Experimental overview of top FCNC and Anomalous couplings

Kirill Skovpen (IPHC Strasbourg)

3rd CMS Single Top workshop

Strasbourg, France

2-3 June 2016

Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

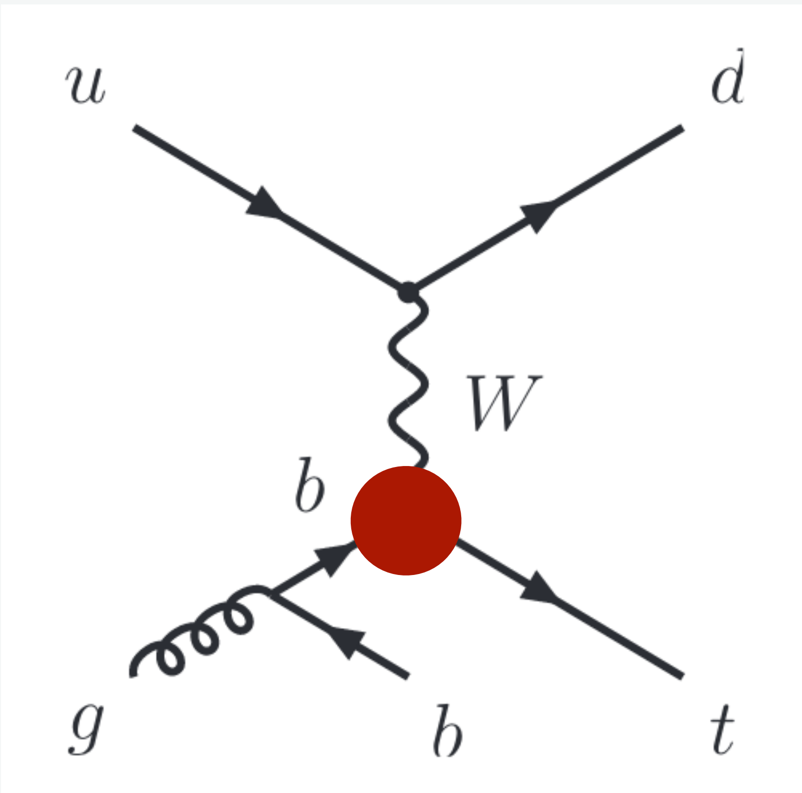
Outline

- Anomalous **Wtb** couplings
- **FCNC** interactions with top quarks

Anomalously delicious

Wtb

Anomalous Wtb couplings



- Single top production cross section is proportional to the strength of Wtb interaction
- Provides the direct measurement of $|V_{tb}|$
- Top quarks are **polarized** in single top production
- **Probe anomalous Wtb couplings: vector (V_R) and tensor (g_L, g_R)**
- **Look for differences in kinematical and angular distributions in the presence of anomalous couplings**

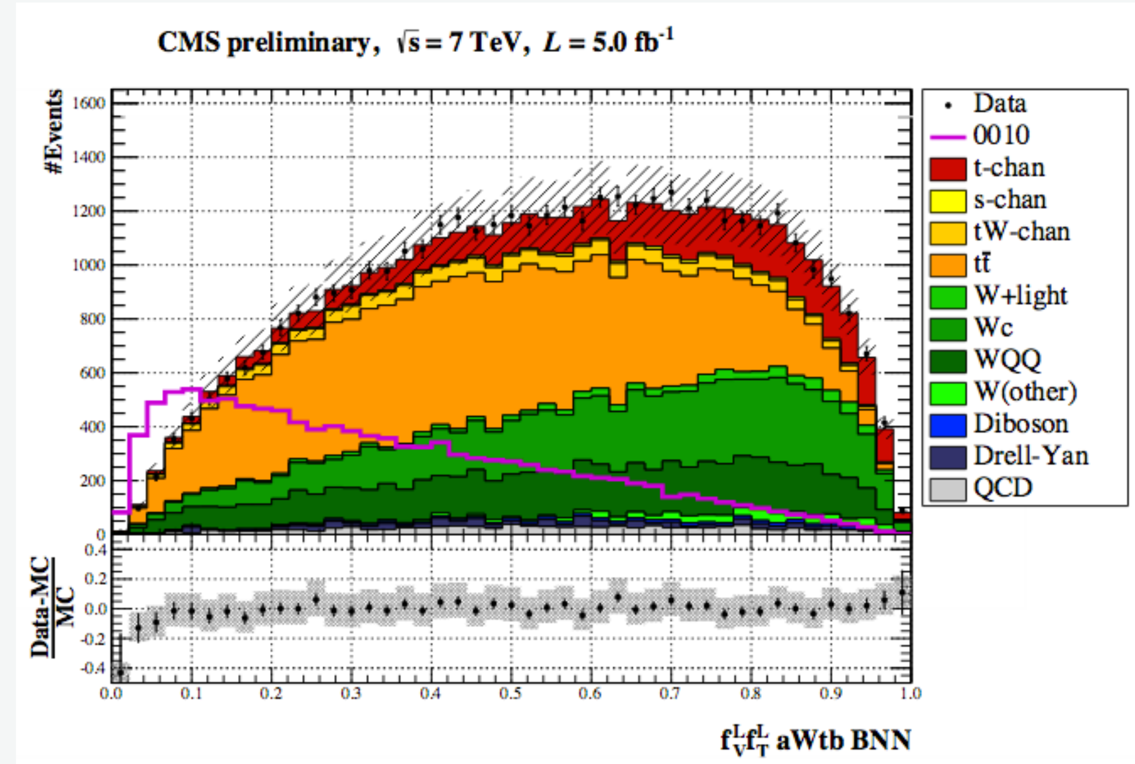
$$\mathcal{L}_{\mathrm{tWb}}^{\mathrm{anom.}} = -\frac{g}{\sqrt{2}}\bar{\mathrm{b}}\gamma^{\mu}(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}})\mathrm{t}W^{-}{}_{\mu} - \frac{g}{\sqrt{2}}\bar{\mathrm{b}}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_{\mathrm{W}}}(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}})\mathrm{t}W^{-}{}_{\mu} + \mathrm{h.c.}$$

In SM: $V_L = V_{tb} \approx 1$ with V_R, g_L and g_R ***vanishing*** at LO

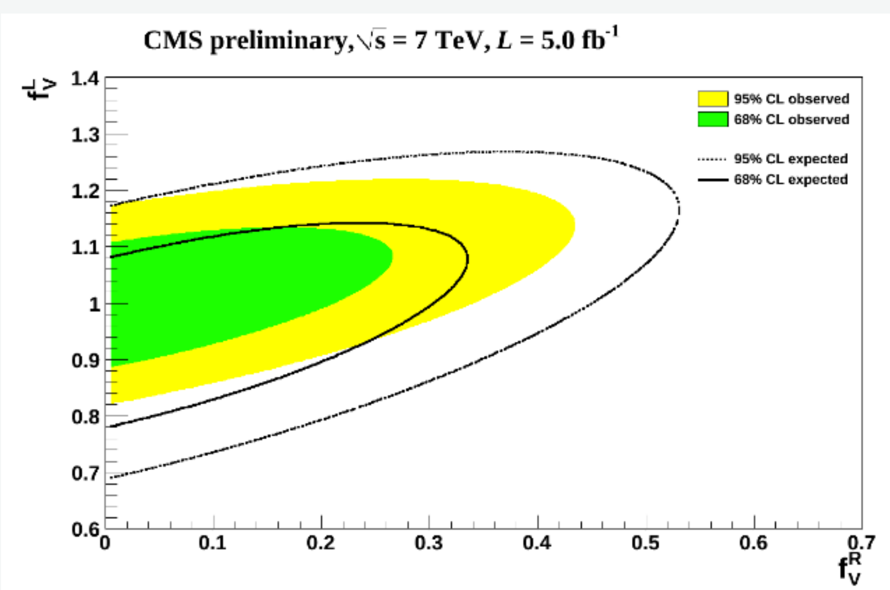
Anomalous Wtb in t-channel

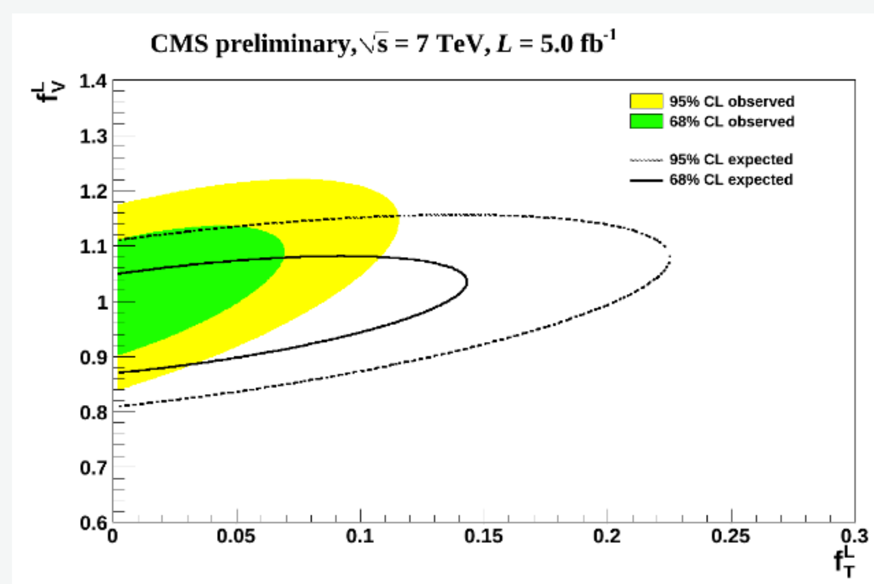
CMS-PAS-TOP-14-007
CMS, 5 fb^{-1}, 7 TeV

- Probe anomalous Wtb coupling in single top t-channel μ+jets events
- Analysis is based on BNN approach to reject QCD (QCD BNN) and to extract the signal (SM BNN)
- An additional **aWtb BNN** to extract the anomalous Wtb contribution



$$f_V^R V_{tb} \equiv V_R,\ f_T^L V_{tb} \equiv g_L,\ f_T^R V_{tb} \equiv g_R$$





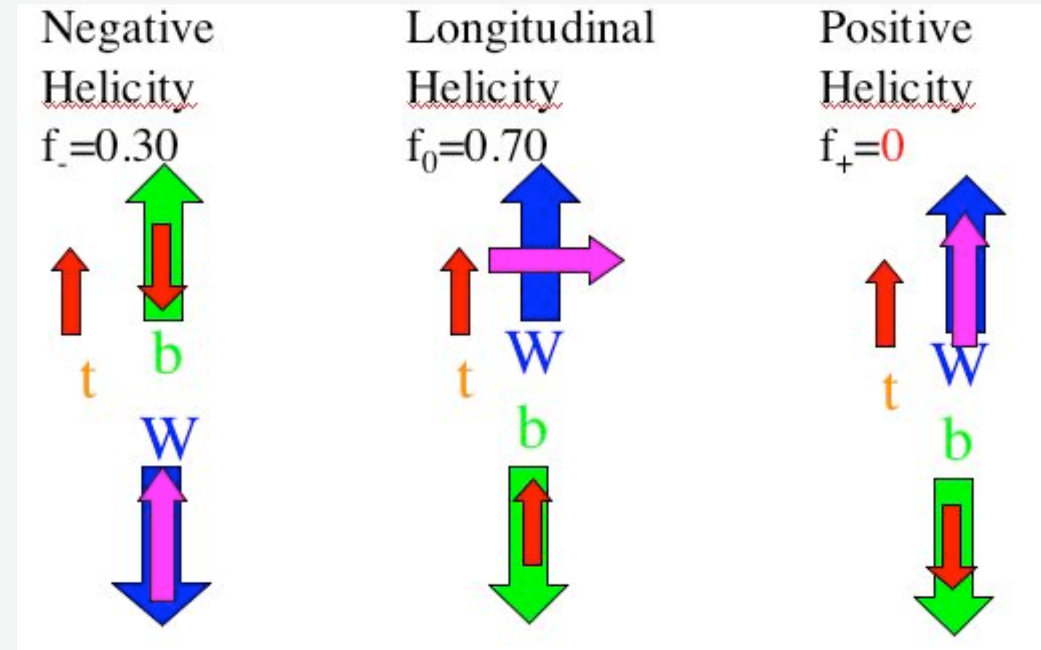
$$|f_V^L| > 0.90\ (0.88)$$
$$|f_V^R| < 0.34\ (0.39)$$

$$|f_V^L| > 0.92\ (0.88)$$
$$|f_T^L| < 0.09\ (0.16)$$

Observed (expected) @ 95% CL

W boson helicity

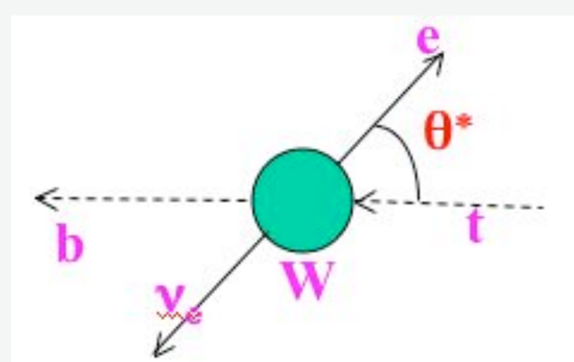
- W helicity - projection of W's spin on its momentum
- Helicity fractions: **$F_{L,R,0}$** = $\Gamma_{L,R,0}$ / $\Gamma(t \rightarrow Wb)$, $\Sigma F_i = 1$
- Helicity is sensitive to the **real part** of **Wtb anomalous couplings**

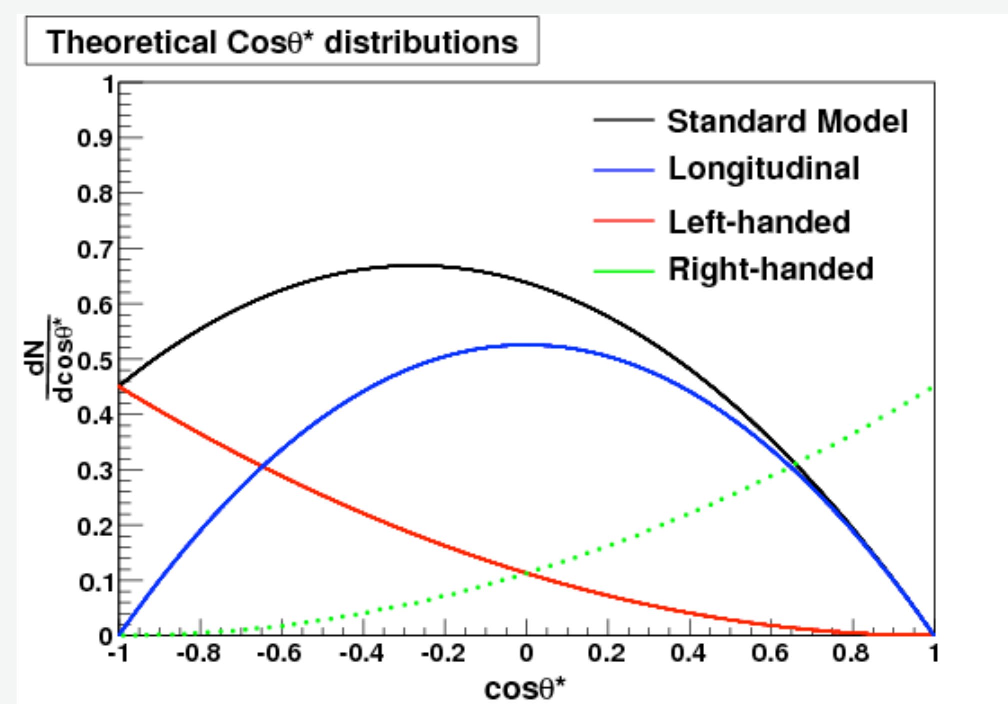


$$\rho(\cos\theta^*_\ell) \equiv \frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*_\ell} = \frac{3}{8}(1-\cos\theta^*_\ell)^2 F_L + \frac{3}{4}\sin^2\theta^*_\ell F_0 + \frac{3}{8}(1+\cos\theta^*_\ell)^2 F_R$$

@NNLO
F_0 = 0.687 ± 0.005
F_L = 0.311 ± 0.005
F_R = 0.0017 ± 0.0001

θ^* helicity angle:



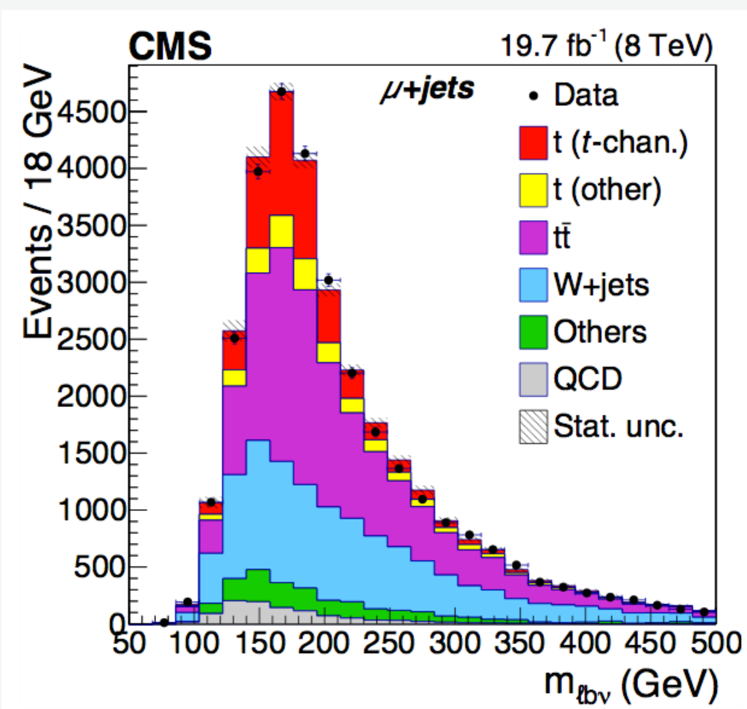


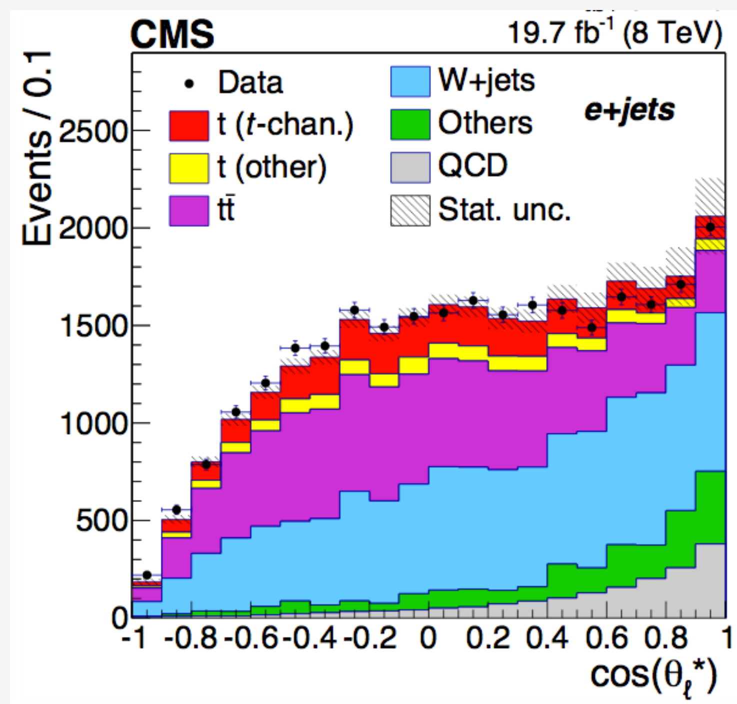
A. Czarnecki et al., Phys. Rev. D81 (2010) 111503

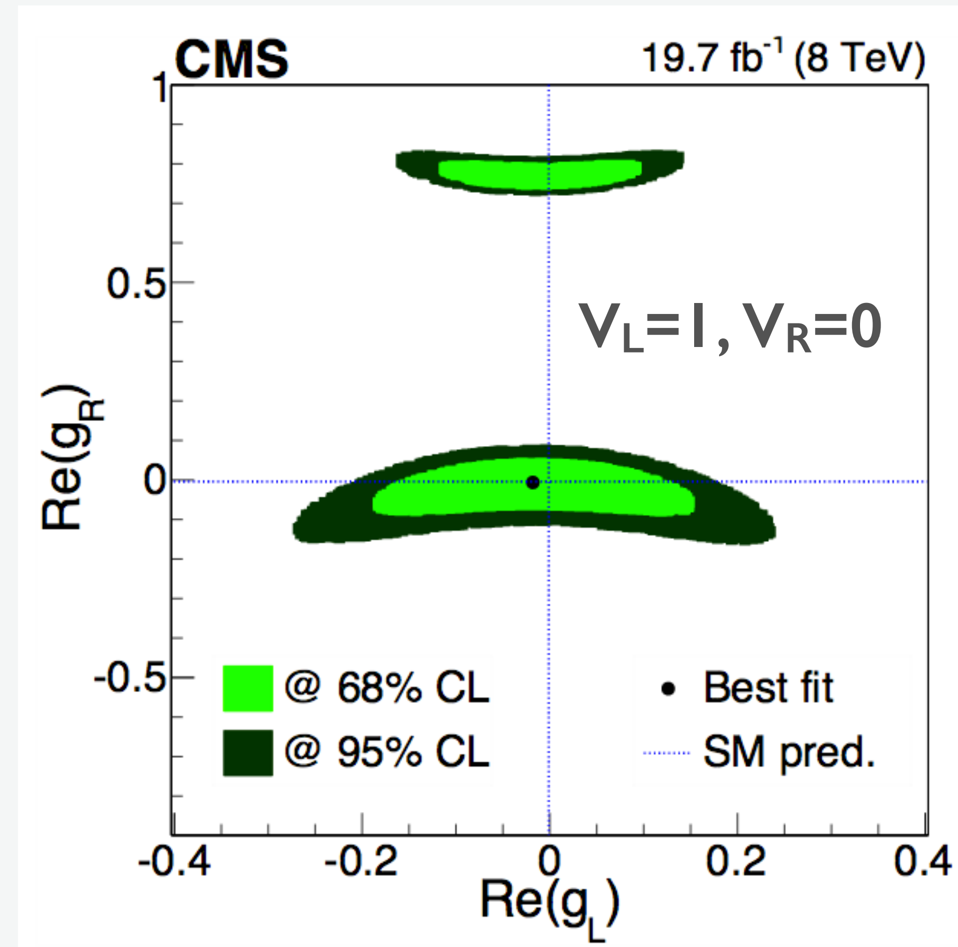
W helicity in single top event topology

JHEP 01 (2015) 053
CMS, 20 fb^{-1}, 8 TeV

- **First measurement** of W boson helicity in **single top quark event topology**
- F_0, F_L and W+jets fraction are free parameters in the fit







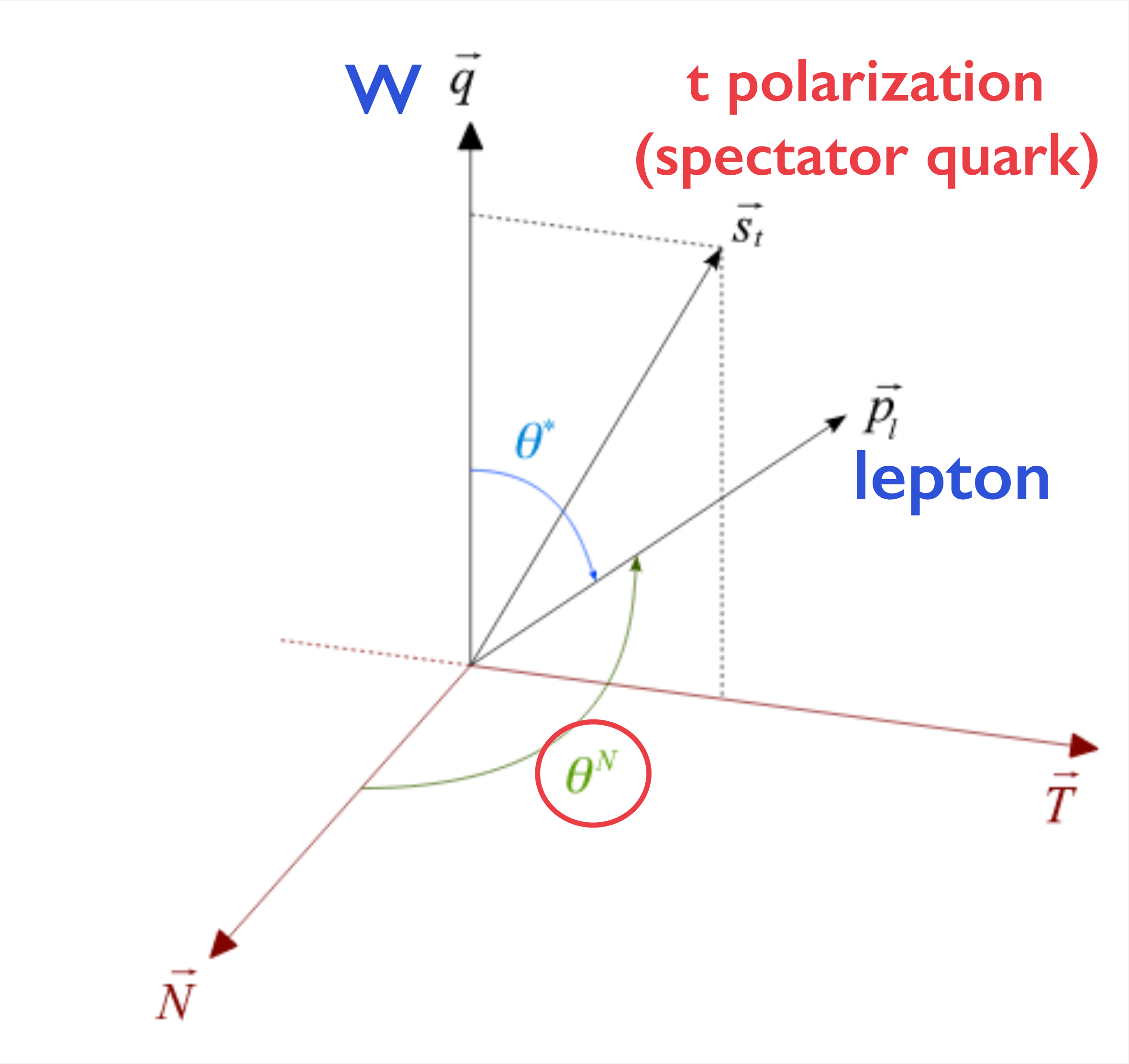
Best fit gives **Re(g_L) = -0.017**, **Re(g_R) = -0.008**

$$F_L = 0.298 \pm 0.028\,(\text{stat}) \pm 0.032\,(\text{syst}),$$
$$F_0 = 0.720 \pm 0.039\,(\text{stat}) \pm 0.037\,(\text{syst}),$$
$$F_R = -0.018 \pm 0.019\,(\text{stat}) \pm 0.011\,(\text{syst}),$$

Measured helicity fractions are consistent with SM

Forward-backward asymmetry

- Measure forward-backward asymmetry in the normal direction (A^N_{FB}) in **single top** events → **probe complex phase of g_R**
- **In ttbar**:
  - Top quarks are only slightly polarized due to EW corrections → no A_{FB} asymmetry
- **In single top**:
  - Top quark is highly polarized (P ≈ 0.9)
  - Two new reference directions: ***N*** and ***T***
- **A presence of FB asymmetry** would be a sign of **CP violation** in top quark decays



$$\vec{N} = \vec{s}_t \times \vec{q}$$
$$\vec{T} = \vec{q} \times \vec{N}$$

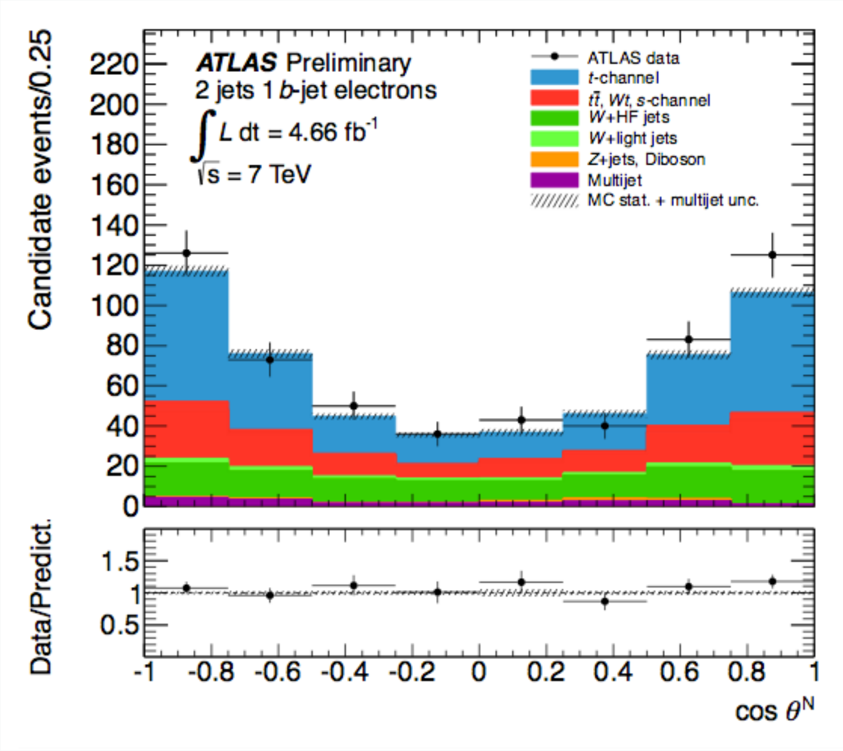
in the top quark rest frame (helicity basis)

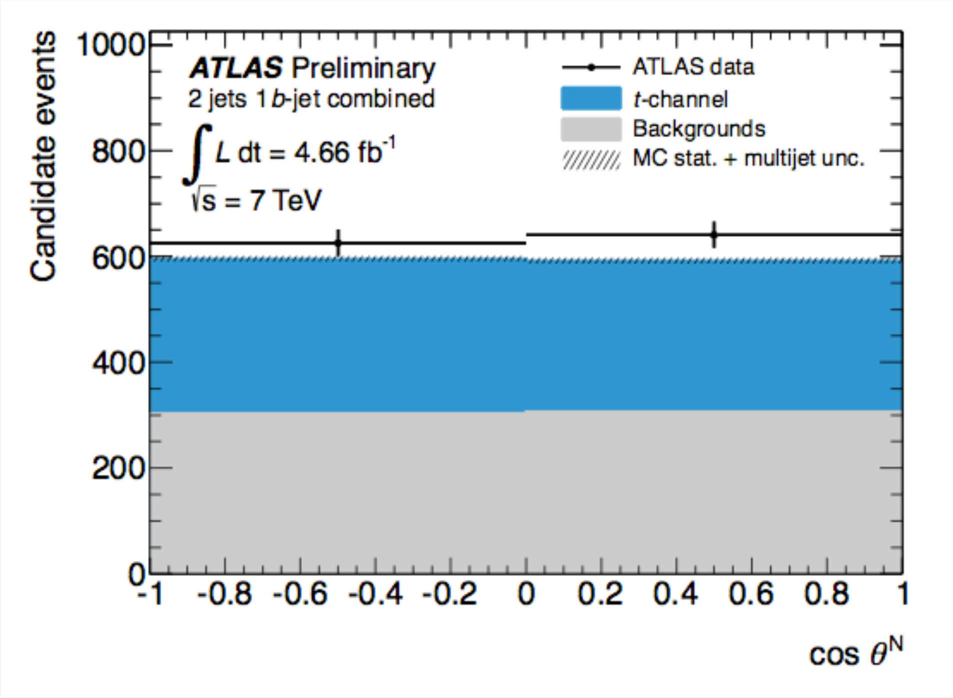
$$A^N_{FB} \equiv \frac{N_{evt}(cos\theta^N > 0) - N_{evt}(cos\theta^N < 0)}{N_{evt}(cos\theta^N > 0) + N_{evt}(cos\theta^N < 0)}$$

A_{FB} in single top

ATLAS-CONF-2013-032
ATLAS, 5 fb^{-1}, 7 TeV

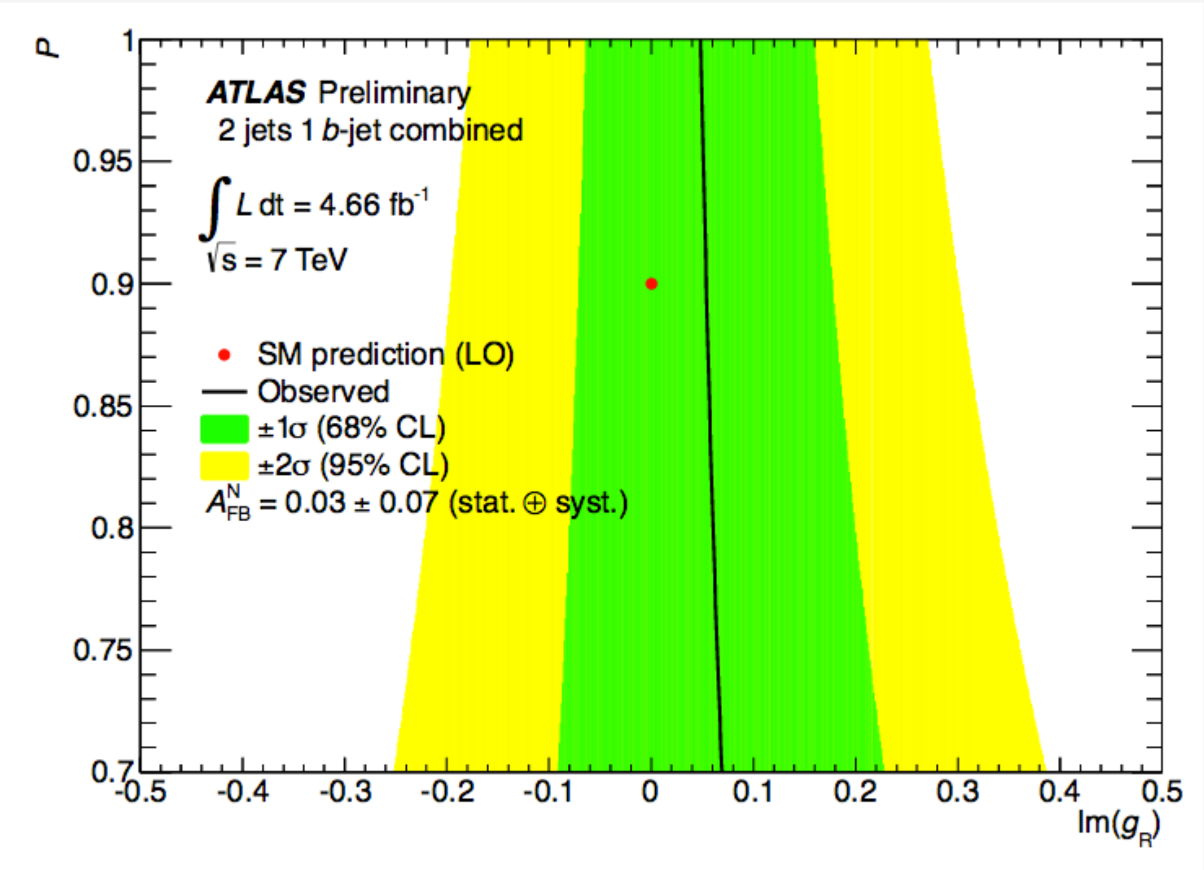
- Measure A_{FB} asymmetry in lepton+jets events
- Asymmetry extracted with unfolding the **$\cos\theta^N$** distribution
- g_R assumed to be purely **imaginary**





$$A_{FB}^{N} = 0.031 \pm 0.065\,(\text{stat.})\,^{+0.029}_{-0.031}\,(\text{syst.})$$

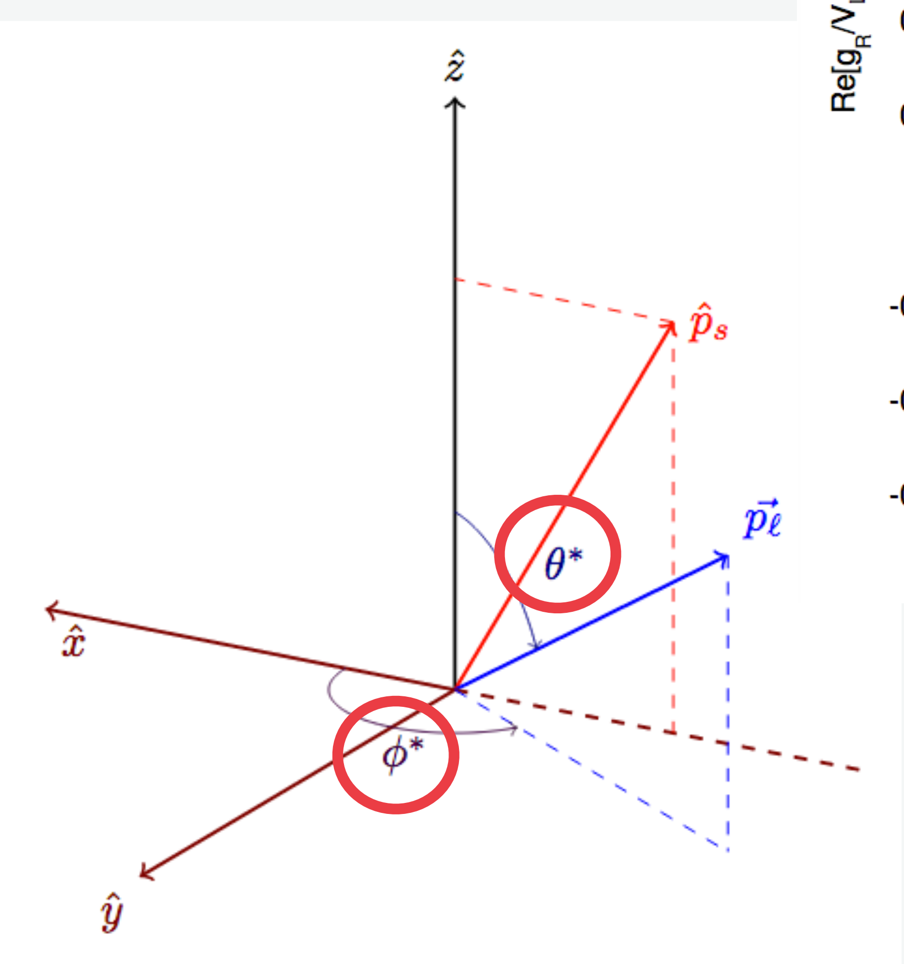
First experimental limit on Im(g_R) of [**-0.20**, **0.30**] at 95% CL



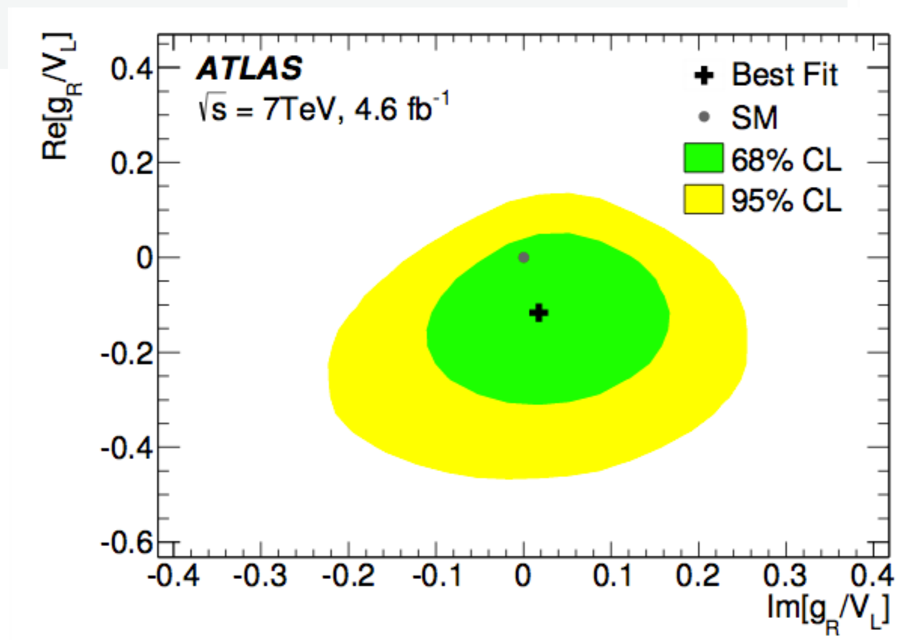
Double differential asymmetry in single top

JHEP 04 (2016) 023
ATLAS, 5 fb^{-1}, 7 TeV

- Perform a **double differential angular measurement** in θ^* and ϕ^*
- Angular distributions are expressed in the form of parametrized spherical harmonics

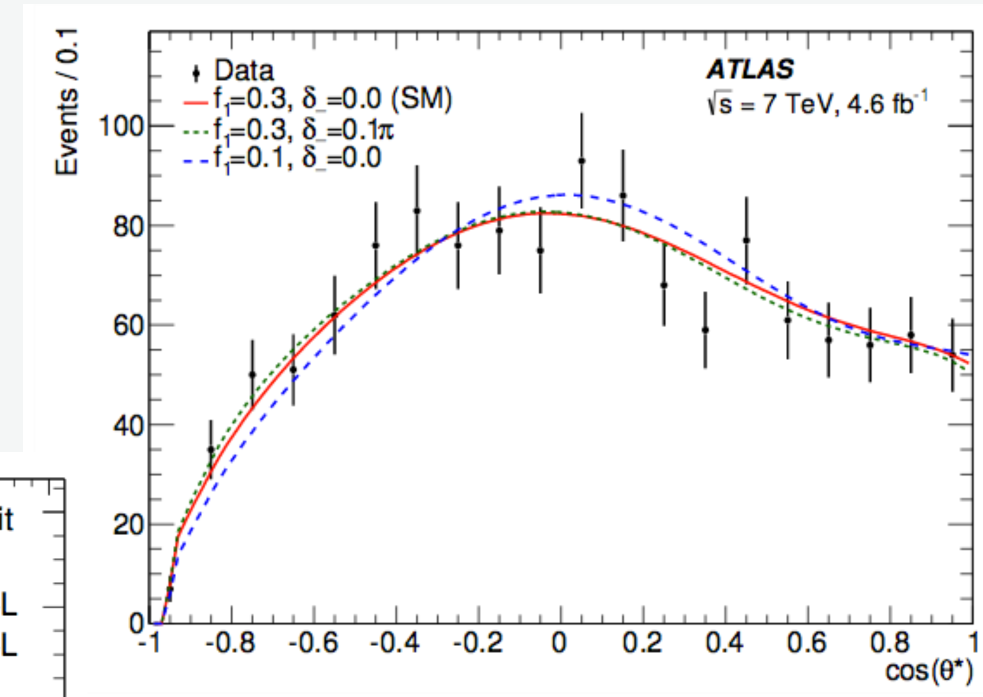


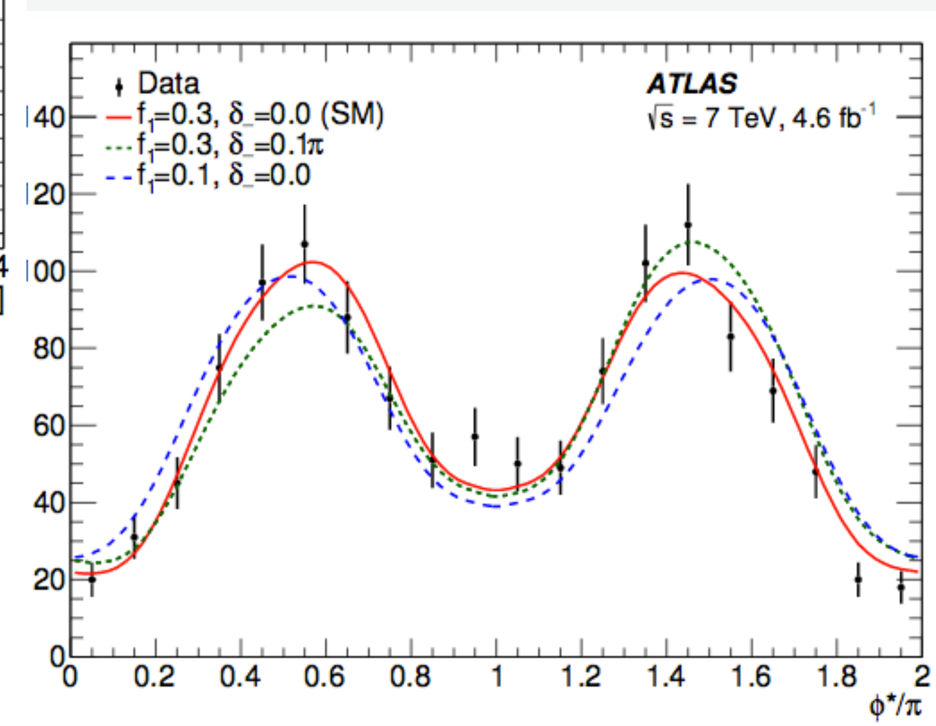
in the top quark rest frame



$$\mathrm{Re}\left[\frac{g_R}{V_L}\right] \in [-0.36, 0.10]$$

$$\mathrm{Im}\left[\frac{g_R}{V_L}\right] \in [-0.17, 0.23]$$





Global fit for Wtb anomalous couplings

- **How to combine and interpret all experimental results** related to Wtb anomalous interactions ?
- Use an **EFT approach** with dimension-6 operators to calculate the deviation from SM in a model independent way at NLO
- **Perform a global fit** of general Wtb couplings using the **constraints from experimental results**

$$f_1^L = \frac{C_{\phi q}^{(3)*} v^2}{\Lambda^2}, \qquad f_1^R = \frac{1}{2} C_{\phi\phi}^* \frac{v^2}{\Lambda^2},$$

$$f_2^L = \sqrt{2} C_{bW}^* \frac{v^2}{\Lambda^2}, \qquad f_2^R = \sqrt{2} C_{tW} \frac{v^2}{\Lambda^2}.$$

Coefficients of effective Wtb couplings are related to Wilson coefficients of dimension-6 operators

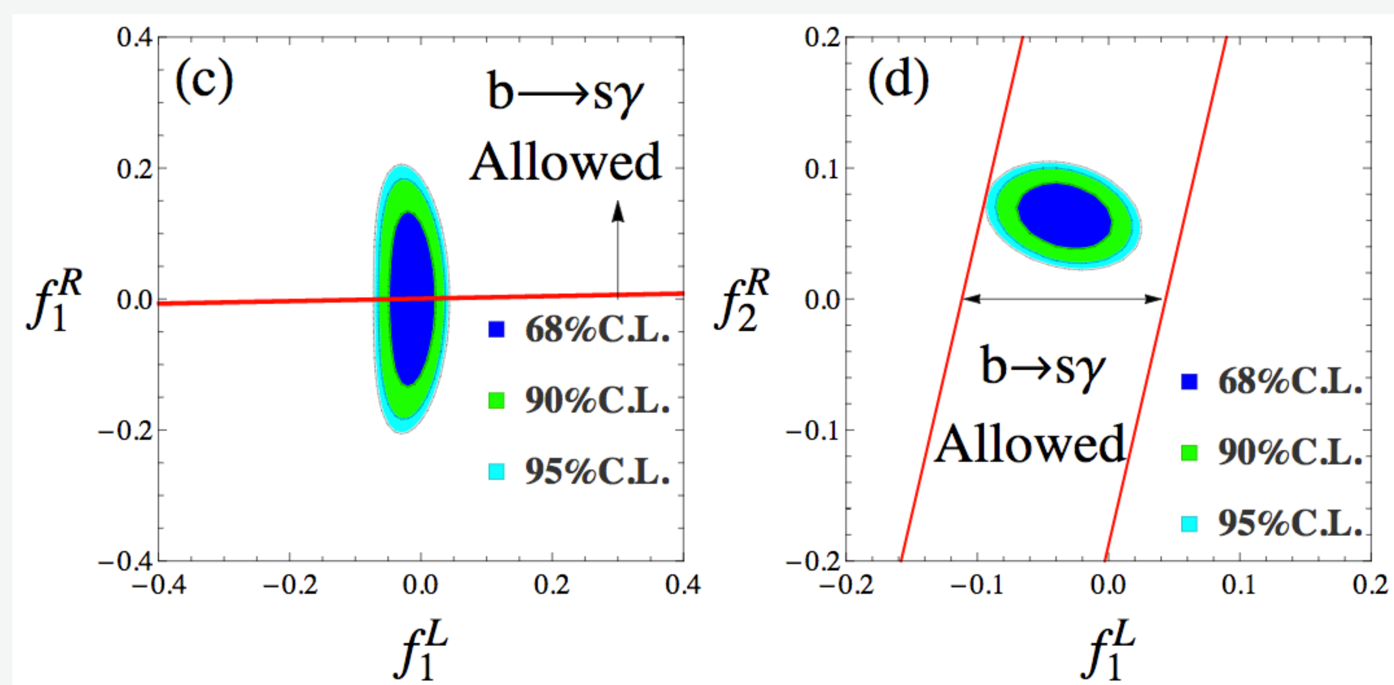
experimental result

theoretical prediction

$$\chi^2 = \sum_i \frac{\left(\mathcal{O}_i^{\rm exp} - \mathcal{O}_i^{\rm th}\right)^2}{\delta\sigma_i^2}$$

total uncertainty in experimental measurement

Q.-H. Cao et al., arXiv:1504.03785



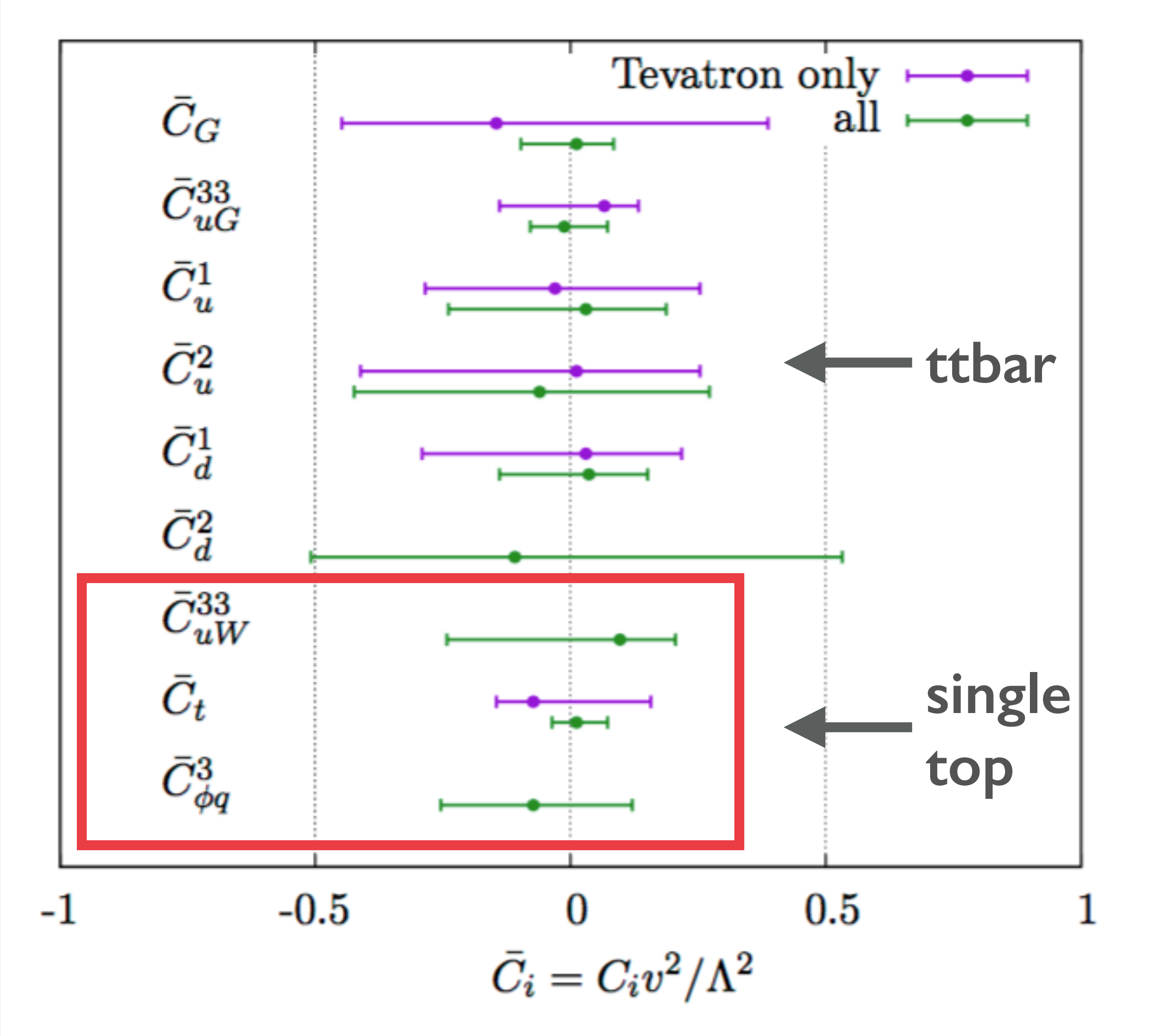
Allowed parameter space for the effective couplings

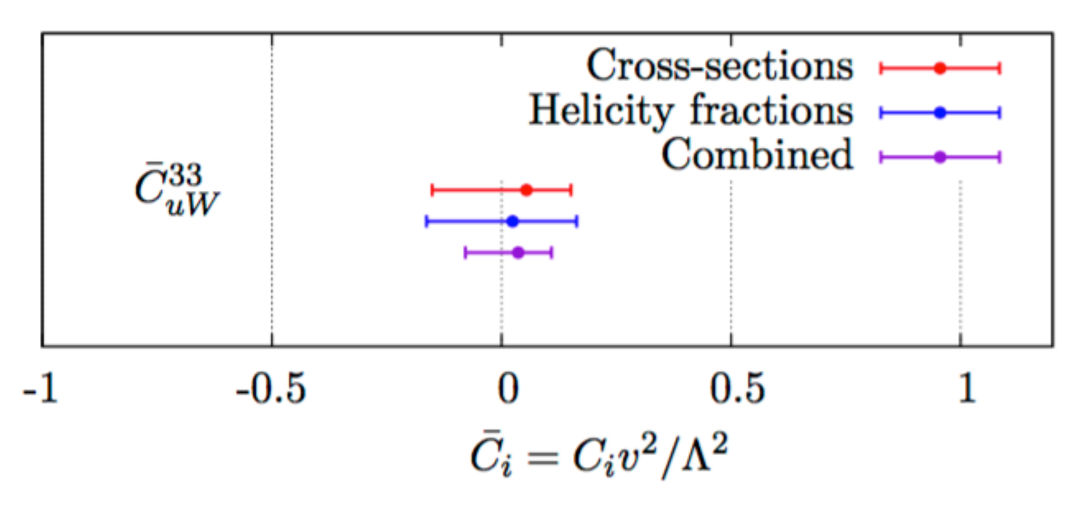
Global fit for Wtb anomalous couplings

- A global fit by TopFitter collaboration to set bounds on dimension-6 operators

$$V_L \to V_{tb} + C^{(3)}_{\varphi q} v^2/\Lambda^2$$
$$g_L \to \sqrt{2} C_{uW} v^2/\Lambda^2$$

$$V_R \to \frac{1}{2} C_{\varphi ud} v^2/\Lambda^2$$
$$g_R \to \sqrt{2} C_{dW} v^2/\Lambda^2$$





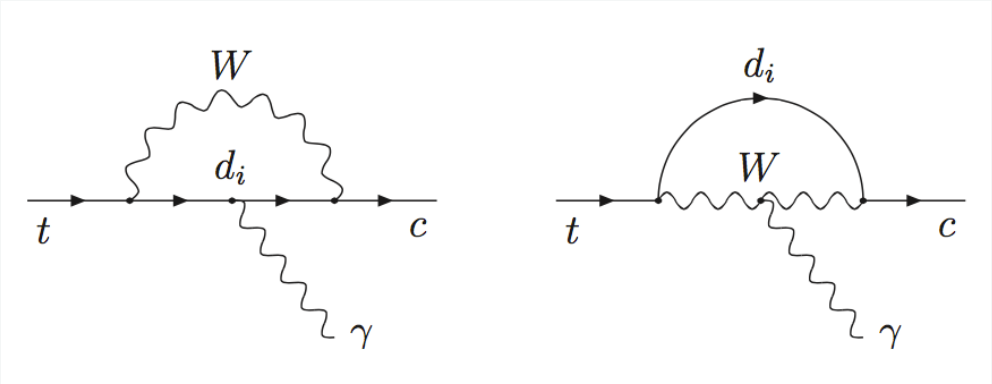
A. Buckley et al., JHEP 04 (2016) 015

FCNC

FCNC interactions

- **Flavour-changing neutral current (FCNC)** → process where a fermion changes its flavour with preserving its charge
- **FCNC amplitudes are forbidden** at tree level by the Glashow-Iliopoulos-Maiani (GIM) mechanism [*Phys. Rev. D2 (1970) 1285*] in the Standard Model (SM)
- FCNC is only possible in SM at higher orders via loops induced processes → **highly suppressed**
- FCNC decays could be enhanced in various BSM

FCNC in SM



BR(t→c**g**) ≃ 5×10^{-12}

BR(t→c**Z**) ≃ 1×10^{-14}

BR(t→c**γ**) ≃ 5×10^{-14}

BR(t→c**H**) ≃ 3×10^{-15}

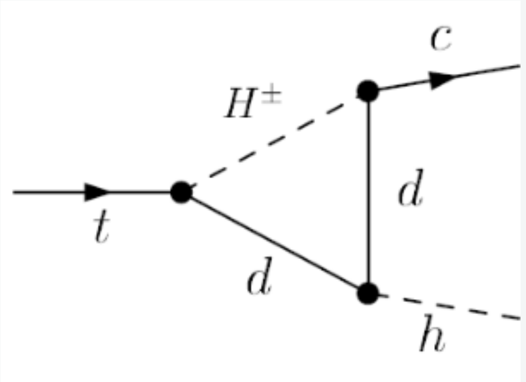
BR(t→**u**X) ≃ BR(t→**c**X) $|V_{ub}/V_{cb}|^2$ ≃ 0.008

J. A. Aguilar-Saavedra, Acta Phys. Polon. B35 (2004) 2695-2710

FCNC in BSM

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

K. Agashe et al., arXiv:1311.2028

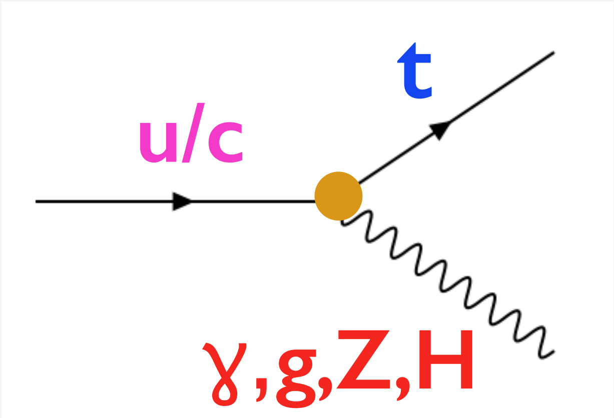


Possible 2HDM FCNC enhancement in one-loop induced process

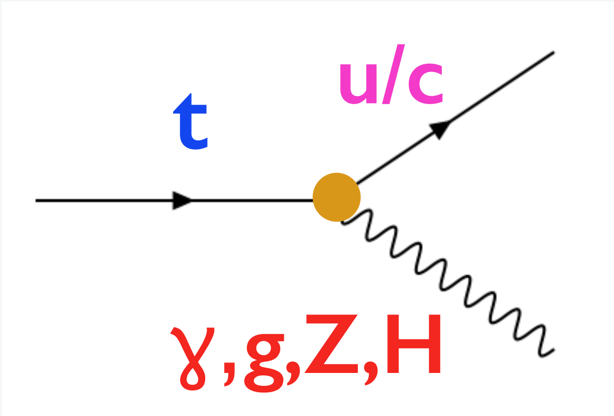
Why top quarks ?

- **Distinctive event signature** of top quark decay
- Several models predict large coupling of new particles to top quarks → enhanced sensitivity to FCNC in the top quark sector
- Search in **single top** (FCNC at production level) and **top quark pair** (FCNC in top quark decays) events - very similar final states in both production channels
- **Single top production is particularly interesting** due to enhanced FCNC production with an up-quark → differentiate between **up** and **charm** FCNC couplings
- With the charm-tagger in place it would be possible to have separate analyses of up and charm FCNC couplings in ttbar events

in single top

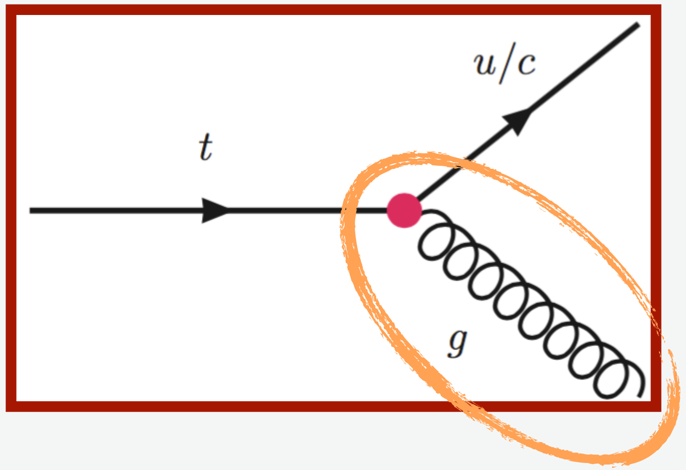


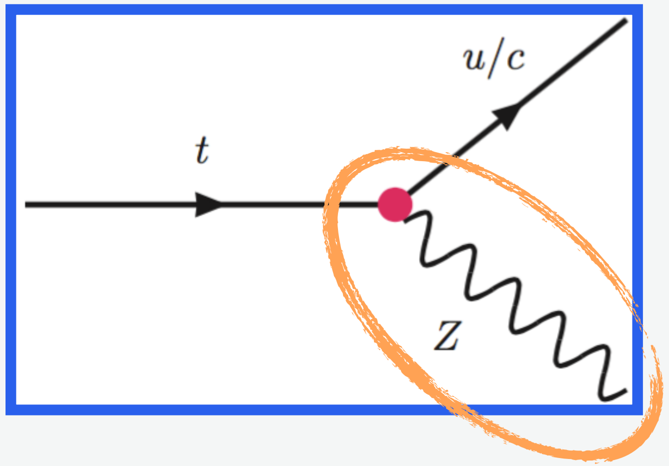
in ttbar



FCNC with top quarks

Top + gluon

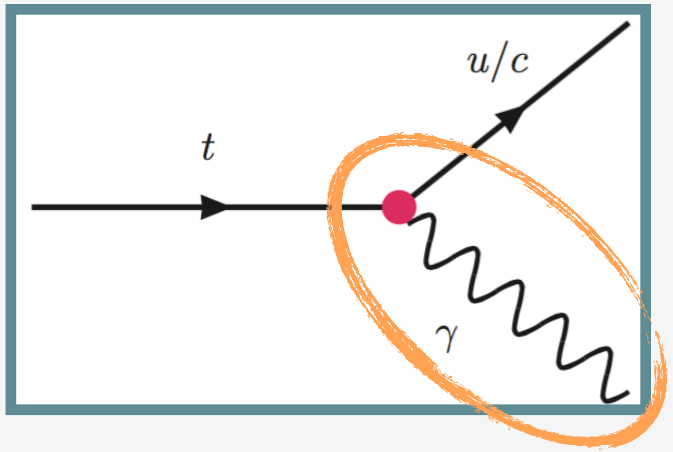


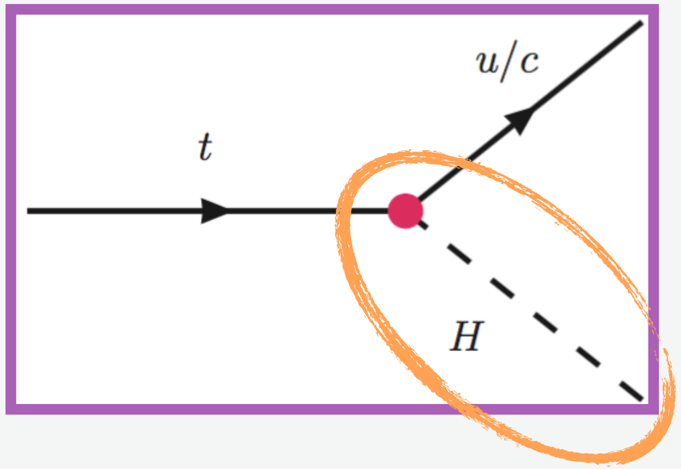


Top + Z

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

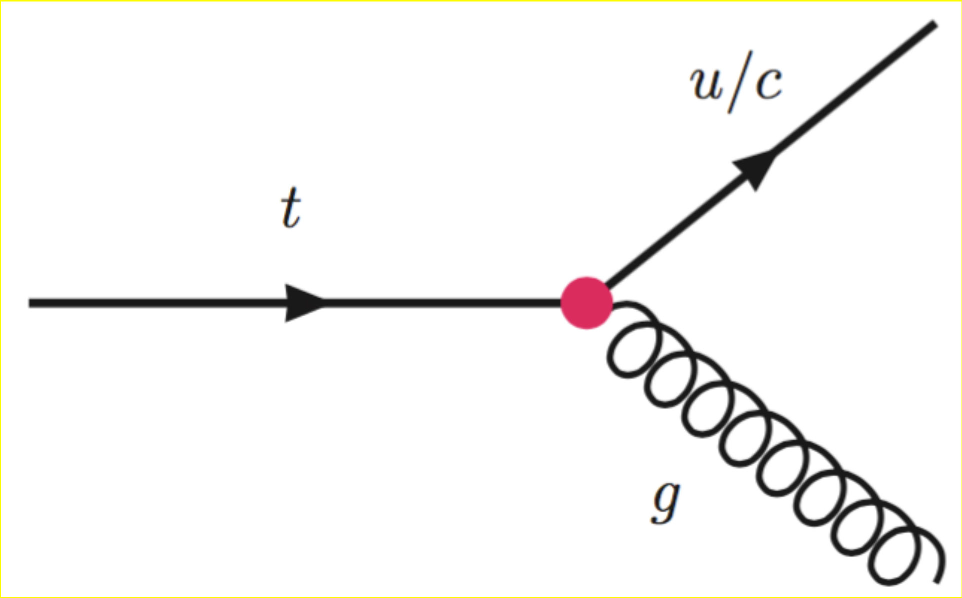
Top + gamma





Top + Higgs

Top + gluon

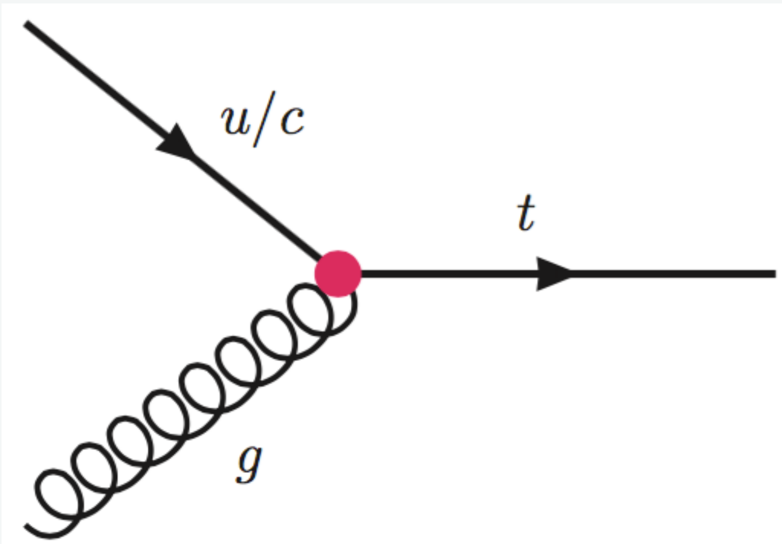


ATLAS: Eur. Phys. J. C (2016) 76:55

CMS: CMS-PAS-TOP-14-007

Search for single top

Eur. Phys. J. C (2016) 76:55
ATLAS, 20 fb^{-1}, 8 TeV

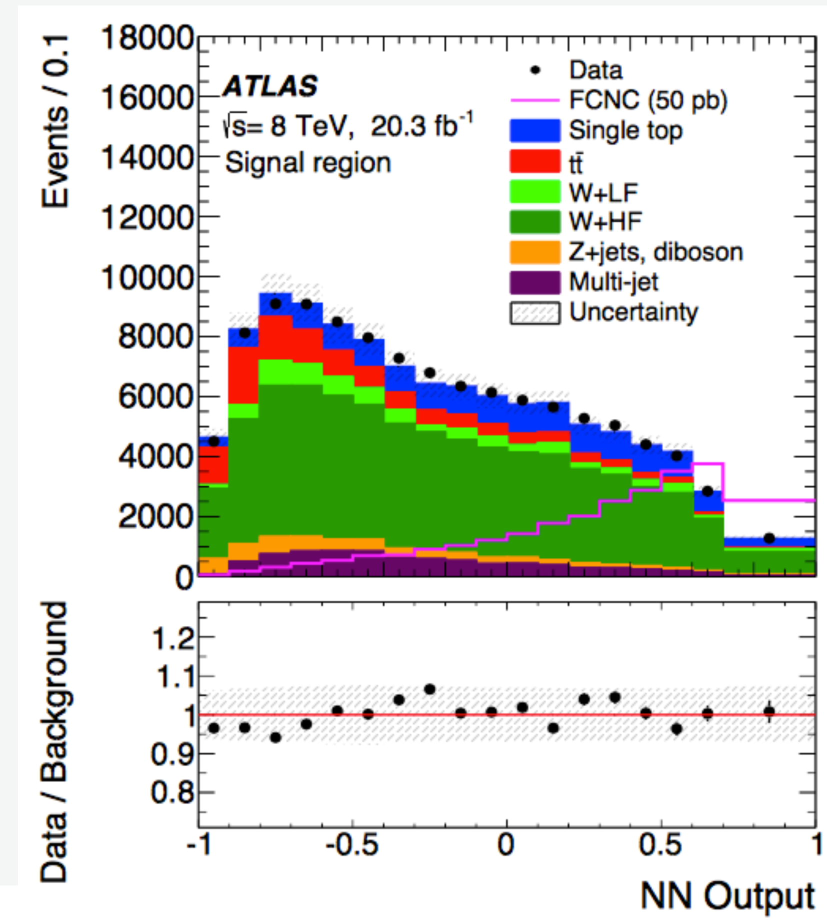


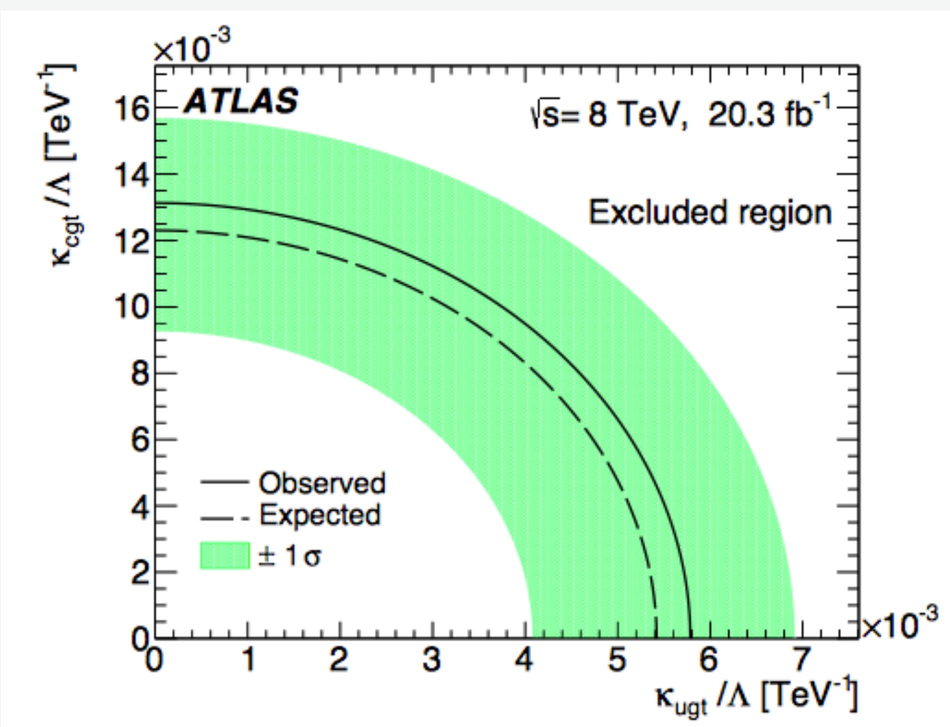
MEtop @NLO (approx.)

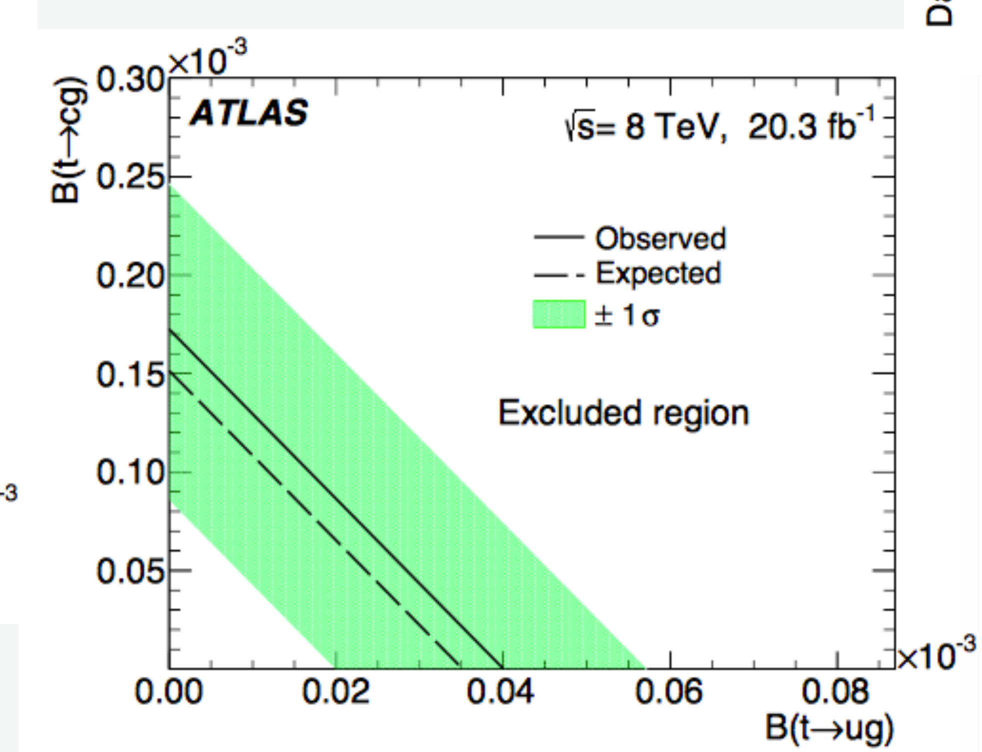
Event signature is **top quark leptonic decay**: exactly one isolated lepton, missing E_T and one b-tagged jet

Background: **W+jets**, QCD multijet, single top, ttbar, Z+jets

QCD multi-jet measured in data from missing E_T template fit







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

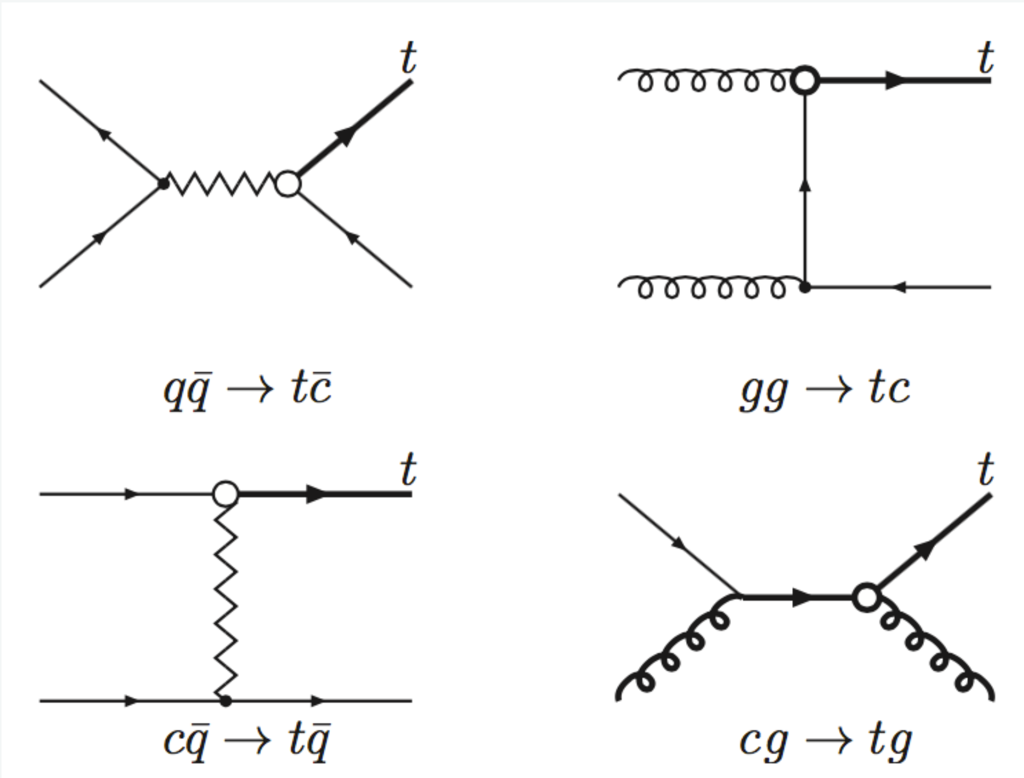
$\kappa_{cgt}/\Lambda < 1.3 \cdot 10^{-2}$ TeV^{-1}

BR(t→gu) < 0.0040 % (obs)
0.0035 % (exp)

BR(t→gc) < 0.017 % (obs)
0.015 % (exp)

Search for single top in t-channel

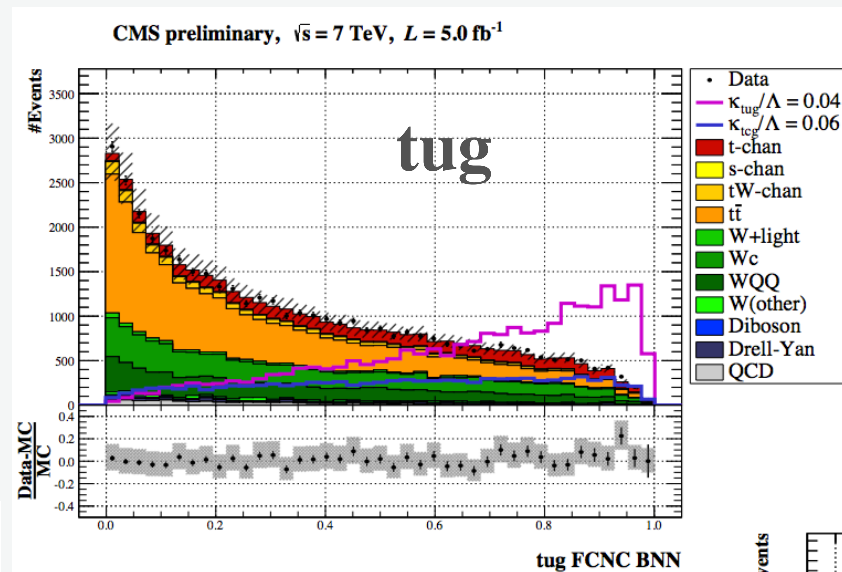
CMS-PAS-TOP-14-007
CMS, 5 fb^{-1}, 7 TeV



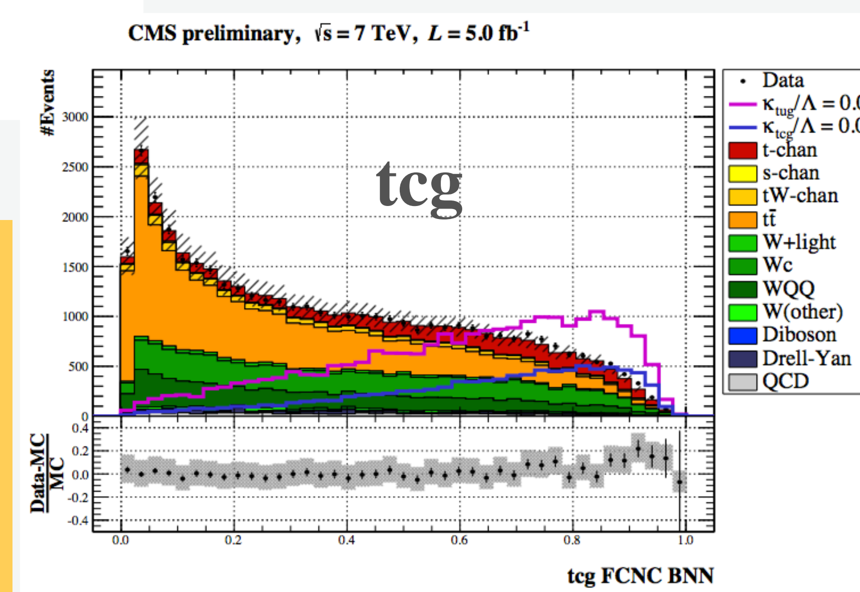
CompHEP @NLO (approx.)

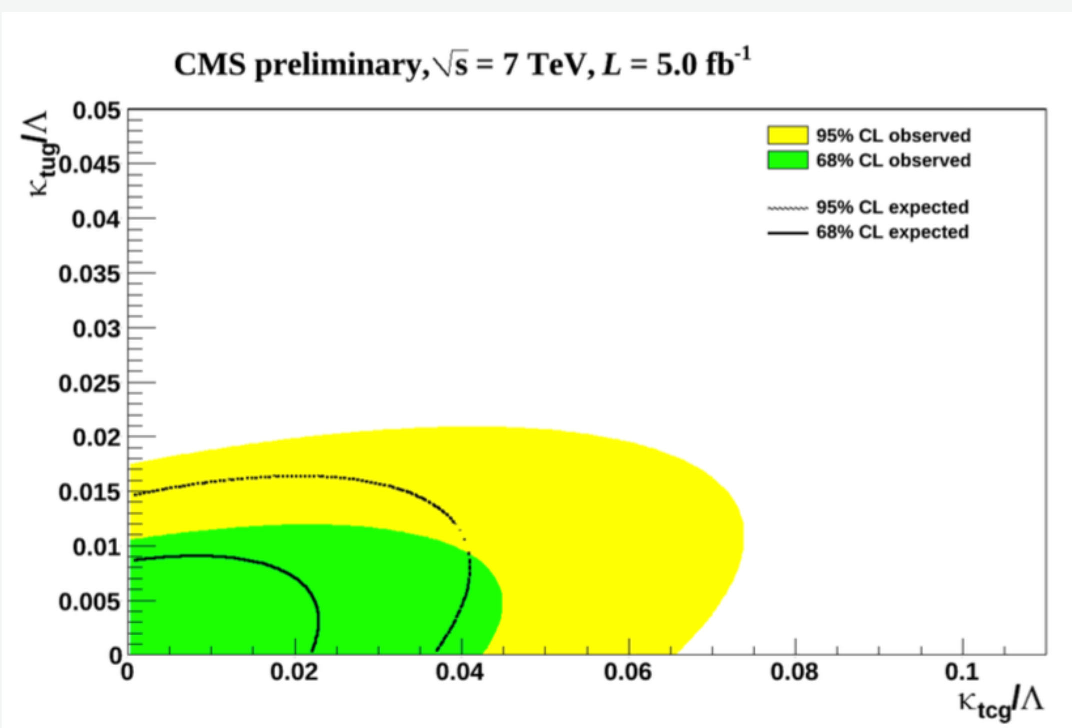
Event signature: one isolated muon, missing E_T, ≥ 1 b jet, ≥ 1 non b jet

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



QCD multi-jet is measured from data using QCD BNN template fit





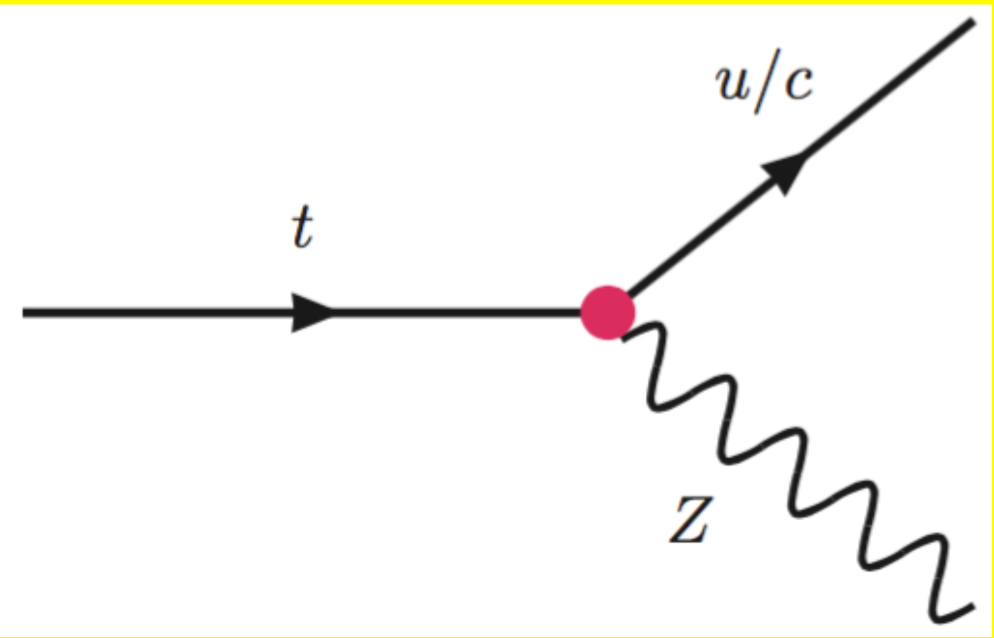
$\kappa_{ugt}/\Lambda < 1.8 \cdot 10^{-2}$ TeV^{-1}

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

BR(t→**g**u) < 0.036 % (obs)
0.016 % (exp)

BR(t→**g**c) < 0.34 % (obs)
0.11 % (exp)

Top + Z



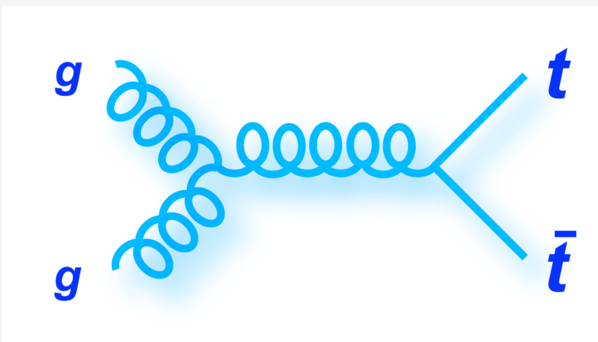
ATLAS: Eur. Phys. J. C76 (2016) 12

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

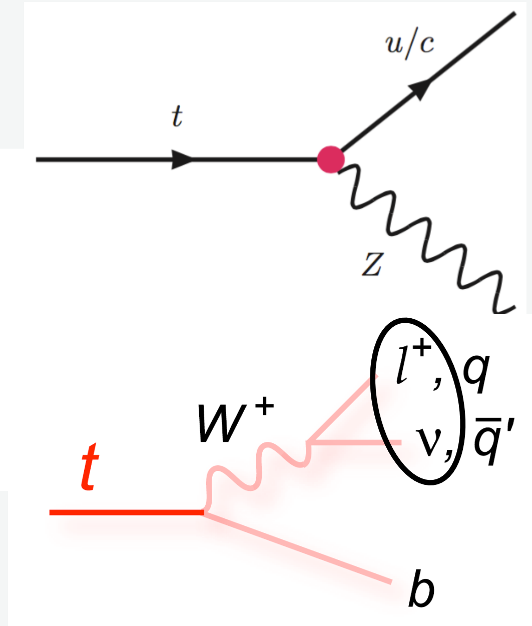
CMS: CMS-PAS-TOP-12-021

Search for t→Zq in ttbar

Eur. Phys. J. C76 (2016) 12
ATLAS, 20 fb^{-1}, 8 TeV



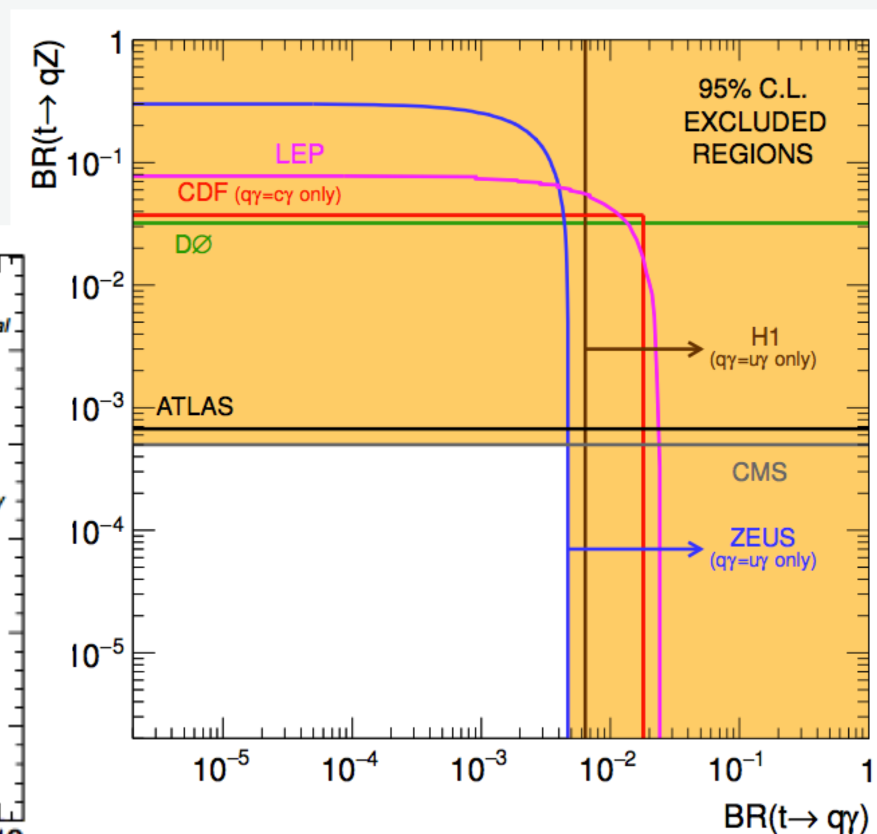
PROTOS @LO

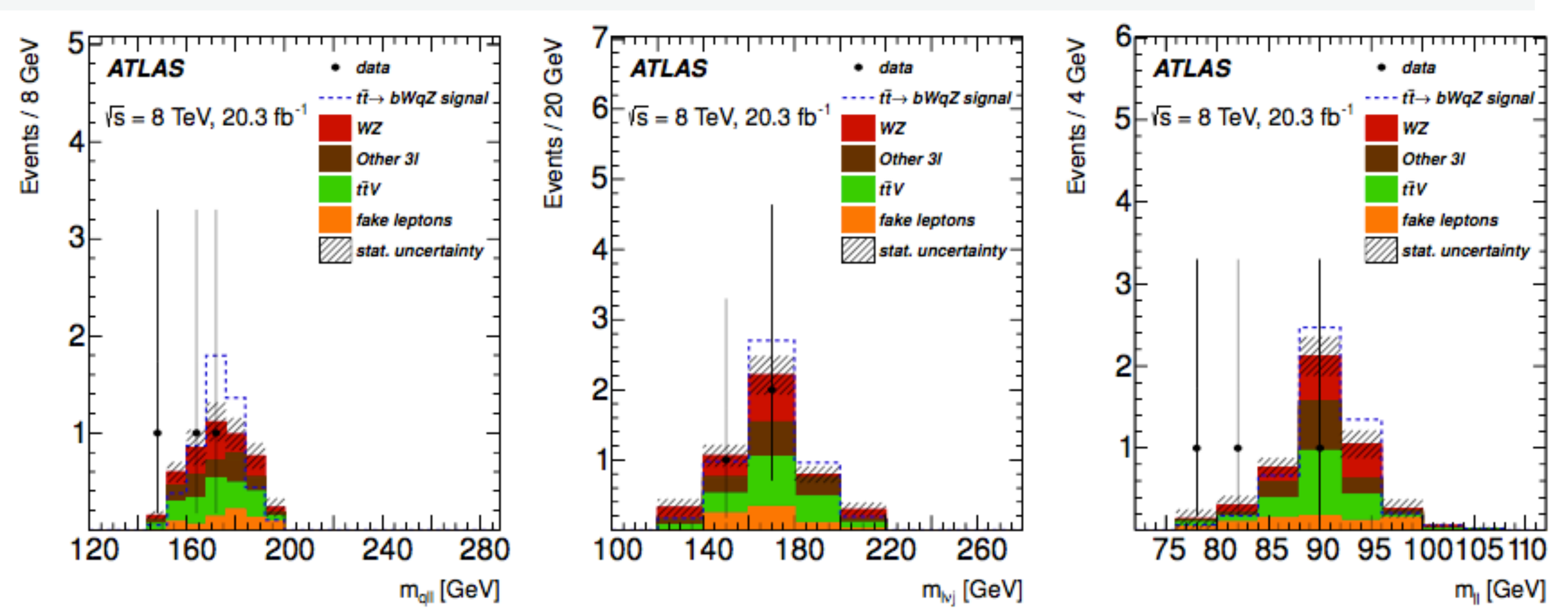


Event signature: three isolated leptons, missing E_T, ≥ 2 jets, of them one or two b jets

Background: **WZ/ZZ +jets**, fake leptons, Z +jets

Fake leptons measured from data with fake matrix method



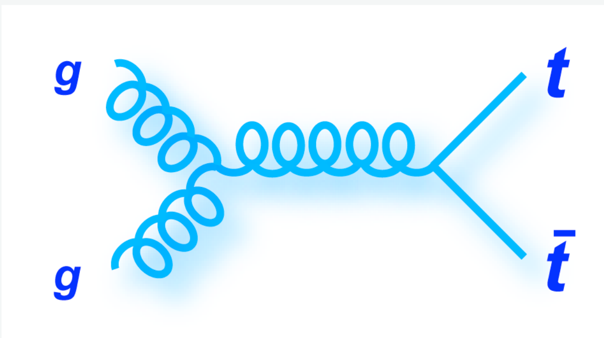


m(qll) **m(lvj)** **m(ll)**

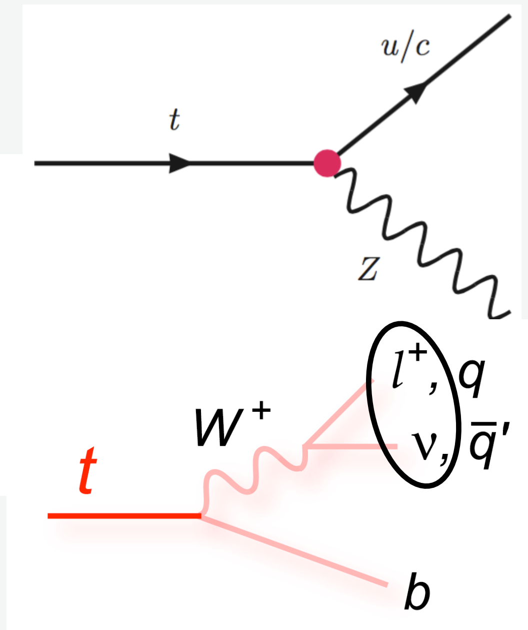
BR(t→Zq) < 0.07 % (obs)
0.08 % (exp)

Search for t→Zq in ttbar

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



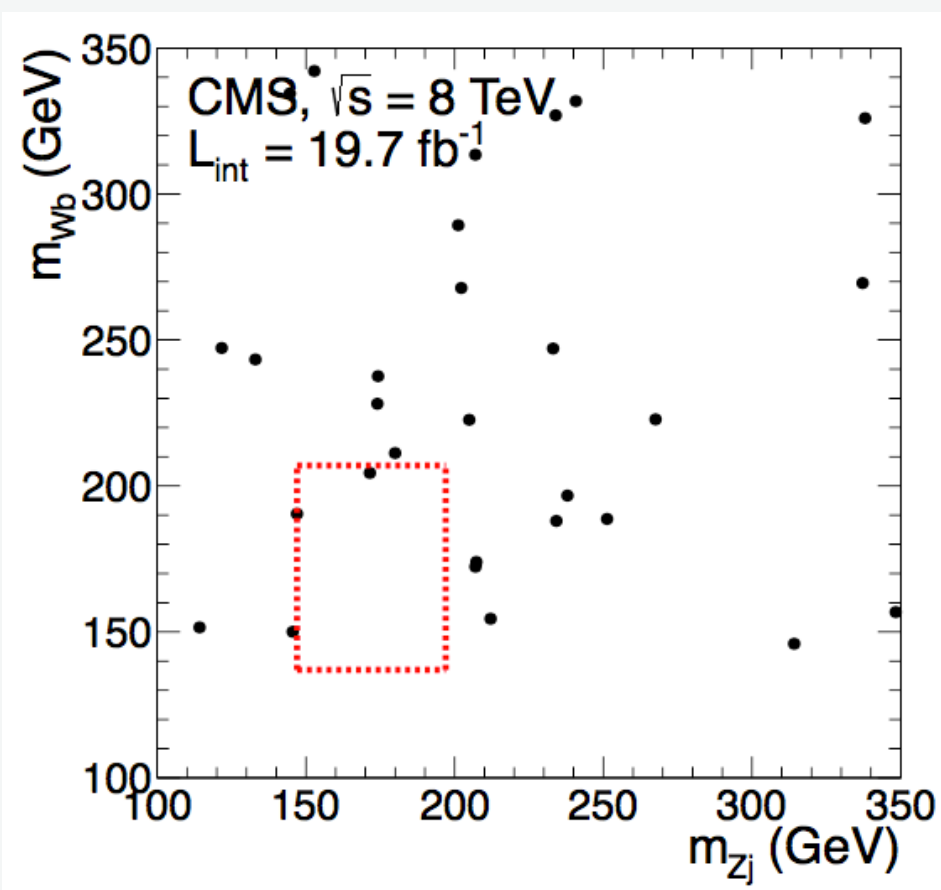
MadGraph @LO

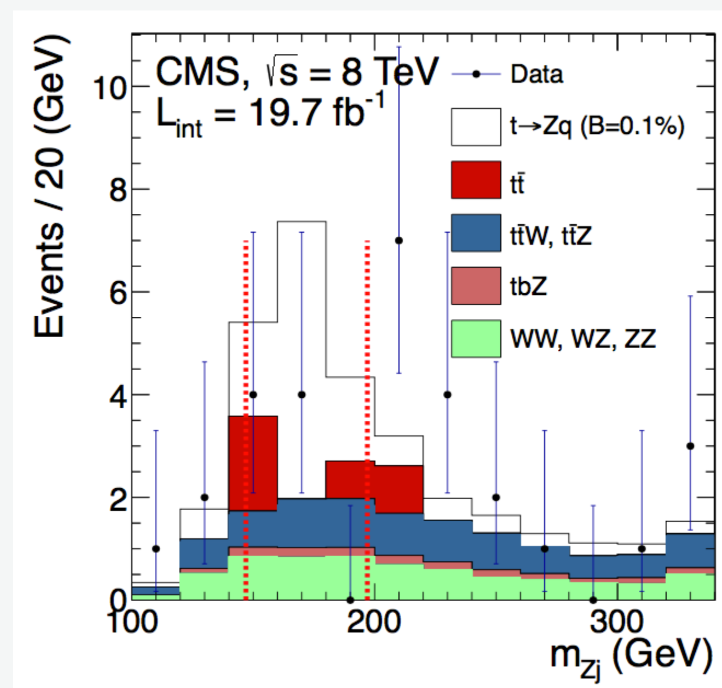


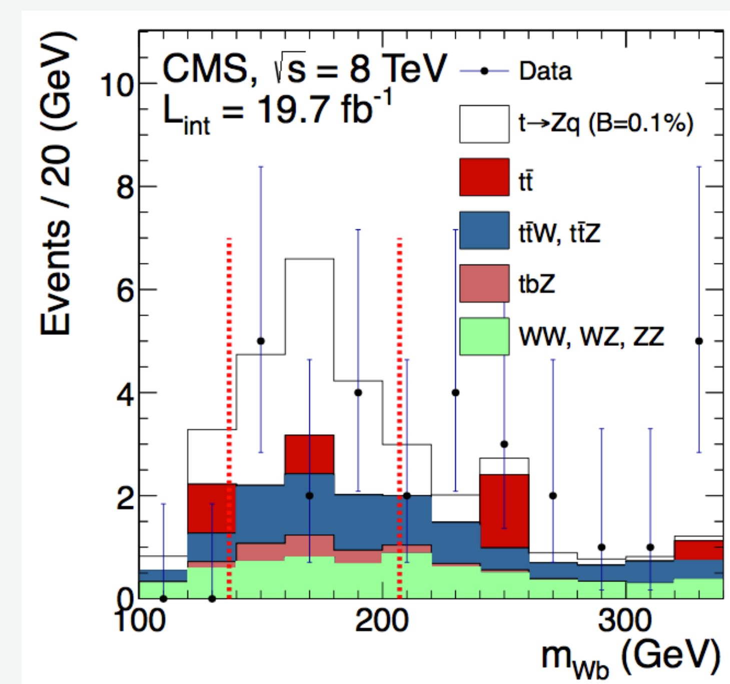
Event signature: three isolated leptons, missing E_T, ≥ 2 jets of which one is b jet

Background: **WW/WZ/ZZ+jets, ttbar+X**

Background estimated from data





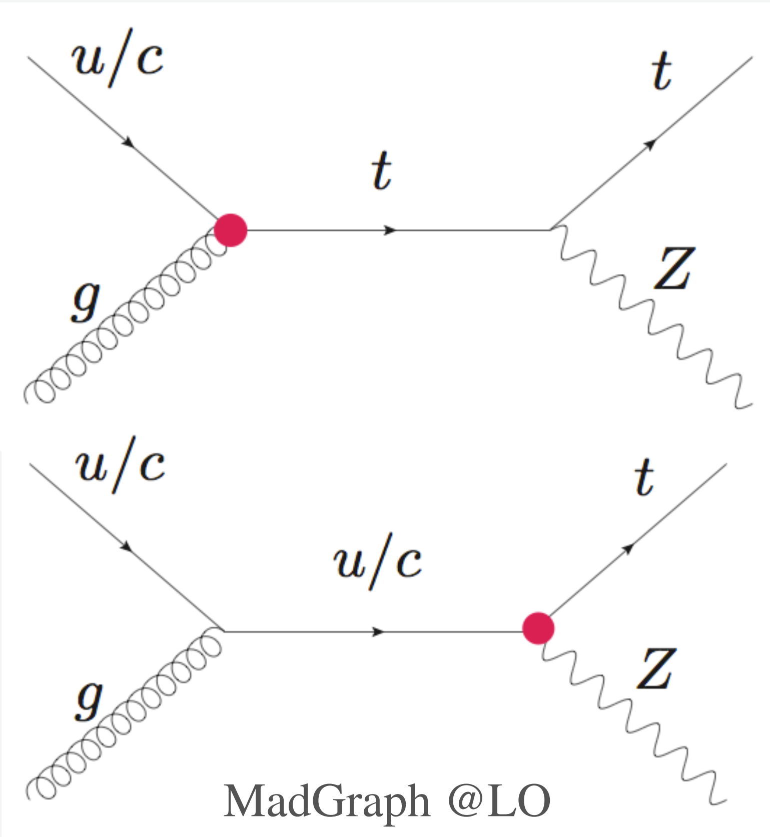


$\mathcal{B}(t \to Zq)$	8 TeV	7 TeV + 8 TeV
Expected upper limit	<0.10%	<0.09%
Observed upper limit	<0.06%	<0.05%
1 σ boundary	0.06–0.13%	0.06–0.13%
2 σ boundary	0.05–0.20%	0.05–0.18%

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

Search for tZ in single top

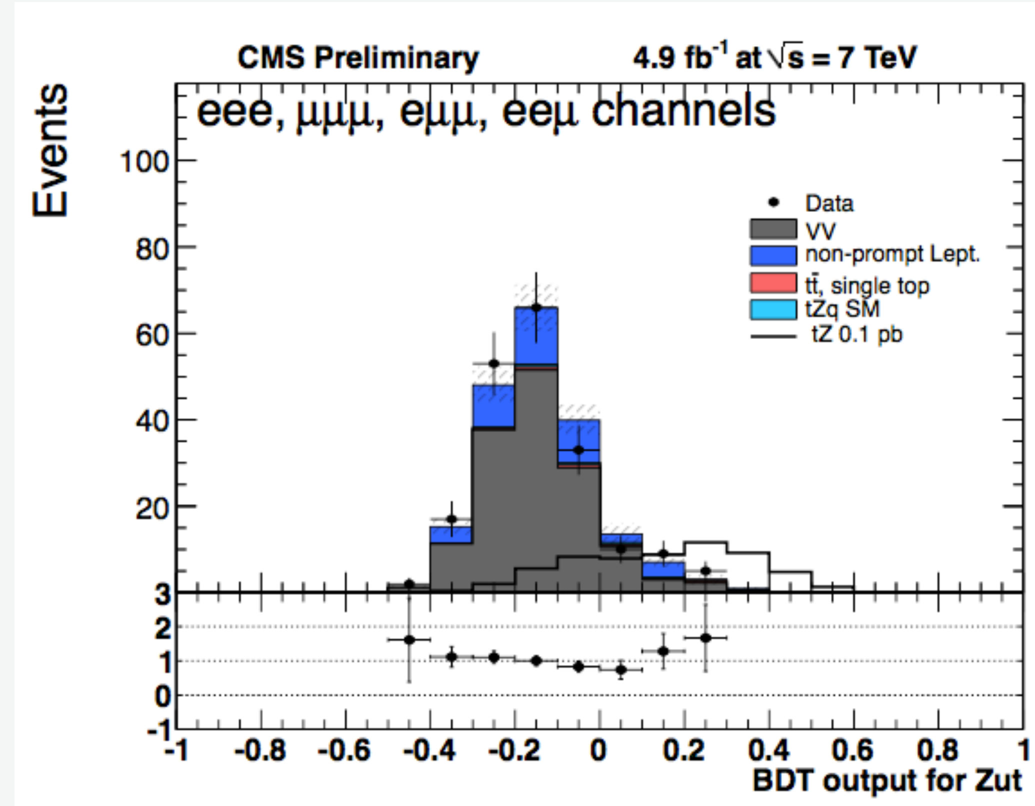
CMS-PAS-TOP-12-021
CMS, 5 fb^{-1}, 7 TeV

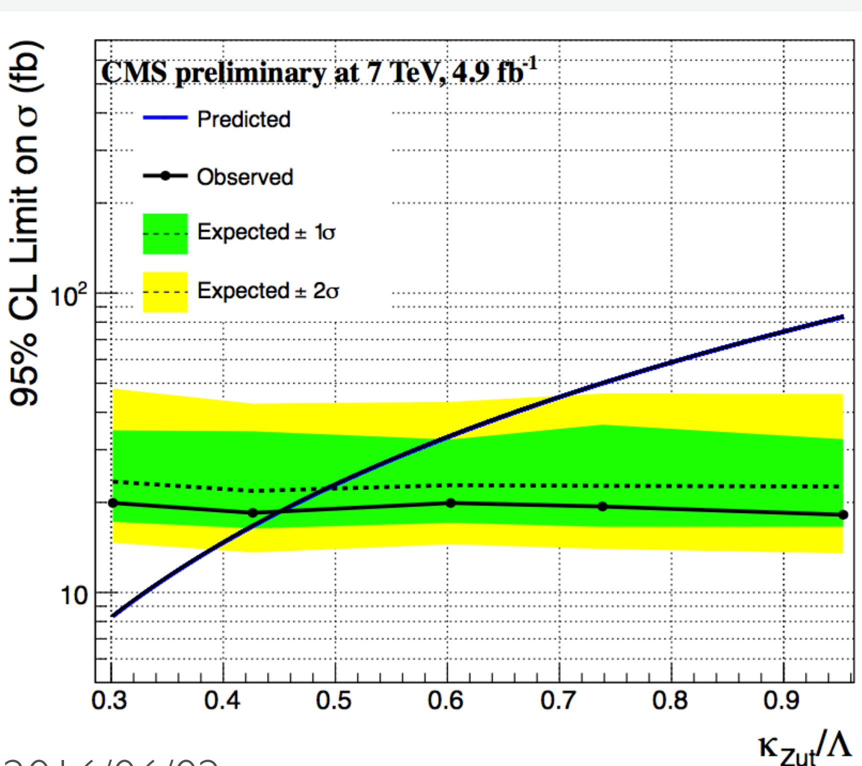


Event signature: three isolated leptons, missing E_T, one b jet

Background: **WZ/ZZ +jets**, fake leptons

VV and fake lepton background measured from data using $m_T(W)$ template fit



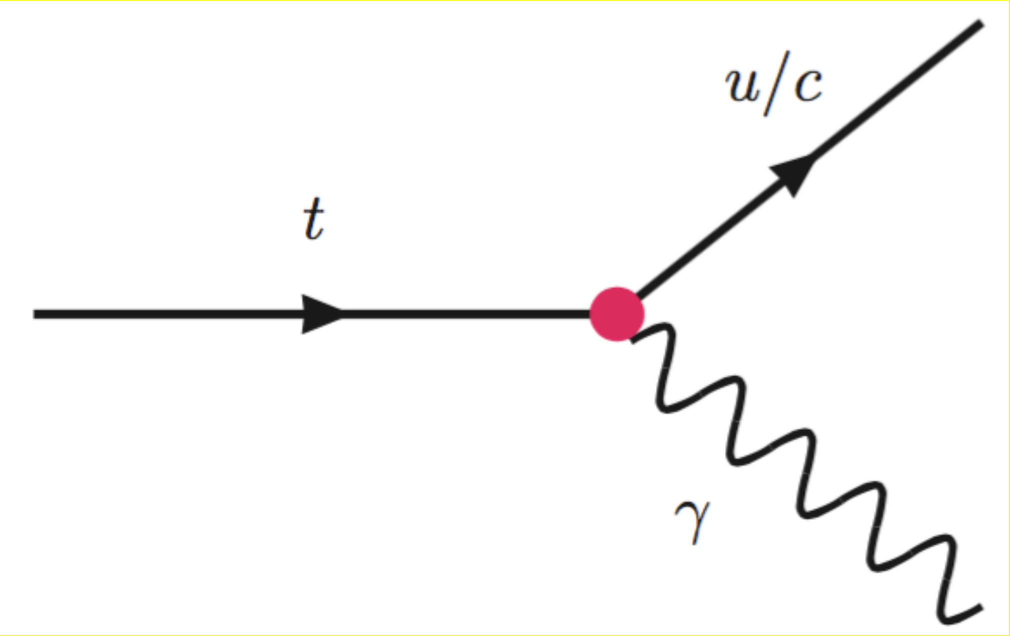


BR(t→**Z**u) < 0.51 % (obs)
0.61 % (exp)
BR(t→**Z**c) < 0.11 % (obs)
0.16% (exp)

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

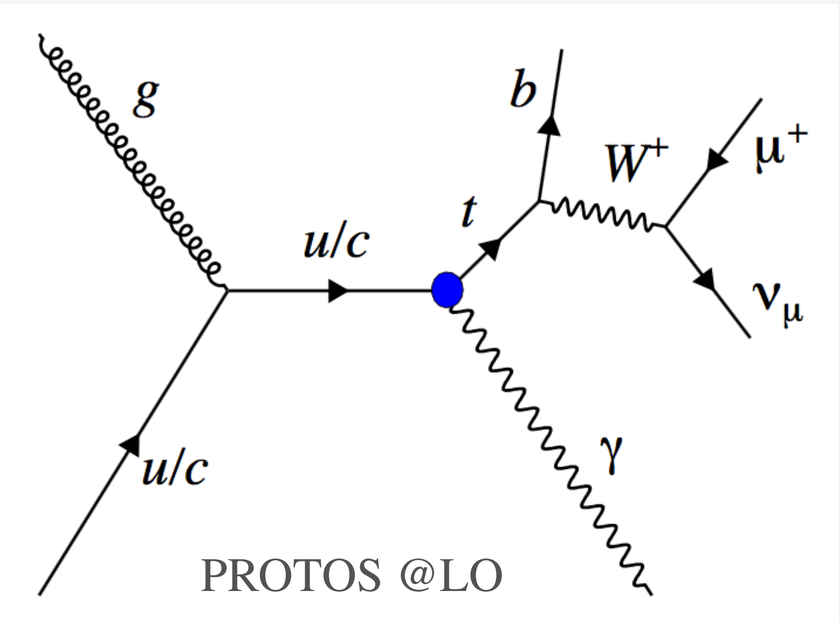
Top + gamma



CMS: JHEP 04 (2016) 035

Search for tgamma in single top

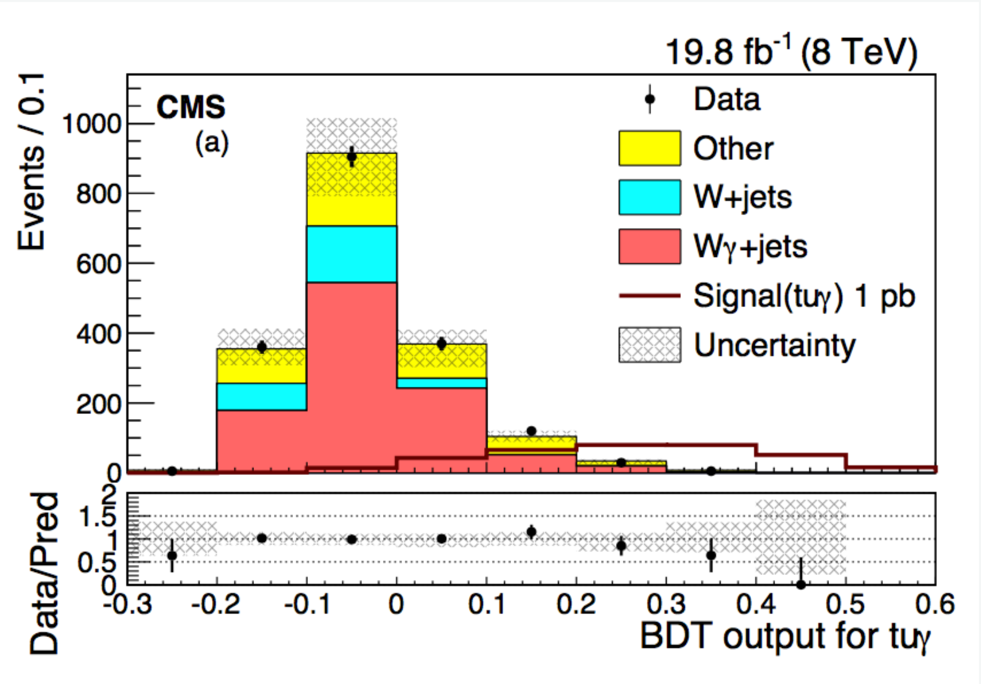
JHEP 04 (2016) 035
CMS, 20 fb^{-1}, 8 TeV

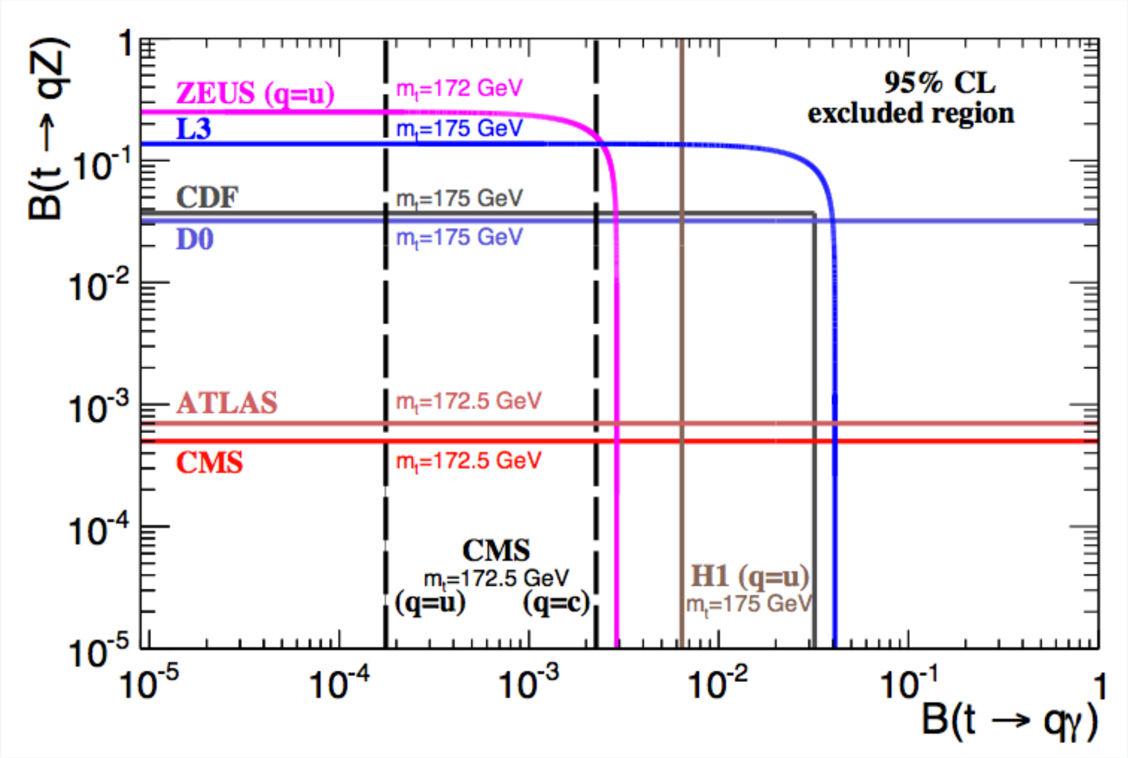


Event signature: one isolated muon, one photon, missing E_T, one b jet

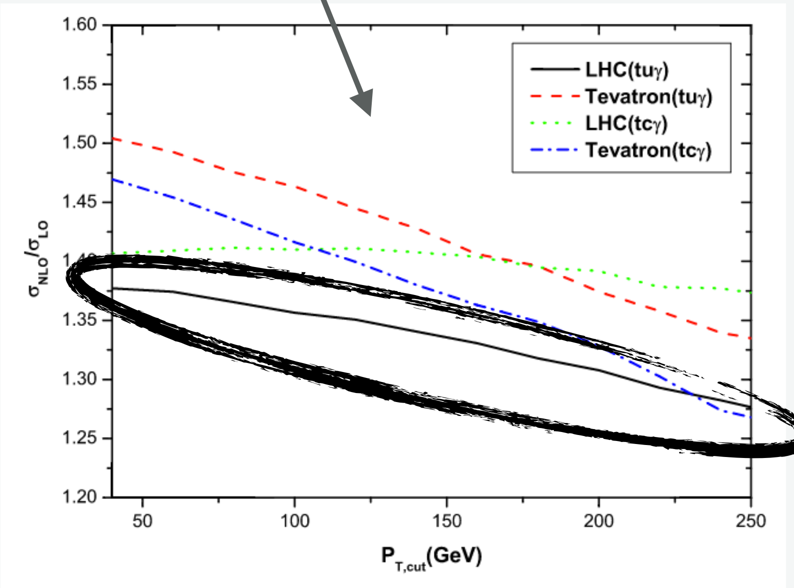
Background: **Wɣ+jets**, W+jets, ttbar, Zɣ+jets

Wɣ+jets and W+jets measured from data using cos(W,ɣ) template fit





FCNC NLO corrections are sizable (k≈1.375 @ 50GeV)



Limits @NLO

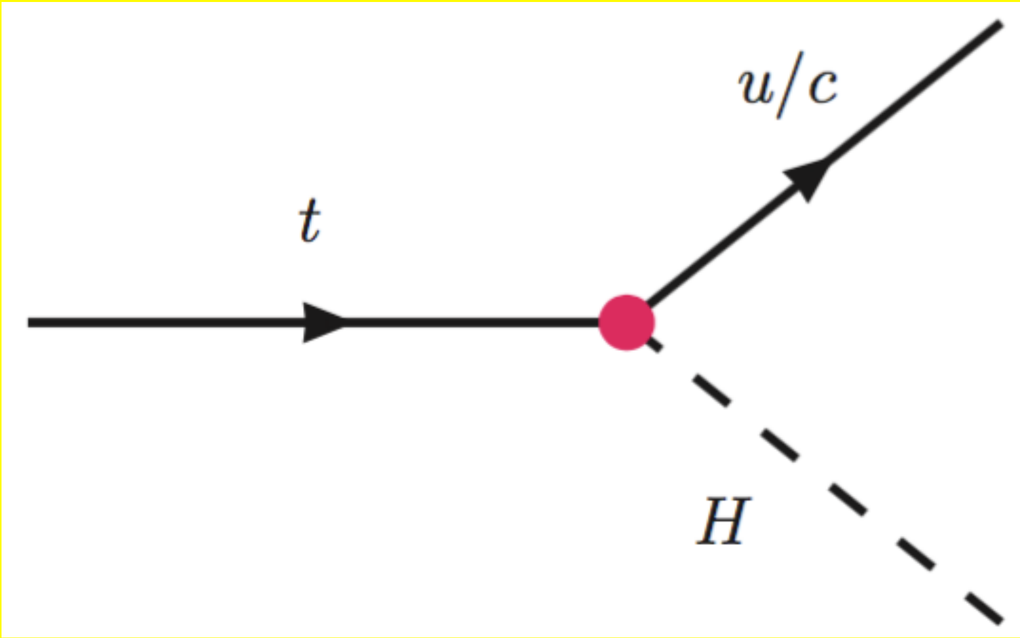
$\kappa_{u\gamma t}/\Lambda < 0.025\ TeV^{-1}$

$\kappa_{c\gamma t}/\Lambda < 0.091\ TeV^{-1}$

BR(t→ɣu) < 0.01 % (obs)
0.02 % (exp)

BR(t→ɣc) < 0.17 % (obs)
0.20 % (exp)

Top + Higgs



ATLAS: JHEP 06 (2014) 008 – $H \to \gamma\gamma$

CMS: CMS-PAS-TOP-14-019 – $H \to \gamma\gamma$

ATLAS: JHEP 12 (2015) 061 – $H \to bb$

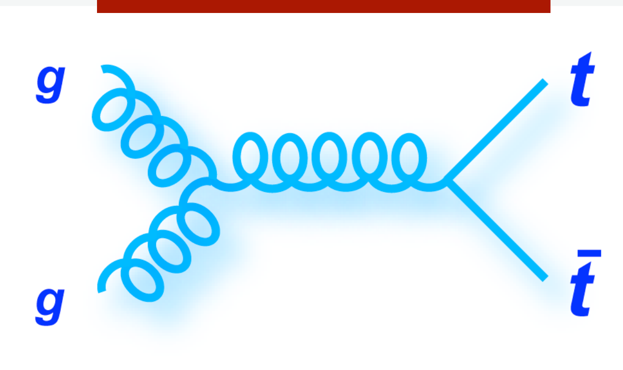
CMS: CMS-PAS-TOP-14-020 – $H \to bb$

CMS: CMS-PAS-TOP-13-017 – $H \to WW/ZZ/\tau\tau$

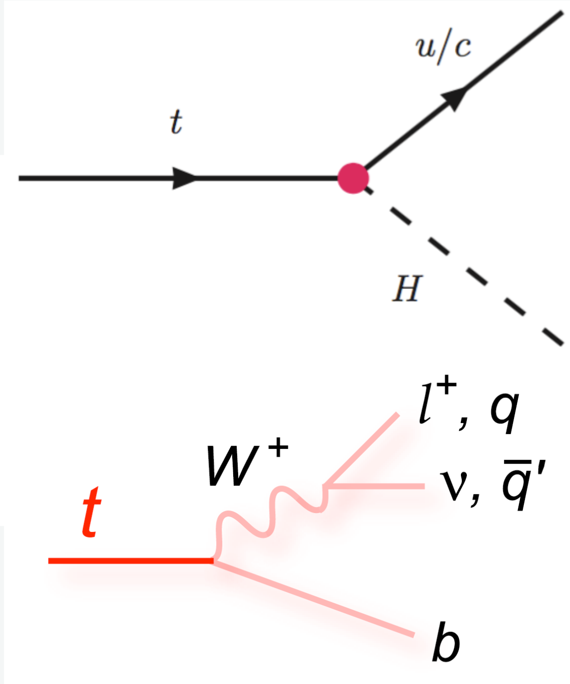
Search for t→Hq in ttbar

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

H→γγ channel



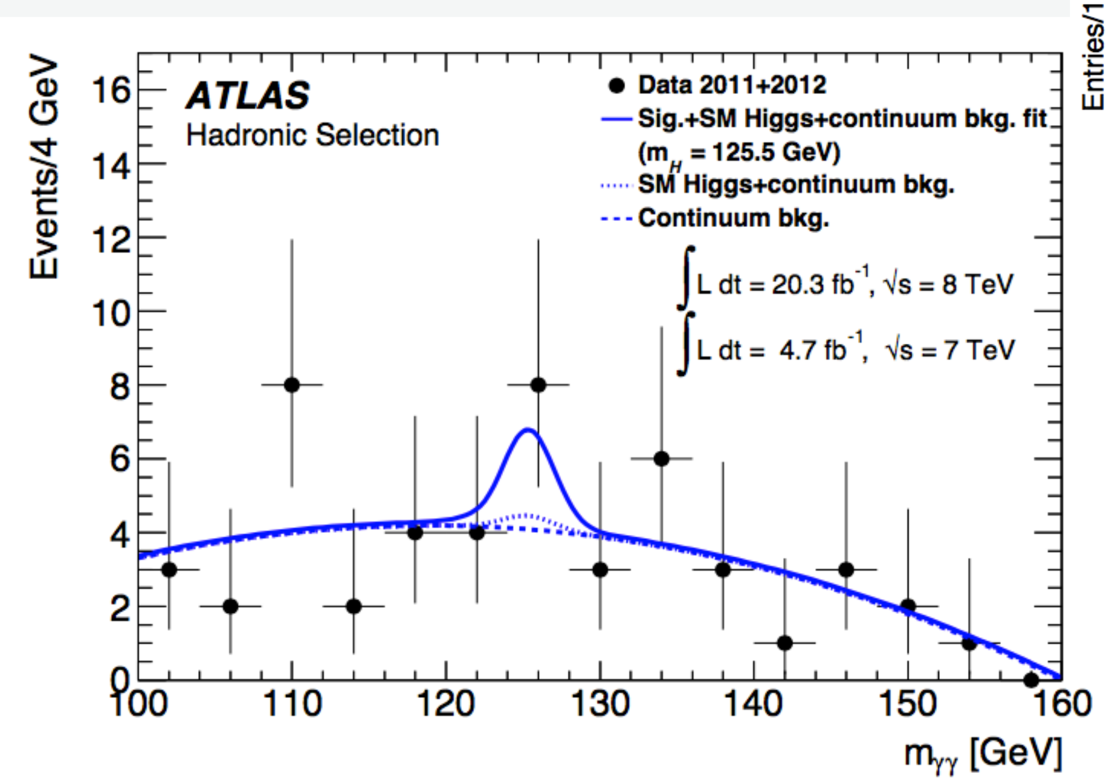
PROTOS @LO

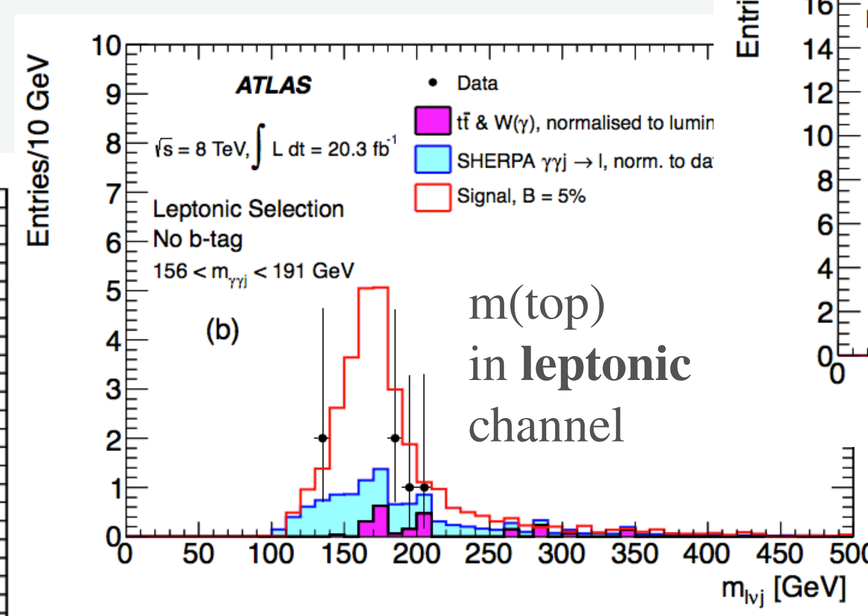


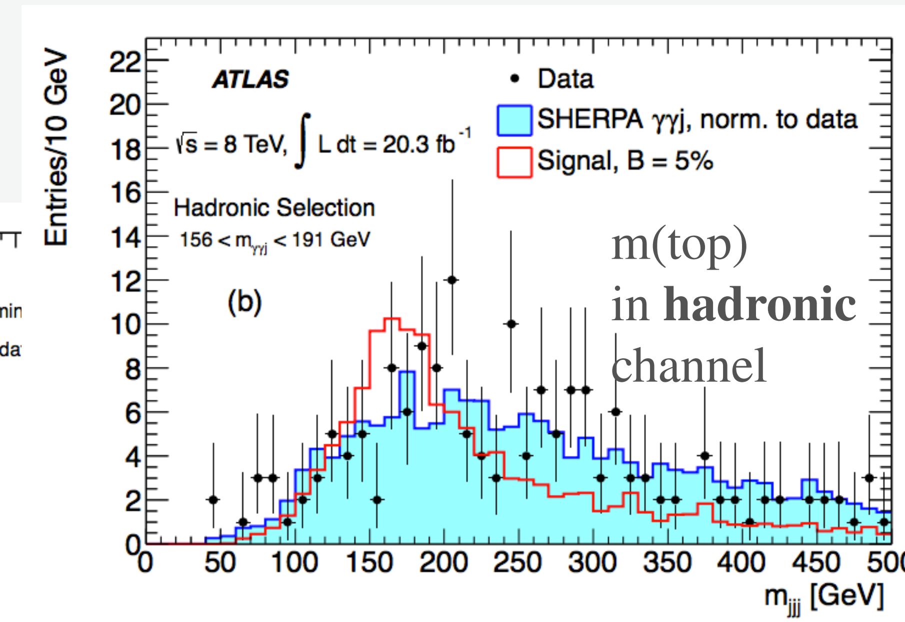
Event signature: two photons, one b jet, 3 jets (hadronic channel) or one isolated lepton, missing E_T and one jet (leptonic channel)

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

Background: **γγ+jets**, W+jets, ttbar







$\kappa_{qHt} < 0.17$

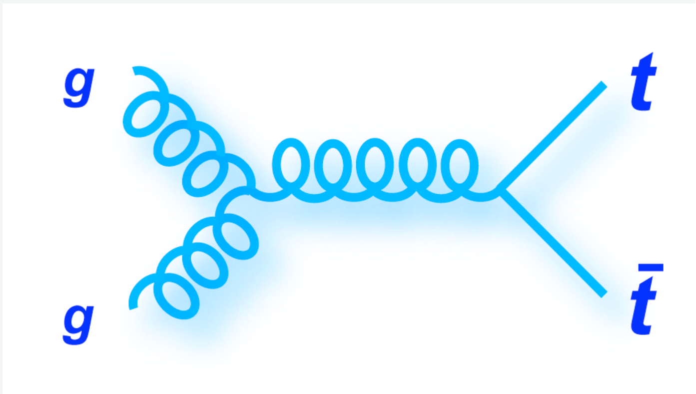
BR(t→**H**q) < 0.79 % (obs)

0.51 % (exp)

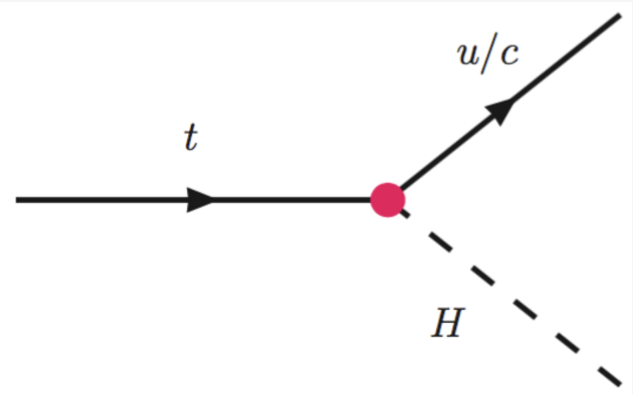
Search for t→Hq in ttbar

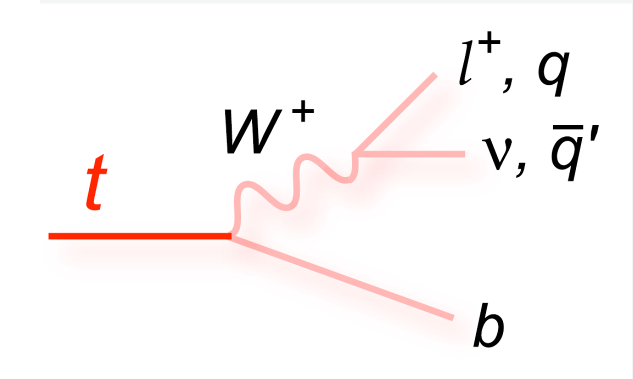
CMS-PAS-TOP-14-019
CMS, 20 fb^{-1}, 8 TeV

H→γγ channel



MadGraph@LO



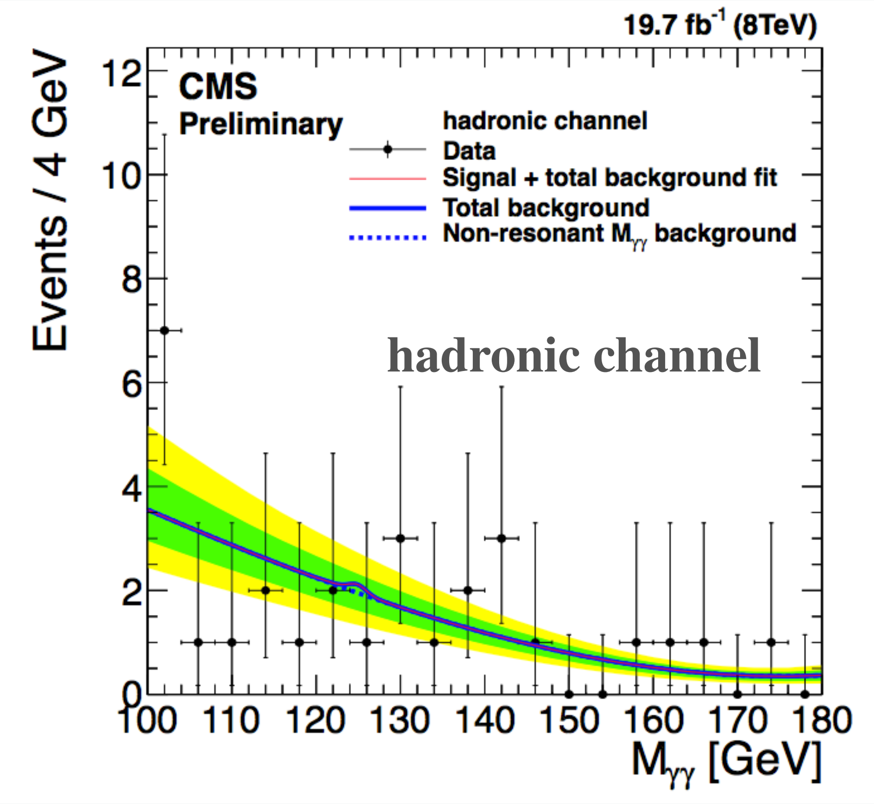


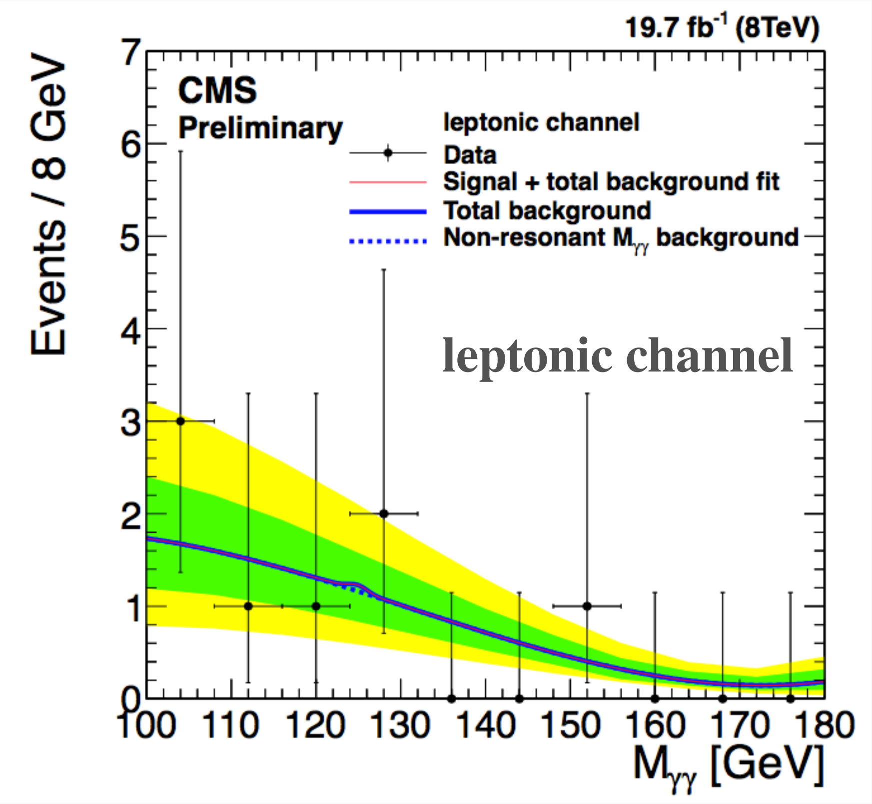
Event signature: two photons, one b jet, 3 jets (hadronic channel) or one isolated lepton, missing E_T and one b jet and one additional jet (leptonic channel)

Background: **γγ+jets**, W+jets, ttbar

Non-resonant γγ+jets background estimated from data

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





Search for t→Hq in ttbar

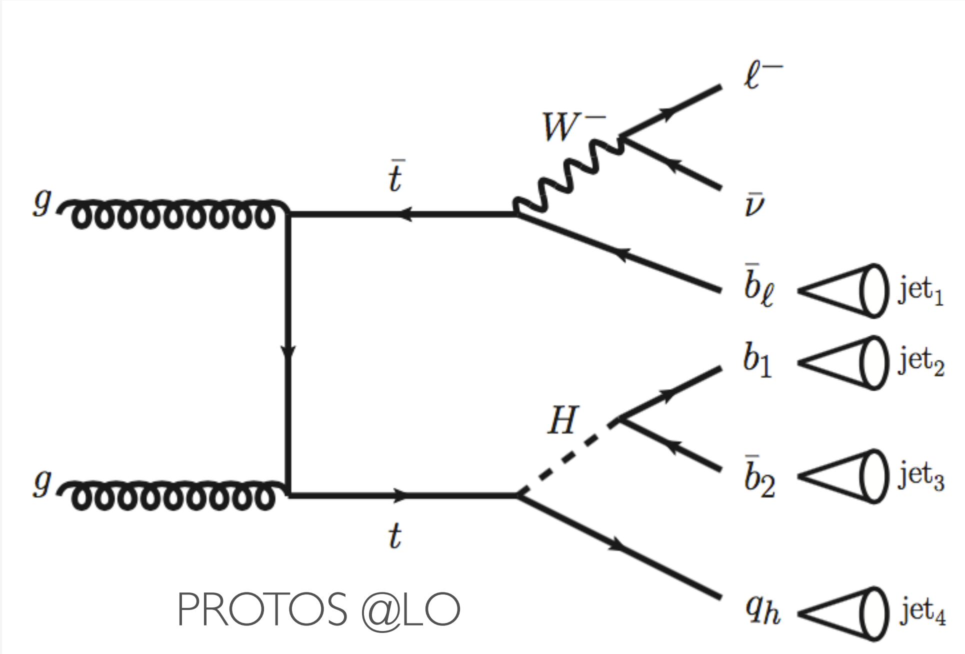
JHEP 12 (2015) 061
ATLAS, 20 fb^{-1}, 8 TeV

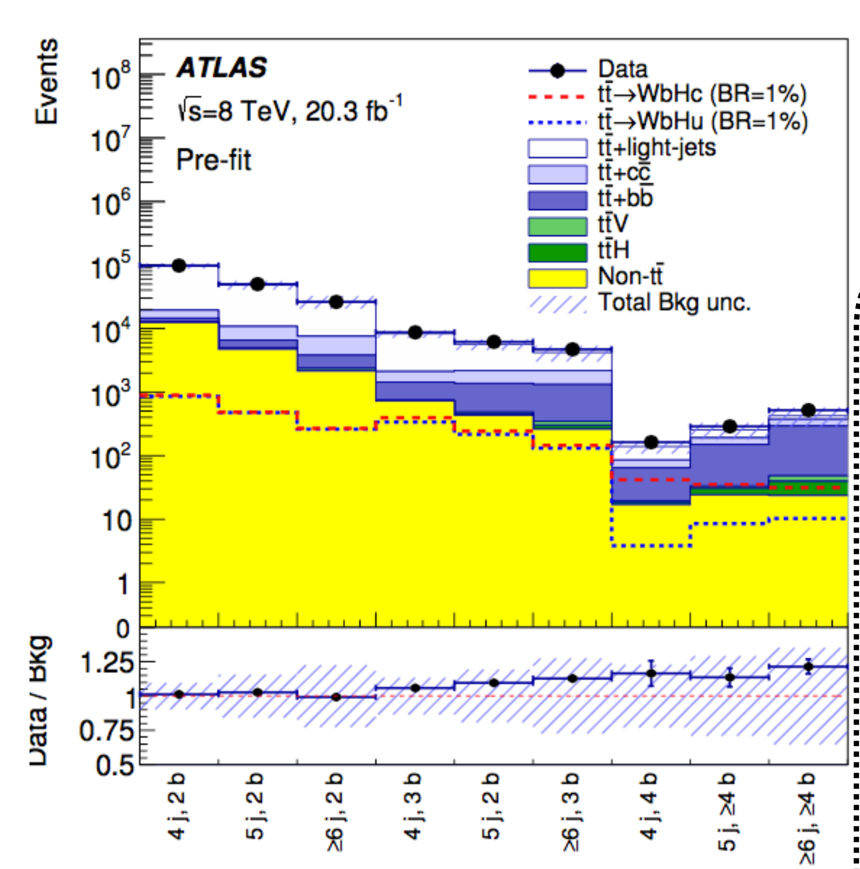
H→bb channel

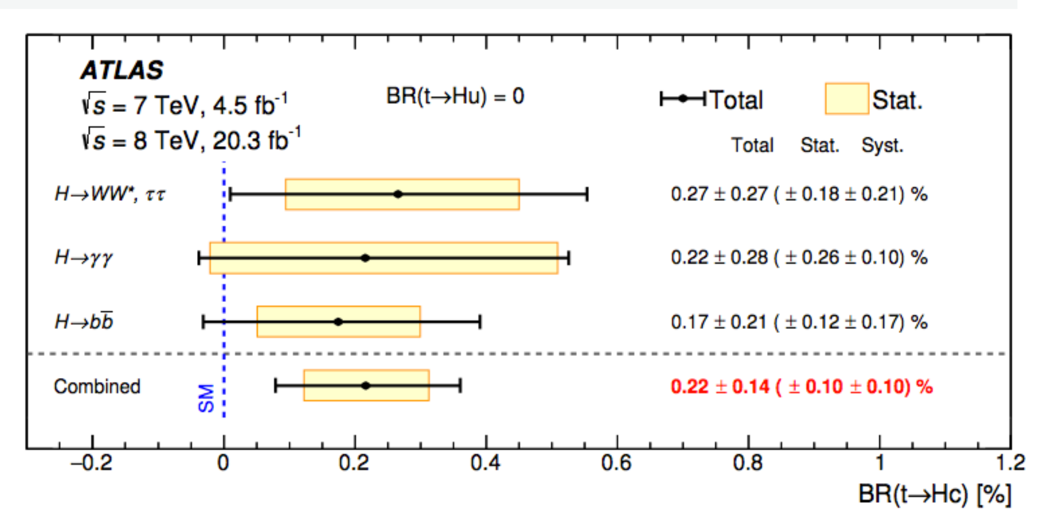
Event signature: ≥ 4 jets of which ≥ 3 jets are b jets, one lepton and missing E_T

Background: ttbar+jets

Background and signal fitted from data







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

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

$\kappa_{uHt} < 0.13$, $\kappa_{cHt} < 0.13$
BR(t→**H**u) < 0.45 % (obs)
0.29 % (exp)
BR(t→**H**c) < 0.46 % (obs)
BR(t→**H**c) < 0.25 % (exp)

Search for t→Hq in ttbar

CMS-PAS-TOP-14-020
CMS, 20 fb^{-1}, 8 TeV

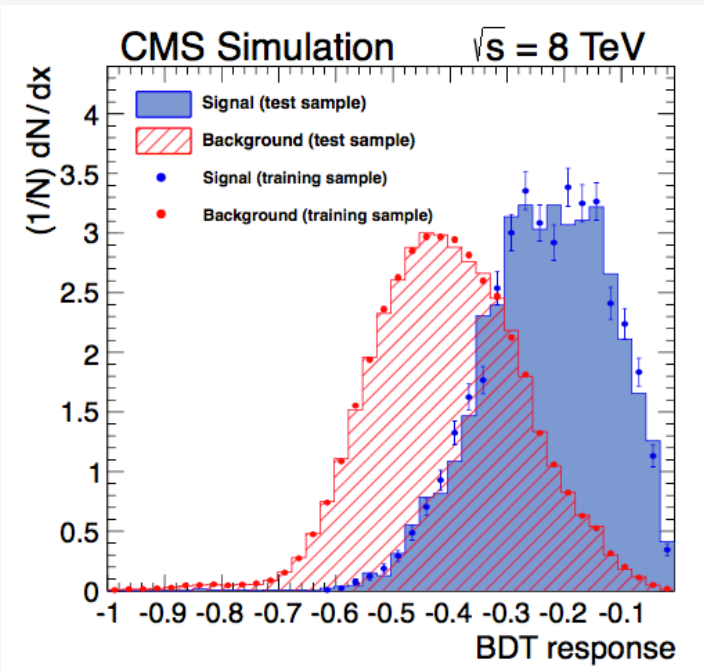
H→bb channel

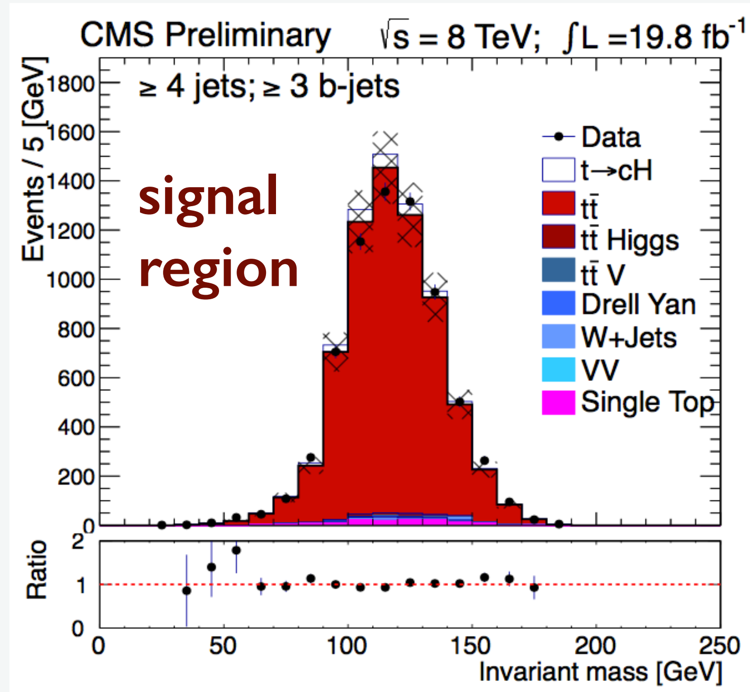
Event signature: ≥ 4 jets of which ≥ 3 jets are b jets, one lepton and missing E_T

Madgraph@LO

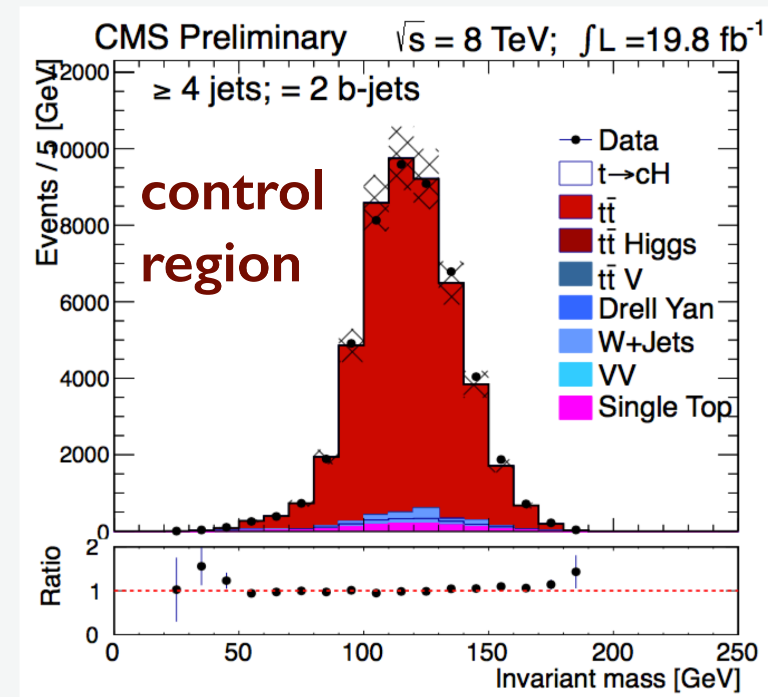
Background: ttbar+jets

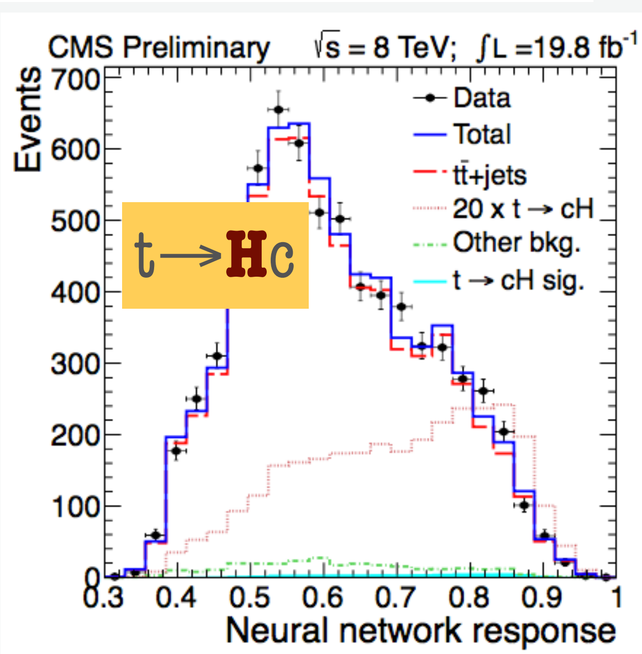
b jet assignment based on MVA

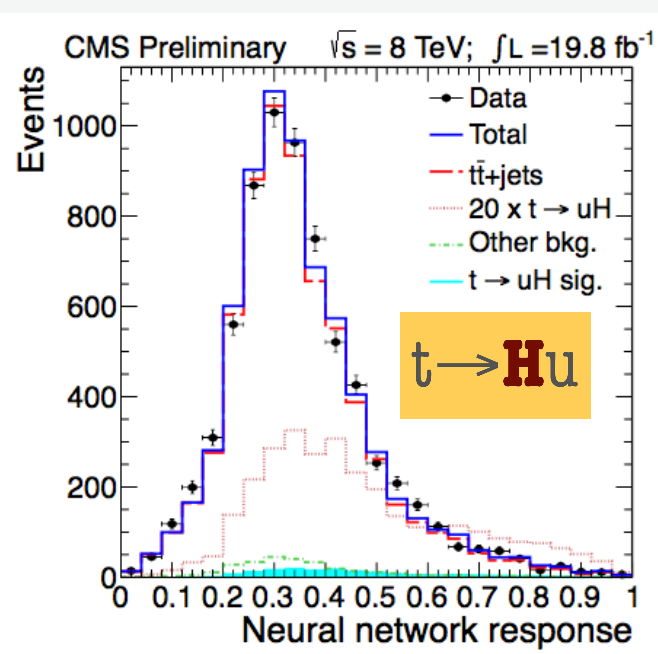




Background validated in data with two b tag jets

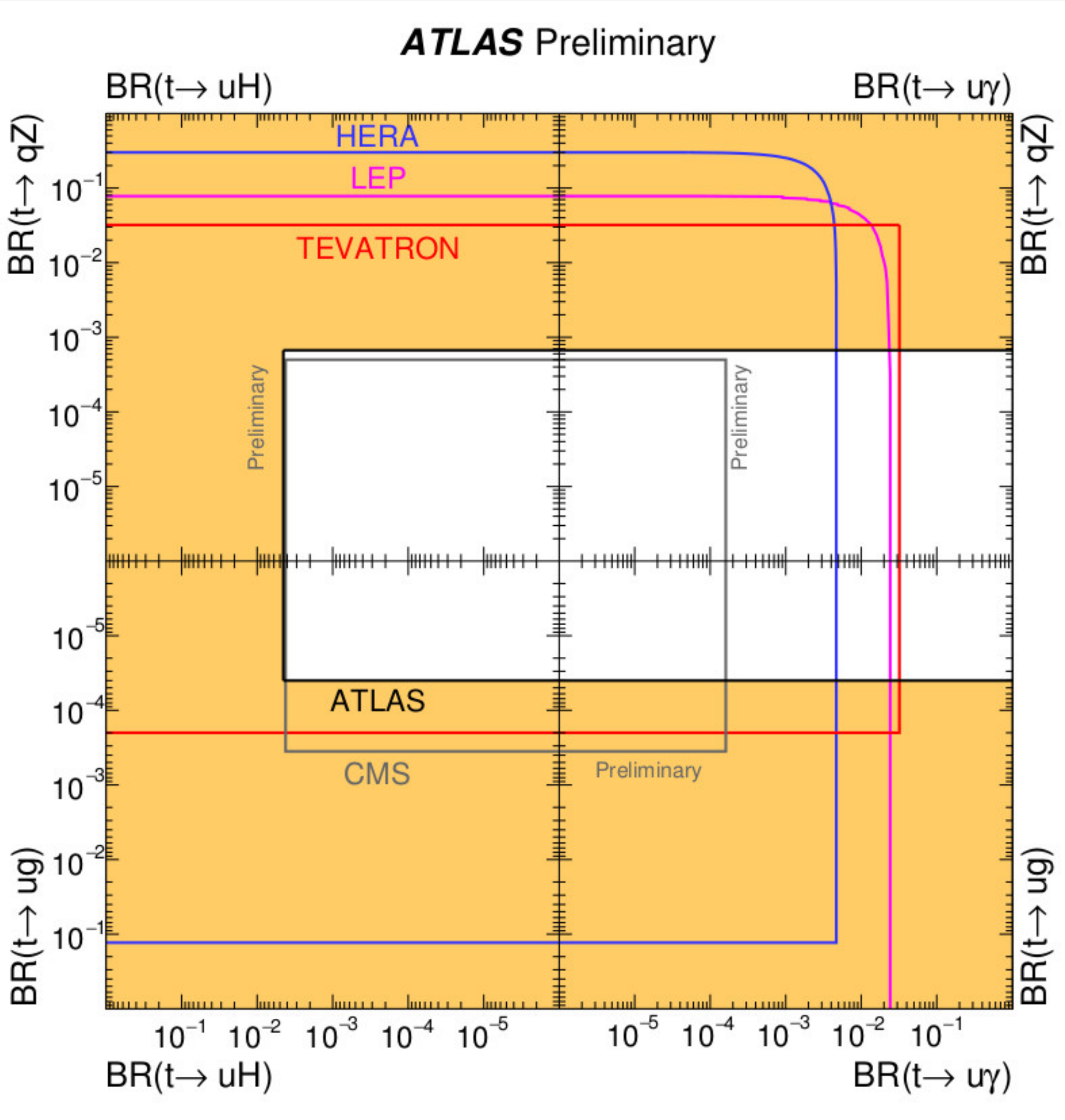






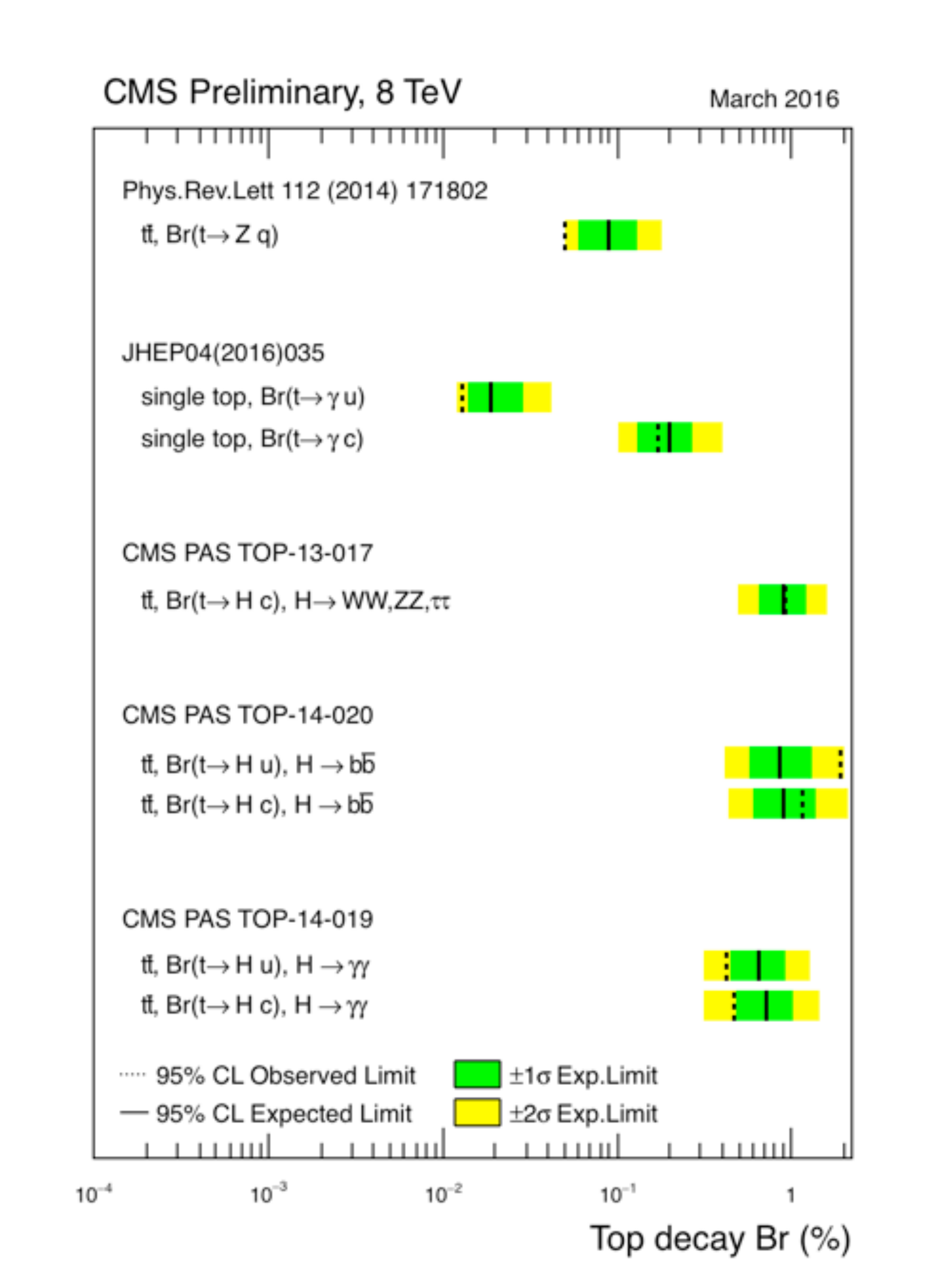
BR(t→Hu) < 1.92 % (obs)
0.85 % (exp)
BR(t→Hc) < 1.16 % (obs)
0.89 % (exp)

Summary on 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*

Summary on CMS top FCNC decays



Global fit for FCNC couplings

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

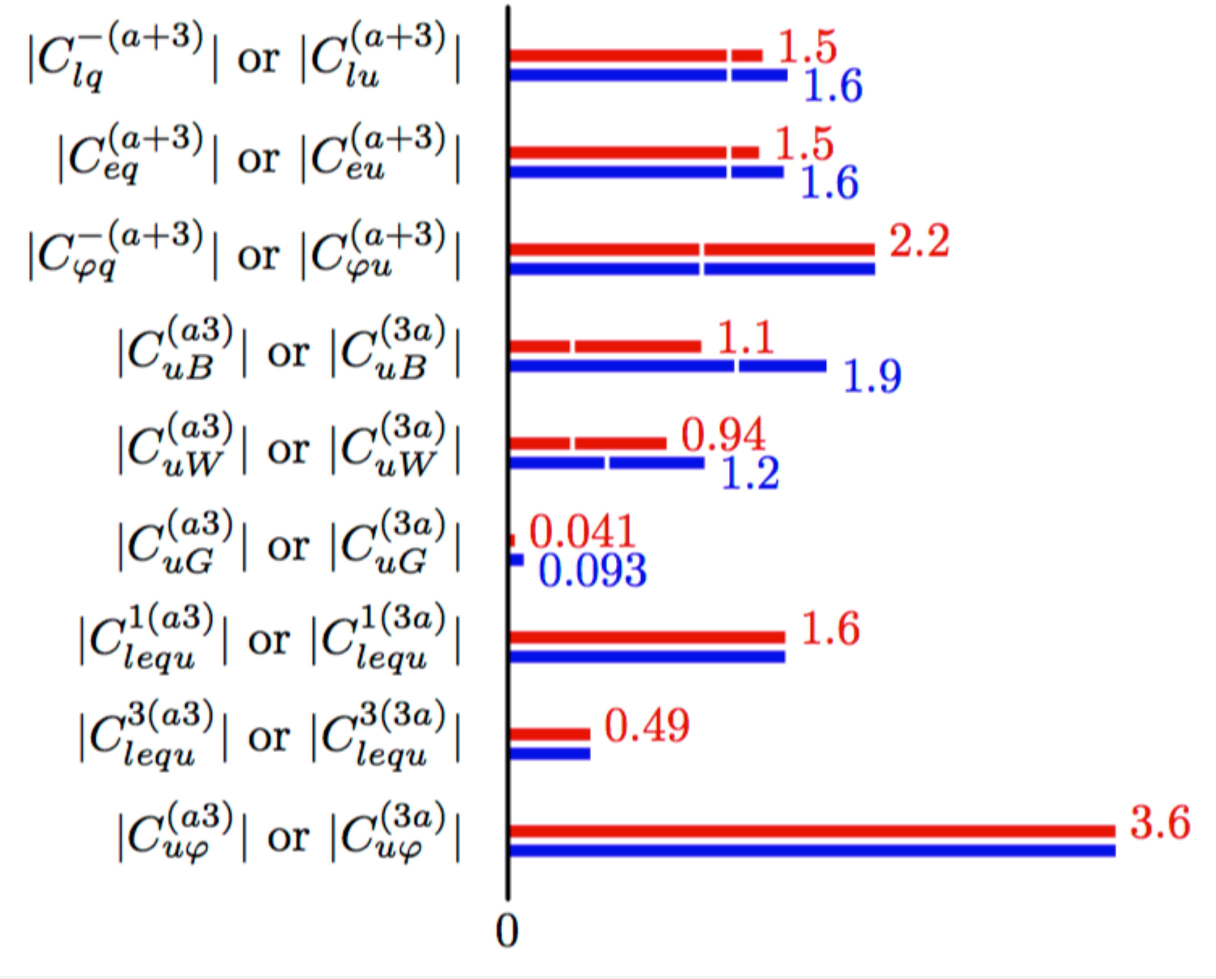
$$-\frac{g_W}{2c_W}\left\{\begin{matrix} v^Z_{tq} \\ -a^Z_{tq}\end{matrix}\right. = \frac{-e}{2s_W c_W}\frac{m_t^2}{\Lambda^2}\left[C^{(a+3)*}_{\varphi u} \pm C^{-(a+3)*}_{\varphi q}\right],$$

$$-\frac{g_W}{2\sqrt{2}}g_{qt}\left\{\begin{matrix} g^v_{qt} \\ g^a_{qt}\end{matrix}\right. = \frac{-2m_t}{v}\frac{m_t^2}{\Lambda^2}\left[C^{(a3)}_{u\varphi} \pm C^{(3a)*}_{u\varphi}\right],$$

$$-e\frac{\kappa^\gamma_{tq}}{\Lambda}\left\{\begin{matrix} f^\gamma_{tq} \\ ih^\gamma_{tq}\end{matrix}\right. = e\frac{m_t}{\Lambda^2}\left[(C^{(3a)}_{uB} + C^{(3a)}_{uW}) \pm (C^{(a3)}_{uB} + C^{(a3)}_{uW})^*\right],$$

$$-\frac{g_W}{2c_W}\frac{\kappa^Z_{tq}}{\Lambda}\left\{\begin{matrix} f^Z_{tq} \\ ih^Z_{tq}\end{matrix}\right. = \frac{-e}{s_W c_W}\frac{m_t}{\Lambda^2}\left[(s_W^2\, C^{(3a)}_{uB} - c_W^2\, C^{(3a)}_{uW}) \pm (s_W^2\, C^{(a3)}_{uB} - c_W^2\, C^{(a3)}_{uW})^*\right],$$

$$-g_s\frac{\kappa^g_{tq}}{\Lambda}\left\{\begin{matrix} f^g_{tq} \\ ih^g_{tq}\end{matrix}\right. = g_s\frac{m_t}{\Lambda}\left[C^{(3a)}_{uG} \pm C^{(a3)*}_{uG}\right].$$



G. Durieux et al., arXiv:1412.7166

Conclusion

- No evidence of top quark anomalous interactions so far
- ATLAS and CMS have **significantly improved the exclusion limits** on anomalous Wtb and FCNC couplings with Run I data
- Run II analyses **ongoing**

The best limits on Wtb anomalous couplings (approximative summary)

$\|V_R\|$	**< 0.3**	TOP-14-007
$\|g_L\|$	**< 0.1**	TOP-14-007
$Re(g_L)$	≈ **[-0.2, 0.2]**	JHEP 01 (2015) 053
$Re(g_R)$	≈ **[-0.1, 0.1]**	JHEP 01 (2015) 053
$Im(g_R)$	≈ **[-0.2, 0.2]**	JHEP 04 (2016) 023

The best limits on FCNC top quark decay BR from the LHC

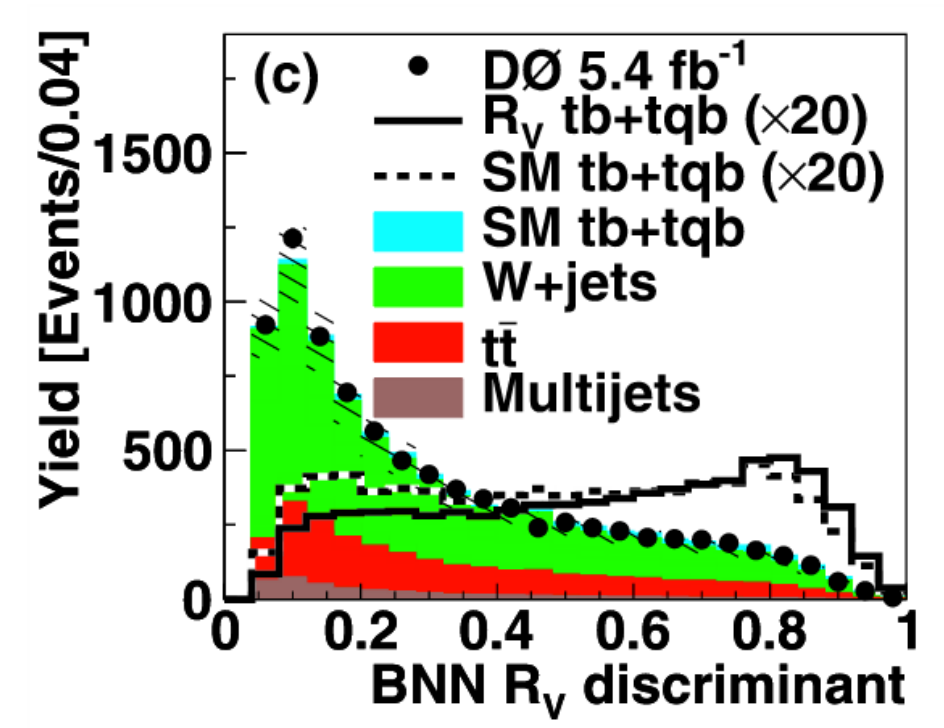
$t \rightarrow gu$	**0.004 %**	Eur. Phys. J. C (2016) 76:55
$t \rightarrow gc$	**0.017 %**	Eur. Phys. J. C (2016) 76:55
$t \rightarrow Zq$	**0.05 %**	Phys. Rev. Lett. 112 (2014) 171802
$t \rightarrow \gamma u$	**0.01 %**	JHEP 04 (2016) 035
$t \rightarrow \gamma c$	**0.17 %**	JHEP 04 (2016) 035
$t \rightarrow Hu$	**0.42 %**	CMS-PAS-TOP-14-019
$t \rightarrow Hc$	**0.46 %**	JHEP 12 (2015) 061

Backup slides

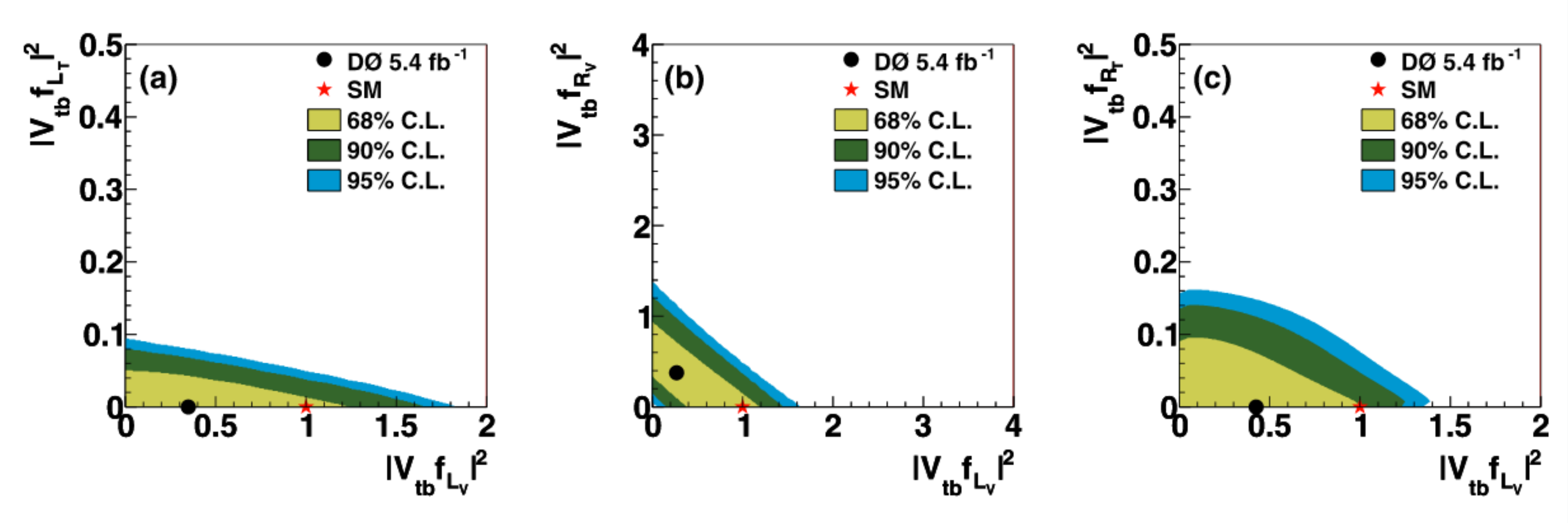
Anomalous Wtb at Tevatron

Phys. Lett. B 708:21-26, 2012
D0, 5.4 fb^{-1}, 1.96 TeV

- Probe **anomalous Wtb coupling** in **single top t- and s-channels**
- Use Bayesian Neural Network (**BNN**) approach to suppress W+jets and ttbar backgrounds
- Consider two non-vanishing couplings at a time (V_L and one anomalous)



$$f_{R_V} V_{tb} \equiv V_R,\ f_{L_T} V_{tb} \equiv g_L,\ f_{R_T} V_{tb} \equiv g_R$$



$$|V_{tb} \cdot f_{L_T}|^2 < 0.06$$
$$|V_{tb} \cdot f_{R_V}|^2 < 0.93$$
$$|V_{tb} \cdot f_{R_T}|^2 < 0.13$$

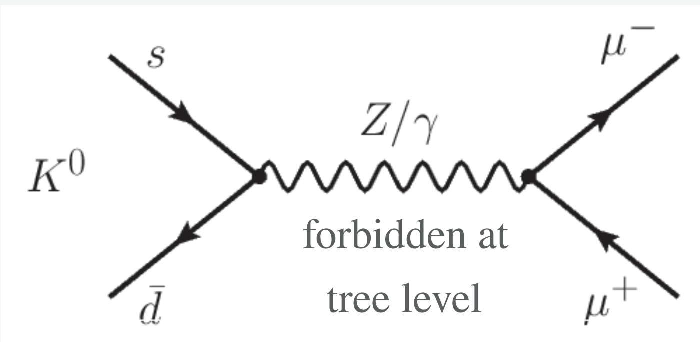
@ 95% CL

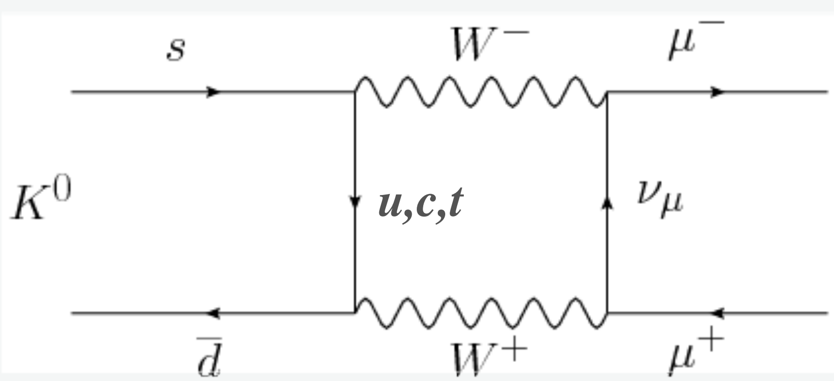
V_L is fixed to the SM value

FCNC without top quarks

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

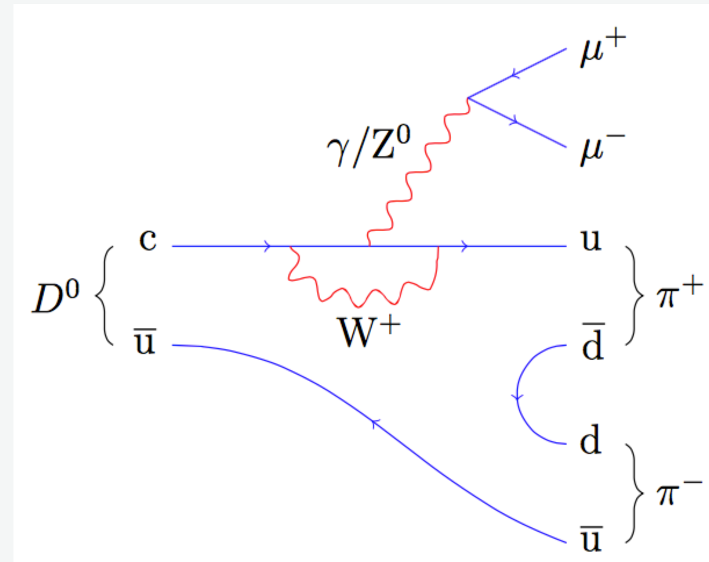
$K_L \to \mu^+\mu^-$





Br$_{exp}$ ≈ 6 • 10^{-9}

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



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

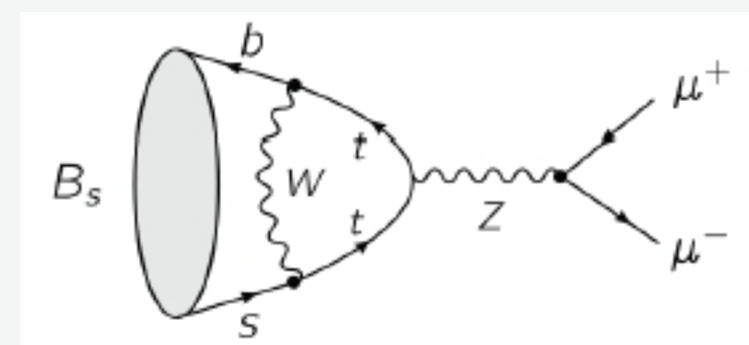
Br$_{exp}$ < 5.5 • 10^{-7} (90% C.L.)

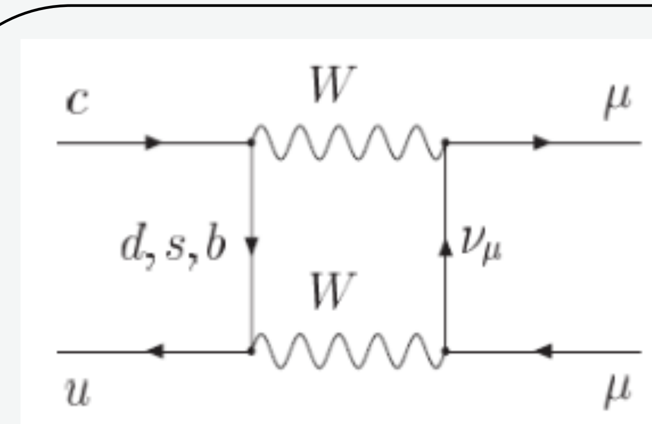
Phys. Lett. B 728 (2014) 234-243

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

Br$_{exp}$ ≈ 3 • 10^{-9}

LHCb-CONF-2013-12





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

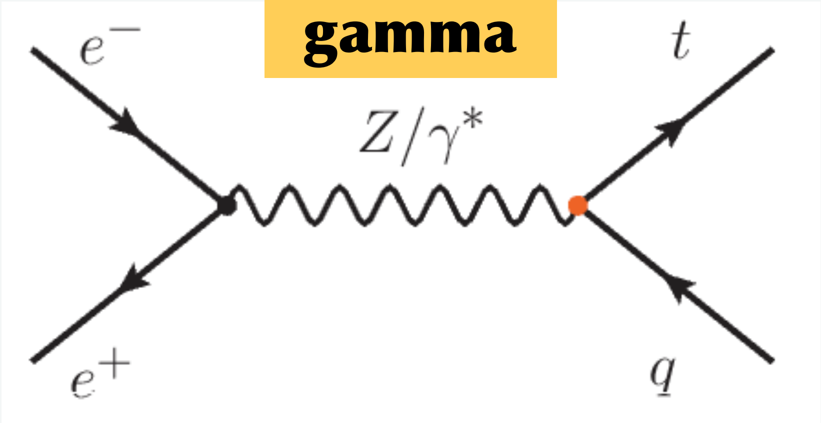
Br$_{exp}$ < 6 • 10^{-9} (90% C.L.)

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

FCNC at LEP and HERA

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

Top + Z/ gamma

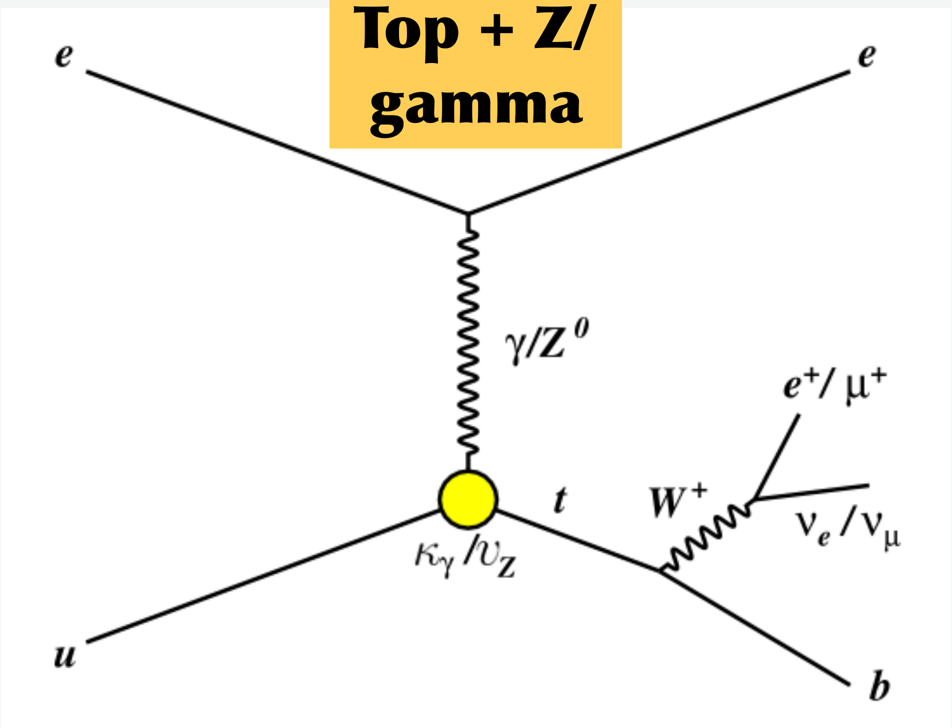


L3 *Phys. Lett. B549 (2002) 290-300*
OPAL *Phys. Lett. B521 (2001) 181-194*
ALEPH *Phys. Lett. B494 (2000) 33*
DELPHI *Phys. Lett. B590 (2004) 21-34*

$BR(t \rightarrow \gamma q) \lesssim 4\ \%$
$BR(t \rightarrow Zq) \lesssim 10\ \%$

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

Top + Z/ gamma



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

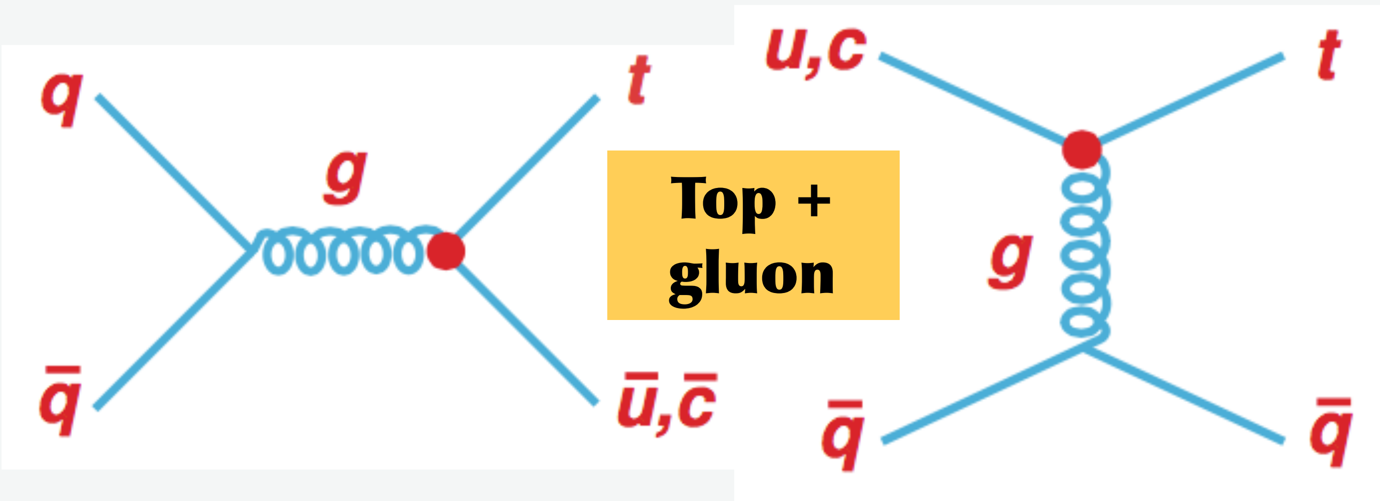
$BR(t \rightarrow \gamma q) \lesssim 0.5\ \%$
$BR(t \rightarrow Zq) \lesssim 4\ \%$

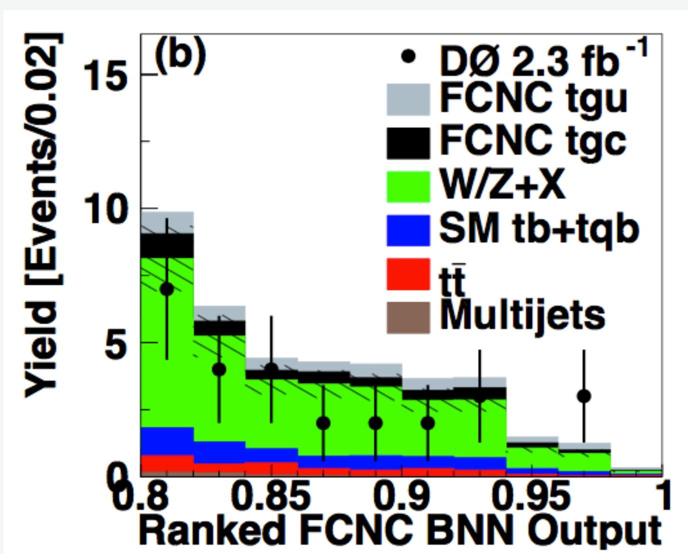
$$\Delta\mathcal{L}_{\text{eff}} = e\, e_t\, \bar{t}\frac{i\sigma_{\mu\nu}p^\nu}{\Lambda}\, \kappa_\gamma\, u\, A^\mu + \frac{g}{2\cos\theta_W}\, \bar{t}\gamma_\mu\, v_Z\, u Z^\mu\, + \text{h.c.}$$

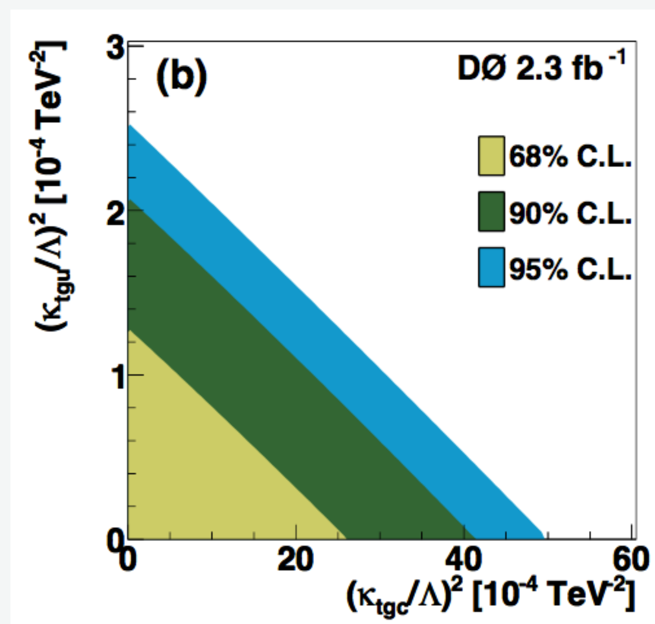
$\Lambda = 175$ GeV

FCNC at Tevatron

Search for **t → g q** at **DØ**





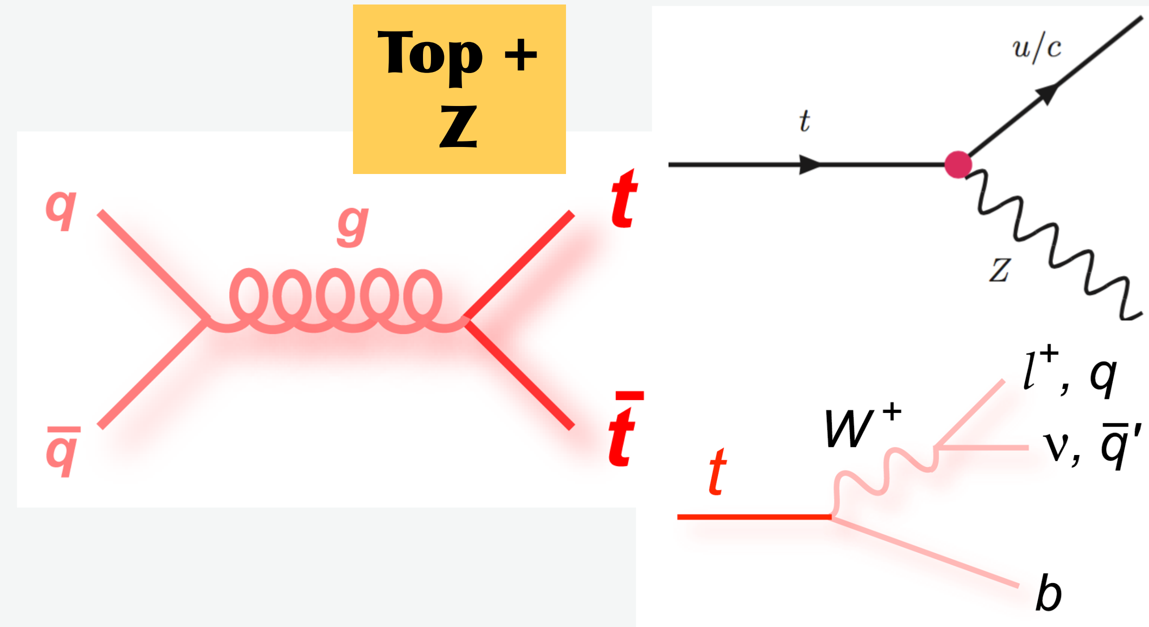


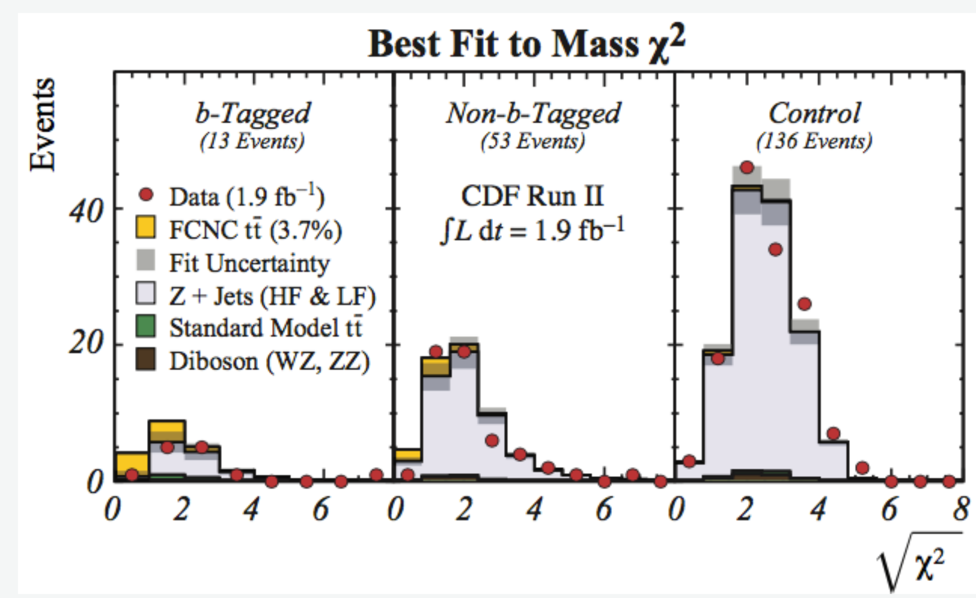
BR(t→**g**u) ≲ 0.02 %

BR(t→**g**c) ≲ 0.4 %

Phys. Lett. B693 (2010) 81-87

Search for **t → Z q** at **CDF**



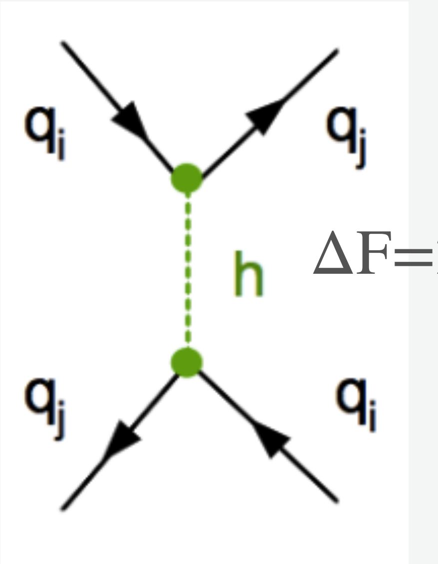


BR(t→**Z**q) ≲ 3.7 %

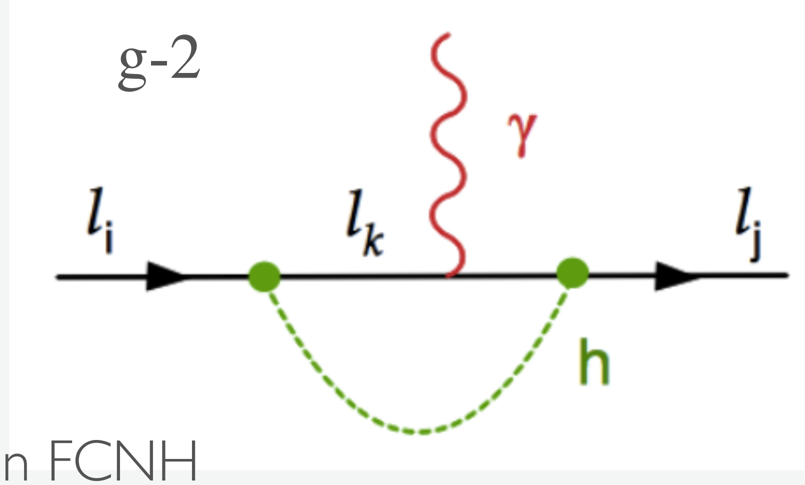
Phys. Rev. Lett. 101 (2008) 192002

FCNHiggs

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



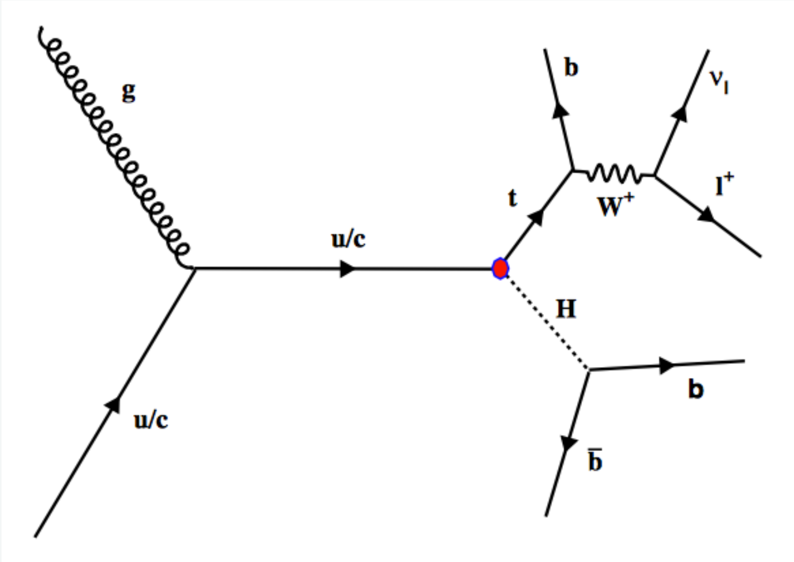
ΔF=2



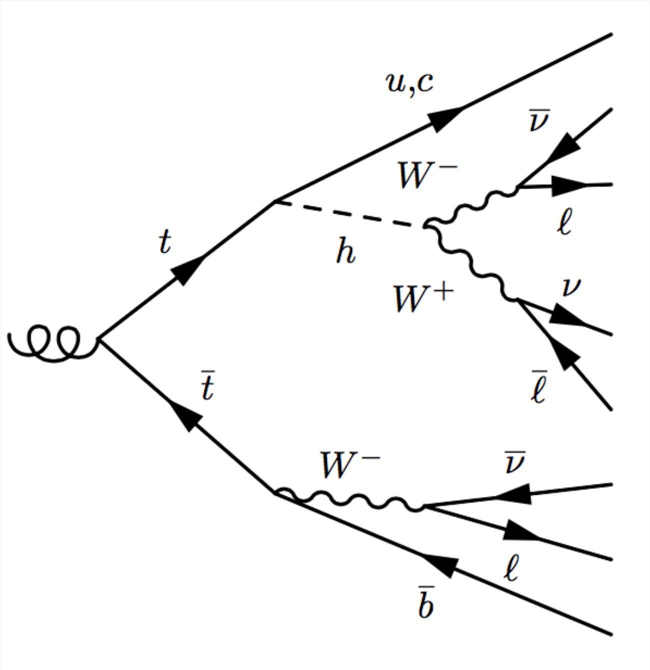
Stringent limits on FCNH couplings to leptons from LFV searches

http://arxiv.org/abs/1202.5704

FCNH in single top



FCNH in ttbar



Expect large coupling with top quark ?

Search for t→Hq in ttbar

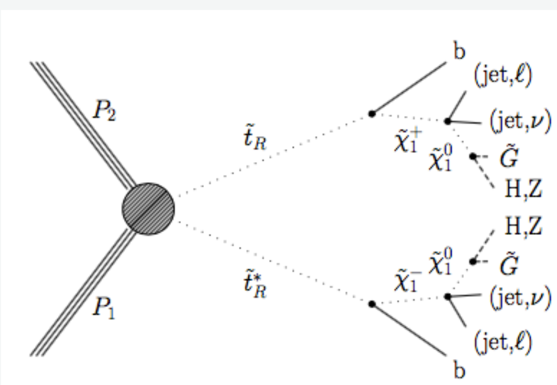
CMS-PAS-HIG-13-034
CMS, 20 fb^{-1}, 8 TeV

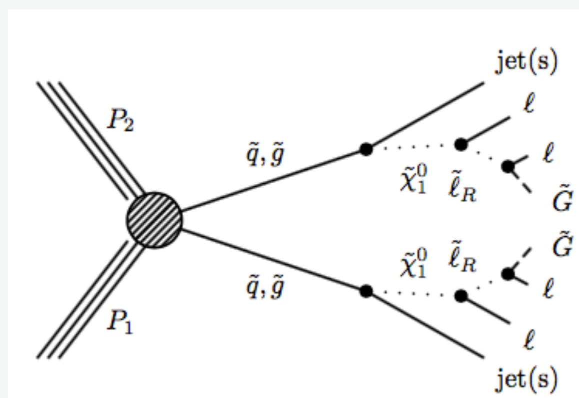
Based on a combination of two analyses performed in multilepton (H→WW/ZZ/ττ) and H→γγ channels

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.





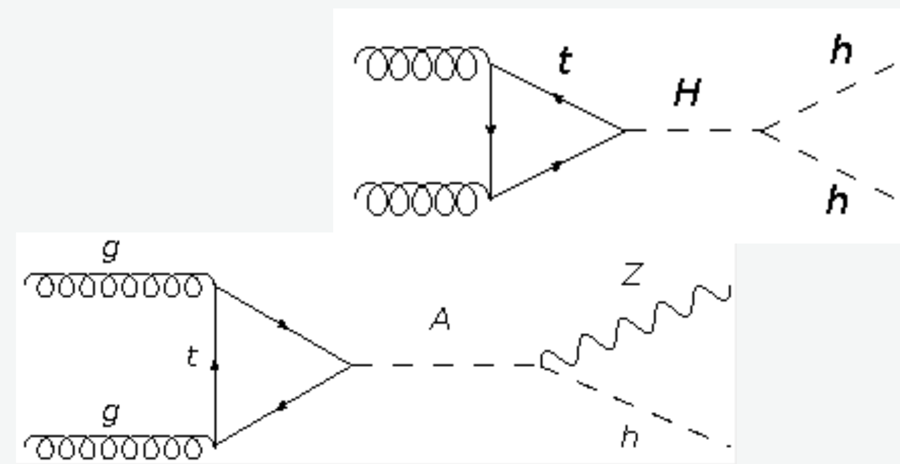
Several SUSY scenarios are probed, also possible to **set limits on FCNH** in this inclusive search:

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→**H**q) < 1.28 %

MadGraph @LO is used for FCNH generation

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



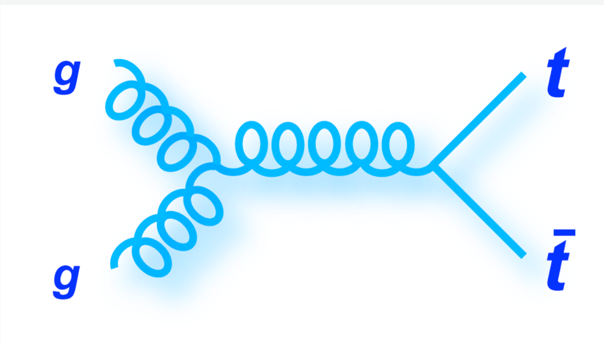
Higgs Decay Mode		observed	expected	1σ range
$H \to WW^*$	($\mathcal{B}$ = 23.1 %)	1.58 %	1.57 %	(1.02–2.22) %
$H \to \tau\tau$	($\mathcal{B}$ = 6.15 %)	7.01 %	4.99 %	(3.53–7.74) %
$H \to ZZ^*$	($\mathcal{B}$ = 2.89 %)	5.31 %	4.11 %	(2.85–6.45) %
combined multileptons (WW^*, $\tau\tau$, ZZ^*)		1.28 %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

Combination of results

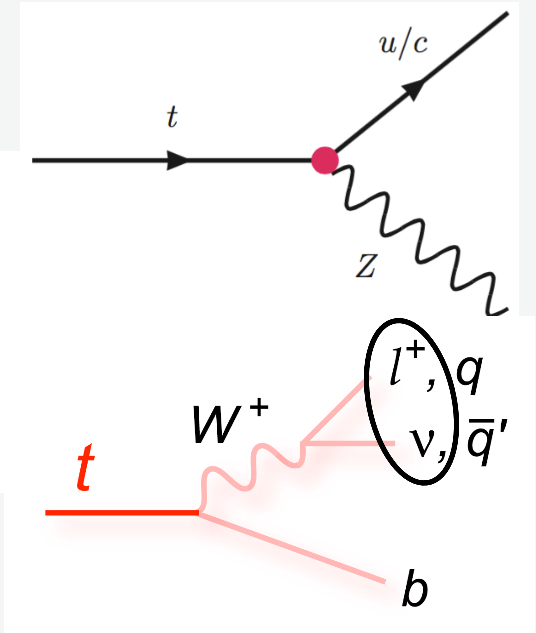
$\kappa_{qHt} < 0.14$
BR(t→**H**q) < 0.56 %

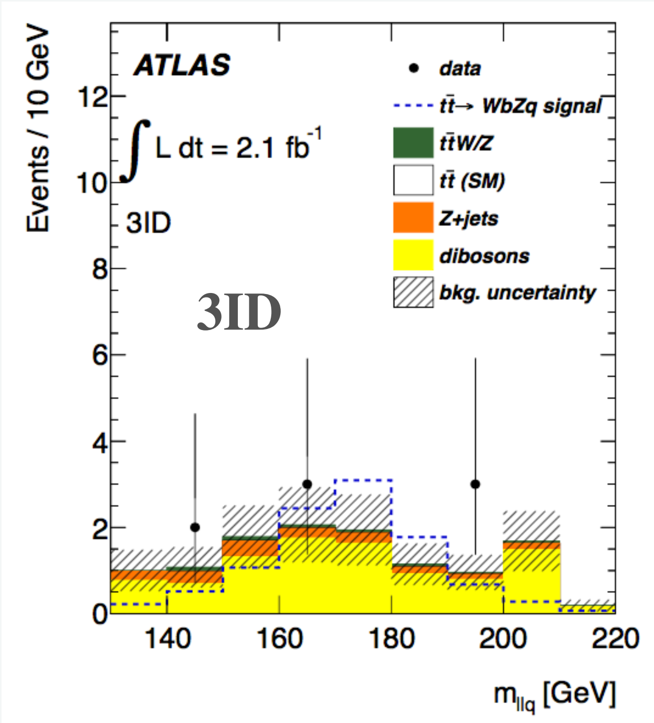
Search for t→Zq in ttbar

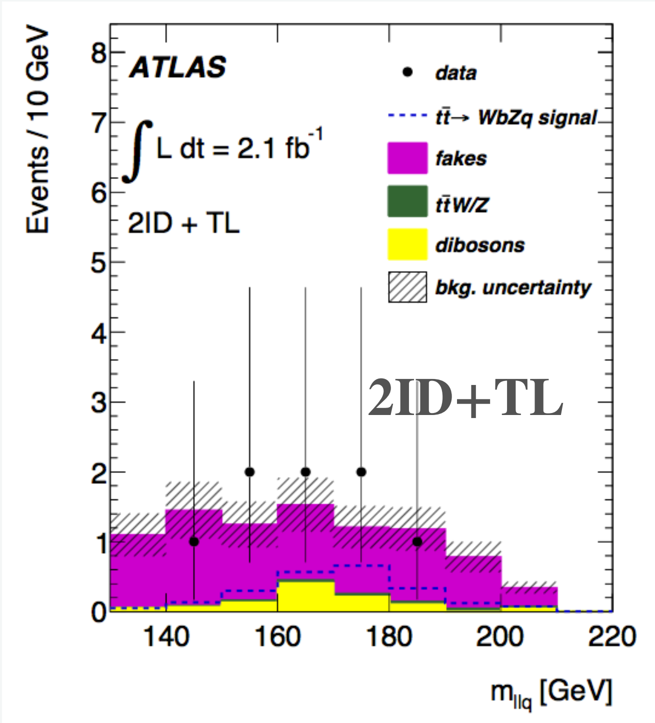
JHEP 1209 (2012) 139
ATLAS, 2 fb^{-1}, 7 TeV



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 χ2 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)

Input variables for MVA

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

gqt

Variable	Definition
m_T(top)	Transverse mass of the reconstructed top quark
p_T^{ℓ}	Transverse momentum of the charged lepton
ΔR(top, ℓ)	Distance in the η–ϕ plane between the reconstructed top quark and the charged lepton
$p_T^{b\text{-jet}}$	Transverse momentum of the b-tagged jet
$\Delta\phi$(top, b-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
$m_T(W)$	W-boson transverse mass
η^{ℓ}	Pseudorapidity of the charged lepton
$\Delta\phi$(top, W)	Difference in azimuth between the reconstructed top quark and the W boson
ΔR(top, b-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

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

Zqt

- 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,

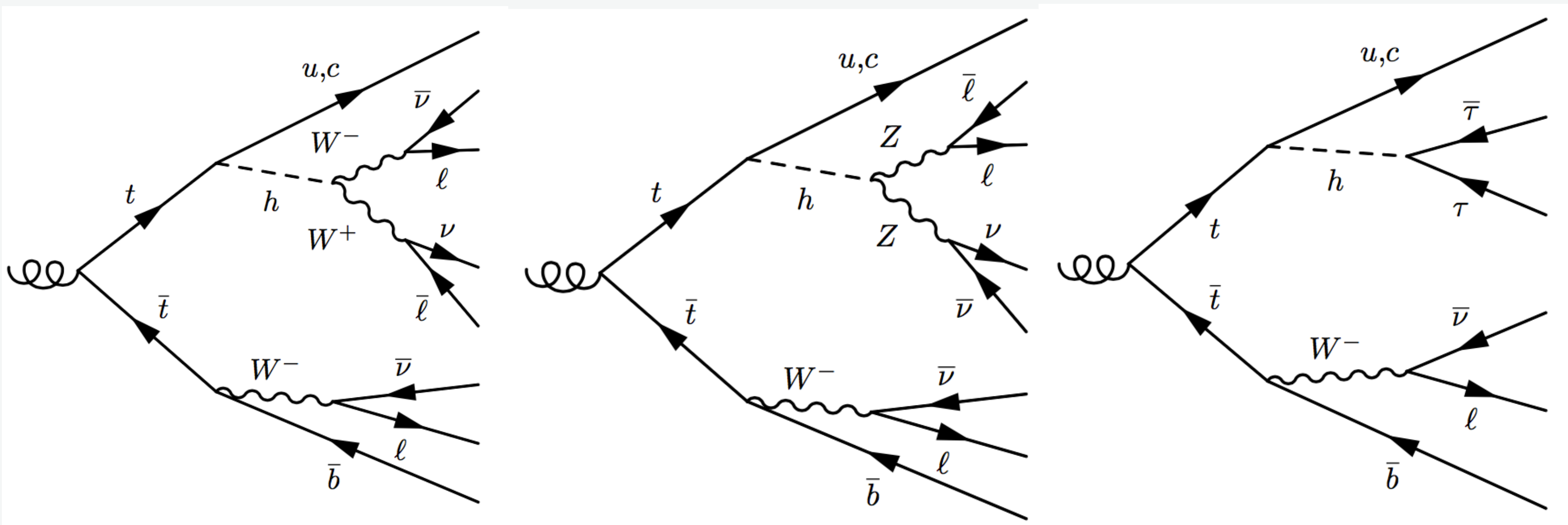
CMS-PAS-TOP-14-003
CMS, 19 fb^{-1}, 8 TeV

γqt

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

Search for t→Hq in ttbar

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



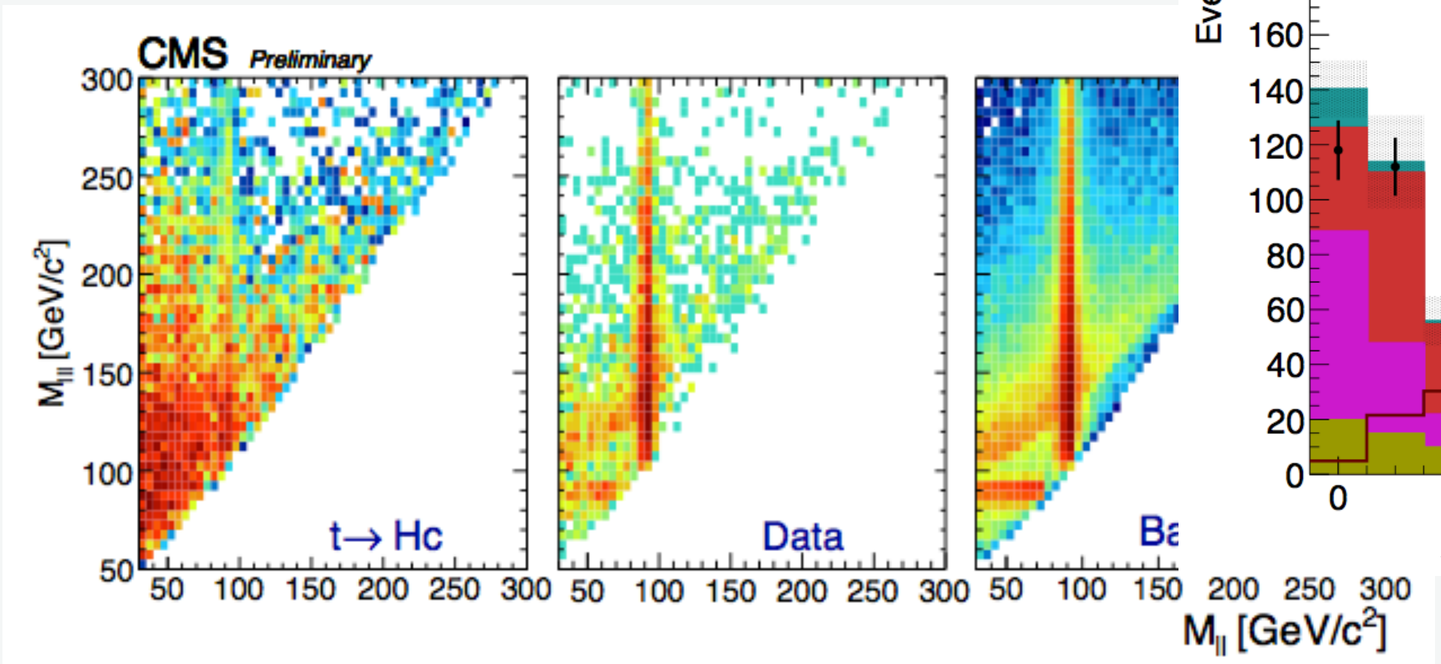
PYTHIA6 @LO

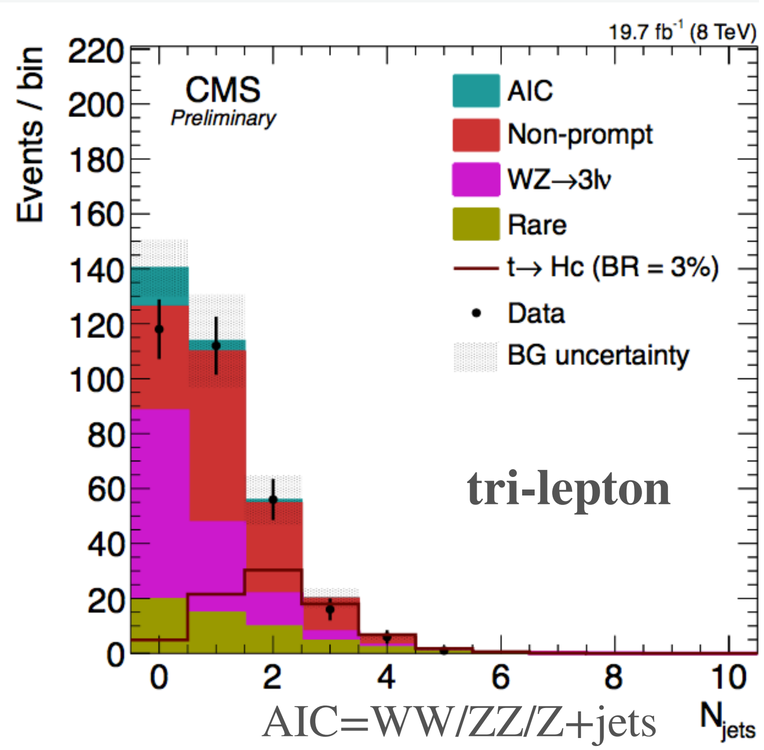
H→WW/ZZ/ττ channel

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

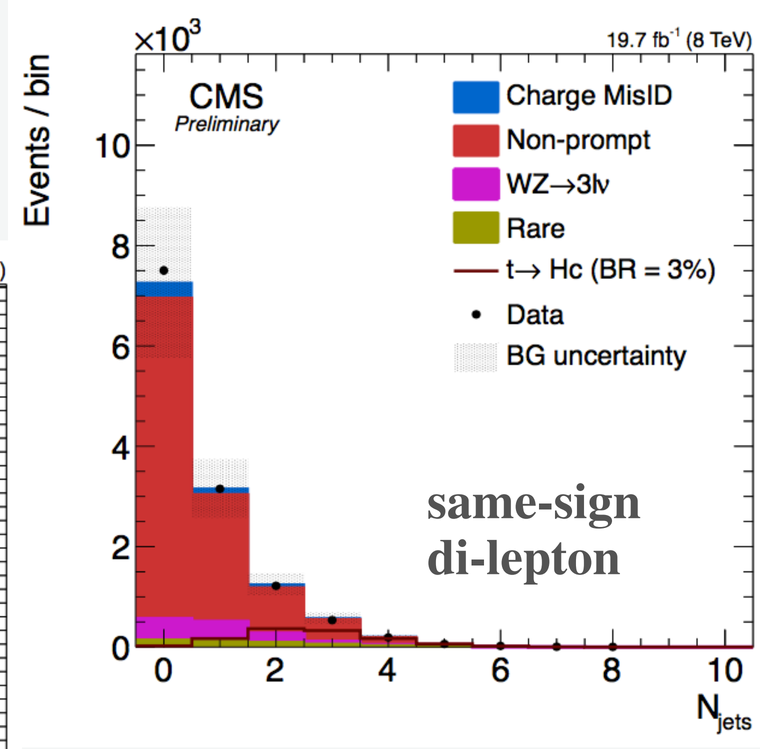
Background: WZ+jets, ttbar+V (tri-lepton), fake leptons, charge mis-ID (same-sign dilepton)

Fake and charge misID lepton backgrounds estimated from data





AIC=WW/ZZ/Z+jets



$\kappa_{\mathrm{qHt}} < 0.18$

BR(t→**H**q) < 0.93 % (obs)

0.89 % (exp)