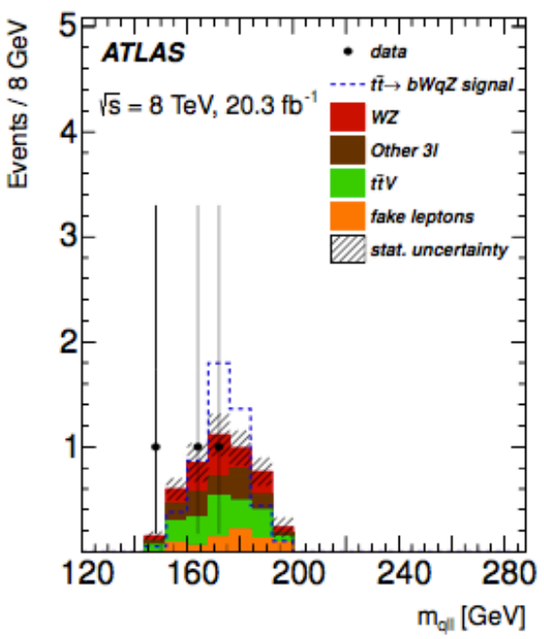
PROTOS @LO

Event signature: three isolated leptons, missing E_T, ≥ 2 jets, of them one or two b-jets

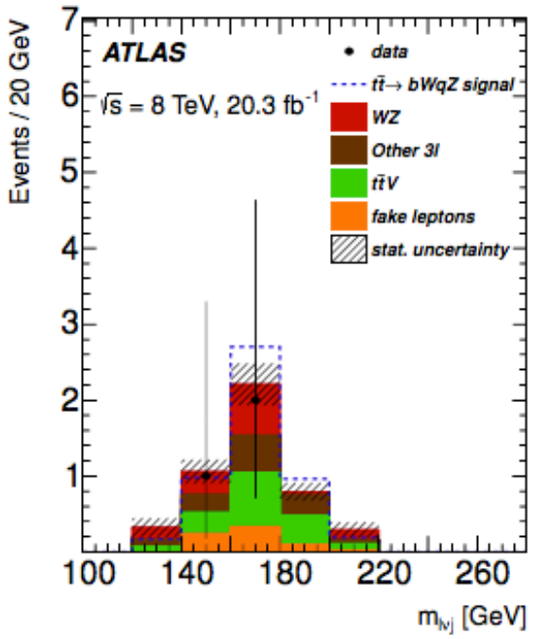
Main background: WZ/ZZ+jets, fake leptons, Z+jets

Fake lepton background is measured in data with fake matrix method

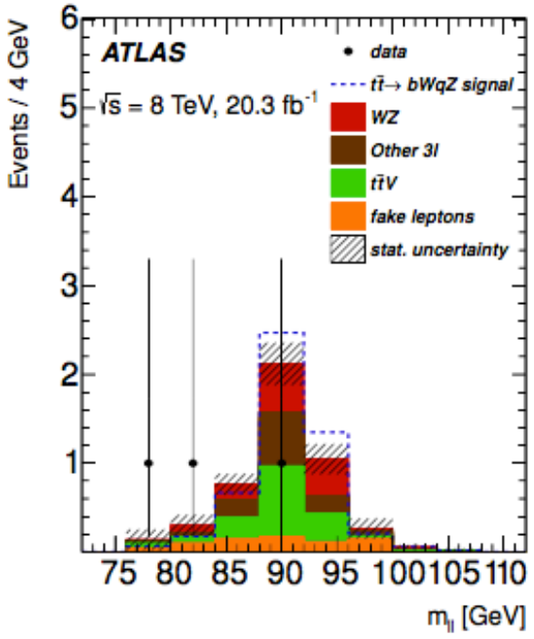




m(qll)



m(lvj)



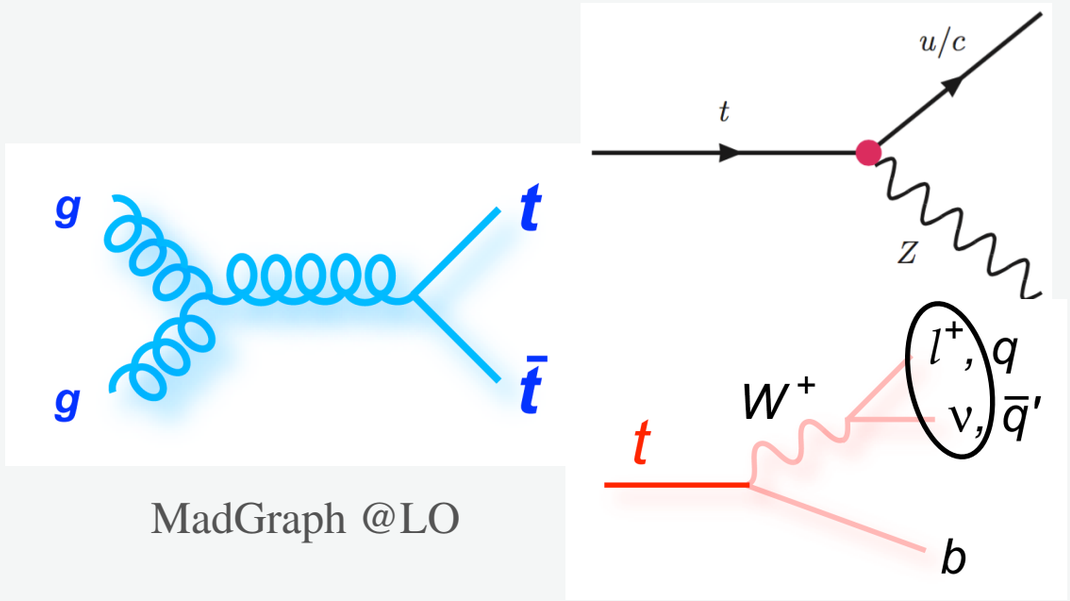
m(ll)

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

Search for t→Zq in ttbar events at CMS

Phys. Rev. Lett. 112 (2014) 171802
CMS, 20 fb^{-1}, 8 TeV

Zqt

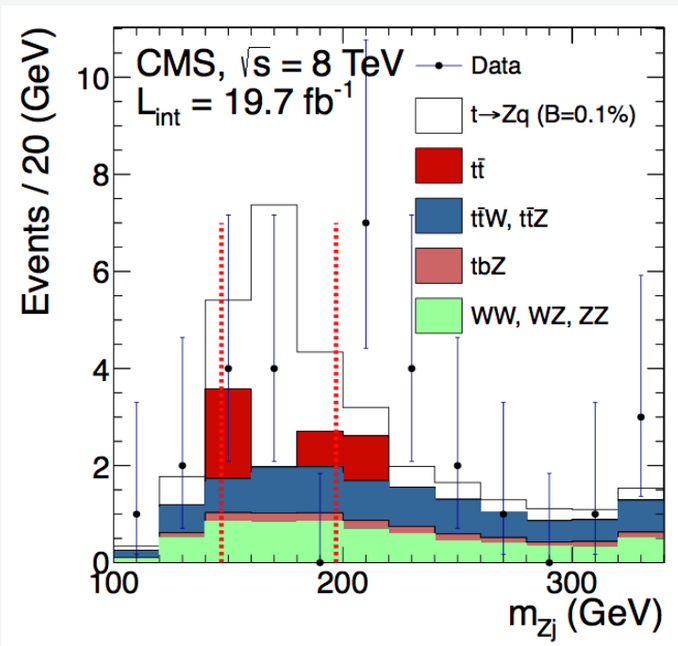


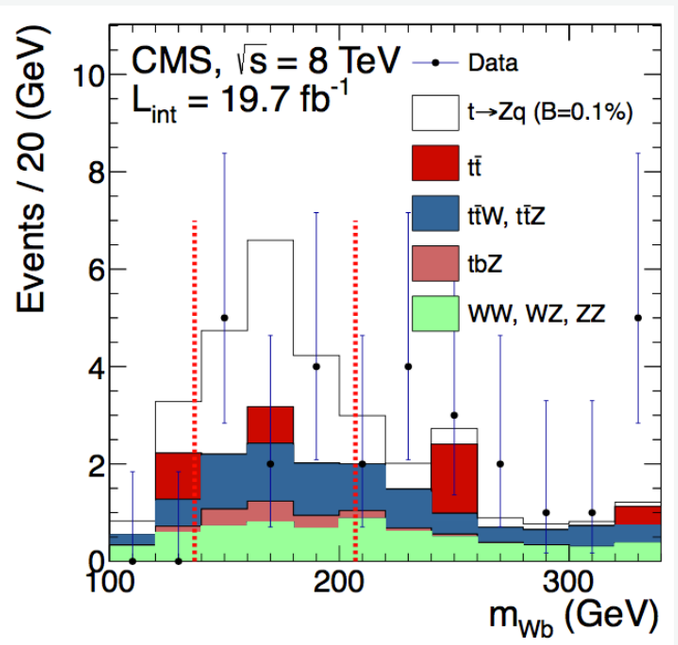
MadGraph @LO

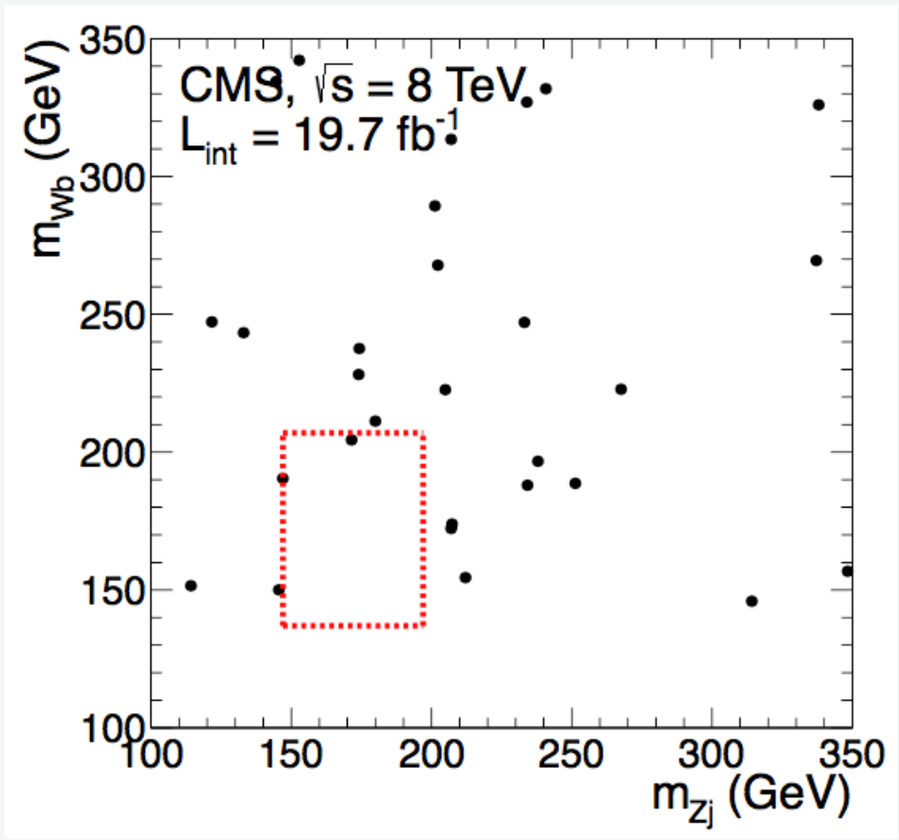
Event signature: three isolated leptons, missing E_T, ≥ 2 jets of which one is b-jet

Main background: WW/WZ/ZZ+jets, ttbar+X

Background estimated from data





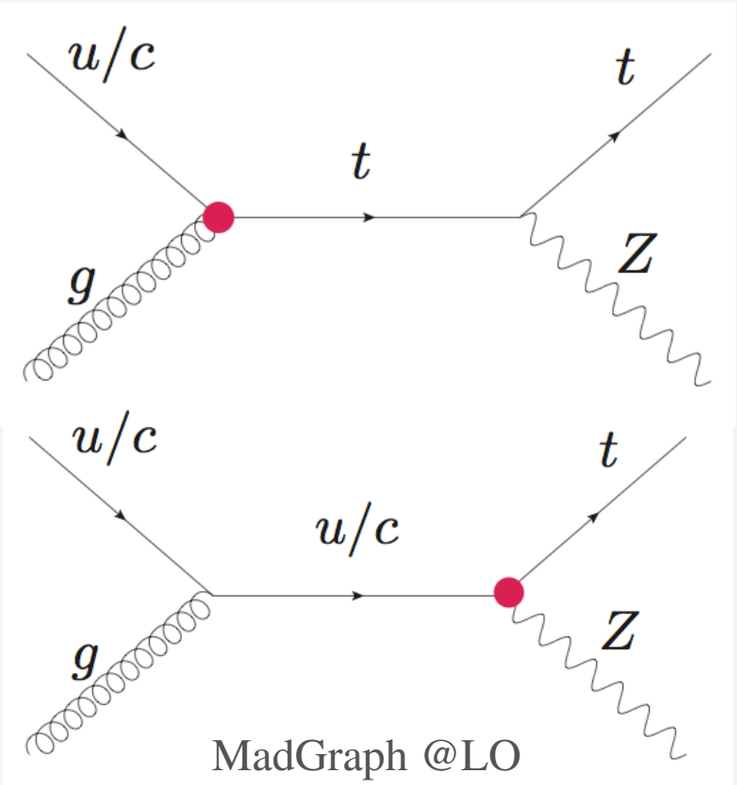


$\mathcal{B}(t \to Zq)$	8 TeV	7 TeV + 8 TeV
Expected upper limit	<0.10%	<0.09%
Observed upper limit	<0.06%	<0.05%
1 σ boundary	0.06–0.13%	0.06–0.13%
2 σ boundary	0.05–0.20%	0.05–0.18%

BR(t→**Z**q) < 0.05 % (obs)
0.09 % (exp)

Search for tZ events in single top at CMS

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

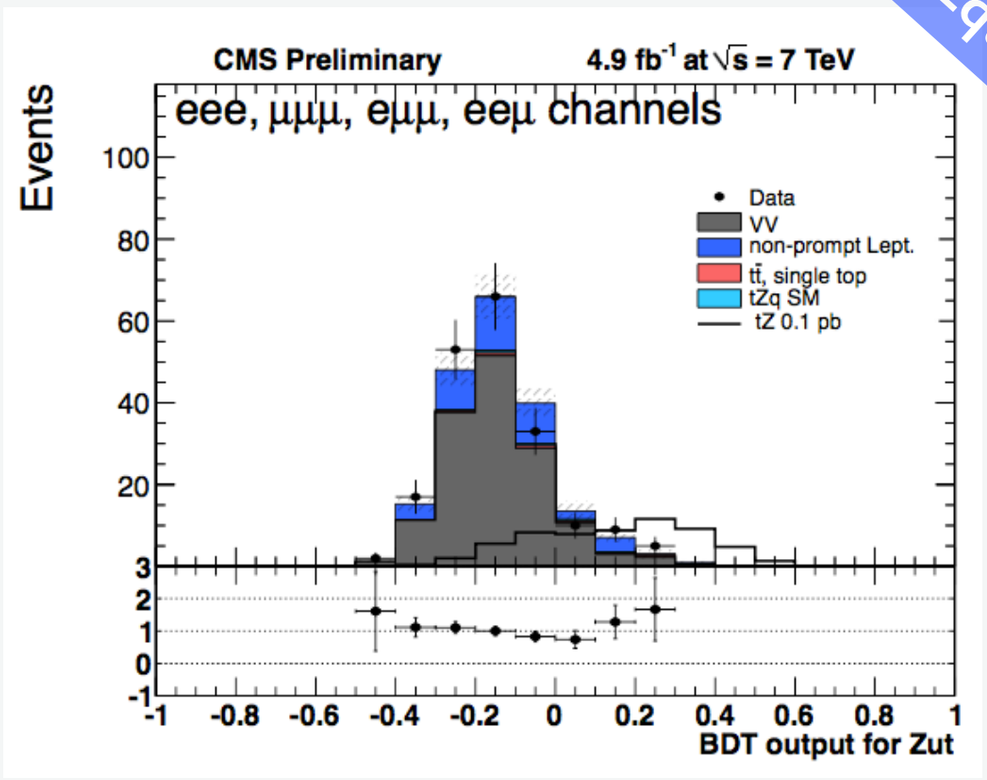


MadGraph @LO

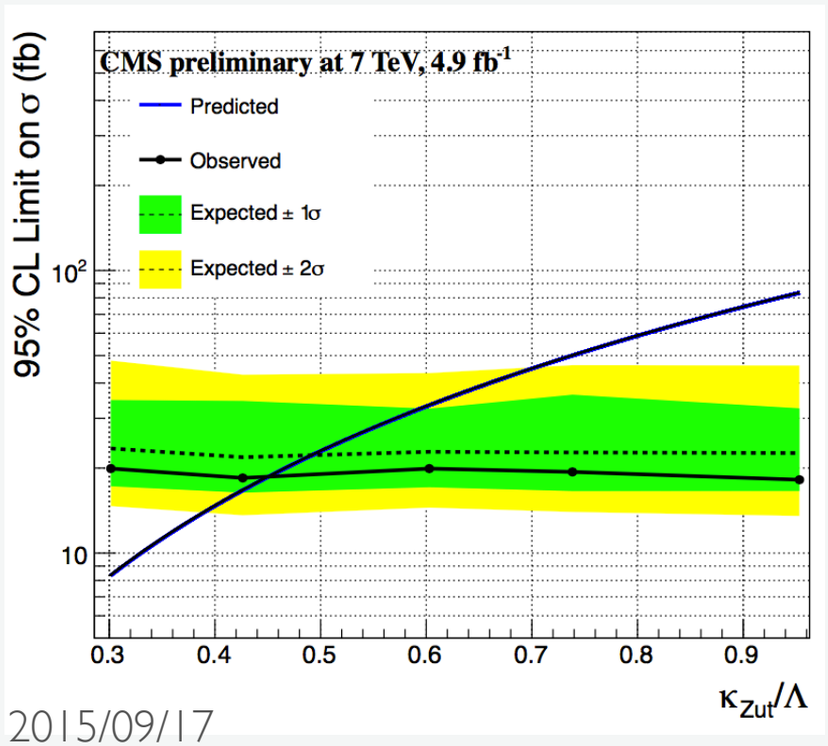
Event signature: three isolated leptons, missing E_T, one b-jet

Main background: WZ/ZZ+jets, fake leptons

VV and **fake lepton background** measured from m_T(W) template fit in data



BDT is used to discriminate signal and background

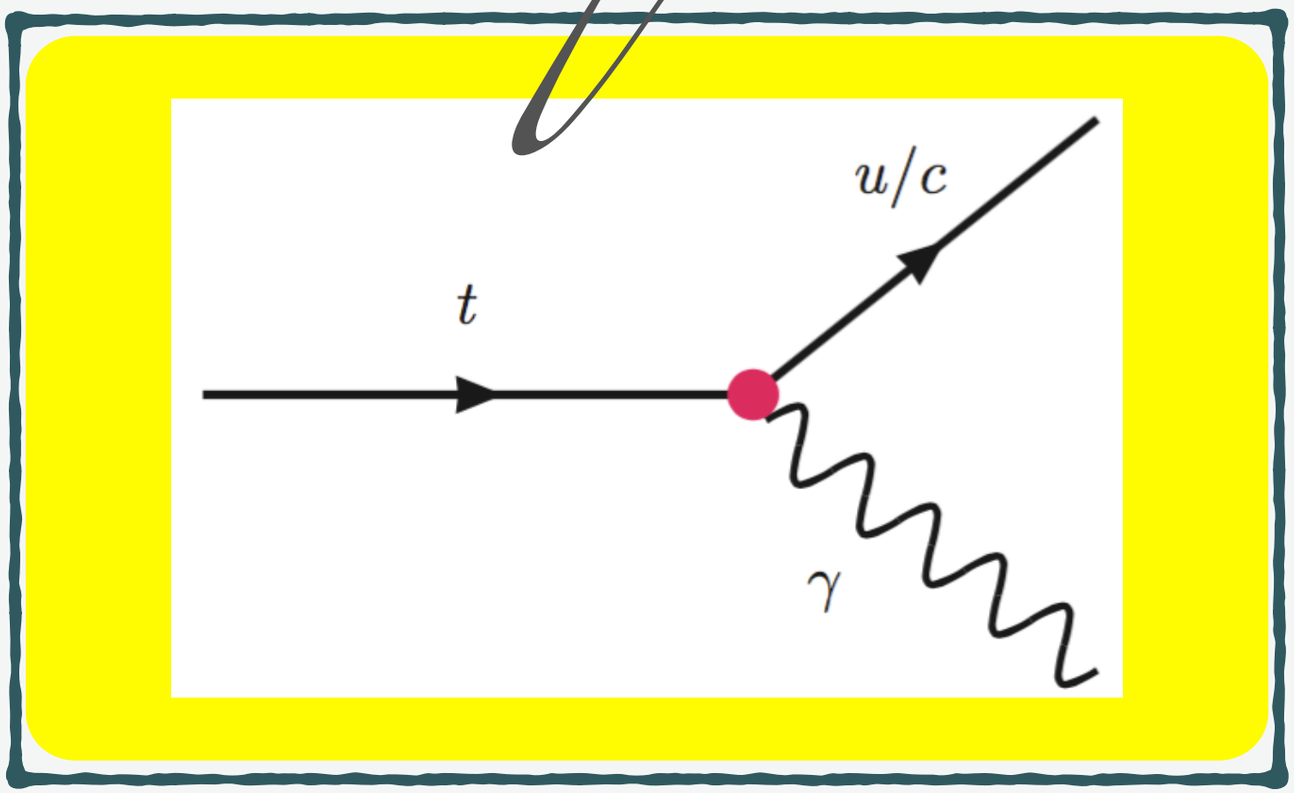


BR(t→**Z**u) < 0.51 % (obs)
0.61 % (exp)
BR(t→**Z**c) < 0.11 % (obs)
0.16% (exp)

BR(t→u**g**) < 0.56 % (obs)
0.56 % (exp)
BR(t→c**g**) < 0.71 % (obs)
1.03 % (exp)

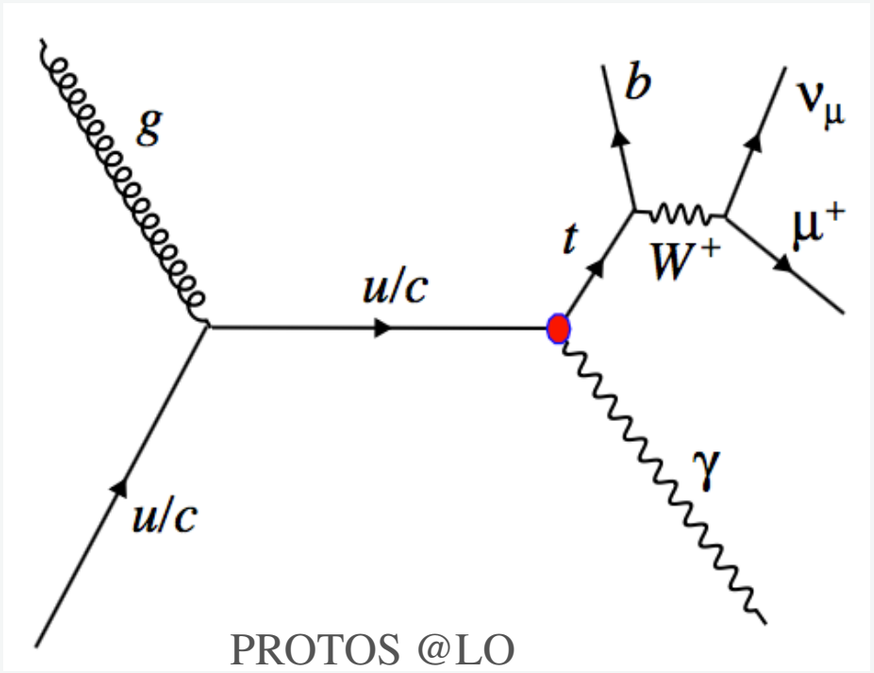
$\kappa_{Zut}/\Lambda < 0.45$ TeV^{-1}
$\kappa_{Zct}/\Lambda < 2.27$ TeV^{-1}
$\kappa_{ugt}/\Lambda < 0.10$ TeV^{-1}
$\kappa_{cgt}/\Lambda < 0.35$ TeV^{-1}

γqt



Search for tγ events in single top at CMS

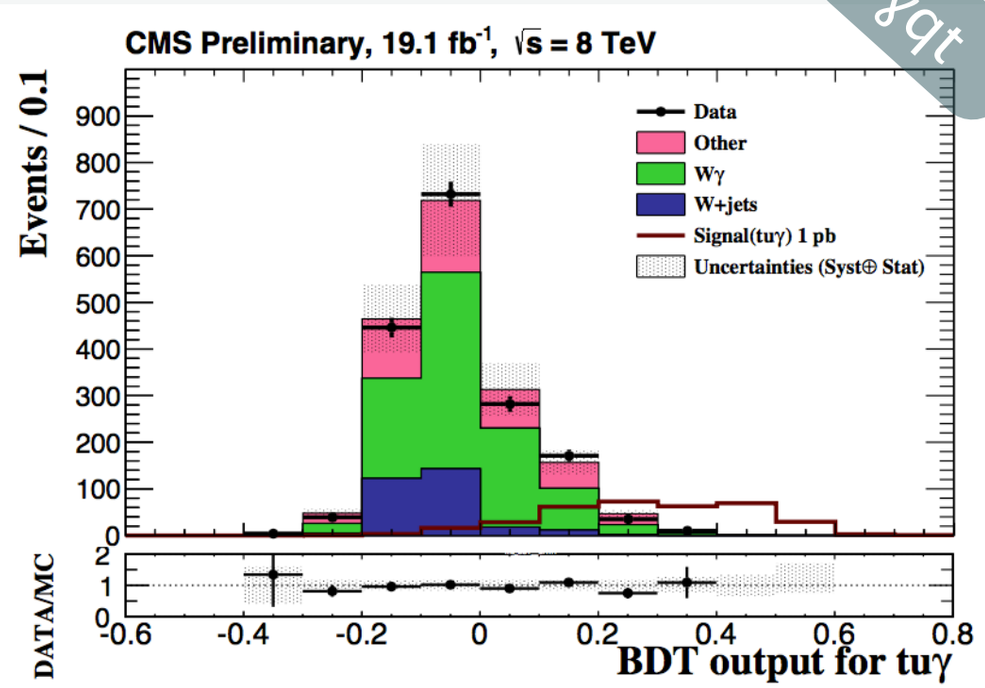
CMS-PAS-TOP-14-003
CMS, 19 fb^{-1}, 8 TeV



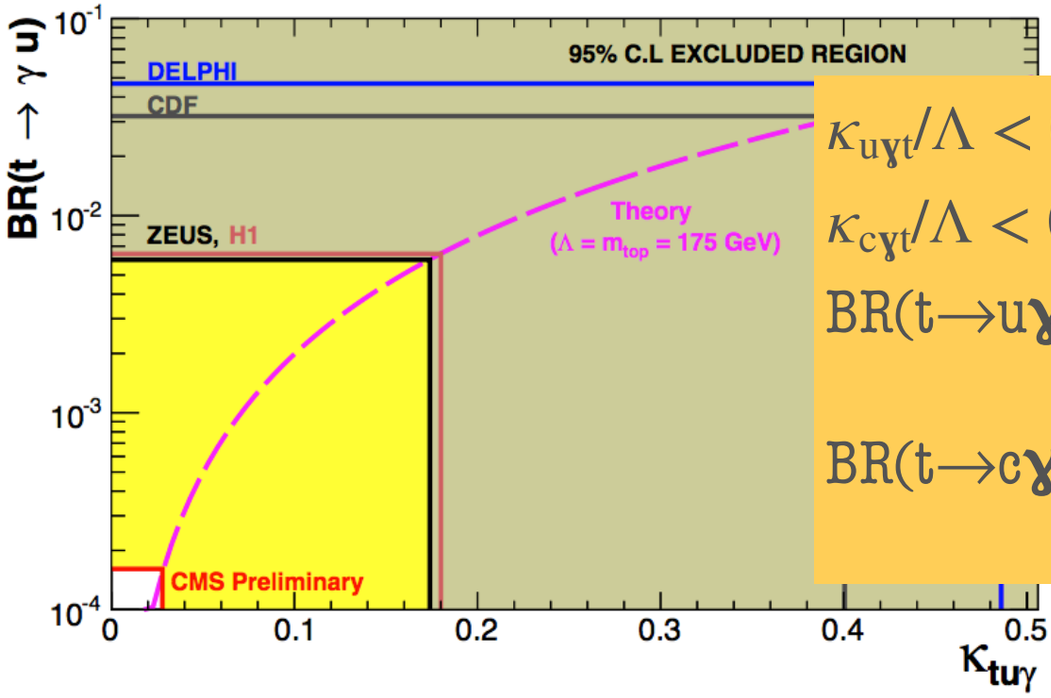
PROTOS @LO

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

Main background: Wγ+jets, W+jets, ttbar, Zγ+jets



Wγ+jets and **W+jets** measured from cos(W,γ) template fit in data

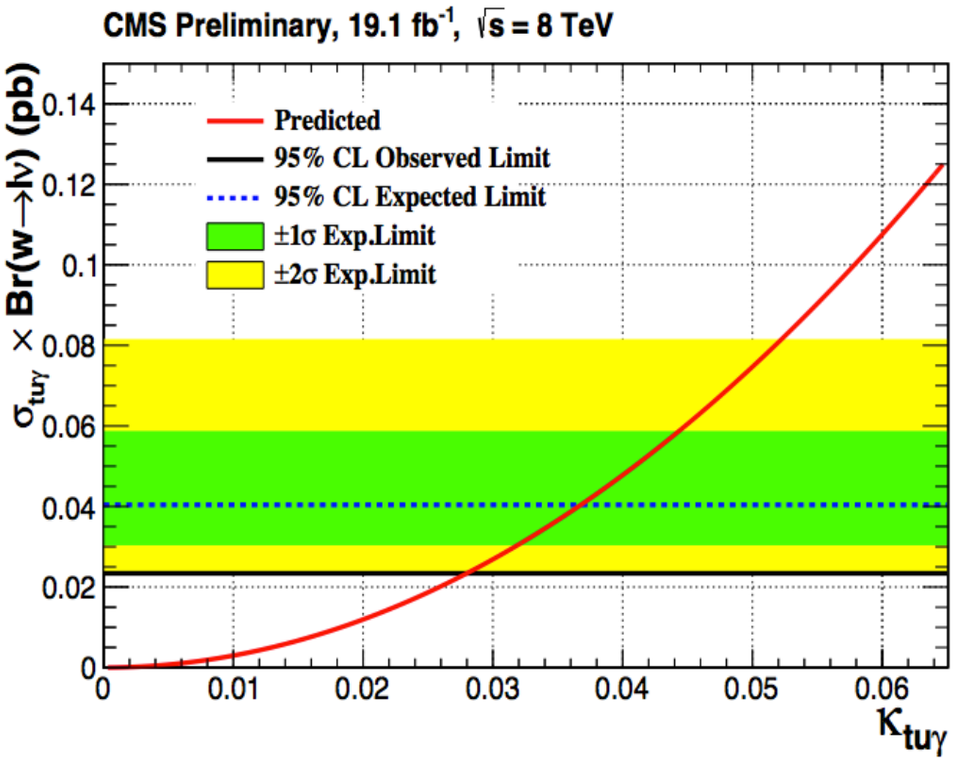


$\kappa_{u\gamma t}/\Lambda < 0.028$ TeV^{-1}

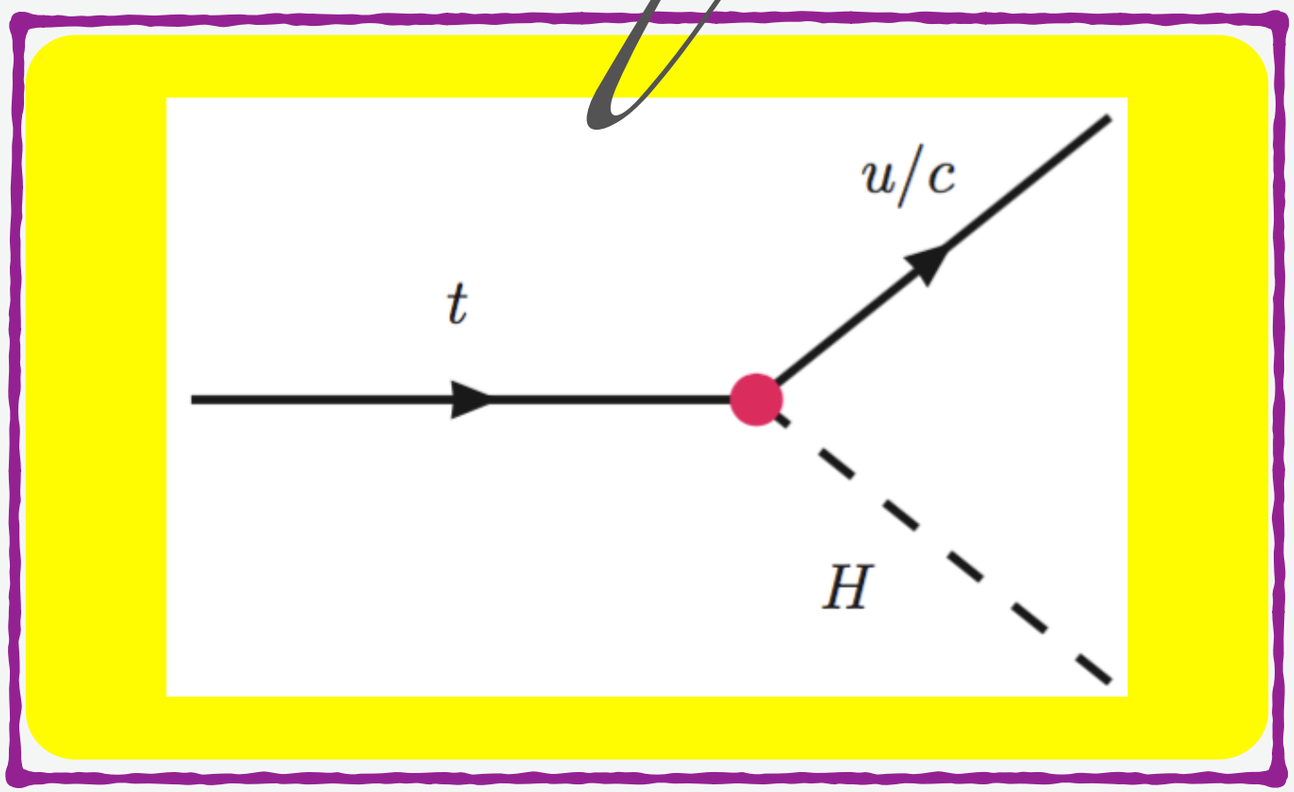
$\kappa_{c\gamma t}/\Lambda < 0.094$ TeV^{-1}

BR(t→uγ) < 0.02 % (obs)
0.03 % (exp)

BR(t→cγ) < 0.18 % (obs)
0.26 % (exp)

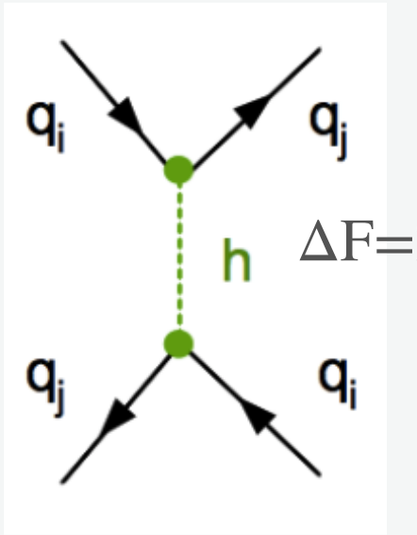


Hqt

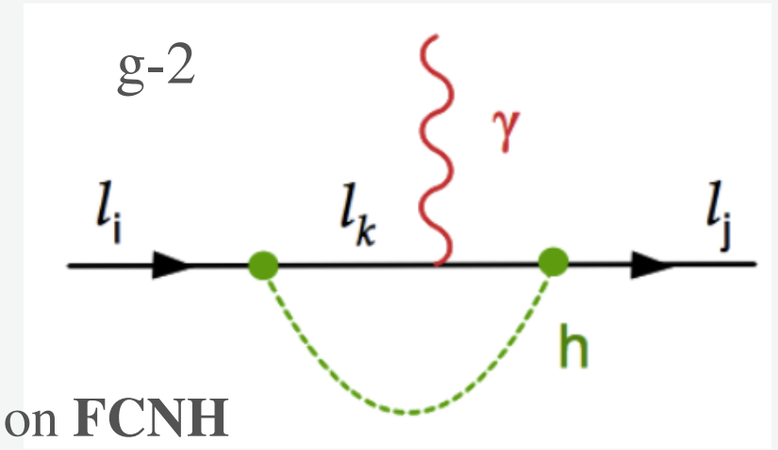


Higgs + FCNC = FCNH

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



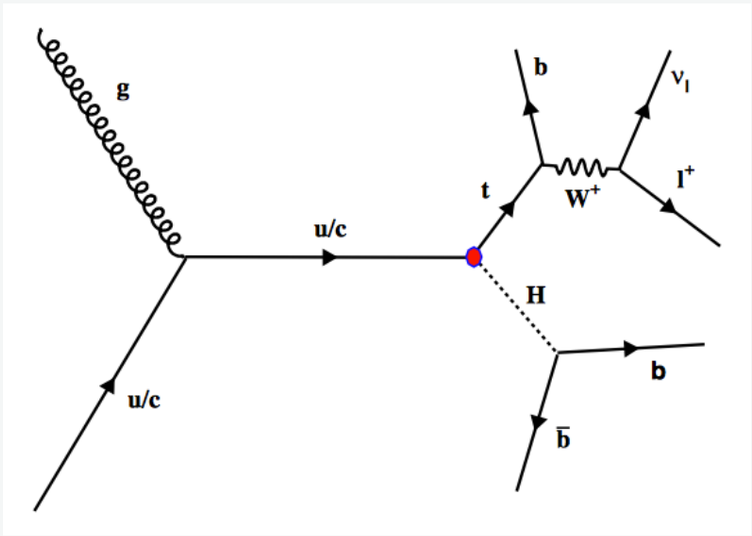
ΔF=2



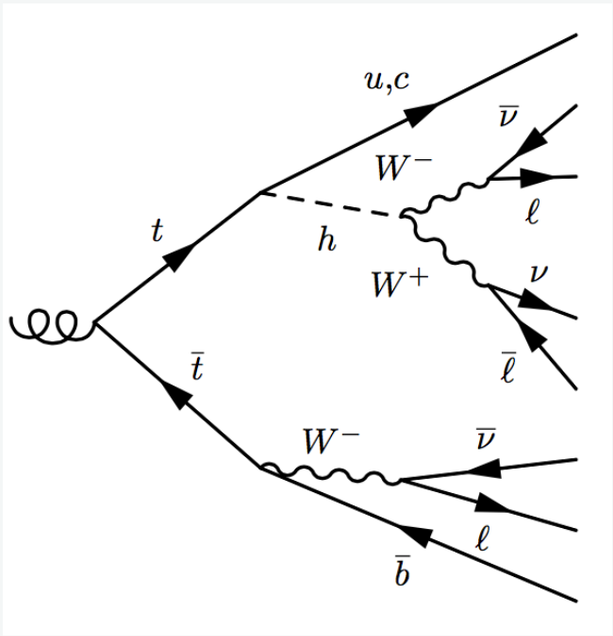
Stringent limits on **FCNH couplings to leptons** from LFV searches

http://arxiv.org/abs/1202.5704

FCNH in single top



FCNH in ttbar



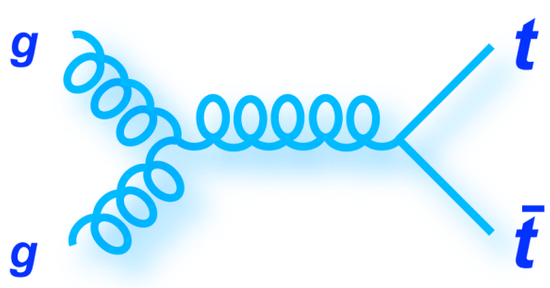
Expect a large coupling strength with a top quark ?

Search for t→Hq in ttbar events at ATLAS

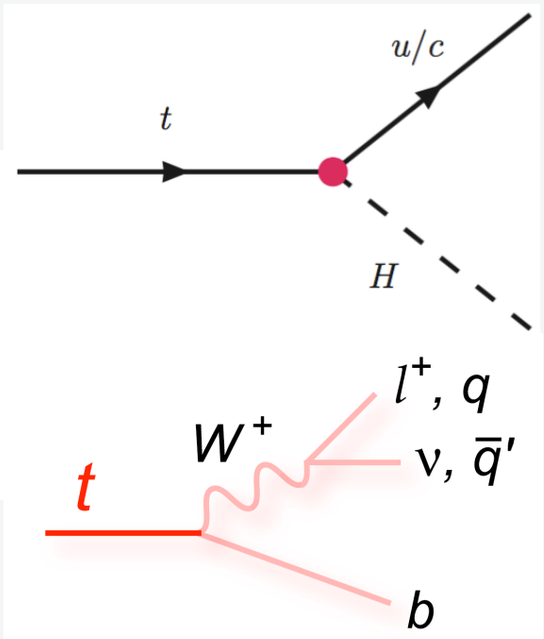
JHEP 06 (2014) 008
ATLAS, 5+20 fb^{-1}, 7+8 TeV

Hqt

H→γγ channel



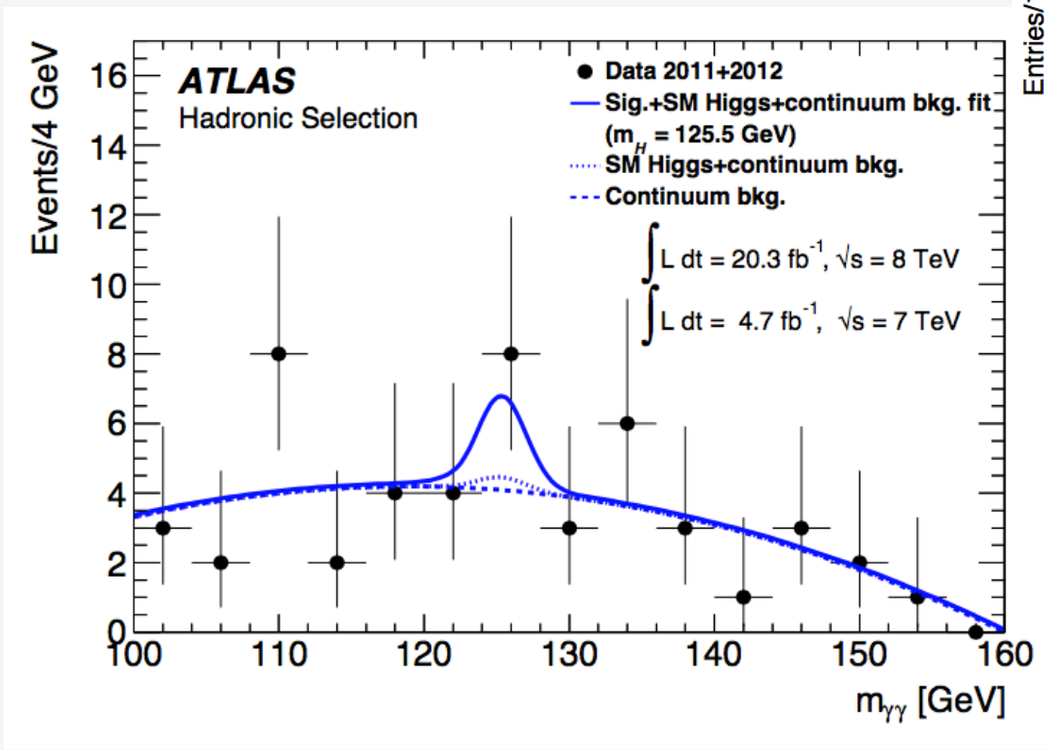
PROTOS @LO

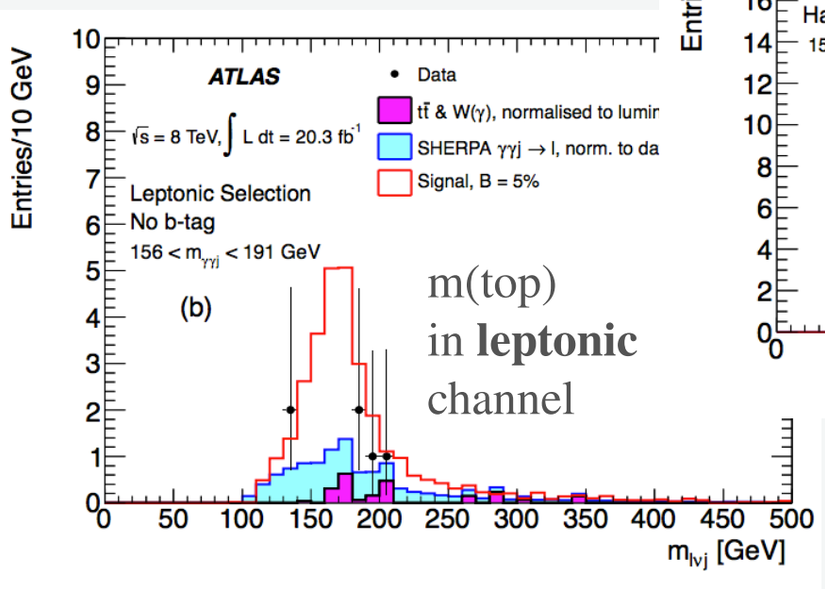


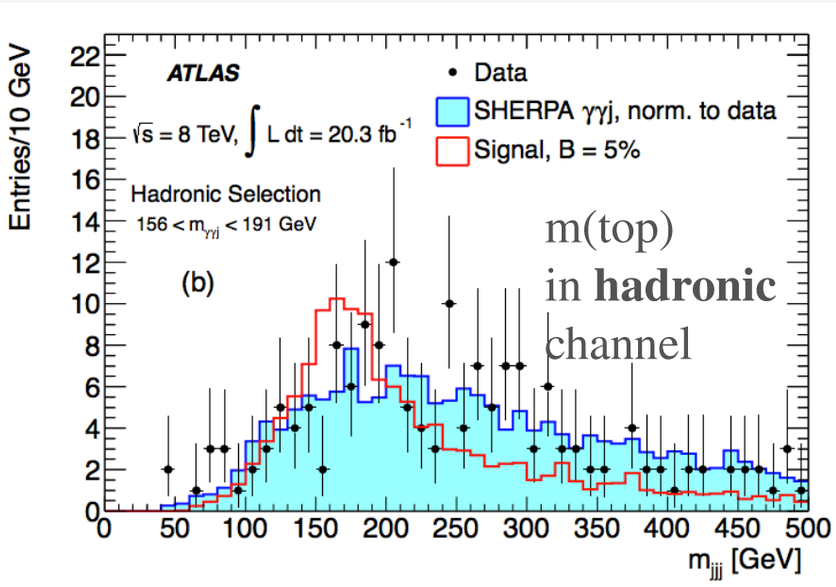
Event signature: two photons, one b-jet, 3 jets (**hadronic** channel) or one isolated lepton, missing E_T and one jet (**leptonic** channel)

Background for **hadronic** channel estimated from γγj data sample, and from γγ(j→l) sample for **leptonic** channel

Main background: γγ+jets, W+jets, ttbar







$\kappa_{qHt} < 0.17$

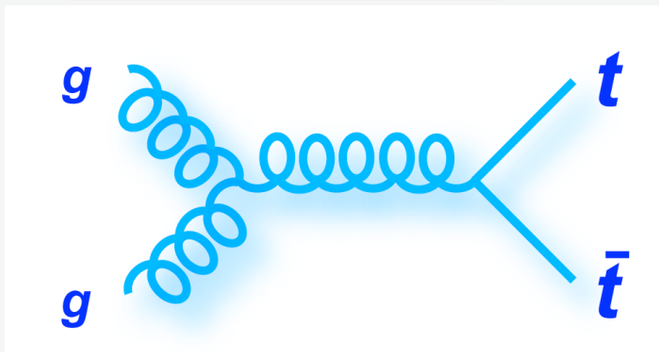
BR(t→q**H**) < 0.79 % (obs)
0.51 % (exp)

Search for t→Hq in ttbar events at CMS

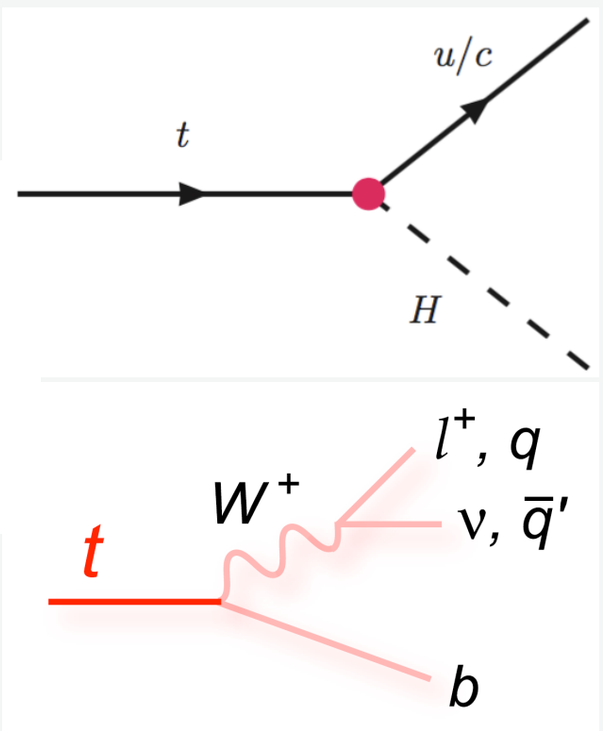
CMS-PAS-TOP-14-019
CMS, 20 fb^{-1}, 8 TeV

Hqt

H→γγ channel



MadGraph@LO

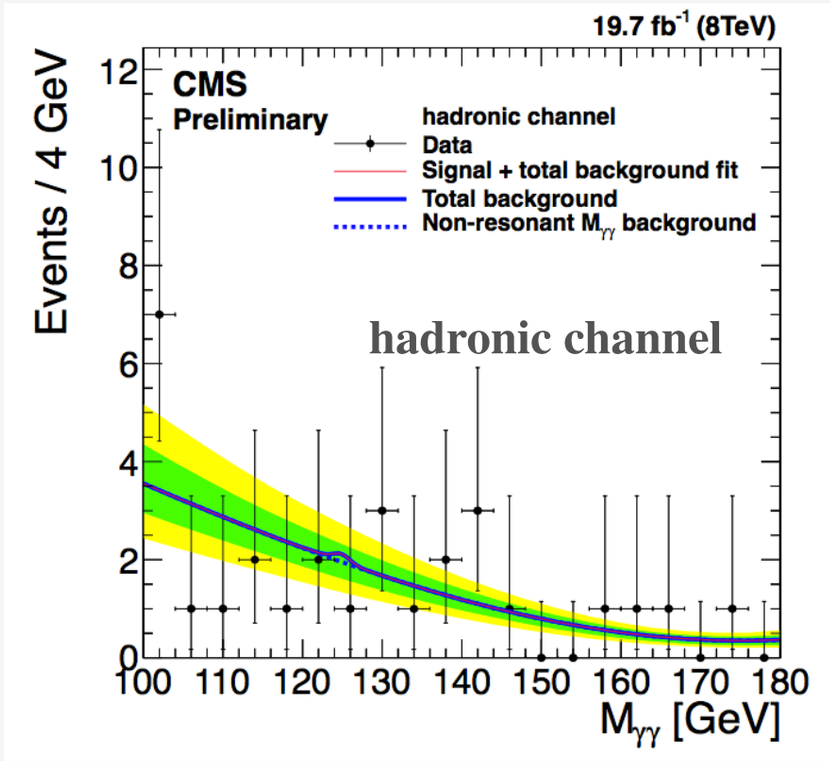


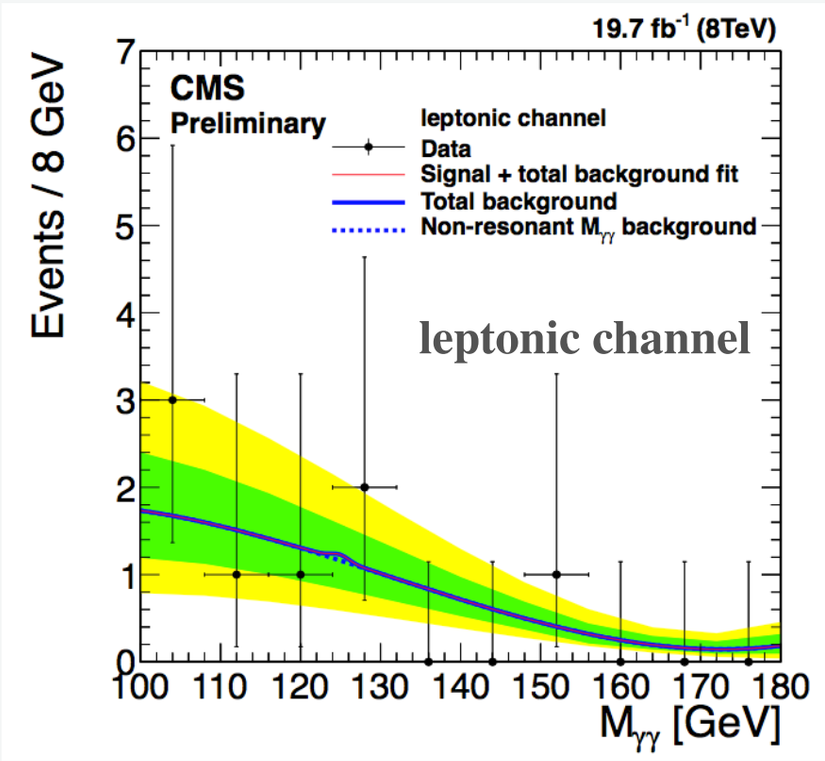
Event signature: two photons, one b-jet, 3 jets (**hadronic** channel) or one isolated lepton, missing E_T and one b-jet and one additional jet (**leptonic** channel)

Main background: γγ+jets, W+jets, ttbar

Non-resonant γγ+jets background estimated from the fit to data

BR(t→u**H**) < 0.42 % (obs)
0.65 % (exp)
BR(t→c**H**) < 0.47 % (obs)
0.71 % (exp)

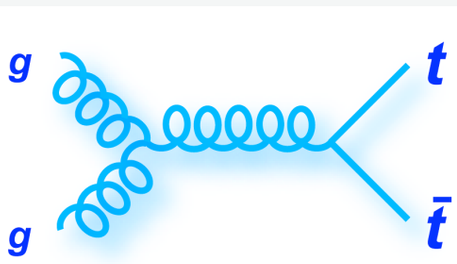


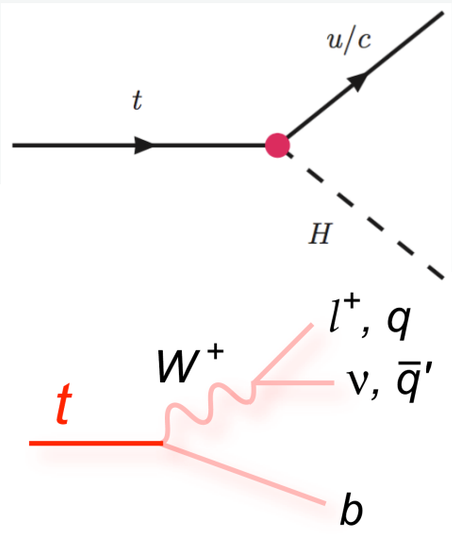


Search for t→Hq in ttbar events at ATLAS

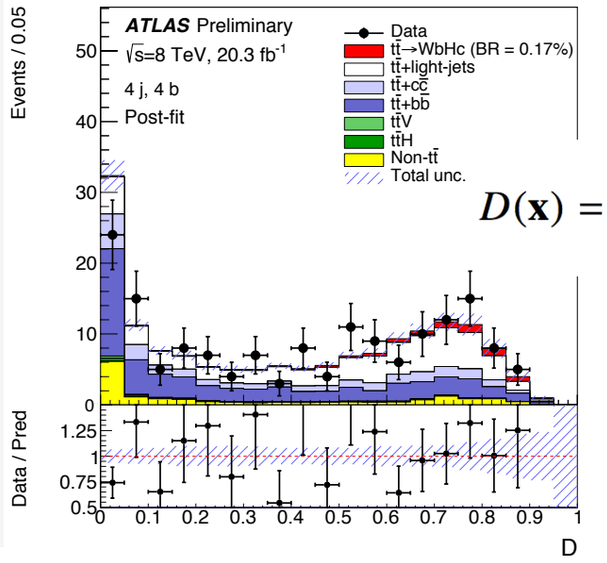
PAPER SOON !
ATLAS, 20 fb^{-1}, 8 TeV

H→bb channel

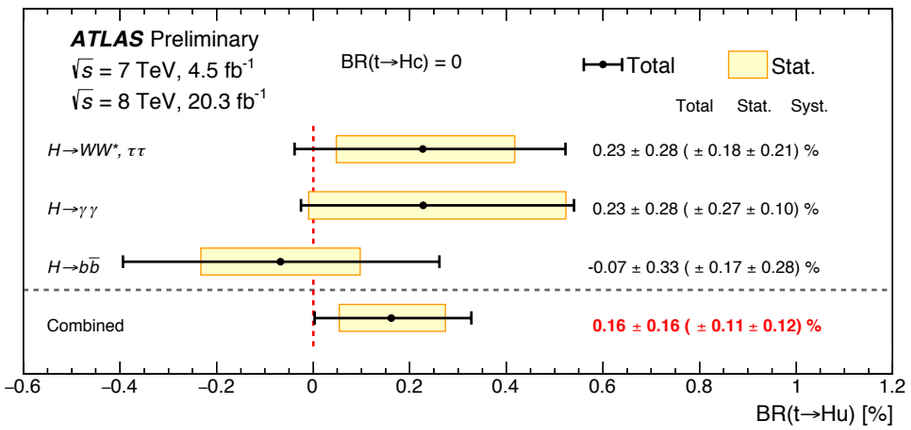




PROTOS @LO



$$D(\mathbf{x}) = \frac{P^{\mathrm{sig}}(\mathbf{x})}{P^{\mathrm{sig}}(\mathbf{x}) + P^{\mathrm{bkg}}(\mathbf{x})}$$



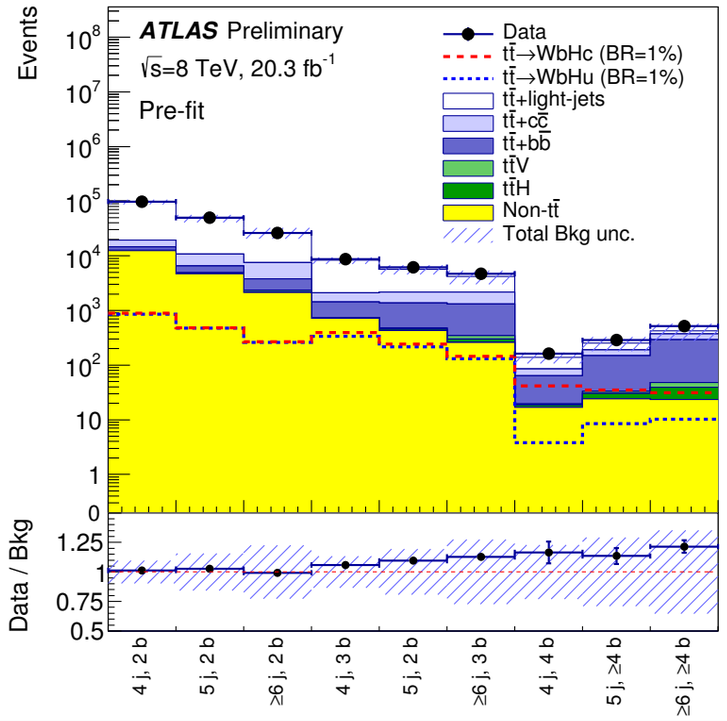
Detailed overview in the talk by Shota Tsiskaridze

Hqt

EXTRA NEW

Event signature: ≥ 4 jets of which ≥ 3 jets are b-jets, one lepton and missing E_T

Main background: ttbar+jets



Background and signal estimated from the likelihood fit to data

Combination with JHEP 06 (2014) 008 (**H→γγ**) and Phys. Lett. B 749 (2015) 519 (**ttH, H→WW/ττ**)

Preliminary

$\kappa_{\mathrm{uHt}} < 0.13$, $\kappa_{\mathrm{cHt}} < 0.13$

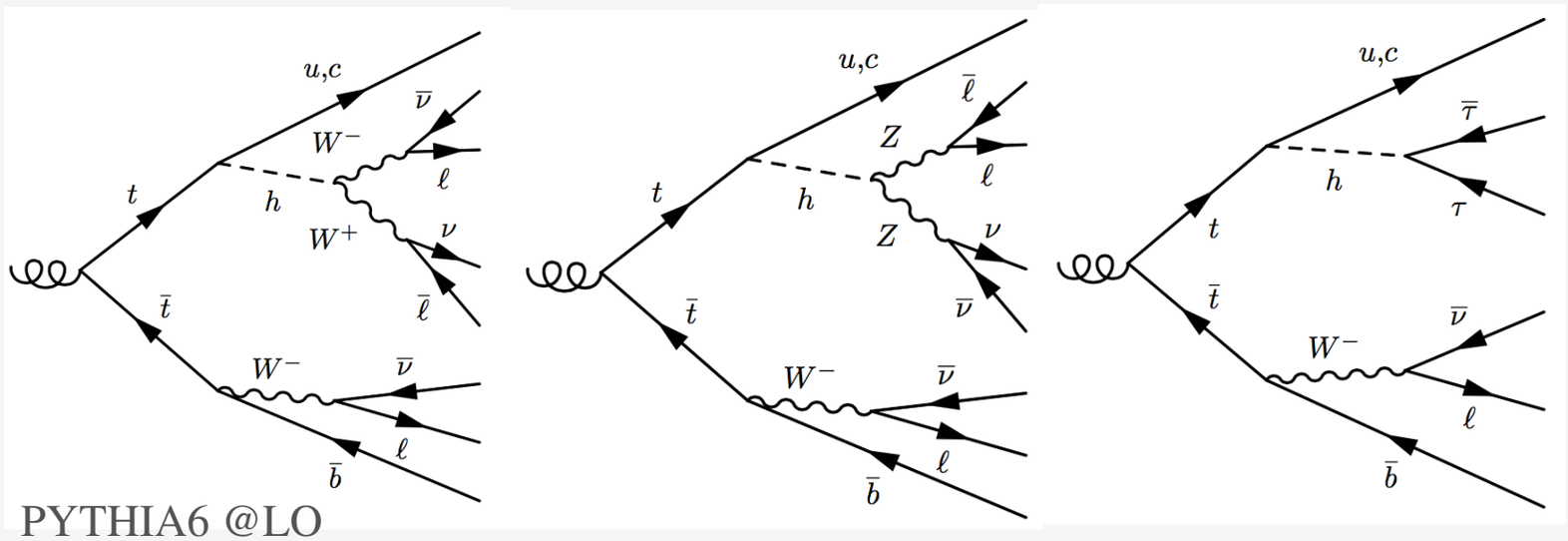
BR(t→u**H**) < 0.45 % (obs)
0.29 % (exp)
BR(t→c**H**) < 0.46 % (obs)
BR(t→c**H**) < 0.25 % (exp)

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

Search for t→Hq in ttbar events at CMS

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

Hqt



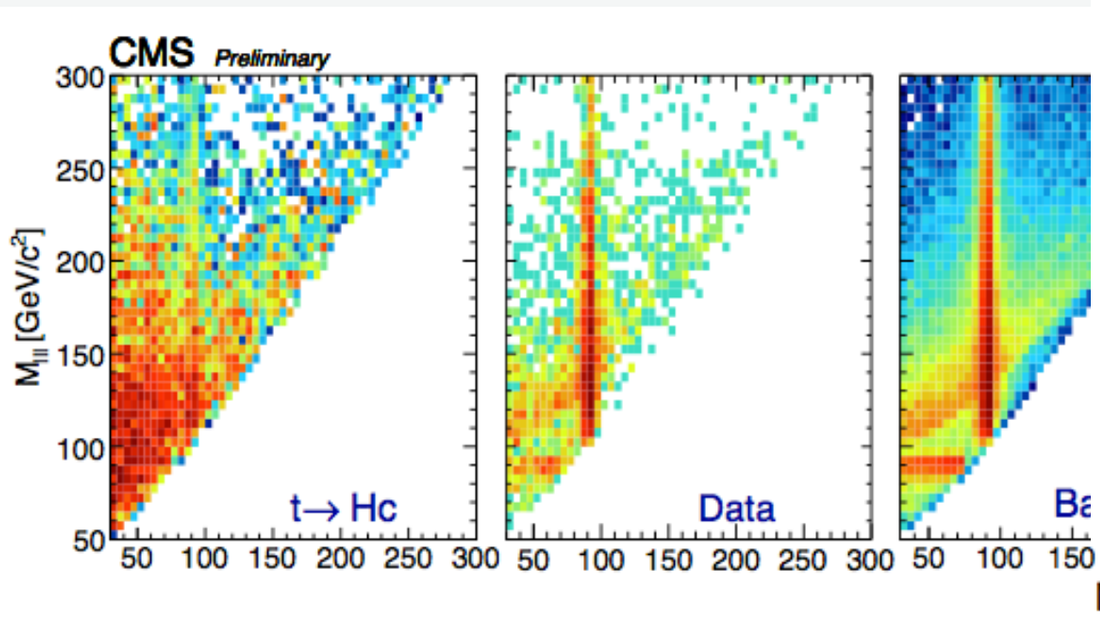
PYTHIA6 @LO

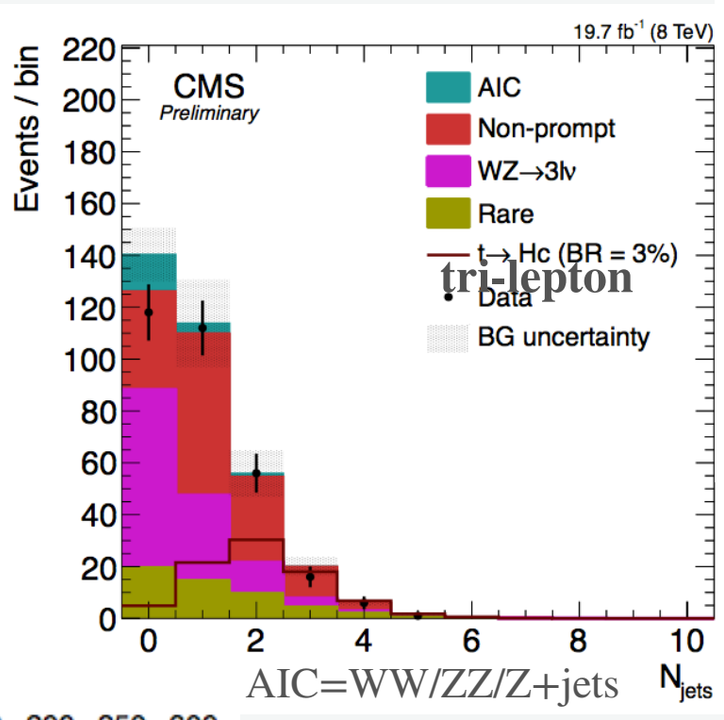
H→WW/ZZ/ττ channel

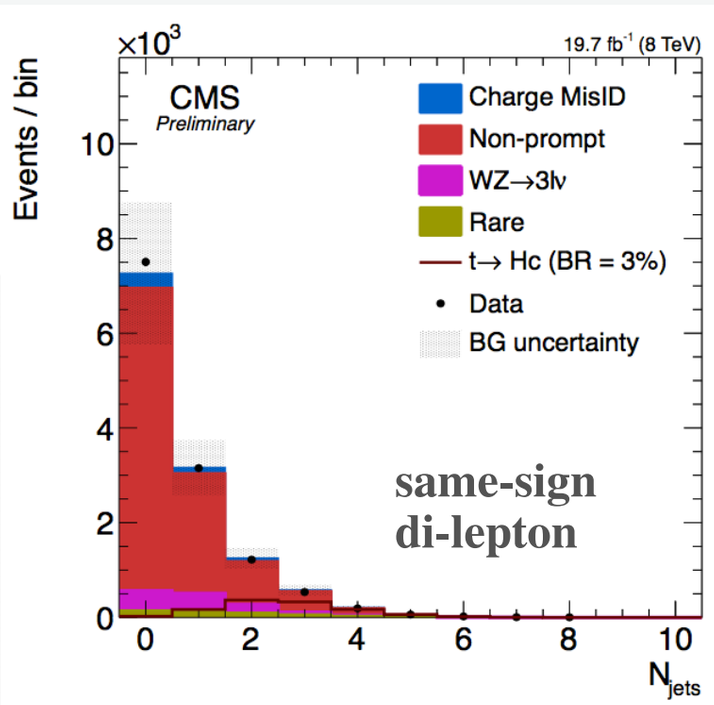
Event signature: **three** or **two same-sign** leptons, one b-jet, missing E_T, ≥ 2 jets

Main background: WZ+jets, ttbar+V (**tri-lepton**), fake leptons, charge mis-ID (**same-sign dilepton**)

Fake and **charge misID** lepton backgrounds estimated from data





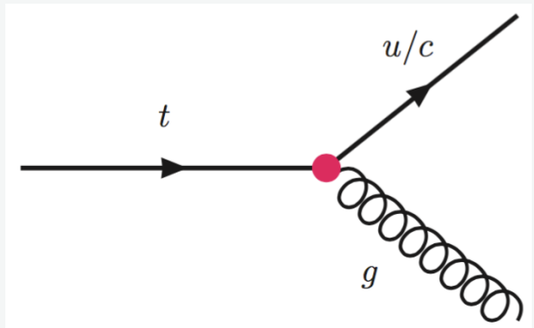


$\kappa_{qHt} < 0.18$

BR(t→q**H**) < 0.93 % (obs)
0.89 % (exp)

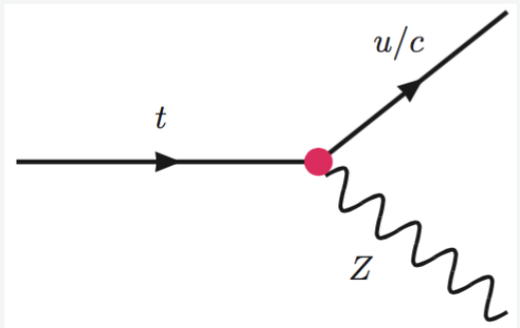
Summary on the best FCNC limits from the LHC

gqt



Experiment	BR(**t→ug**)	BR(**t→cg**)	Reference
ATLAS	0.004 %	0.017 %	arXiv:1509.00294v1
CMS	0.036 %	0.34 %	CMS-PAS-TOP-14-007

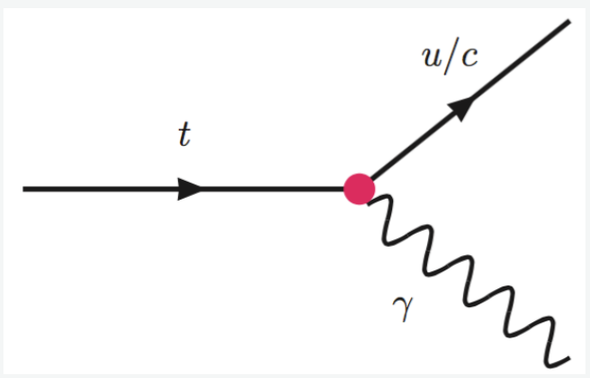
Zqt



Experiment	BR(**t→uZ**)	BR(**t→cZ**)	Reference
ATLAS	0.07 %		arXiv:1508.05796
CMS	0.05 %		Phys. Rev. Lett. 112 (2014) 171802

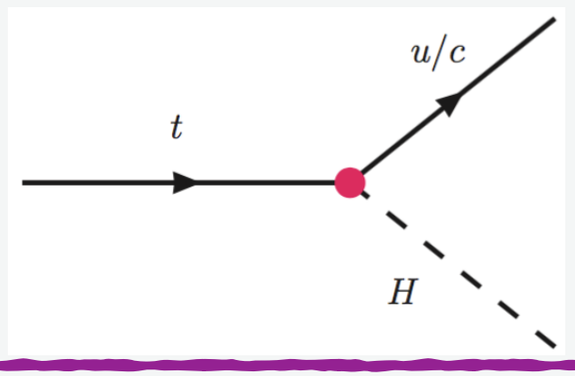
Experiment	BR(**t→uγ**)	BR(**t→cγ**)	Reference
CMS	0.02 %	0.18 %	CMS-PAS-TOP-14-003

γqt

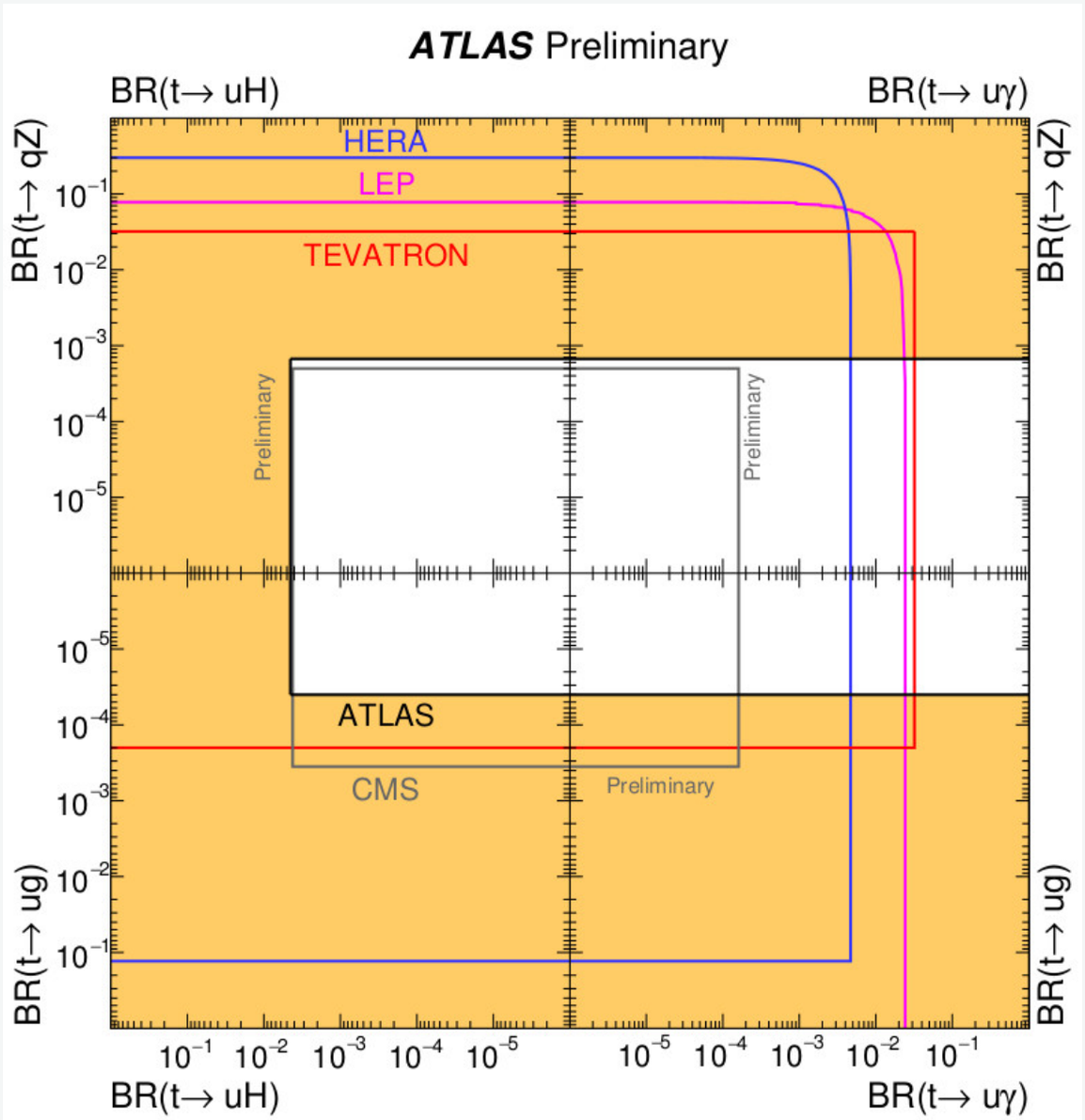


Experiment	BR(**t→uH**)	BR(**t→cH**)	Reference
ATLAS	0.45 %	0.46 %	PAPER SOON !
CMS	0.42 %	0.47 %	CMS-PAS-TOP-14-019

Hqt



Summary on the best FCNC limits



- HERA:
  ZEUS Collaboration, Phys. Lett. B708 (2012) 27; H1 Collaboration, Phys. Lett. B 678 (2009) 450; A.A. Ashimova and S.R. Slabospitsky, Phys. Lett. B668 (2008) 282
- LEP:
  ALEPH Collaboration, Phys. Lett. B543 (2002) 173; DELPHI Collaboration, Phys. Lett. B590 (2004) 21; OPAL Collaboration, Phys. Lett. B521 (2001) 181; L3 Collaboration, Phys. Lett. B549 (2002) 290; LEP Exotica WG, LEP Exotica WG 2001-01
- TEVATRON:
  CDF Collaboration, Phys. Rev. Lett. 101 (2008) 192002; DØ Collaboration, Phys. Lett. B701 (2011) 313; CDF Collaboration, Phys. Rev. Lett. 102 (2009) 151801; DØ Collaboration, Phys. Lett. B693 (2010) 81; CDF Collaboration, Phys. Rev. Lett. 80 (1998) 2525
- CMS:
  CMS Collaboration, Phys. Rev. Lett. 112 (2014) 171802; *CMS Collaboration, CMS-PAS-TOP-14-007*; *CMS Collaboration, CMS-PAS-TOP-14-003*; *CMS Collaboration, CMS-PAS-TOP-14-019*
- ATLAS:
  ATLAS Collaboration, arXiv:1509.00294; ATLAS Collaboration, arXiv:1508.05796; *ATLAS Collaboration, TOPQ-2014-14*

Conclusion

- An experimental review on FCNC searches with top quark was presented
- All possible 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
- Run II analyses are on their way

The best limits on FCNC top quark decays from the LHC :

BR(**t→ug**)	0.004 %	arXiv:1509.00294v1
BR(**t→cg**)	0.017 %	arXiv:1509.00294v1
BR(**t→qZ**)	0.05 %	Phys. Rev. Lett. 112 (2014) 171802
BR(**t→uγ**)	0.02 %	CMS-PAS-TOP-14-003
BR(**t→cγ**)	0.18 %	CMS-PAS-TOP-14-003
BR(**t→uH**)	0.42 %	CMS-PAS-TOP-14-019
BR(**t→cH**)	0.46 %	ATLAS PAPER SOON !

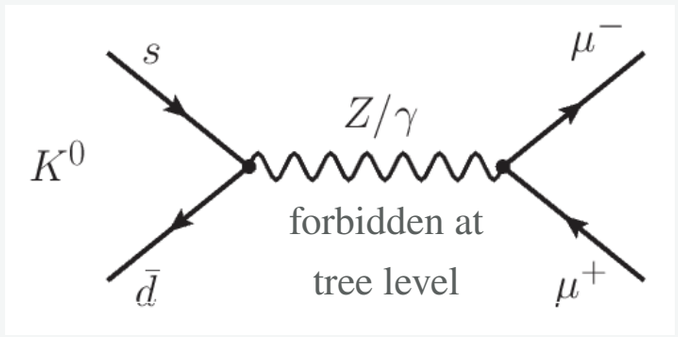
A dedicated combination effort would improve the existing limits further

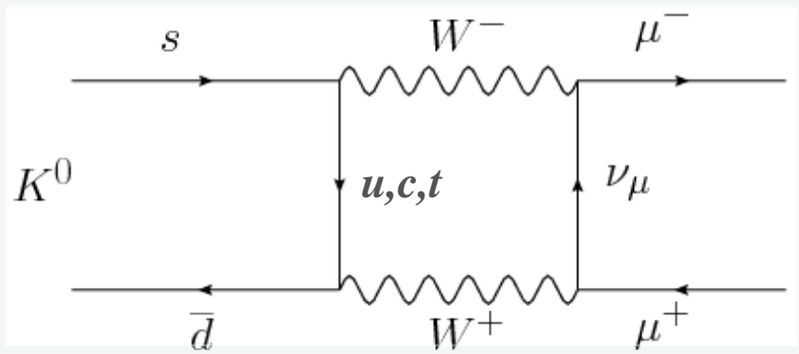
Backup slides

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

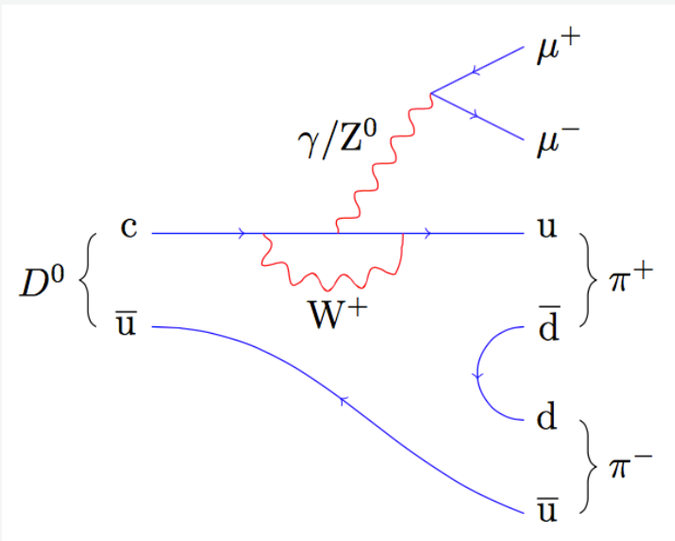
$K_L \to \mu^+\mu^-$





$Br_{exp} \approx 6 \cdot 10^{-9}$

Phys.Rev.Lett. 63 (1989) 2185 (AGS, BNL)



Search for **$D^0 \to \pi^+\pi^-\mu^+\mu^-$** at LHCb

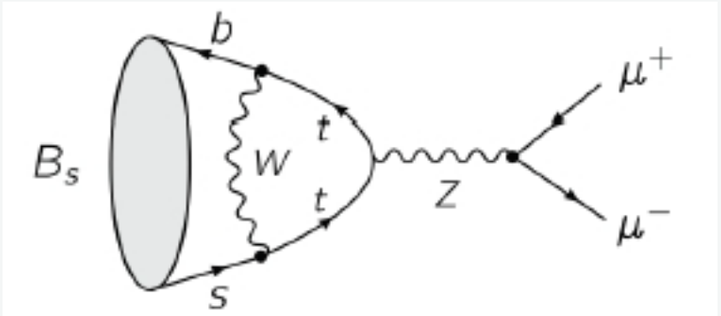
$Br_{exp} < 5.5 \cdot 10^{-7}$ (90% C.L.)

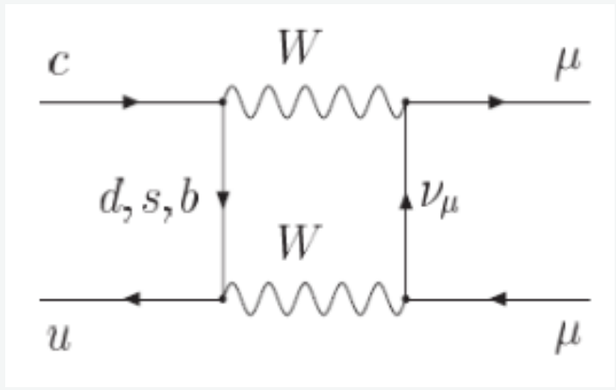
Phys. Lett. B 728 (2014) 234-243

Observation of **$B_s \to \mu^+\mu^-$** at LHCb and CMS

$Br_{exp} \approx 3 \cdot 10^{-9}$

LHCb-CONF-2013-12





Search for **$D^0 \to \mu^+\mu^-$** at LHCb

$Br_{exp} < 6 \cdot 10^{-9}$ (90% C.L.)

Phys. Lett. B 725 (2013) 15-24

Search for t→Hq in ttbar events at CMS

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

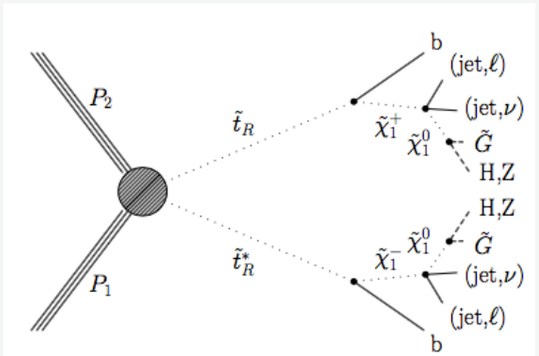
Hqt

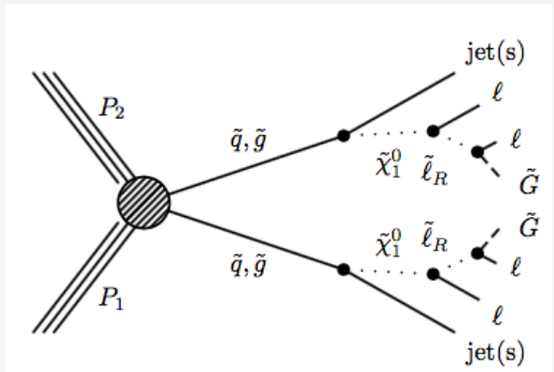
Based on a combination of two analyses performed in multilepton (H→WW/ZZ/ττ) and H→γγ channels

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

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

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





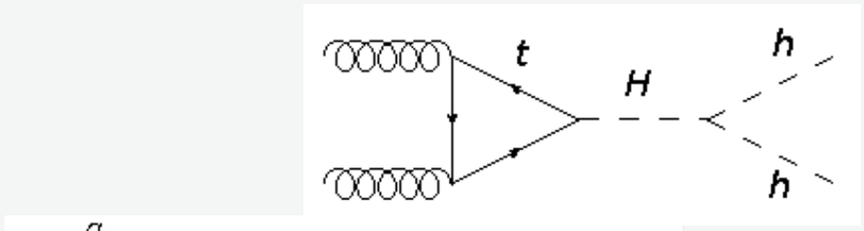
Several SUSY scenarios are probed, also possible to **set limits on FCNH** in this inclusive search:

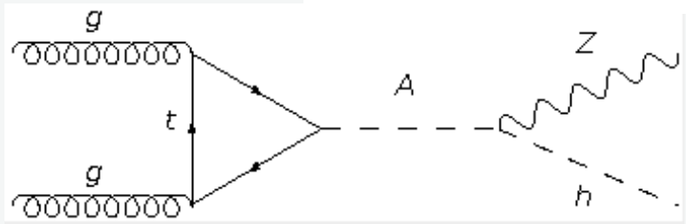
Higgs boson decay mode		Upper limits on $\mathcal{B}(t \to cH)$ Obs.	Exp.	1σ range
$\mathcal{B}(H \to WW^*)$	$= 23.1\%$	1.6 %	1.6%	(1.0–2.2)%
$\mathcal{B}(H \to \tau\tau)$	$= 6.2\%$	7.01%	5.0 %	(3.5–7.7)%
$\mathcal{B}(H \to ZZ^*)$	$= 2.9\%$	5.3%	4.11%	(2.9–6.5)%
Combined		1.3%	1.2%	(0.9–1.7)%

$\kappa_{qHt} < 0.21$
BR(t→q**H**) < 1.28 %

MadGraph @LO is used for FCNH generation

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





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

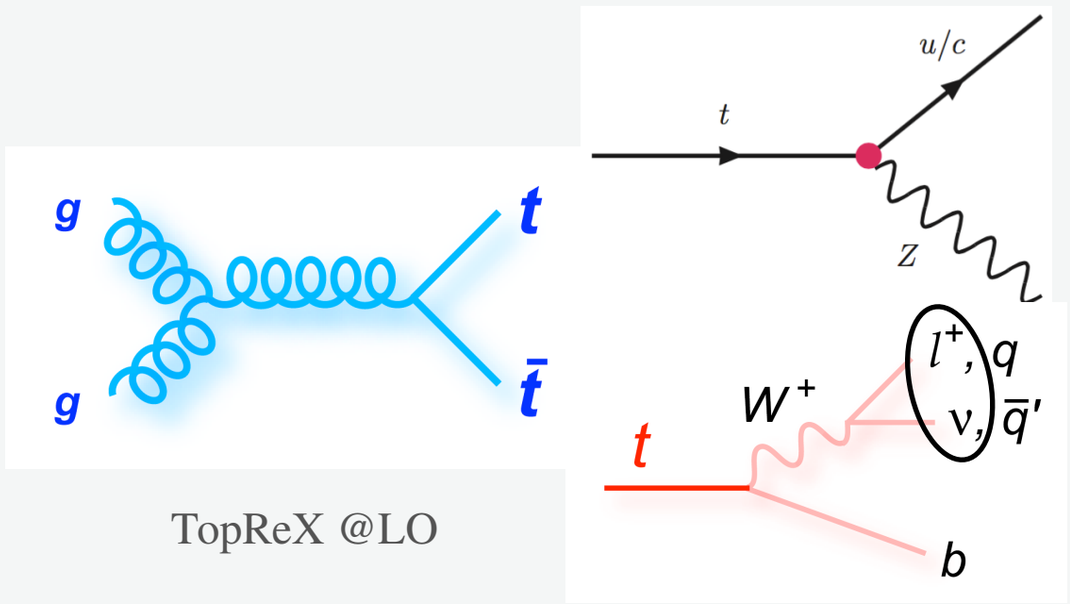
Combination of results

$\kappa_{qHt} < 0.14$
BR(t→q**H**) < 0.56 %

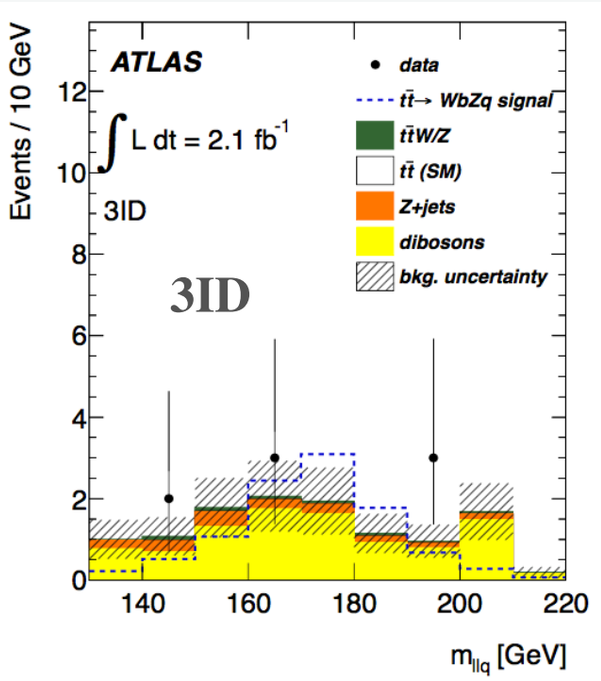
Search for t→Zq in ttbar events at ATLAS

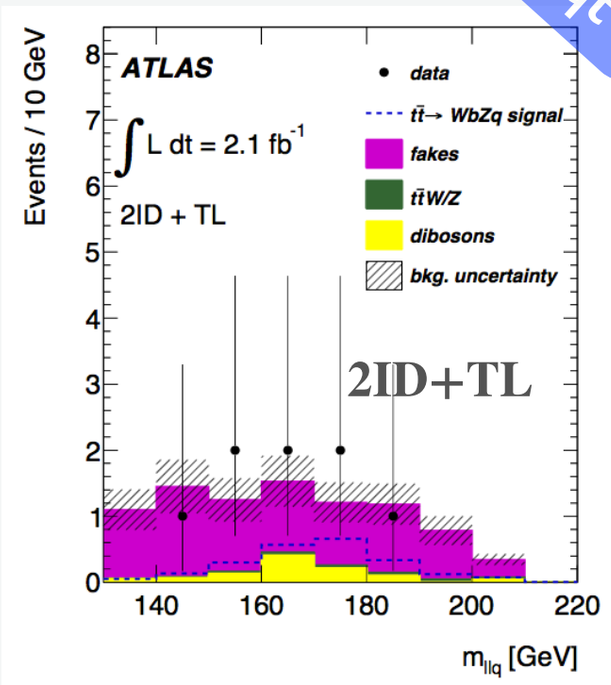
JHEP 1209 (2012) 139
ATLAS, 2 fb^{-1}, 7 TeV

Zqt



TopReX @LO





Reconstructed top candidate mass

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 ttbar→WbZq process by $\chi 2$ minimisation

Limits extracted using binned likelihood fit

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%

BR(t→**Z**q) < 0.73 % (obs)
0.93 % (exp)

MVA discriminating variables

Variable	Definition
$m_{\mathrm{T}}(\mathrm{top})$	Transverse mass of the reconstructed top quark
p_{T}^{ℓ}	Transverse momentum of the charged lepton
$\Delta R(\mathrm{top}, \ell)$	Distance in the η–ϕ plane between the reconstructed top quark and the charged lepton
$p_{\mathrm{T}}^{b\text{-jet}}$	Transverse momentum of the b-tagged jet
$\Delta\phi(\mathrm{top}, b\text{-jet})$	Difference in azimuth between the reconstructed top quark and the b-tagged jet
$\cos\theta(\ell, b\text{-jet})$	Opening angle of the three-vectors between the charged lepton and the b-tagged jet
q^{ℓ}	Charge of the lepton
$m_{\mathrm{T}}(W)$	W-boson transverse mass
η^{ℓ}	Pseudorapidity of the charged lepton
$\Delta\phi(\mathrm{top}, W)$	Difference in azimuth between the reconstructed top quark and the W boson
$\Delta R(\mathrm{top}, b\text{-jet})$	Distance in the η–ϕ plane between the reconstructed top quark and the b-tagged jet
η^{top}	Pseudorapidity of the reconstructed top quark
p_{T}^{W}	Transverse momentum of the W boson

arXiv:1509.00294v1
ATLAS, 20 fb^{-1}, 8 TeV

gqt

- photon transverse momentum,
- b-jet transverse momentum,
- muon transverse momentum,
- angular separation between the photon and the muon ($\Delta R($
- angular separation between the photon and the b-jet ($\Delta R(b$
- CSV discriminant value for the b-tagged jet,
- jet multiplicity,
- cosine of the angle between the reconstructed top quark and the photon,

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

γqt

- reconstructed top-quark mass,
- $\Delta\varphi(l_W - b)$, azimuthal angle between the lepton from the W candidate and the b-jet candidate,
- $q|\eta|$, with q and η the electric charge and the pseudorapidity of the W candidate, respectively,
- p_T of the Z boson candidate,
- η of the Z boson candidate,
- jet multiplicity,
- b-tagged jet multiplicity,
- $\Delta\varphi(Z - \not{E}_T)$, azimuthal angle between the Z candidate and the direction of the $\not{E}_T$ vector,
- CSV b-tagging discriminator,
- η of the leading jet,
- $\Delta\varphi(l_W - Z)$, azimuthal angle between the lepton from the W candidate and the Z candidate,

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

Zqt