LHC results on EFTs from top quark measurements (couplings and FCNC)

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on behalf of ATLAS & CMS collaborations

SM@LHC 2017 - Amsterdam

Top quark Effective Field Theory

$$\mathcal{L}_{eff} = \mathcal{L}_{SM}^{(4)} + \sum \frac{C_x}{\Lambda^2} O_{6,x} + h.c.$$

$O_{6,x}$ dimension-6 gauge-invariant operators

C_x Wilson coefficients (complex constants)

Λ Energy scale of new physics

- Generic extension of the Standard Model

  based on limited approximations

- Way to look for New Physics in SM precision measurements

- Deviations from higher-order SM predictions due to interference of NP with SM; sensitive to NP even if new particles are too massive to be created at LHC energy

Top quark vertices

- General couplings (SM contribution)
  - **Wtb, ttg, ttZ, ttγ, ttH**
- Flavor Changing Neutral Currents (FCNC) couplings
  - **tgq, tγq, tZq, tHq** (q=u or c)
- Lagrangian of each top vertex can be expressed with a minimal set of independent (anomalous) couplings related to (one or several) Wilson coefficient C_x

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)\, tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_L P_L + g_R P_R)\, tW_{\mu}^{-} + \text{h.c.} \quad \text{with e.g. } g_R = \sqrt{2}C_{uW}^{33}\frac{v^2}{\Lambda^2}$$

- Experimental measurements allow to set limits on these couplings or the C_x directly

Observables

- Productions:
  - top-quark pair, single-top, associated productions
- Observables:
  - cross-sections: total or differential
  - distributions: p_T spectrum, angular asymmetries, ...
- Interpretations:
  - global analysis (like TopFitter but with limited correlations informations)
  - individual measurements with EFT interpretation

Only LHC Run 1 results (8 TeV or 7&8 TeV) will be shown

Wtb anomalous couplings

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_{\rm L}P_{\rm L} + V_{\rm R}P_{\rm R}\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}\left(g_{\rm L}P_{\rm L} + g_{\rm R}P_{\rm R}\right)tW_{\mu}^{-} + \text{h.c.}$$

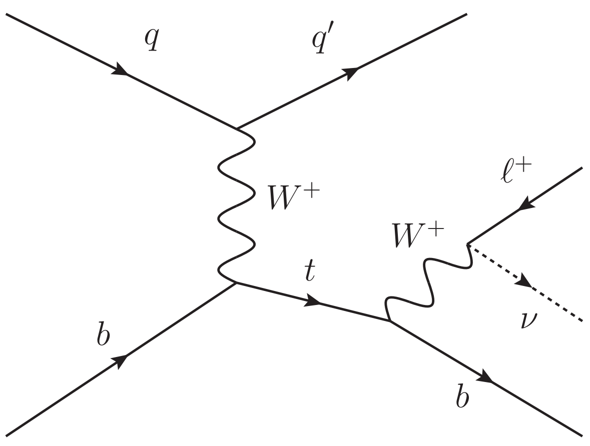
$V_{L,R}$: left/right-handed vector couplings
$g_{L,R}$: left/right-handed tensor couplings
$P_{L,R}$: left/right-handed projection operators

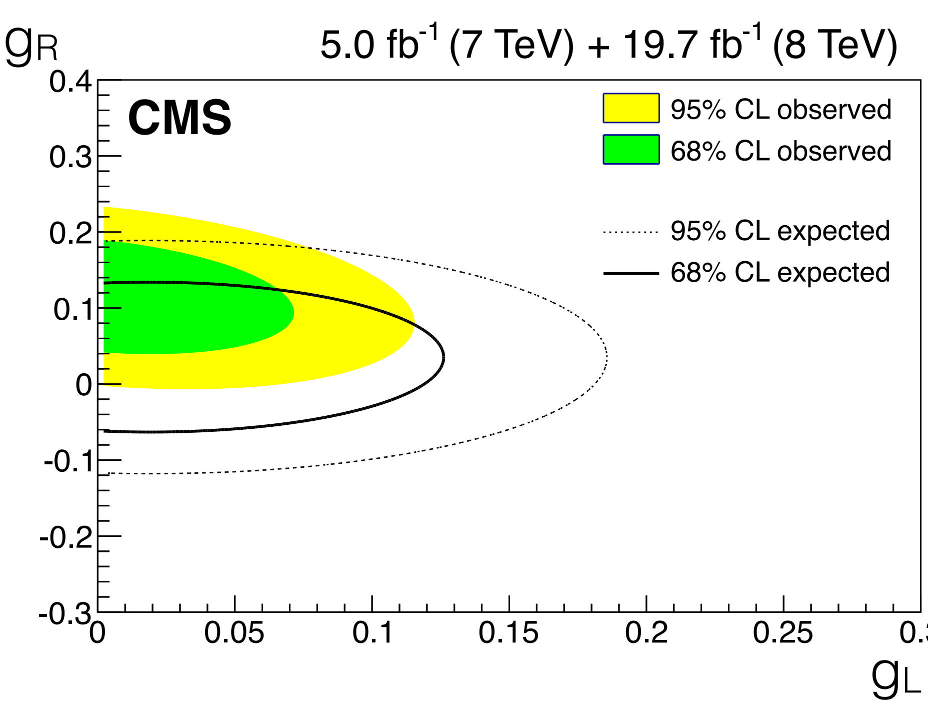
- In SM: $V_L = V_{tb} \sim 1$, $V_R = g_L = g_R = 0$
- Each of these parameters is directly connected to one effective operator coefficient
- Studies of top decays and single-top production
- Tight constraints on V_R, g_L of $\mathcal{O}(10^{-3})$ from B mesons decays

Single-top production

JHEP 02 (2017) 028

- t-channel at 7&8 TeV, W muonic decay
- Selection of t-channel with a Bayesian Neural Network (BNN)
- 3 additionnal BNNs to separate contributions from V_R, g_L, g_R couplings from the SM expectation
- Interference terms between g_L and g_R, V_R and g_R negligible → 3-dimensional analyses performed with V_L allowed to be different than 1
- 95% CL limits:





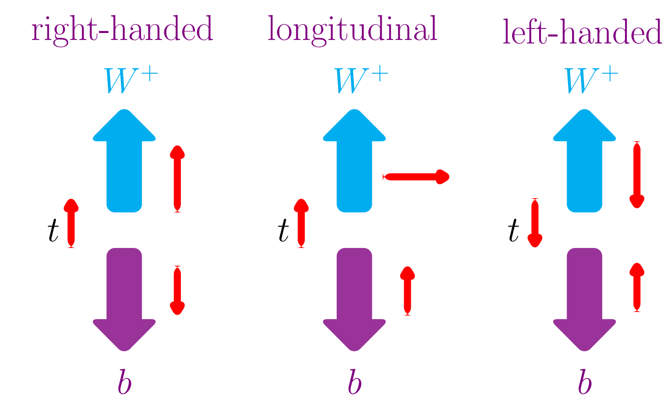
$|V_R|<0.16$ $|g_L| < 0.057$ $-0.049 < g_R < 0.048$

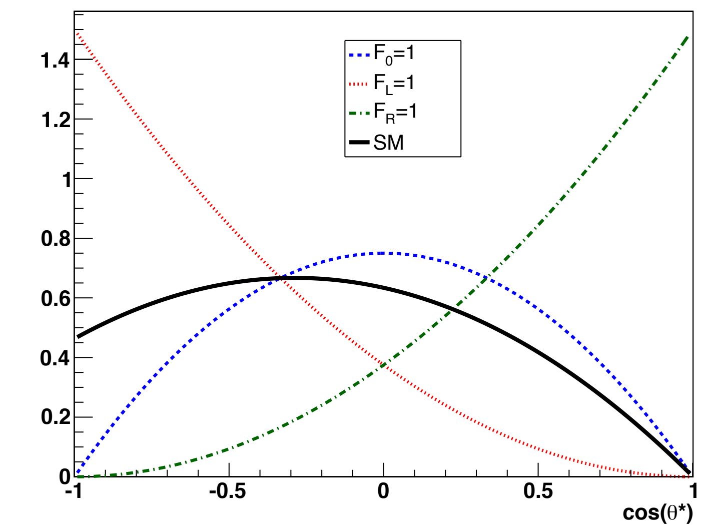
W helicity

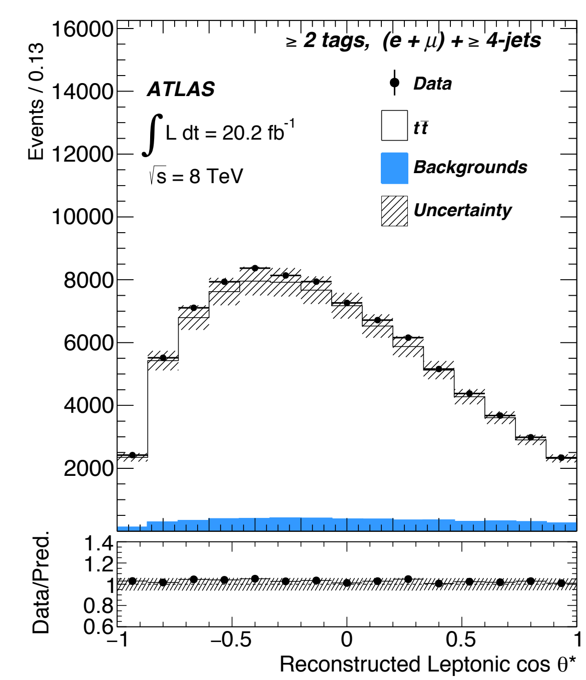
- W boson can be produced in different helicities (spin direction with respect to its motion): left-handed, right-handed or longitudinal
- Studied in top decays through the angle θ* between direction of charged lepton (or down-type quark) and the reverse direction of b quark in W rest frame
- Distribution is fitted with templates for each helicity

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

- Helicity fractions depend on Wtb anomalous couplings
- In these results assumption of CP conservation → real couplings

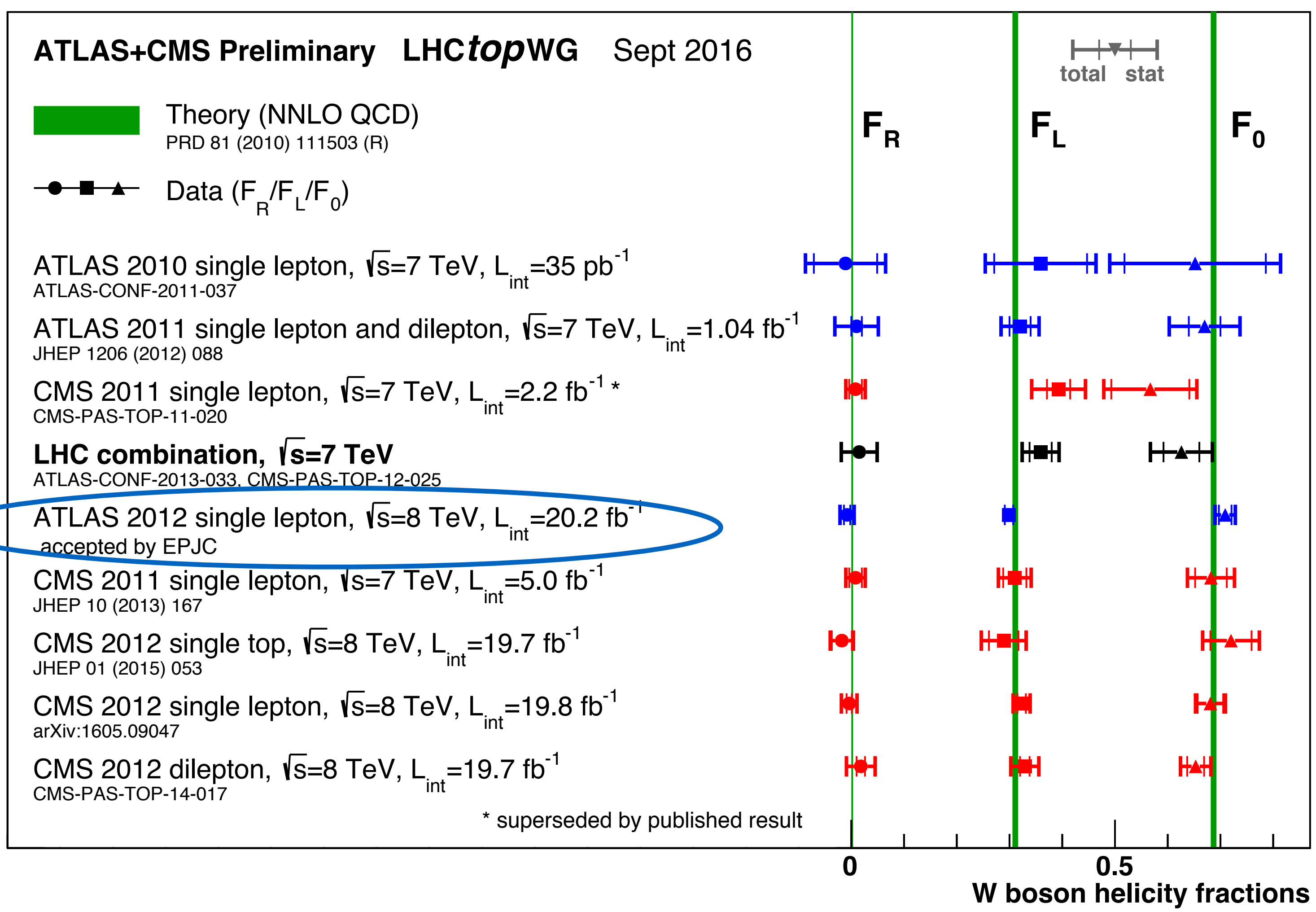




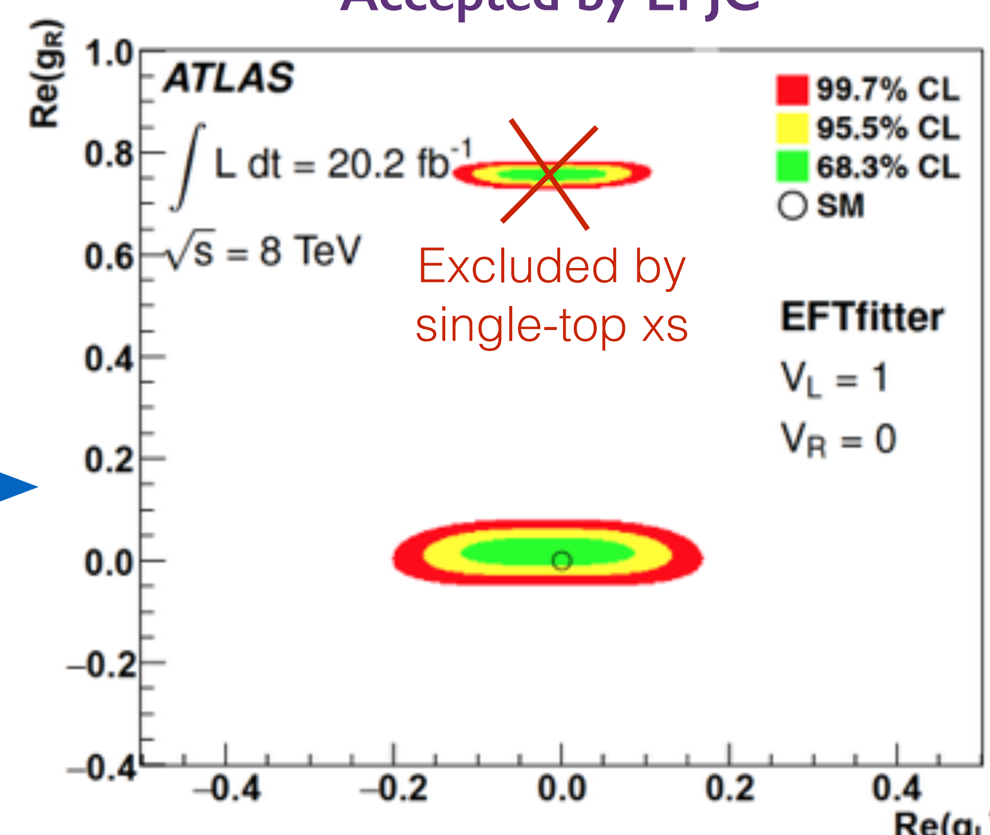


W helicity

- Repetitively measured by both experiments at 7&8 TeV; mainly in ttbar, but also in single-top
- Needs top reconstruction → use of kinematic fits
- Last and most precise result is from ATLAS: ttbar→l+jets; used both leptonic and hadronic decays, but leptonic decay alone gives best limit



arXiv:1612.02577
Accepted by EPJC



$-0.02 < Re(g_R) < 0.06$

Angular asymmetries

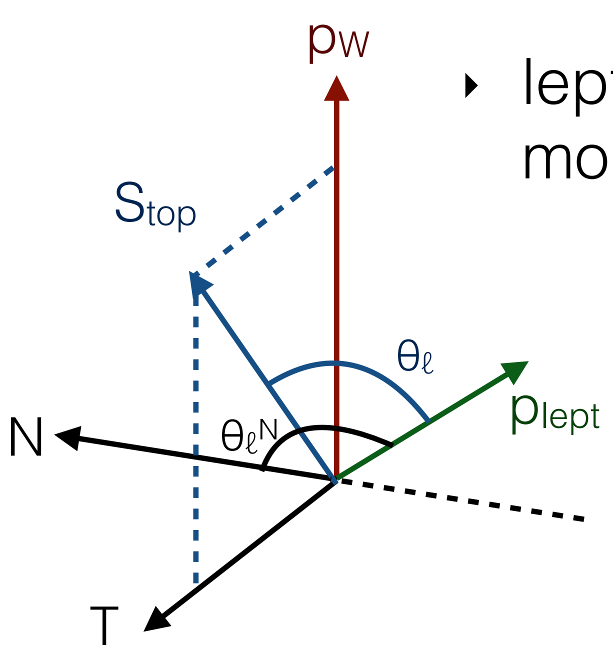
arXiv:1702.08309
Submitted to JHEP

- t-channel at 8 TeV, cut-based selection, leptonic decay of W
- top and W polarisation observables extracted from asymmetries in angular distributions (unfolded to parton-level)
- Limits on **Im(g_R)** from simultaneous measurement of A^N_{FB} and A^ℓ_{FB}

forward-backward asym. of angle θ between:

$$A_{FB} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

- lepton momentum and top spin direction (≡spectator quark direction) for A^ℓ_{FB}
- lepton momentum and normal axis to plane defined by W momentum and top-spin direction for A^N_{FB}



in top quark rest frame

$$A^N_{FB} = 0.64\, P\, Im(g_R) \qquad A^l_{FB} = \frac{1}{2}\alpha_l P$$

P: degree of polarisation of top
α_ℓ: spin analysing power of the lepton

$CL_{95\%}$: -0.18 < Im(g_R) < 0.06

A^ℓ_{FB} and the distribution of $\cos(\theta_\ell)$ have been measured by CMS in JHEP 04 (2016) 073

ttg - spin correlation

Phys. Rev. D 93 (2016) 052007

$$\mathcal{L}_{ttg} = \mathcal{L}_{SM} - \frac{\tilde{\mu}_t}{2}\bar{t}\sigma^{\mu\nu}T^a t G^a_{\mu\nu} - \frac{\tilde{d}_t}{2}\bar{t}i\sigma^{\mu\nu}\gamma_5 T^a t G^a_{\mu\nu}$$

chromo-magnetic and chromo-electric dipole moments

$$\left(\tilde{\mu}_t = \frac{g_s}{m_t}\hat{\mu}_t \;,\; \tilde{d}_t = \frac{g_s}{m_t}\hat{d}_t\right)$$

- ttbar events at 8 TeV
- ttbar spin correlation and top polarization from angular distributions
- Some of the observables have a direct relation with the anomalous couplings
- **$\Delta\Phi_{l+l-}$** difference in azimutal angle of charge leptons in lab. frame, sensitive to spin correl.
- **$A_{\cos\varphi}$** asymmetry in distribution of angle between leptons in rest frame of their top parents, sensitive to spin correl.

$\rightarrow Re(\hat{\mu}_t)$

- **$P^{CPV}=A_{P+}-A_{P-}$** difference in top polarization for +/- charged leptons, 0 if CP-invariance

$\rightarrow Im(\hat{d}_t)$

ttg - spin correlation

Measurements unfolded to parton level

- $\Delta\Phi_{l+l-}$: fit of the distribution with templates functions

  for small NP contribution: $f_{SM}(\Delta\Phi) + Re(\mu t) * f_{NP}(\Delta\Phi)$

  $-0.053 < Re(\mu_t) < 0.042$

- $\mathbf{D = -2\ A_{\cos\varphi}} = D_{SM} + Re(\mu_t) * D_{NP}$

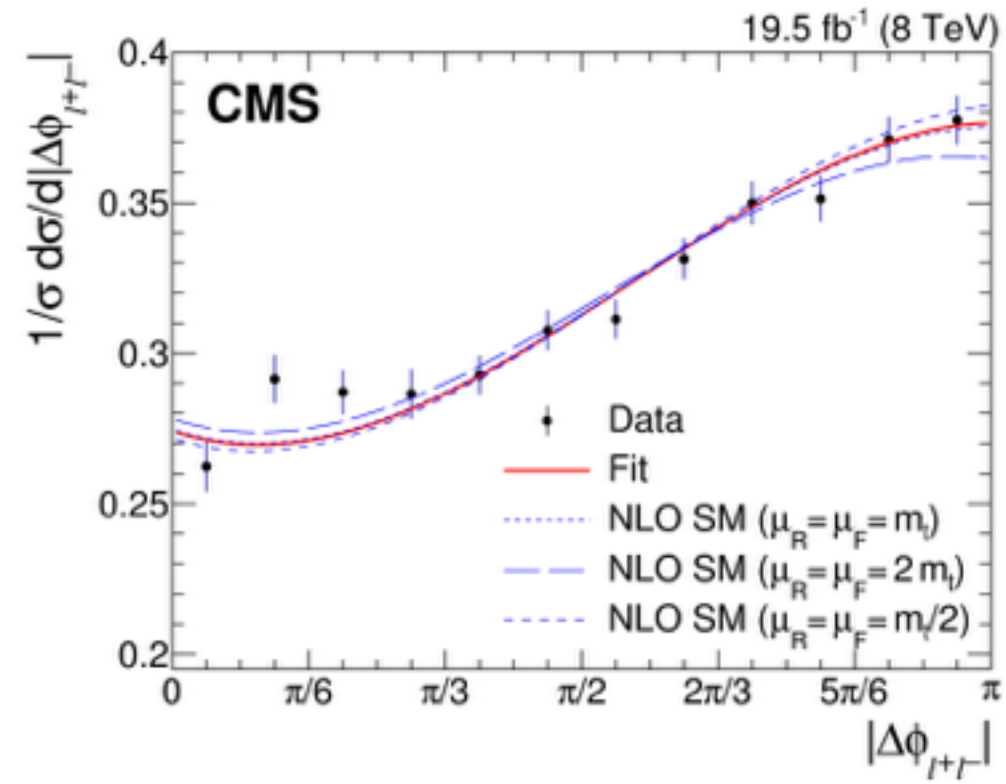
  $D = 0.205 \pm 0.031$

  $-0.053 < Re(\mu_t) < 0.026$

- $\mathbf{P^{CPV} = A_{P+} - A_{P-}} = Im(d_t) * P^{CPV}_{NP}$

  $P^{CPV} = 0.000 \pm 0.016$

  $-0.068 < Im(d_t) < 0.067$



stronger constraint, because smaller theoretical uncertainty in SM NLO

- Measurement of a full set of 15 top-quark spin observables (polarisations+correlations) in ttbar events

- Will allow to probe all the coefficients of the ttbar spin-density matrices and puts limits on anomalous couplings neglected in the Lagrangian previously shown

ATLAS EXPERIMENT

JHEP 03 (2017) 113

ttZ coupling - ttZ/W x-sections

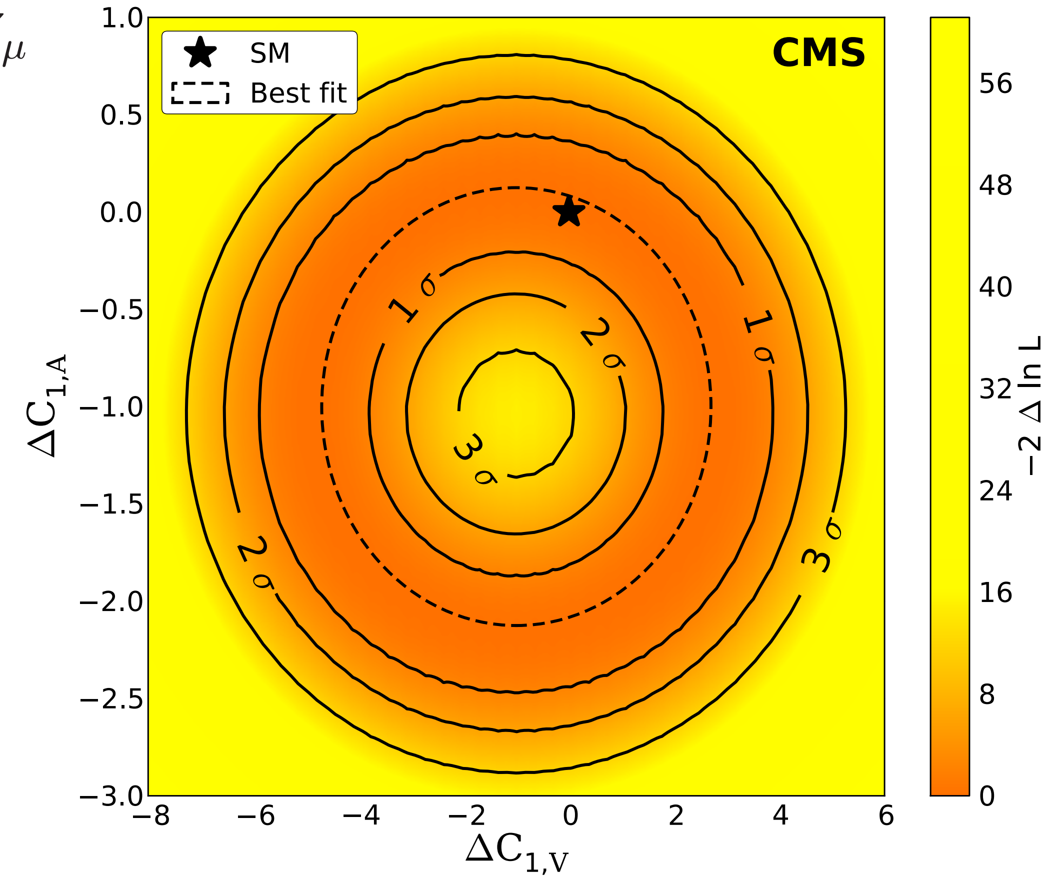
JHEP 01 (2016) 096

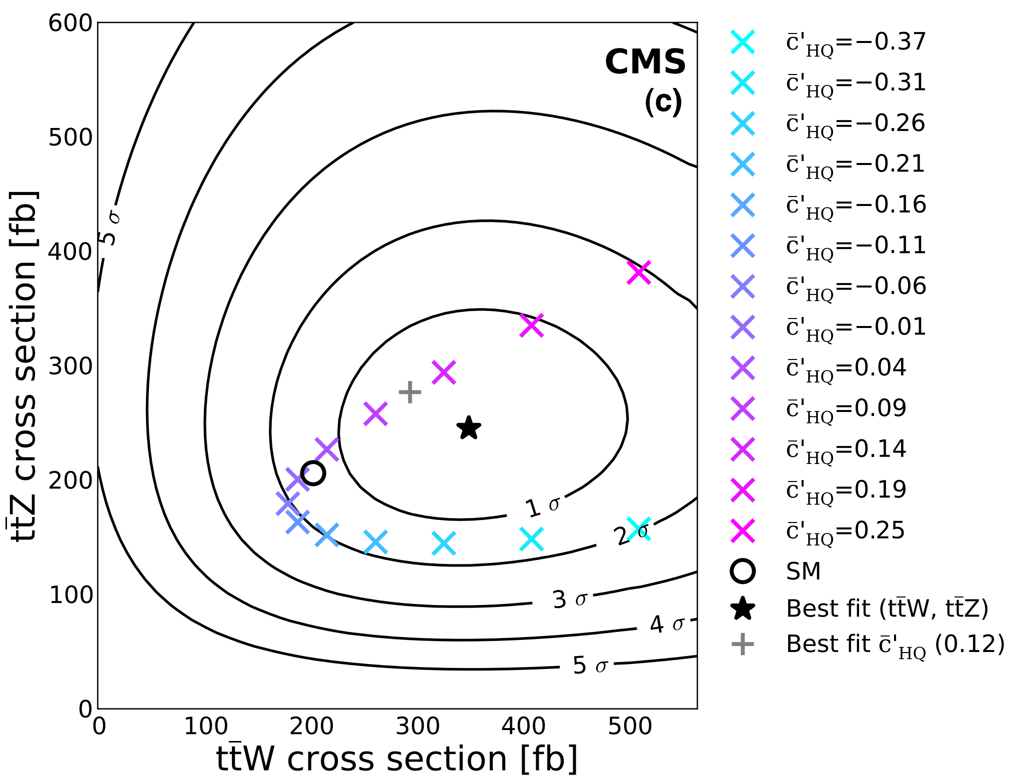
$$\mathcal{L}_{t\bar{t}Z} = e\bar{u}(p_t)\left[\gamma^\mu\left(C_{1,V} + \gamma_5 C_{1,A}\right) + \frac{i\sigma_{\mu\nu}q_\nu}{M_Z}\left(C_{2,V} + i\gamma_5 C_{2,A}\right)\right]v(p_{\bar{t}})Z_\mu$$

neglected

- $C_{1,V/A}$ vector and axial couplings depends on three dim-6 operators + SM component
- From ttZ xs at 8 TeV → contours on $\Delta C_{1,V/A}$

with $\Delta C = \frac{C}{C^{SM}} - 1$





ttZ/W x-sections

- Constraints directly on dim-6 operators with simultaneous fit of ttZ and ttW x-sections
- Selected 5 operators that does not influence H and ttbar productions
- Vary only one operator at a time. Operators impact only ttZ, only ttW or both

Top quark FCNC couplings

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

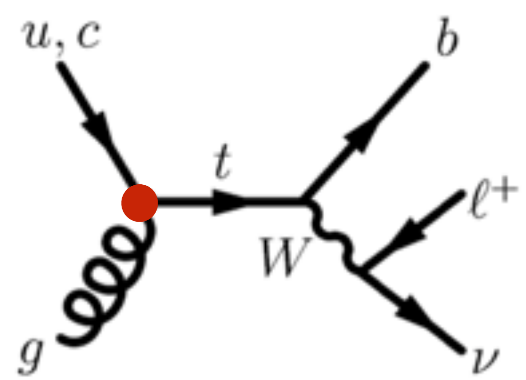
neglected here

- Flavor Changing Neutral Currents are largely suppressed in SM $\mathcal{O}(10^{-14})$ by GIM mechanism
- With approximations, only 1 parameter per coupling
- Limits given on branching ratios for better comparison. Different conventions are used to define the coupling parameters
- These couplings are studied both in top production and decay, depending on analyses
- More sensitivity on couplings u (compared to c) because larger cross sections

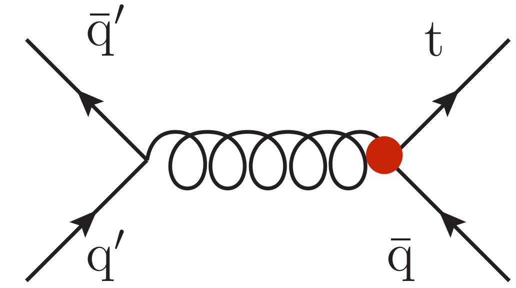
tgq coupling

Eur. Phys. J. C76 (2016) 55

JHEP 02 (2017) 028



- Look for anomalous single-top production
- Kinematic difference with SM: lower top p_T



Unlike SM channels, search for **top quark produced singly** without associated particles

- Leptonic decays of W
- Multi-jet bkg normalisation from a data-template fit of MET
- Top reconstruction
- Enhance signal extraction using NN

ATLAS

BR(t->gu) < 4.10^{-5}

BR(t->gc) < 2.10^{-4}

Final state similar to SM single-top in t-channel

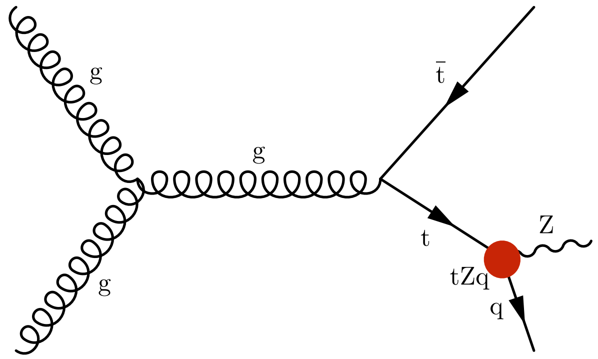
- Only W→μν
- Multi-jet normalisation from fit of BNN output used to reject it
- Top reconstruction
- BNN to distinguish FCNC production
- Combination of 7&8 TeV data

BR(t->gu) < 2.10^{-5}

BR(t->gc) < 4.10^{-4}

CMS

tZq coupling



Eur. Phys. J. C76 (2016) 12
Phys. Rev. Lett. 112 (2014) 171802

Results from **top decays in ttbar events** (from both experiments)

- Looking for events with one top decaying to Zq (q= u or c)
- Similar analyses. Different ways to optimize assignments of particles to tops.
- CMS results is combined with 7TeV result

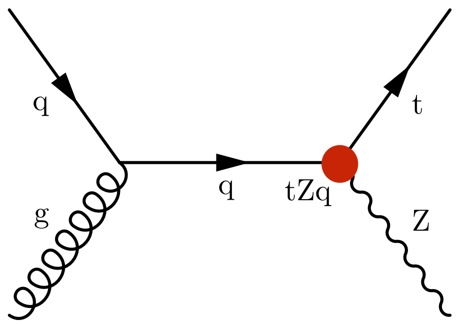
ATLAS **BR(t->Zq) < 7.10^{-4}**

CMS **BR(t->Zq) < 5.10^{-4}**

Search for a **t+Z production** by CMS

arXiv:1702.01404
Submitted to JHEP

- t+Z possible via tZq and tgq couplings. Poor sensitivity on tgq compared to other channels, so not considered in the analysis
- Look also for ttbar ->Zq Wb and combine results in a common fit
- Channels:
  - trilepton final state + 1-b-jet for t+Z
  - trilepton finale state + >= 2 jets (with >= 1b-jet) for ttbar
- Result from the simultaneous fit of the BDT discriminants of both channels with templates



BR(t->Zu) < 2.10^{-4}

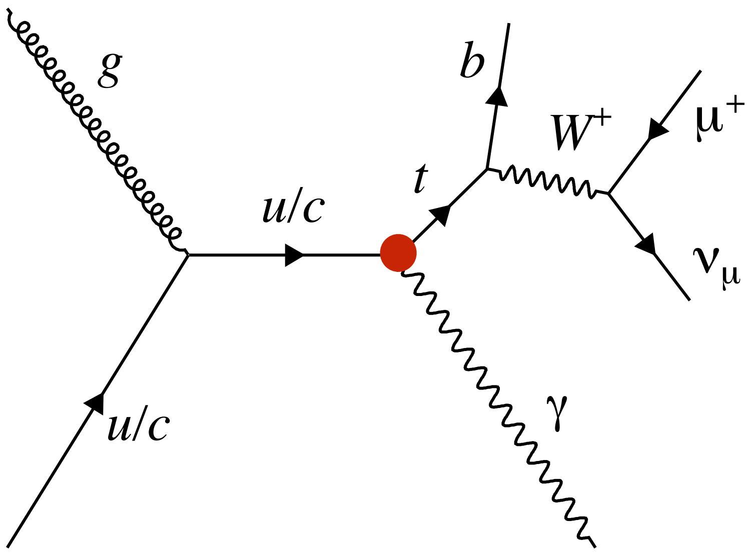
BR(t->Zc) < 5.10^{-4}

tγq coupling

JHEP 04 (2016) 035

tγ production with t→Wb and W→μν

- High p_T photon
- Main backgrounds W+jets and Wγ+jets estimated from data
- Top fully reconstructed
- Signal extraction with a BDT
- Separate training for tγu and tγc
- Limits on BR and measurement of a fiducial cross-section

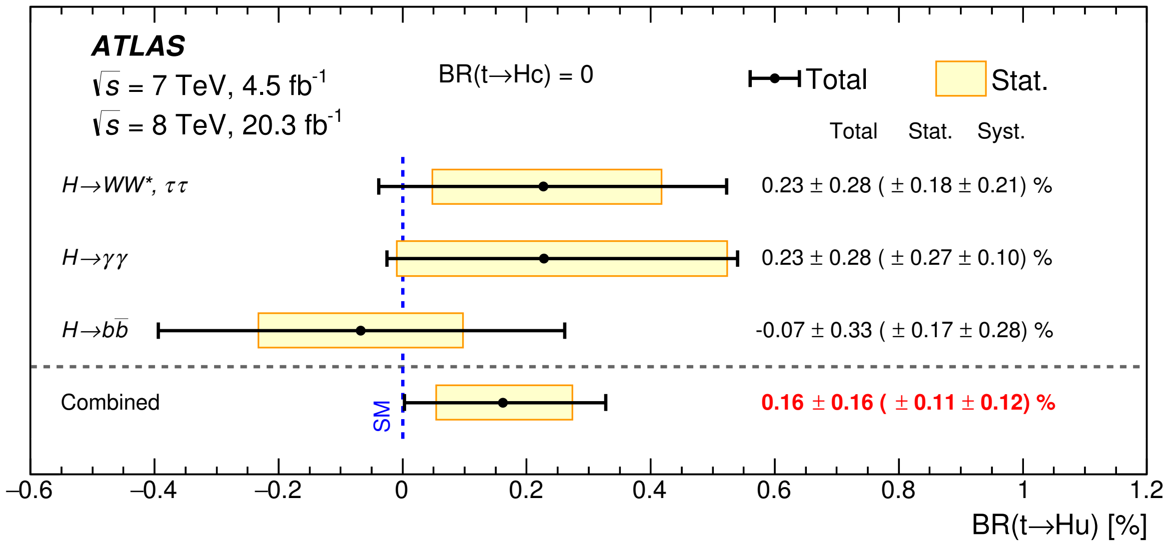


BR(t->γu) < 1.3×10^{-4}　　**BR(t->γc) < 1.7×10^{-3}**

tHq coupling

JHEP 12 (2015) 061

JHEP 02 (2017) 079



ATLAS:

Re-interpretation of some channels of ttH analysis for the H→WW,ττ channel

CMS:

No hadronic taus taken into account

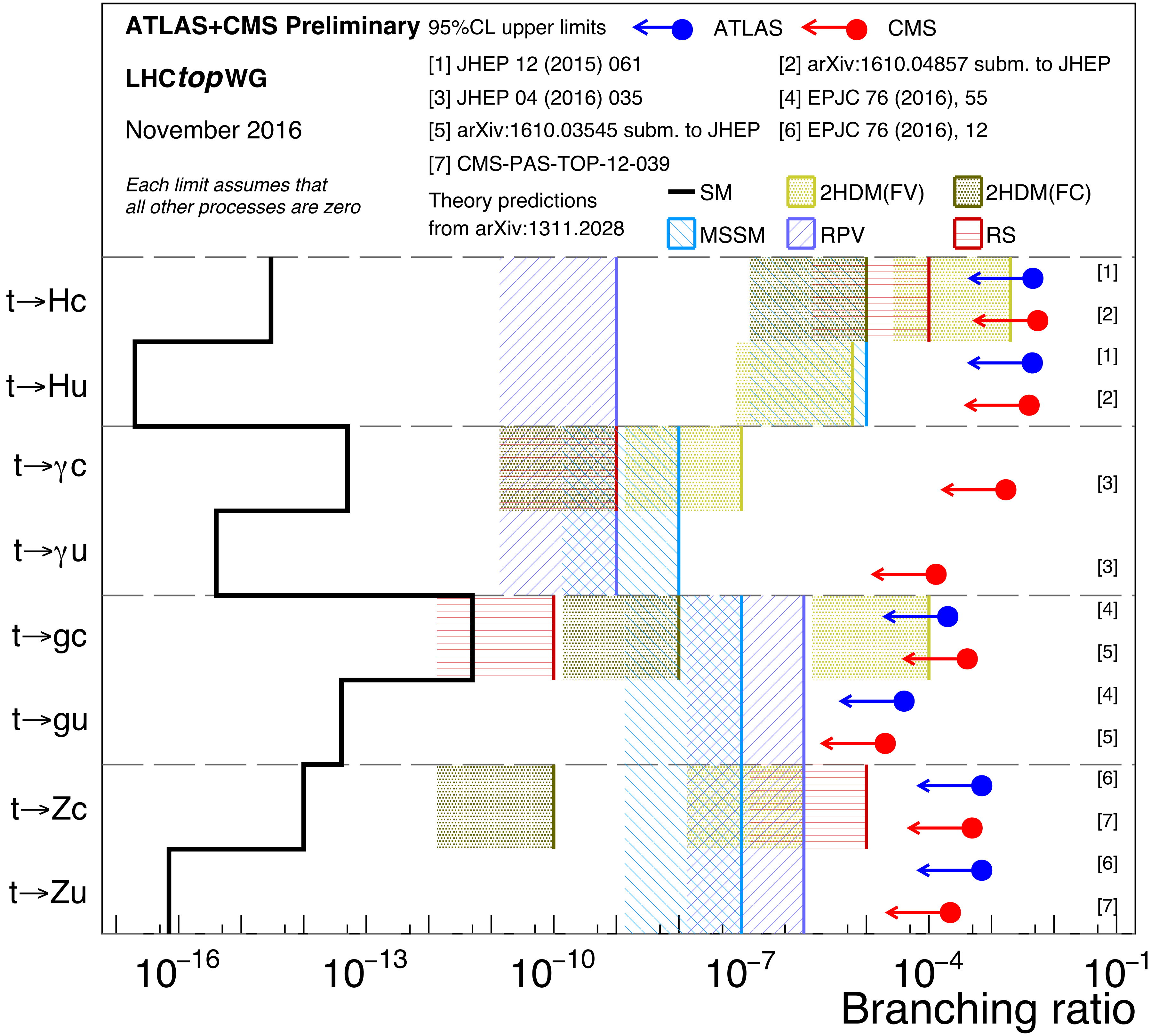
Combination results of search of top decay t→Hq with H→bb, γγ, WW, ττ in ttbar events

- H→γγ is the most sensitive channel, with a better background estimation (from sideband)
- H→bb has largest branching ratio, but large multi-jet background. Advanced techniques to find the right jet combination to reconstruct tops
- Different sensitivities to u/c because of b-jets in final state and different mis-tagging rates
- H→WW,ττ : multi-lepton channels (2 same-sign and 3 leptons channels)

ATLAS **BR(t->Hu) < 4.5x10^{-3}**
BR(t->Hc) < 4.6x10^{-3}

CMS **BR(t->Hu) < 4.0x10^{-3}**
BR(t->Hc) < 5.5x10^{-3}

Top quark FCNC couplings



Summary

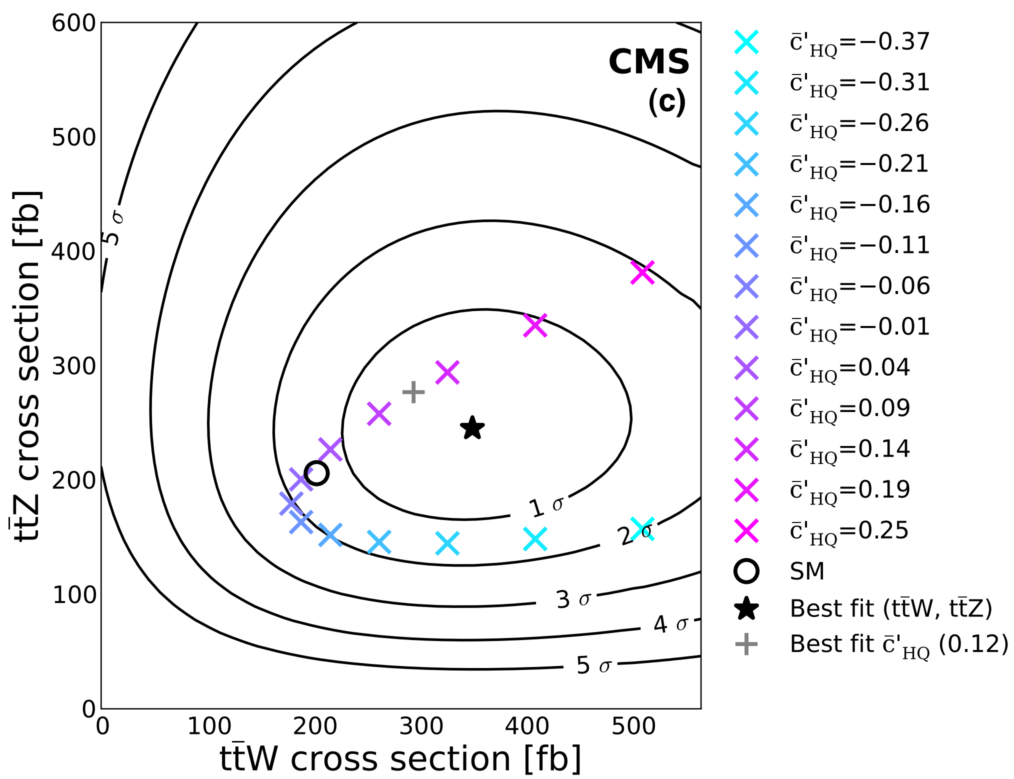
- Large set of results of anomalous top production or impacts on top properties
- Allows to set limits on anomalous couplings, and so on new physics models
- Limits will be strengthened with 13 TeV data

back-up

ttZ / ttW cross-sections

arXiv:1510.01131

- Measured at 8 TeV using leptonic decays of Z/W
- Exclusive channels by lepton charge, flavor and number of jets
- Full event reco of ttbar using a linear discriminant for matching scores. Signal extraction with BDT
- Constraints directly on dim-6 operators with simultaneous fit of ttZ / ttW x-sections
- Selected 5 operators that does not influence H and ttbar productions
- Vary only one operator at a time. Operators impact only ttZ, only ttW or both



Operator	2 standard deviation CL
$\bar{c}_{\mathrm{uB}}$	$[-0.14, 0.14]$
$\bar{c}_{\mathrm{3W}}$	$[-0.43, 0.43]$
$\bar{c}'_{\mathrm{HQ}}$	$[-0.33, -0.24]$ and $[-0.02, 0.23]$
$\bar{c}_{\mathrm{Hu}}$	$[-0.71, 0.37]$
$\bar{c}_{\mathrm{HQ}}$	$[-0.31, 0.63]$

Systematics limiting the sensitivity

- Single-top anomalous production
  - similar magnitude for signal modeling and objects systematics
- W helicity
  - leptonic channel: JES, JER, stat on MC templates, signal modelling
  - hadronic channel: b-tagging, JER, ttbar modeling
- Angular asymmetry
  - for A^{N}_{FB} : simulation statistics, jet reco resolution & efficiency, SM top events modeling
- ttbar spin correlation
  - for $A_{\Delta\Phi}$: top quark p_T modeling
  - for P^{CPV} : unfolding (simulation statistical)
- ttZ/ttW x-sections
  - b-tagging, signal modeling; for ttW: rates of non-prompt bkg (from loosened lepton id)

Systematics limiting the sensitivity

- tgq
  - ATLAS: JES, MET modeling (fitted to normalize backgrounds), normalisation and modeling of multi-jet background
  - CMS: similar magnitude for signal modeling and objects systematics
- tZq
  - with tt events: generator parameters
- tγq
  - tγu: background normalisation (W+jets), pile-up effects
  - tγc: several effects of same magnitude
- tHq
  - H->γγ: background simulation, tt x-section
  - H->bb: jet tagging, JES, ttbb and tt modeling
  - H->WW,ZZ: backgrounds normalization, lepton mis-id