MEASUREMENT OF TOP QUARK PROPERTIES AND EFT INTERPRETATIONS

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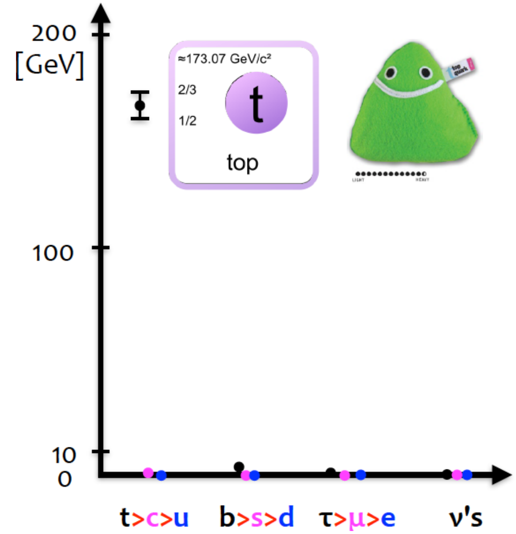
On behalf of the ATLAS and CMS Collaborations
HEFT2016 workshop, 26-28 October 2016, Copenhagen



- Top quark is the heaviest known fundamental particle.

It has the largest coupling with the SM Higgs

$\lambda_{top} = \sqrt{2}m_{top}/v \approx 1$, so it plays a special role in EWSB.

- Top quark is a short lived particle:

$\Gamma_{top} = 1.4$ GeV corresponding to $\tau_{top} \approx 10^{-25}$ s $<< 10^{-23}$ s
→ It decays before hadronization.

- Top has a distinctive event signature. It decays almost exclusively to t → W+b

Small branching fraction for the other decay modes: B(t→Ws)=0.18%, B(t→Wd)= 0.02%.

- The measurement of the top quark properties provides a powerful test of the SM.

Precision test of perturbative QCD to high orders, PDF and PS.

- Hints of BSM: new particles W',Z' … could decay preferentially to top quarks.

Processes including top are backgrounds for new physics such as stop→t+LSP.
New physics could be looked for using the effective field theory approach which affects top quark production and decay.

-Measurements of total and differential cross sections of top pair production at the LHC and single top quark production.

-The top quark charge, mass, and spin.

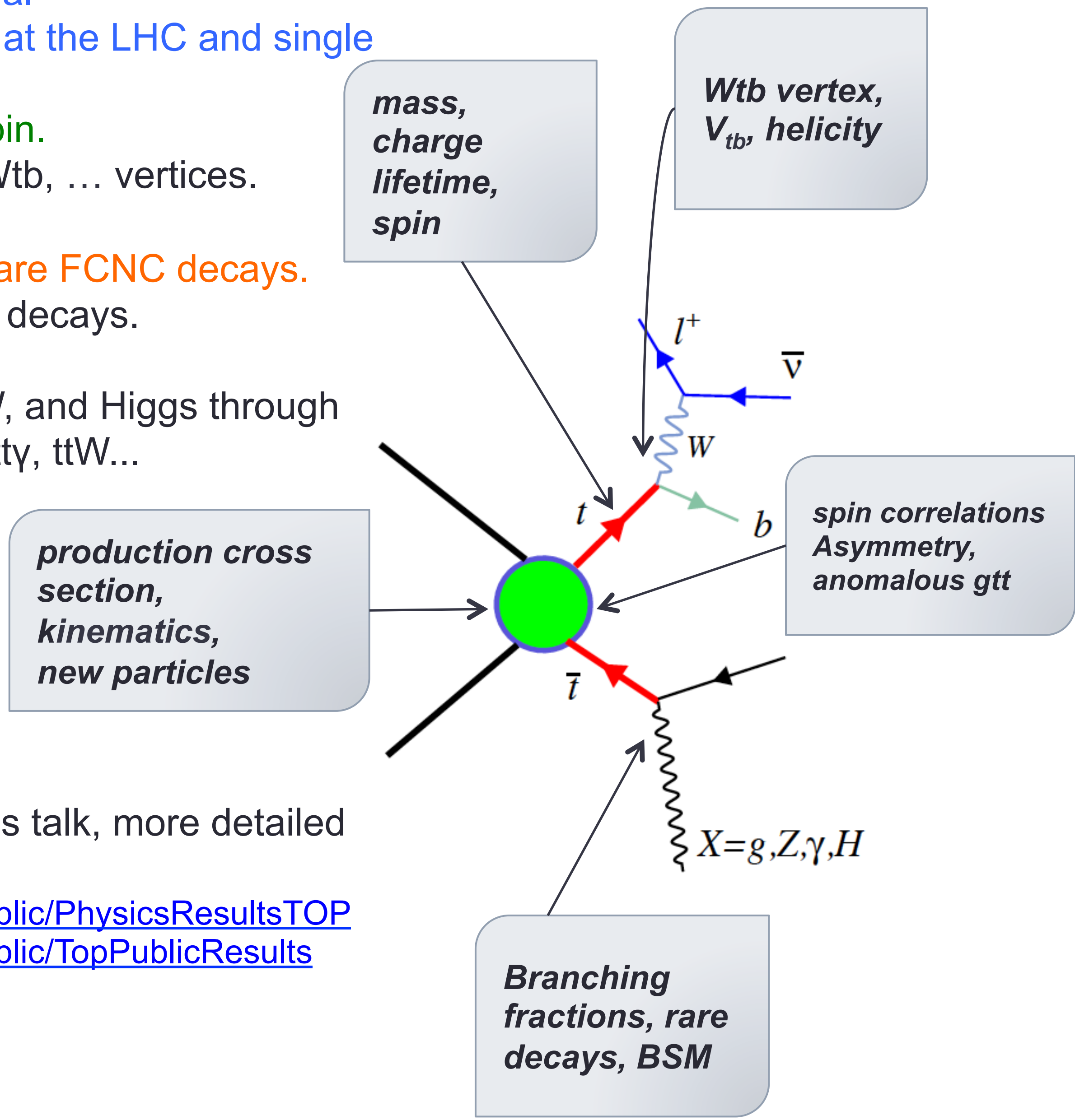
-Exploring the structures of gtt and Wtb, … vertices.

-V_{tb} measurement.

-Top quark branching fractions and rare FCNC decays.

-Helicity of the W-boson in top quark decays.

-Top quark couplings to photon, Z, W, and Higgs through studying associated productions ttZ,ttγ, ttW...

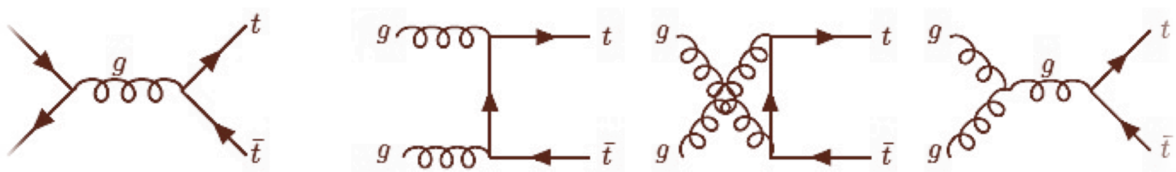


Some of the topics are covered in this talk, more detailed results could be found in:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

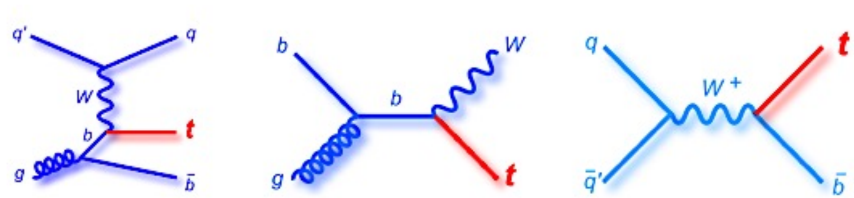
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

Pair production:



-Dominant production mode.
-Gluon fusion is the dominant contribution.
-Cross section = 177.3 pb @ 7 TeV, 252.9 pb @ 8 TeV, and 831.8 pb @ 13 TeV (calculated for a top quark mass of 172.5 GeV at NNLO in QCD with Top++ v2.0.)
-The cross section increased by a factor of more than 3 when moving to the center-of-mass energy of 13 TeV.

Single top production:



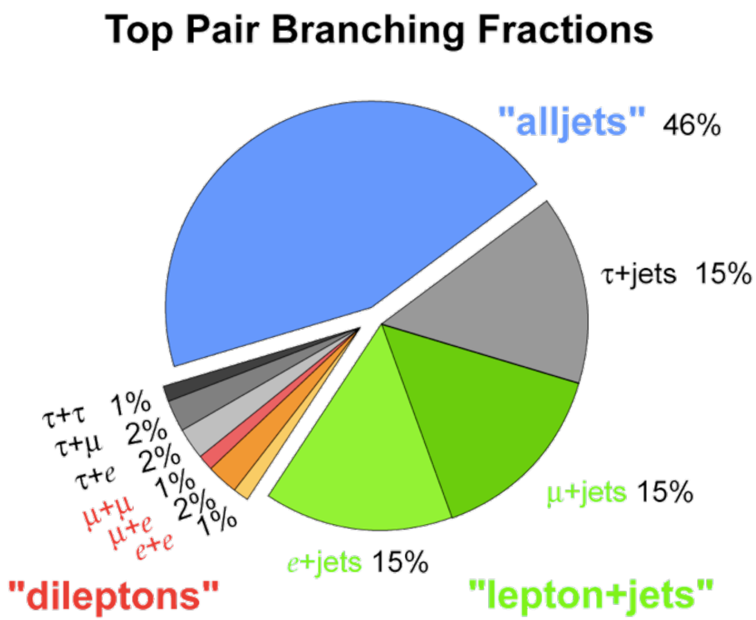
t-channel (*Wt*-prod.) (*s*-channel)

-EW production (sensitive to V_{tb})
-Test of physics BSM (FCNC , new resonances)

c.o.m energy	t-channel	s-channel	tW-channel
7 TeV	63.9 pb	4.29 pb	15.74 pb
8 TeV	84.7 pb	5.24 pb	22.37 pb
13 TeV	217.0 pb	10.3 pb	71.7 pb

The cross sections are increased by a factor 2-3 when going to the energy of 13 TeV.

Calculated for a top quark mass of 172.5 GeV at NLO in QCD with Hathor v2.1



30% l+jets

l=e,μ

- Isolated high p_T lepton.
- missing energy (E^T_{miss}).
- 2 b-jet from top decay.
- 4 high p_T jets.

-high branching ratio.
-reasonable S/B.
-main background: W+jets.

4% di-leptonic

- 2 Isolated high p_T leptons.
- missing energy (E^T_{miss}).
- 2 b-jet from top decay.

-small branching ratio.
-very good S/B.
-there are 3 main channels: ee , μμ, e μ.

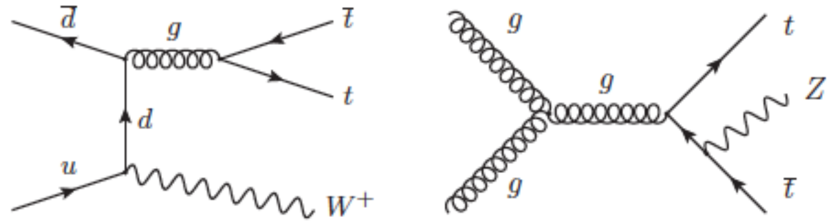
46% all hadronic

- 2 b-jet from top decay.
- 6 high p_T jets.

-large QCD background.
-the largest branching ratio.

Studying ttbar+V (V=Z,W) is very important as:

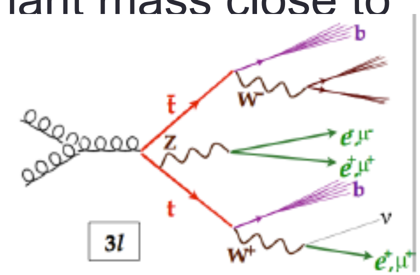
- ttZ and ttW backgrounds to new physics searches and ttH.
- Both σ(ttW) and σ(ttZ) would be altered in a variety of new physics models that can be parameterized by dimension-six operators added to the SM Lagrangian.

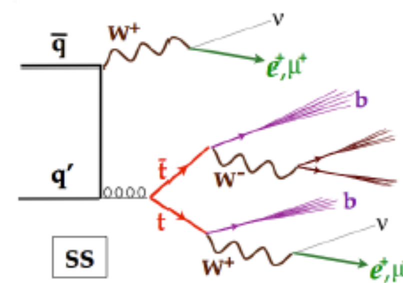


Dominant production processes at leading order.

- The ttZ process is measured in channels with two, three, or four leptons, with exactly one pair of same-flavor opposite-sign leptons with an invariant mass close to the Z boson mass.

- The ttW process is measured in channels with two same-sign leptons or three leptons, where no lepton pair is consistent with coming from a Z boson decay.





Most sensitive:

3 leptons to ttZ, 2 leptons SS to ttW.

Cross sections are extracted for ttZ and ttW simultaneously in a binned profile likelihood fit using multi-lepton final state (e+μ) channels:

$\sigma(ttZ) = 176^{+52}_{-48}(stat) \pm 44(syst)$ fb

$\sigma(ttW) = 369^{+86}_{-79}(stat) \pm 44(syst)$ fb

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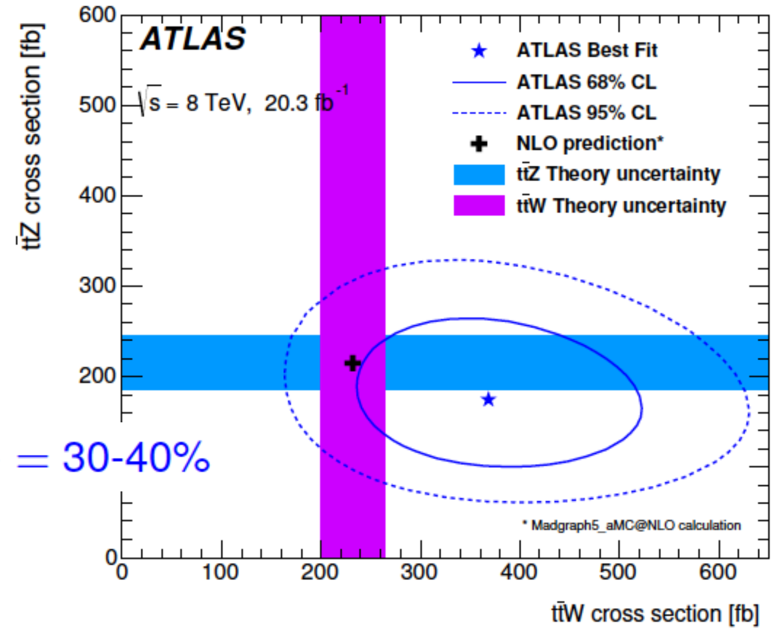


$\Delta\sigma_{t\bar{t}V}/\sigma_{t\bar{t}V} =$ 30-40%

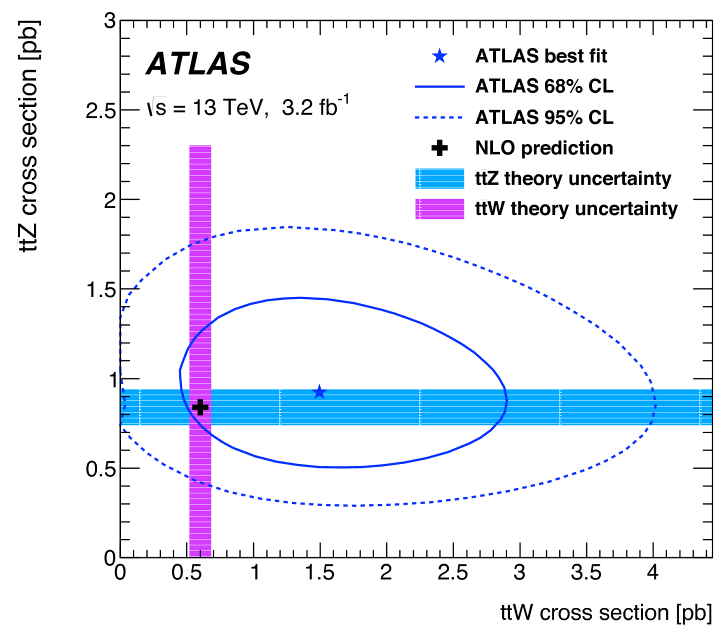
8 TeV

Channel	$t\bar{t}W$ significance Expected	$t\bar{t}W$ significance Observed	$t\bar{t}Z$ significance Expected	$t\bar{t}Z$ significance Observed
2ℓOS	0.4	0.1	1.4	1.1
2ℓSS	2.8	5.0	-	-
3ℓ	1.4	1.0	3.7	3.3
4ℓ	-	-	2.0	2.4
Combined	3.2	5.0	4.5	4.2

Also measured at **13 TeV** with 2015 data (3.2/fb)

- σ(ttZ) = 0.9 ± 0.3 pb (3.9σ) (1σ)
- σ(ttW) = 1.5 ± 0.8 pb (2.2σ) (3.4σ)

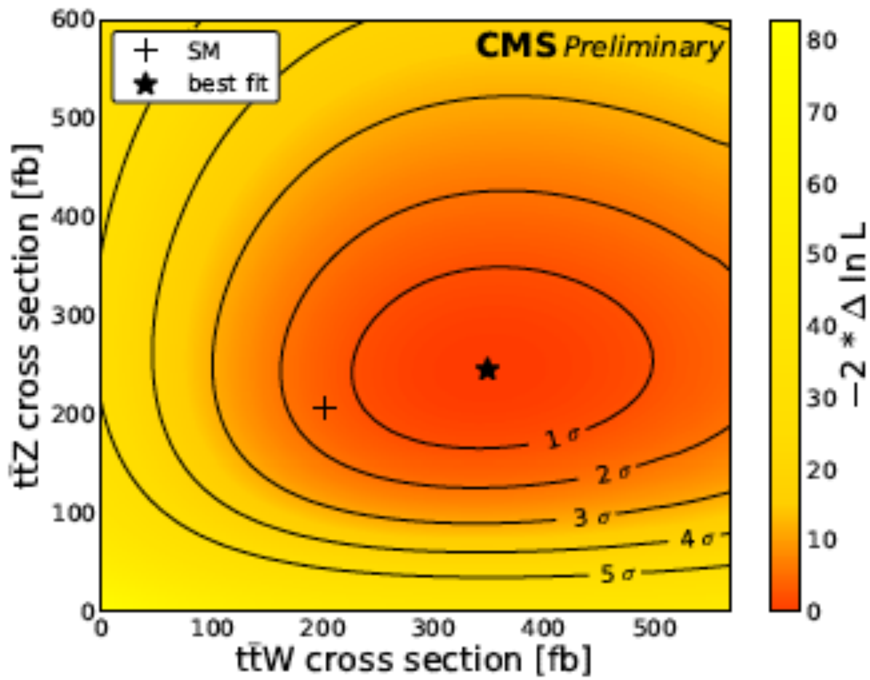
arXiv:1609.01599



CMS @ 8 TeV, 19.5/fb, CMS-PAS-TOP-14-021

$\sigma(ttZ) = 176^{+52}_{-48}(\text{stat}) \pm 44(\text{syst})$ fb (4.8σ)

$\sigma(ttW) = 369^{+86}_{-79}(\text{stat}) \pm 44(\text{syst})$ fb (6.4σ)



$\Delta\sigma_{t\bar{t}V}/\sigma_{t\bar{t}V} =$ 20-30%, sig. of $4.8\sigma(6.4\sigma)$ over back. for $t\bar{t}W(t\bar{t}Z)$

CMS @ 13 TeV, 12.9/fb, CMS-PAS-TOP-16-017

$\sigma(ttZ) = 0.7^{+0.16}_{-0.15}(\text{stat})^{+0.14}_{-0.12}(\text{syst})$ pb with the observed significance of 3.9σ

$\sigma(ttW) = 0.98^{+0.23}_{-0.22}(\text{stat})^{+0.22}_{-0.18}(\text{syst})$ pb with the observed significance of 4.6σ

All measurements are in agreement with SM predictions (statistically limited) so interpretation of ttZ cross section in terms of constraints to new physics within the framework of an effective field theory could be done.

The effective Lagrangian can be written as an expansion in the inverse of the cutoff energy scale, 1/Λ:

$$\mathcal{L}^{\text{eff}} = \sum \frac{C_x}{\Lambda^2} O_x + \dots$$

O_x = dim 6 gauge invariant operators

The vector and axial couplings of Ztt C^{SM}_V and C^{SM}_A receive some contributions from the dimension six operators:

$$C_{1,V} = C_V^{\text{SM}} + \frac{1}{4\sin\theta_w\cos\theta_w}\frac{v^2}{\Lambda^2}\text{Re}[\bar{c}'_{HQ} - \bar{c}_{HQ} - \bar{c}_{Hu}],$$

$$C_{1,A} = C_A^{\text{SM}} - \frac{1}{4\sin\theta_w\cos\theta_w}\frac{v^2}{\Lambda^2}\text{Re}[\bar{c}'_{HQ} - \bar{c}_{HQ} + \bar{c}_{Hu}].$$

JHEP01(2016)096

Using the measured cross sections, limits have been placed on the vector and axial couplings of the Z boson to the top quark, and on the Wilson coefficients of five dimension-six operators parameterizing new physics:

Operator	Best fit point(s)	1 standard deviation CL	2 standard deviation CL
$\bar{c}_{uB}$	−0.07 and 0.07	[−0.11, 0.11]	[−0.14, 0.14]
$\bar{c}_{3W}$	−0.28 and 0.28	[−0.36, −0.18] and [0.18, 0.36]	[−0.43, 0.43]
$\bar{c}'_{HQ}$	0.12	[−0.07, 0.18]	[−0.33, −0.24] and [−0.02, 0.23]
$\bar{c}_{Hu}$	−0.47 and 0.13	[−0.60, −0.23] and [−0.11, 0.26]	[−0.71, 0.37]
$\bar{c}_{HQ}$	−0.09 and 0.41	[−0.22, 0.08] and [0.24, 0.54]	[−0.31, 0.63]

JHEP01(2016)096

The most general, lowest-dimension, CP-conserving Lagrangian for the Wtb vertex has the following form:

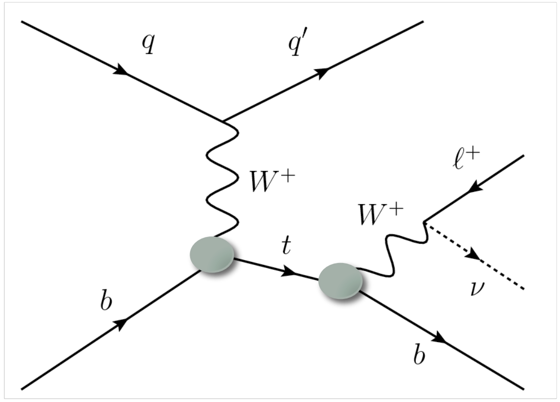
$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\,(V_{\rm L}P_{\rm L} + V_{\rm R}P_{\rm R})\,t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\,(g_{\rm L}P_{\rm L} + g_{\rm R}P_{\rm R})\,t\,W_{\mu}^{-}$$

$V_L = V_{tb}$ and Vector (V_R) and Tensor like couplings (g_L, g_R) zero @ tree level in SM.
-Deviations from zero would provide hints of new physics.
-Complex values could imply top quark decay has a CP-violating component.

New effective Wtb coupling can affect:

-The t-channel single top quark production.

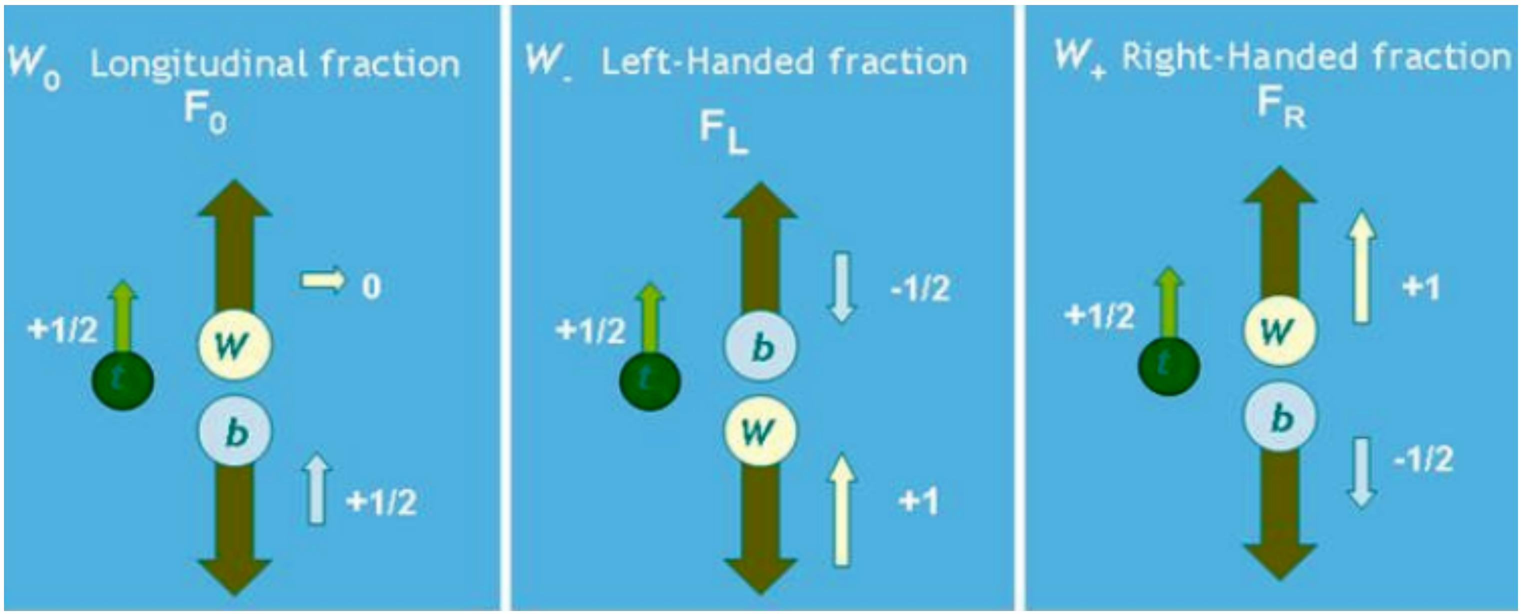
$$\sigma = \sigma_{\rm SM}\left(V_L^2 + \kappa^{V_R}\,V_R^2 + \kappa^{V_L V_R}\,V_L V_R + \kappa^{g_L}\,g_L^2 + \kappa^{g_R}\,g_R^2 + \kappa^{g_L g_R}\,g_L g_R + \ldots\right)$$



-W helicity fractions.

-Single top polarization, asymmetries.

The W boson helicity fractions are defined as the partial decay rate for a given helicity state divided by the total decay rate:
$F_{L,R,0} = \Gamma_{L,R,0}/\Gamma_{top}$, where F_L, F_R, and F_0 are the left-handed, right-handed, and longitudinal helicity fractions, respectively.



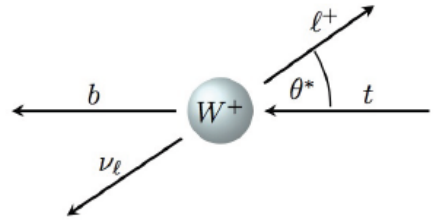
$$F_0^{SM} = 0.687 \pm 0.005 \quad F_L^{SM} = 0.311 \pm 0.005 \quad F_R^{SM} = 0.0017 \pm 0.0001,$$
$$(F_0 + F_L + F_R = 1)$$

@ NNLO QCD calculation, Phys. Rev. **D81** (2010) 111503

W helicity, anomalous Wtb coupling

Experimentally, the W boson helicity can be measured through the study of angular distributions of the top quark decay products. The distribution for the cosine of the helicity angle depends on the helicity fractions:

$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*_\ell} = \frac{3}{2}\left[F_0\left(\frac{\sin\theta^*_\ell}{\sqrt{2}}\right)^2 + F_\mathrm{L}\left(\frac{1-\cos\theta^*_\ell}{2}\right)^2 + F_\mathrm{R}\left(\frac{1+\cos\theta^*_\ell}{2}\right)^2\right]$$



$\theta^*_\ell \rightarrow$ the angle between the ℓ (in W rest frame) and the W (in t rest frame)

CMS-TOP-13-008, ttbar, l+jets, 19.8/fb @ 8TeV

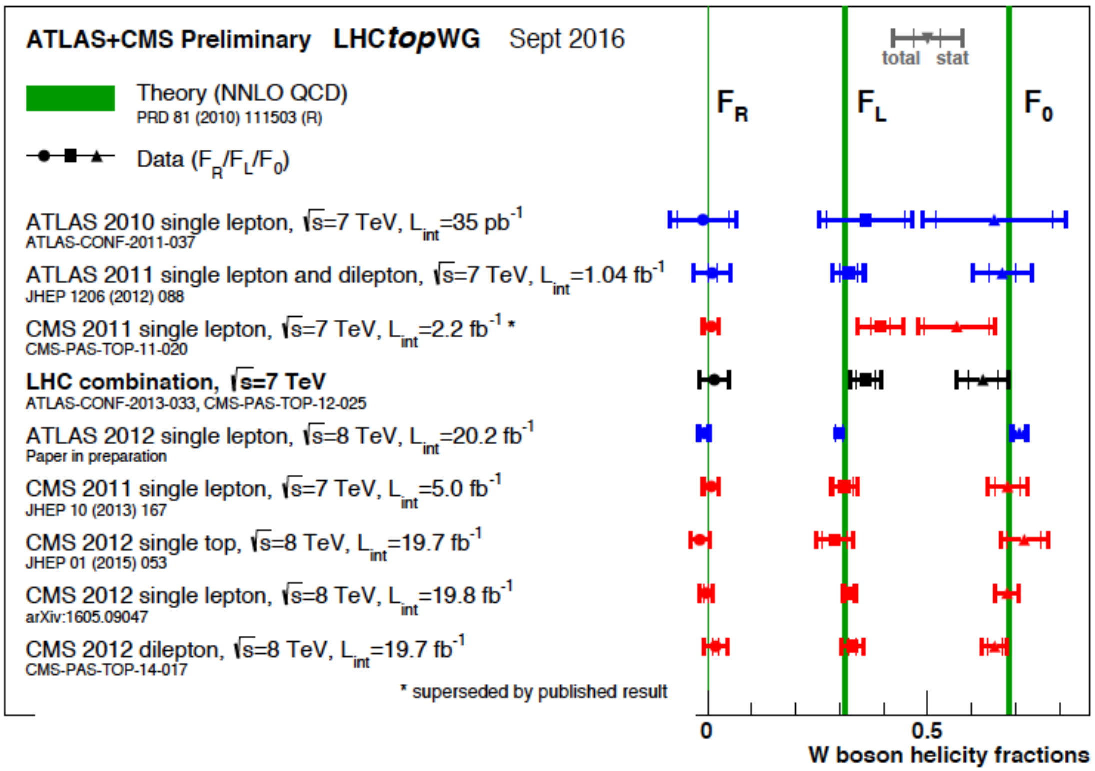
F_R = -0.004 ± 0.014
F_L = 0.323 ± 0.014
F_0 = 0.681 ± 0.026

JHEP01 053(2015), CMS, single top, 19.7/fb @ 8TeV

F_R = -0.018 ± 0.019
F_L = 0.298 ± 0.028
F_0 = 0.720 ± 0.039

TOPQ-2016-02, Recent ATLAS results, l+jets, 20.2/fb @ 8 TeV

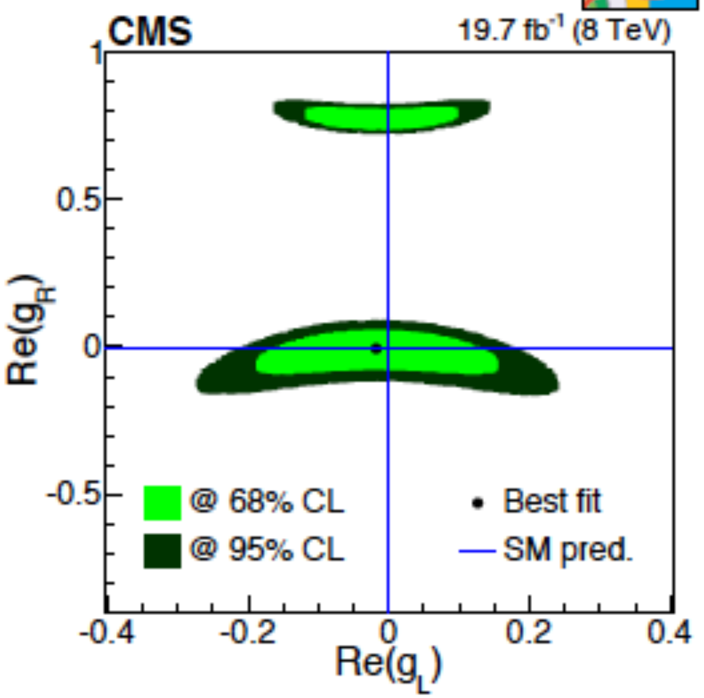
F_R = -0.008 ± 0.006
F_L = 0.299 ± 0.008
F_0 = 0.709 ± 0.012



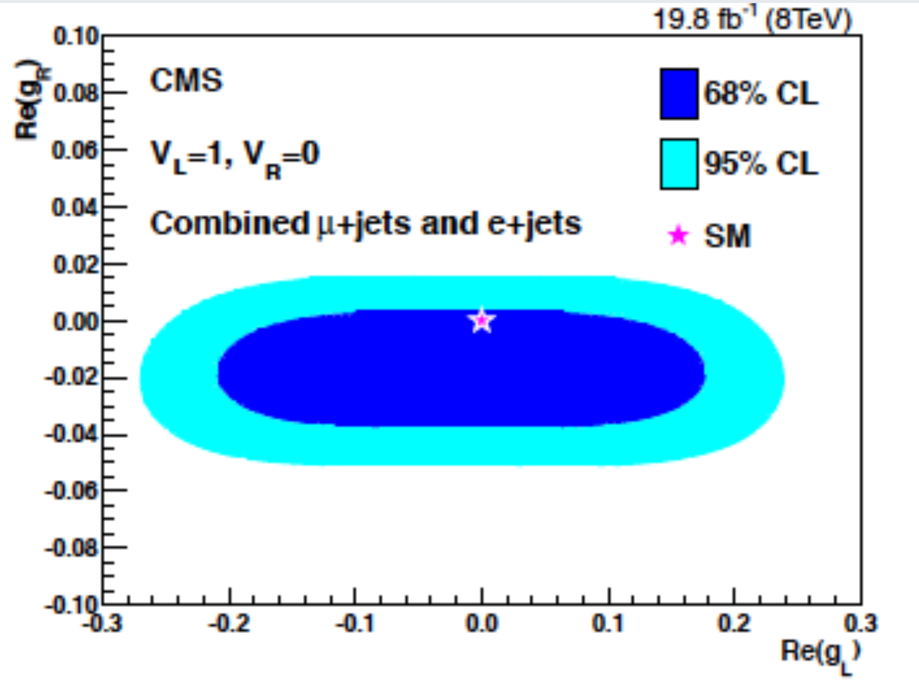
All measurements consistent with SM Expectations, leading to constraints on the real part of V_R, g_L and g_R.

Stringent limits on right-handed tensor couplings is obtained.

JHEP01 053 (2015)



$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)\,t\,W^-_{\mu} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_L P_L + g_R P_R)\,t\,W^-_{\mu}$$



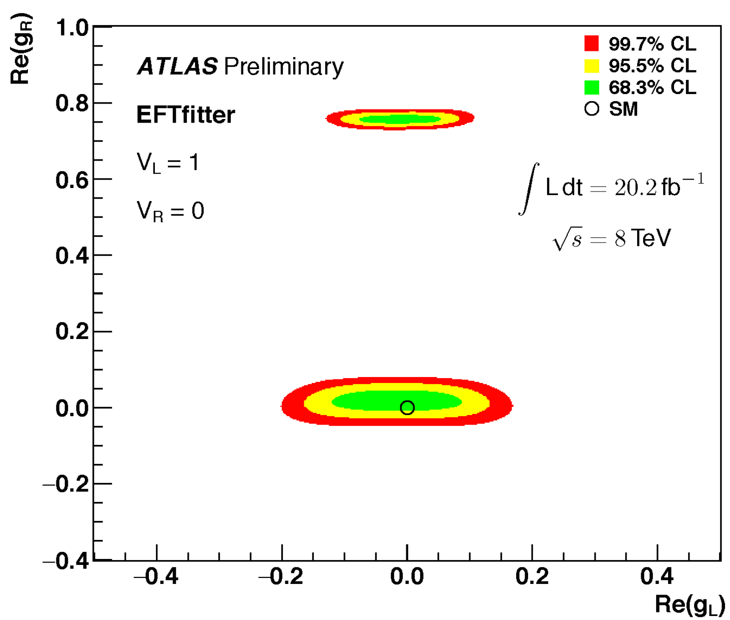
arXiv:1605.09047 (10.1016/j.physletb.2016.10.007)

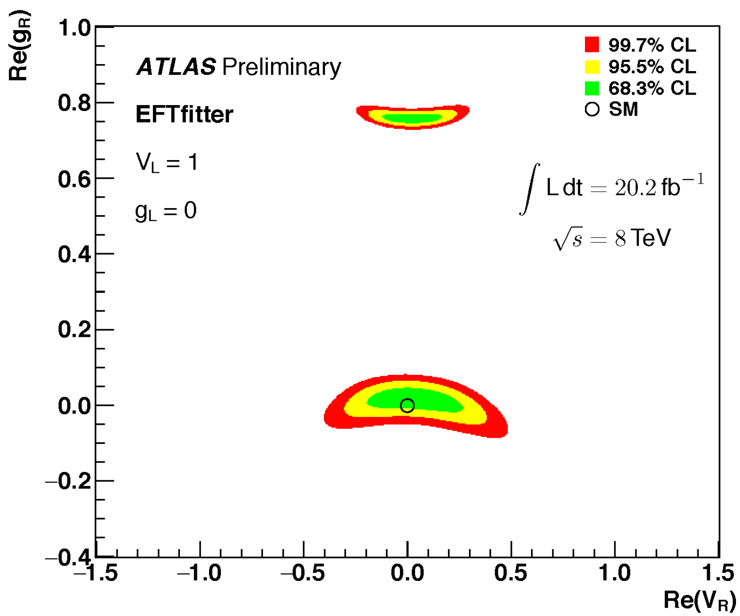
W helicity, anomalous Wtb coupling - ATLAS

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)\,t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_L P_L + g_R P_R)\,t\,W_{\mu}^{-}$$

TOPQ-2016-02, l+jets, 20.2/fb @ 8 TeV, Recent ATLAS results.

Coupling	95 % CL limit
V_R	[−0.24, 0.31]
g_L	[−0.14, 0.11]
g_R	[−0.02, 0.06], [0.74, 0.78]

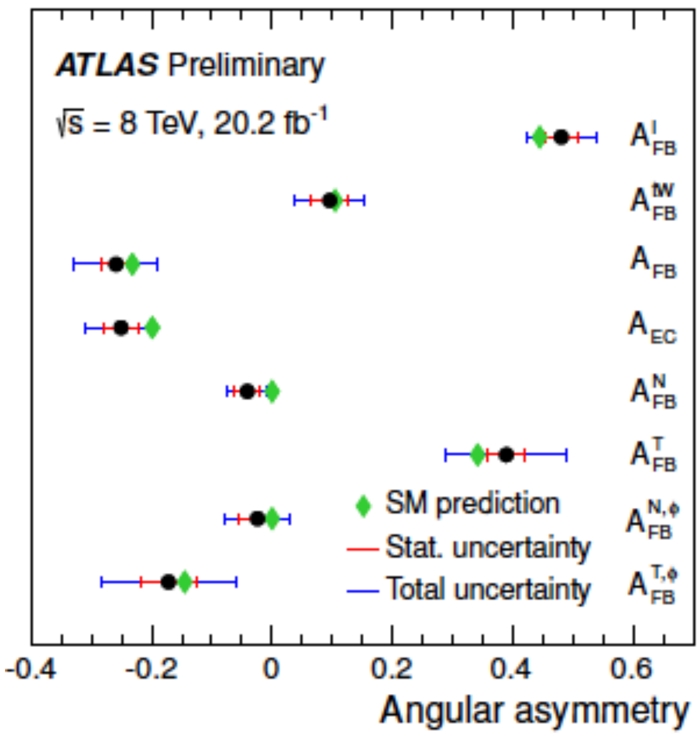


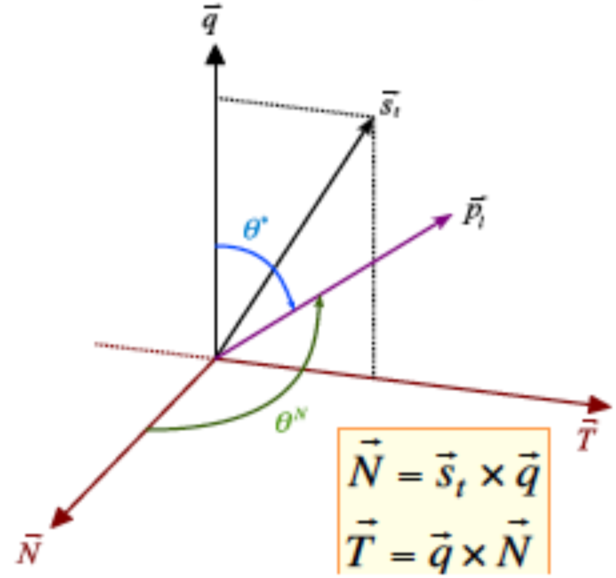


$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_{\rm L}P_{\rm L} + V_{\rm R}P_{\rm R}\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}\left(g_{\rm L}P_{\rm L} + g_{\rm R}P_{\rm R}\right)tW_{\mu}^{-}$$

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

Using A_{FB}^{l} and A_{FB}^{N}, $Im(g_R)$ is constrained.





ATLAS-CONF-2016-097

$$A_{FB}^{N} \approx 0.64 \cdot P \cdot Im(g_R)$$

Assuming $V_L = 1$ and all anomalous couplings other than $Im(g_R)$ vanishing ($V_R = g_L = 0$ and $Re(g_R) = 0$), the limits set at the 95% confidence level are $Im(g_R)$: [-0.17, 0.06].

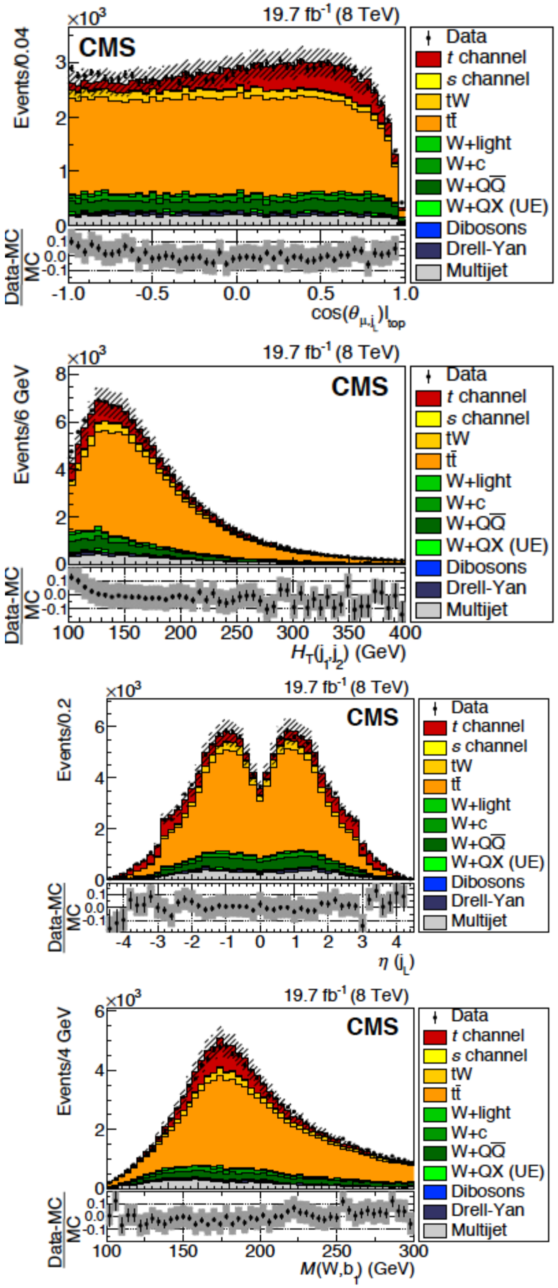
Due to the presence of two Wtb vertices in single top (production and decay), the cross section is highly sensitive to Wtb anomalous couplings.

BNN is considered in the analysis, which requires the training of the BNN (SM BNN) to distinguish the t-channel single top quark production process from other SM processes.

Distributions of four representative variables for data and simulated events are shown.

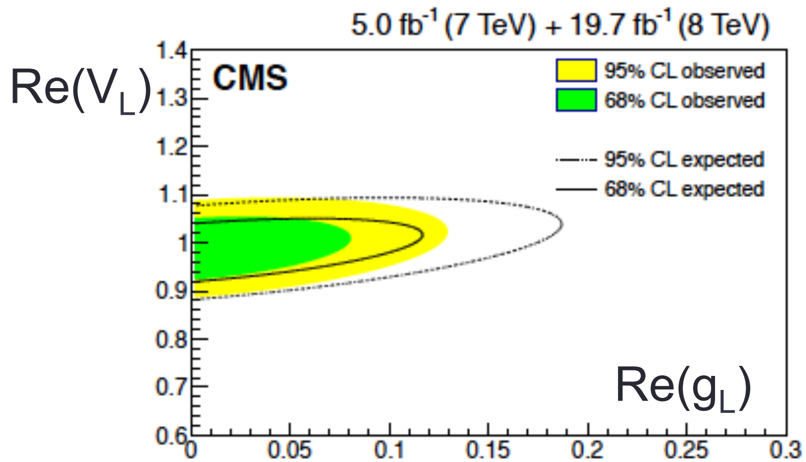
The data is in agreement with SM prediction, angular and other kinematic distributions.

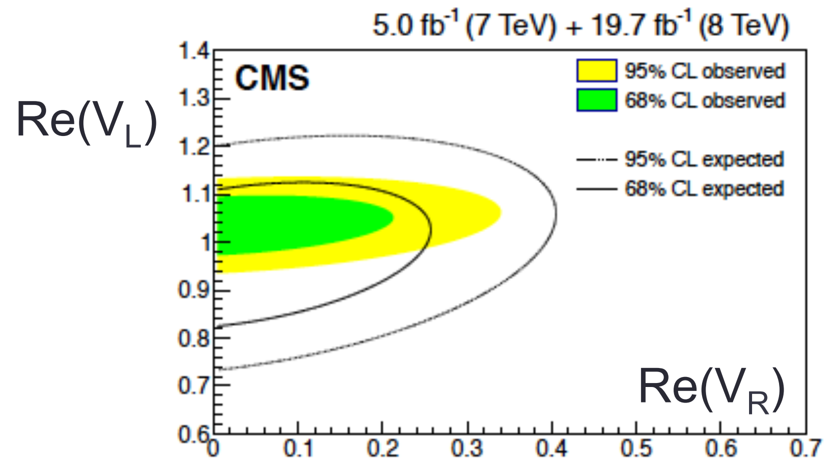
Three additional BNNs (Wtb BNN) are used to separate the individual contributions of right-handed vector (g_R), and left-handed (g_L) and right-handed (g_R) tensor couplings from the left-handed vector coupling (V_L)expected in the SM.



arXiv:1610.03545

-Two dimensional statistical analysis is performed on the Wtb BNN to obtain the exclusion limits.
-The combined observed and expected two-dimensional contours in the (V_L , V_R), (V_L , g_L), and (V_L , g_R) spaces are shown.





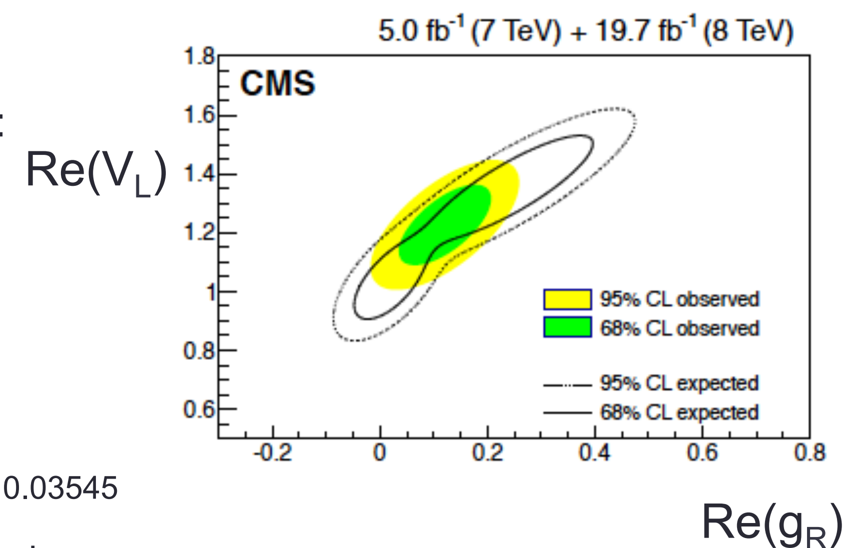
Three-dimensional scenarios with simultaneous variation of couplings leads to the following limits:

$Re(V_L) > 0.98$

$-0.16 < Re(V_R) < 0.16$

$-0.057 < Re(g_L) < 0.057$

$-0.049 < Re(g_R) < 0.048$



CMS-TOP-14-007, arXiv:1610.03545

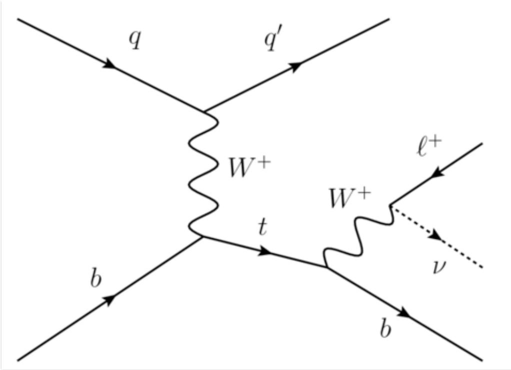
Imaginary part of the anomalous couplings is assumed to be zero.

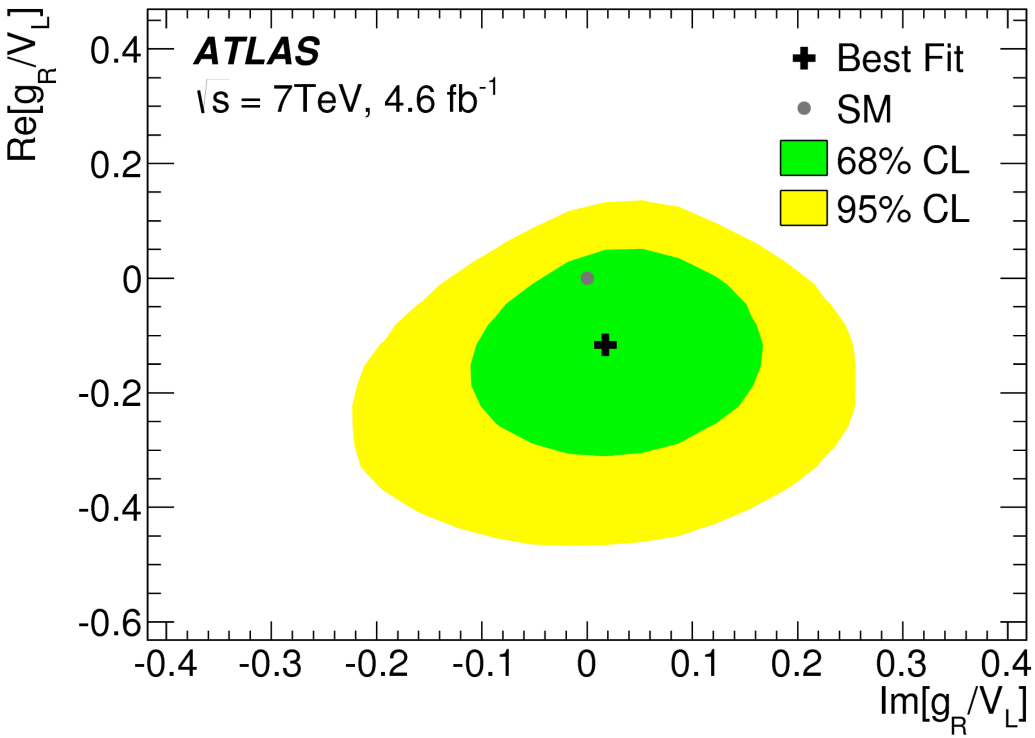
t-channel

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

-Bounds are derived using double differential angular distribution.

-Interpret as limits on g_R/V_L.





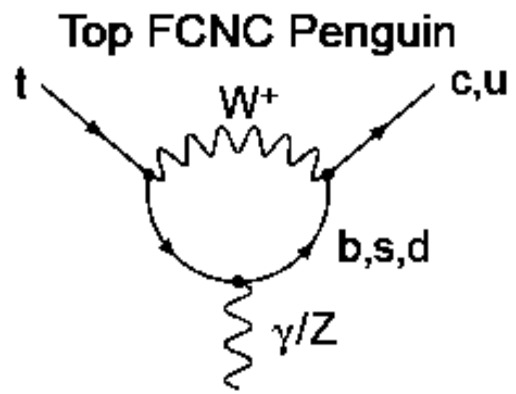
JHEP 04 (2016) 023

- Flavor-changing neutral current (FCNC) interactions: Transition from a quark with flavor-X and charge-Q to another quark of flavor-Y but with the same charge-Q.

-FCNC are forbidden at tree level and only allowed via higher order corrections such as penguin diagrams and strongly suppressed: due to GIM mechanism and smallness of the related CKM matrix elements.

-Top decays through FCNC are enhanced in many models beyond the SM. The enhancement mechanisms depends on the model. It can be done via weaker GIM cancellation by new particles in loop corrections.

-Any signal above SM expectations would indicate new physics.



$Br(t \to cg)$	$\mathcal{O}(10^{-11})$
$Br(t \to cZ)$	$\mathcal{O}(10^{-13})$
$Br(t \to c\gamma)$	$\mathcal{O}(10^{-13})$

Phys. Rev. D 44, 1473 (1991); Phys. Lett. B 435, 401 (1998).

Model	$BR(t \to Zq)$
Standard Model	$\mathcal{O}(10^{-14})$
$q = 2/3$ Quark Singlet	$\mathcal{O}(10^{-4})$
Two Higgs Doublets	$\mathcal{O}(10^{-7})$
MSSM	$\mathcal{O}(10^{-6})$
R-Parity violating SUSY	$\mathcal{O}(10^{-5})$

Acta Phys. Polor B35 (2004) 2695

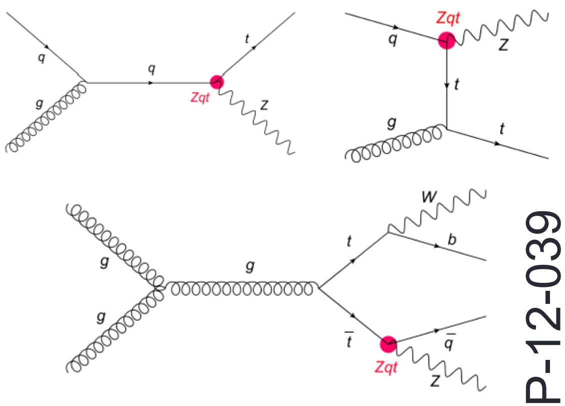
-The searches for FCNC are performed either in decays of ttbar events or in single top production. The results that are shown come from both ttbar and single top.

-To search for FCNC effects in the top sector, a useful way is to adopt a model independent approach using an effective Lagrangian:

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

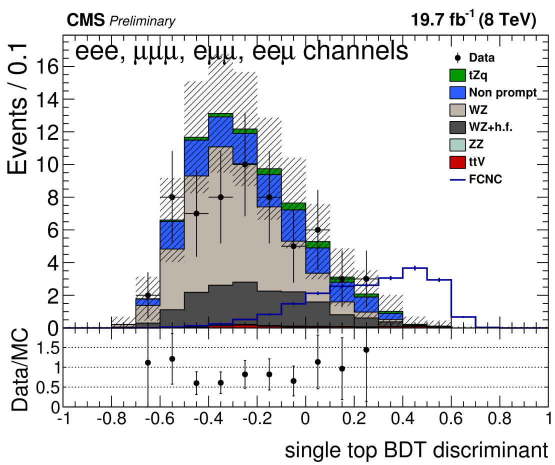
FCNC: tqZ- CMS

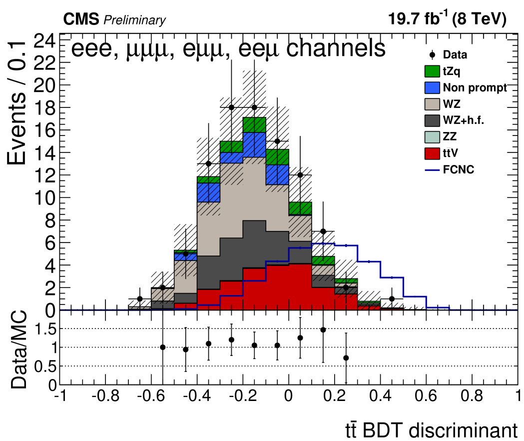
- Three leptons, 2 lepton (Z) and 1 lepton (W)
- missing transverse energy > 40 GeV and M_W^T > 10 GeV
- For single top: 1 b-jet and for the ttbar: ≥ 2 jets (≥ 1 b-jet)

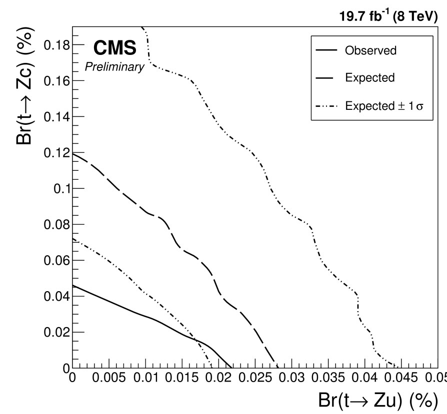


- A BDT is used to discriminate signal from SM processes.
- Variables related to the top quark and Z boson as well as jets and b-jets kinematics are used.

CMS-PAS-TOP-12-039







Branching ratio	Expected	1σ range	2 σ range	Observed
$\mathcal{BR}$(t→ Zu) (%)	0.027	0.018-0.042	0.014-0.065	0.022
$\mathcal{BR}$(t→ Zc) (%)	0.118	0.071-0.222	0.049-0.484	0.049

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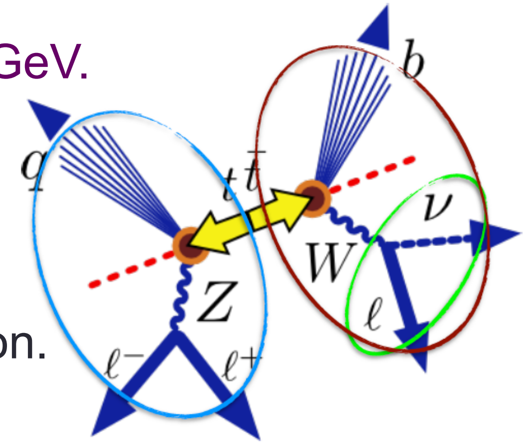
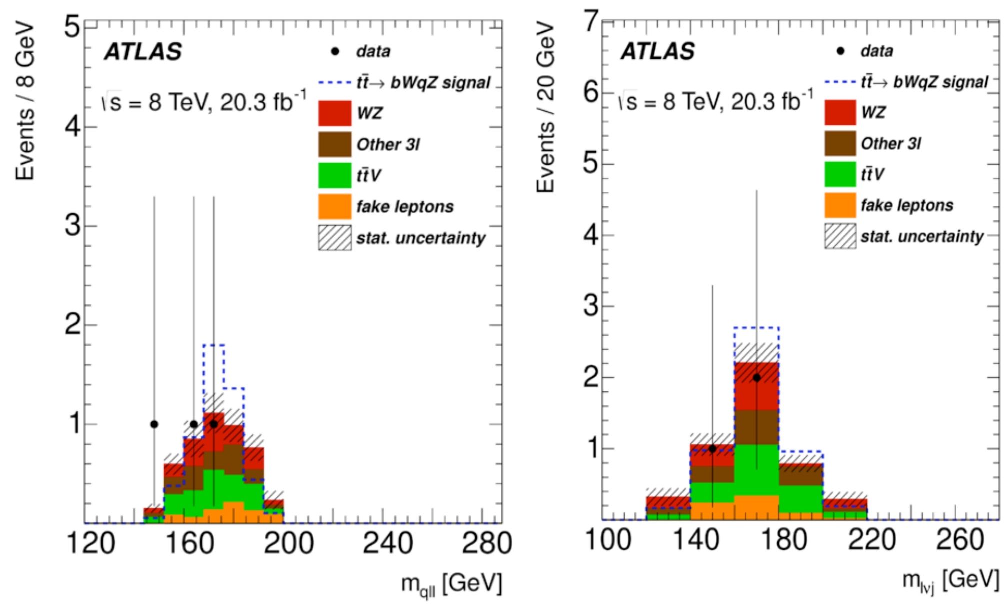
- 3 Isolated high p_T lepton.
- one pair of same-flavor and opposite sign with $|m_{ll}-m_Z| < 15$ GeV.
- missing transverse energy > 20 GeV
- $\geq$ 2 jets ($\geq$ 1 b-jet)



Reconstruction of top anti-top system through a χ^2 minimisation.

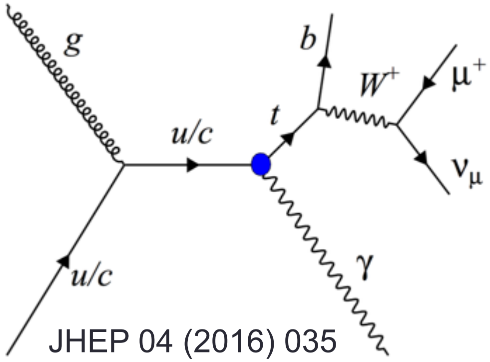
$$\chi^2 = \frac{\left(m^{\text{reco}}_{j_a\ell_a\ell_b} - m_{t\text{FCNC}}\right)^2}{\sigma^2_{t\text{FCNC}}} + \frac{\left(m^{\text{reco}}_{j_b\ell_c\nu} - m_{t\text{SM}}\right)^2}{\sigma^2_{t\text{SM}}} + \frac{\left(m^{\text{reco}}_{\ell_c\nu} - m_W\right)^2}{\sigma^2_W},$$

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



FCNC: tqγ - CMS

- Search for FCNC interactions in tuγ and tcγ vertices.
- High p_T isolated photon due to recoil with the top quark.
- Focus on the muonic decay of the W→$\mu\nu$; cleanest signature.
- No electrons are allowed.
- At least one jet (at most one can be tagged as a b-jet).
- Events with more than one b-jet are vetoed to suppress tt+γ.



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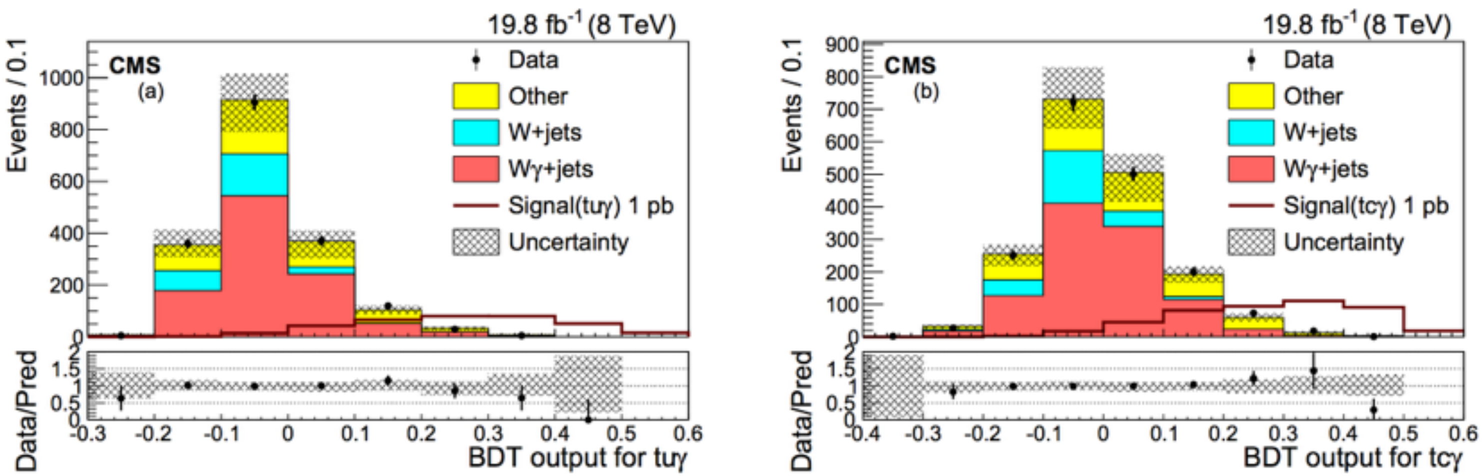
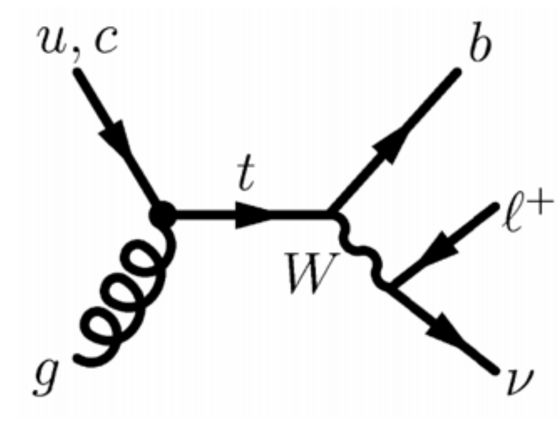
-A neural network is used to describe Wγ+jets and W+jets background from data.
-A BDT is used to discriminate signal from background:



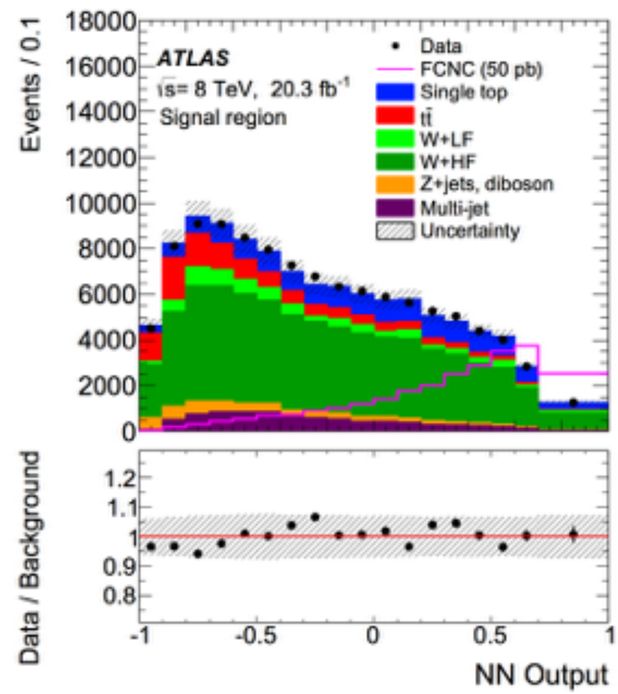
BR(t→u+γ) < 1.3 ×10^{-4} ; BR(t→c+γ) < 1.7 ×10^{-3}



-The anomalous tqg coupling leads to production of a top quark.

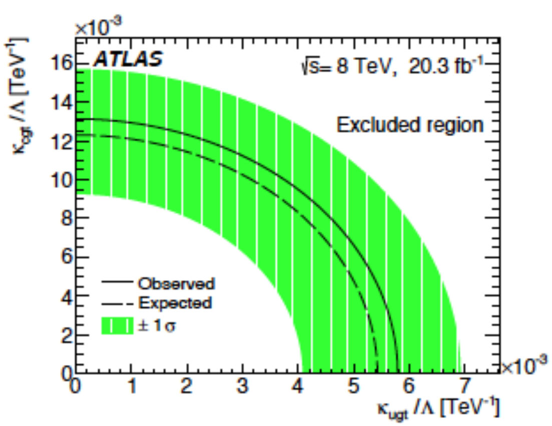
-Event signature is the top-quark decay: exactly one isolated lepton, missing E_T and one b-tagged jet.

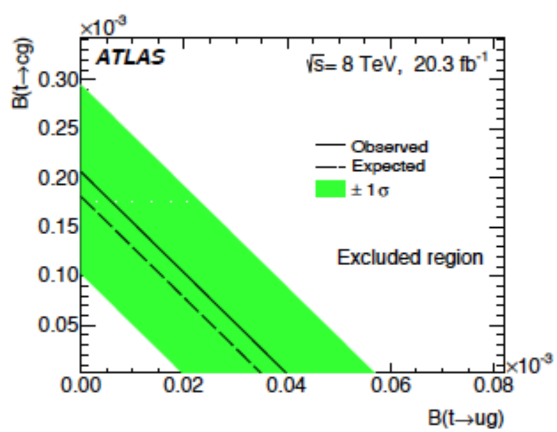
-A neural network is used in order to discriminate signal from background.



95% C.L. upper limit on BR

- BR(t->ug) < 4 x 10^{-5}
- BR(t->cg) < 2 x 10^{-4}





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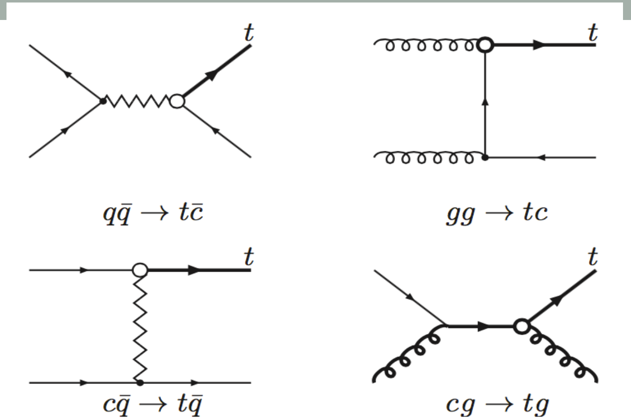
FCNC: tqg - CMS



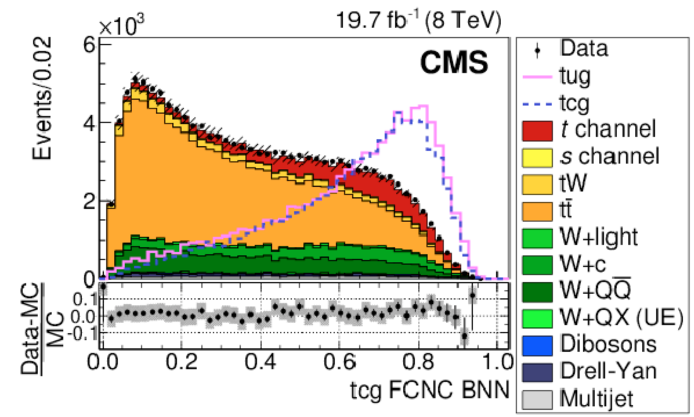
Focused on a singly produced top quark with leptonic decay of the W boson:

- Request exactly on isolated muon (rejection is applied on extra leptons passing quality criteria).

- Either 2 or 3 jets with at least one tagged as b-jet.

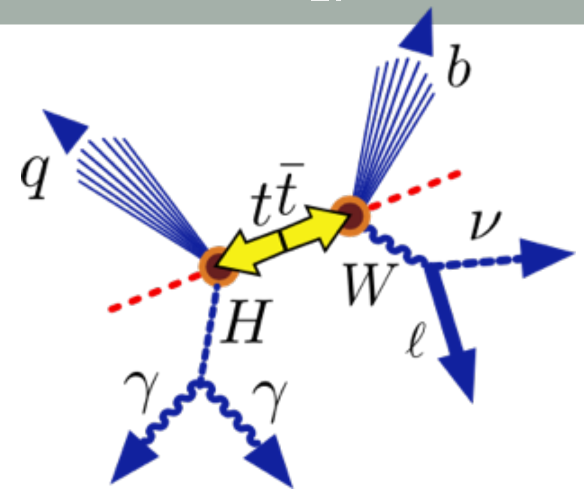
After preselection 2 neural networks are defined for tug and tcg.

A neural network is also used to diminish QCD background contamination.



$\sqrt{s}$	$\lvert\kappa_{tug}\rvert/\Lambda\ (\mathrm{TeV}^{-1})$	$\mathcal{B}(t \to ug)$	$\lvert\kappa_{tcg}\rvert/\Lambda\ (\mathrm{TeV}^{-1})$	$\mathcal{B}(t \to cg)$
7 TeV	$14\ (13) \times 10^{-3}$	$24\ (21) \times 10^{-5}$	$2.9\ (2.4) \times 10^{-2}$	$10.1\ (6.9) \times 10^{-4}$
8 TeV	$5.1\ (5.9) \times 10^{-3}$	$3.1\ (4.2) \times 10^{-5}$	$2.2\ (2.0) \times 10^{-2}$	$5.6\ (4.8) \times 10^{-4}$
7 and 8 TeV	$4.1\ (4.8) \times 10^{-3}$	$2.0\ (2.8) \times 10^{-5}$	$1.8\ (1.5) \times 10^{-2}$	$4.1\ (2.8) \times 10^{-4}$

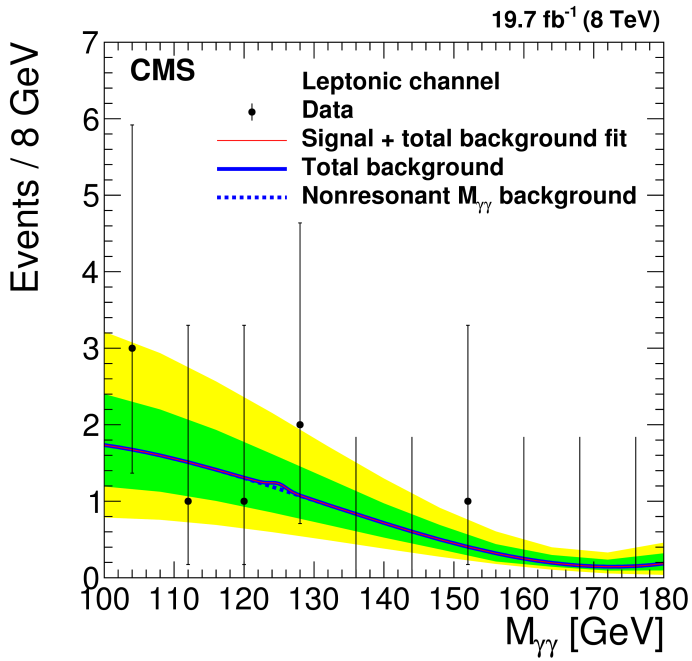
arXiv:1610.03545



- **Direct search multileptonic final state:**
  - Focused on the WW, ZZ and $\tau\tau$ Higgs decay channels.
  - Trilepton and same-sign di-lepton channel are considered.
  - Cut based analysis.

- **Diphoton channel:**
  - W decay from SM top quark both hadronic and leptonic.
  - Clean signature.
  - Most stringent limit.

- **H->bb channel:**
  - A BDT is used to select the best objects combination for each top quark reconstruction.
  - A neural network is used afterward to define a template fit and extract signal from background.



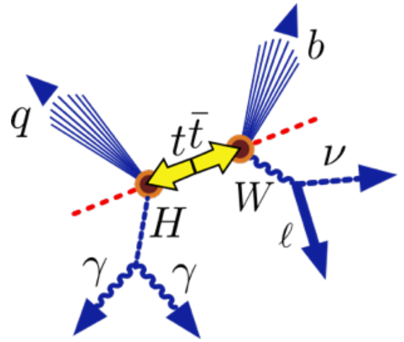
arXiv:1610.04857

No significant excess is observed above the expected standard model background, and an upper limit at the 95% confidence level is set on the branching fraction:

	$\mathcal{B}_{obs}(t \to Hc)$	$\mathcal{B}_{exp}(t \to Hc)$	$\mathcal{B}_{exp}+\sigma$	$\mathcal{B}_{exp}-\sigma$
Trilepton	1.26	1.33	1.87	0.95
Same-sign dilepton	0.99	0.93	1.26	0.68
Multilepton combined	0.93	0.89	1.22	0.65
Diphoton hadronic	1.26	1.33	1.87	0.95
Diphoton leptonic	0.99	0.93	1.26	0.68
Diphoton combined	0.47	0.67	1.06	0.44
b jet + lepton	1.16	0.89	1.37	0.60
Full combination	0.40	0.43	0.64	0.30
	$\mathcal{B}_{obs}(t \to Hu)$	$\mathcal{B}_{exp}(t \to Hu)$	$\mathcal{B}_{exp}+\sigma$	$\mathcal{B}_{exp}-\sigma$
Trilepton	1.34	1.47	2.09	1.05
Same-sign dilepton	0.93	0.85	1.16	0.62
Multilepton combined	0.86	0.82	1.14	0.60
Diphoton hadronic	1.26	1.33	1.87	0.95
Diphoton leptonic	0.99	0.93	1.26	0.68
Diphoton combined	0.42	0.60	0.96	0.39
b jet + lepton	1.92	0.84	1.31	0.57
Full combination	0.55	0.40	0.58	0.27

Limits are in %

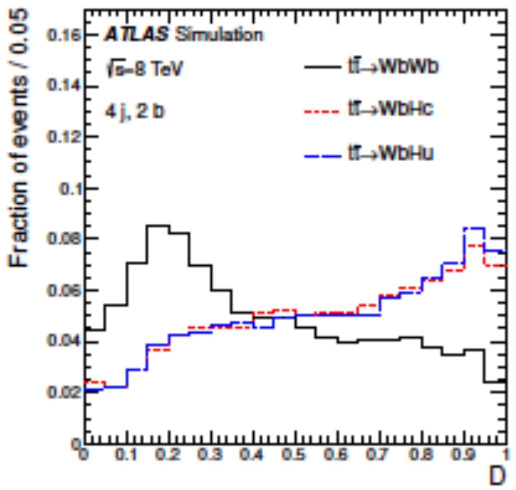
FCNC: tqH - ATLAS



The searches have been performed in diphoton, multilepton, and bb channels. In H→ bb channel, several control and signal regions are defined.

In order to discriminate signal from background a discriminant is defined:

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



$P^{sig}(x)$ and $P^{bkg}(x)$ are probability density functions defined based on kinematic information of reconstructed objects.

In the H->γγ channel, the analysis is done using hadronic and leptonic decays of the top quark with the proper event selection

In the H->W^+W^-, $\tau^+\tau^-$ channels, different regions are defined based on the number of leptons and hadronic taus.

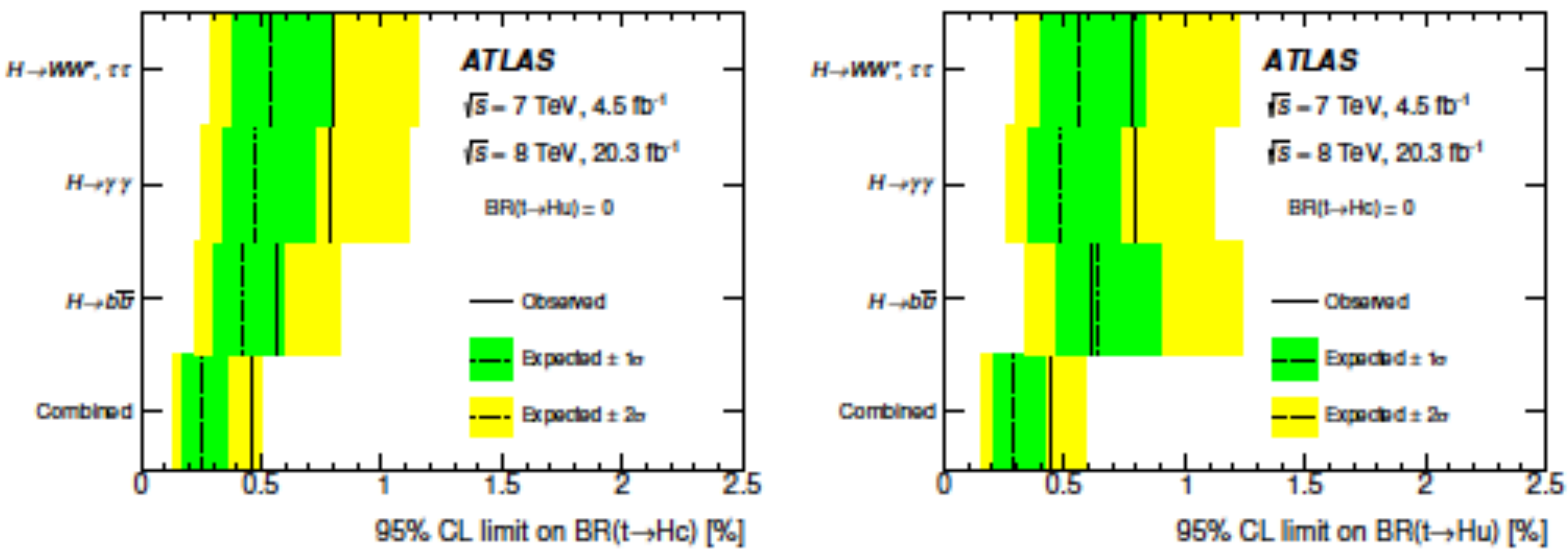
JHEP12 (2015) 061, JHEP 1406 (2014) 008, Phys. Lett. B 749 (2015) 519-541

FCNC: tqH - ATLAS

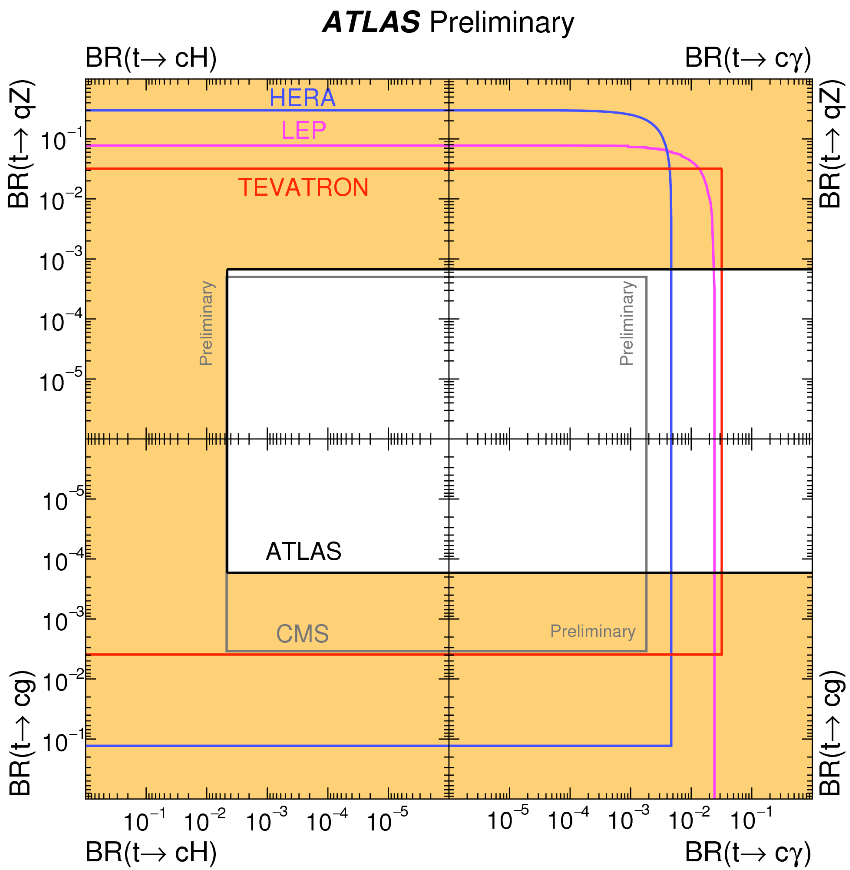
No significant excess of events above the background expectation is found and upper limits are set on the branching fractions of t → Hc and t → Hu.

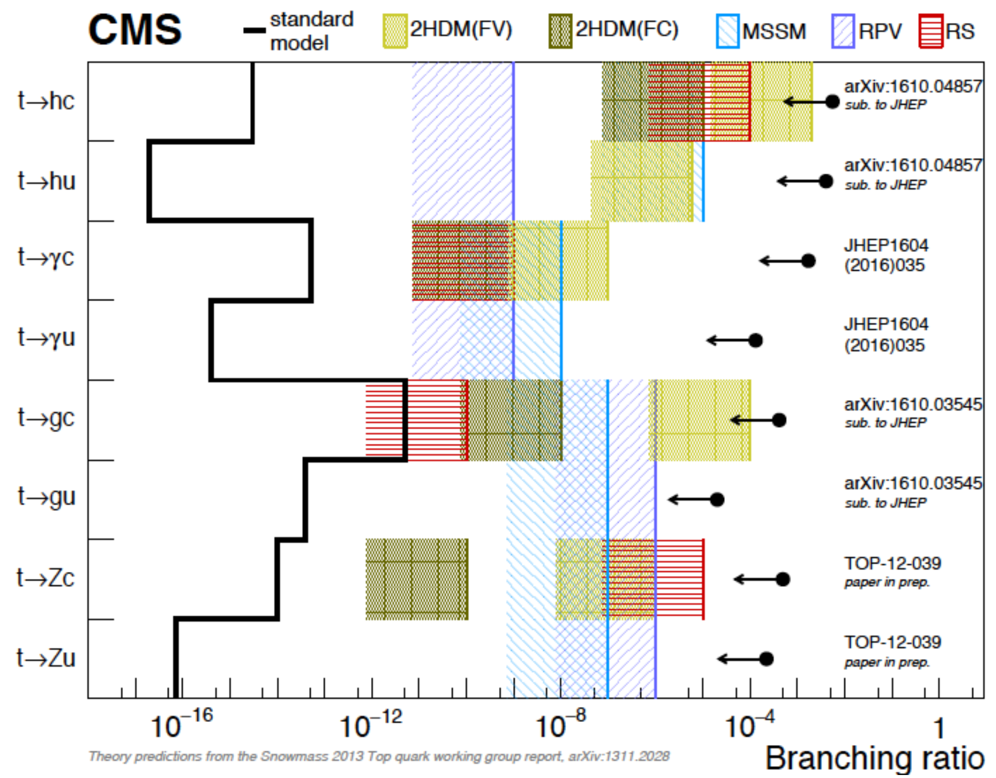
All searches have comparable sensitivity, and their combination represents a significant improvement over the individual results.

The observed 95% CL combined upper limits of on the t → Hc and t → Hu branching ratios are 0.46% and 0.45% , respectively.



JHEP12 (2015) 061



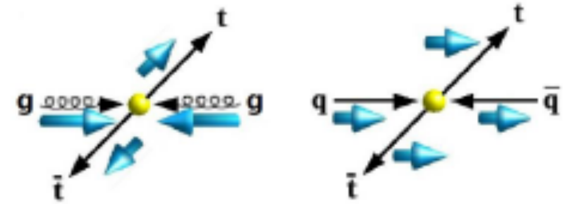


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOPSummaryFigures

-Top quark spin in ttbar is correlated at production.

-At low tt invariant masses, the production is dominated by the fusion of pairs of gluons with the same helicities → top quark pairs with antiparallel spins in the tt center-of-mass frame.

-For larger tt invariant masses, the dominant production is via the fusion of gluons with opposite helicities
→ tt pairs with parallel spins.



-Due to top very short lifetime, information of spin propagates to the daughter particles. Therefore, the spin correlation can be extracted from angular variables (dilepton $\Delta\varphi_{\ell\ell}$, c = cos θ_l)

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+^a d\cos\theta_-^b} = \frac{1}{4}(1 + B_+^a \cos\theta_+^a + B_-^b \cos\theta_-^b - C(a,b)\cos\theta_+^a \cos\theta_-^b),$$

B^a, B^b and C(a; b) are the polarisations and spin correlation

-In di-lepton ttbar events, the difference in azimuthal angle of the charged leptons in the laboratory frame, $\Delta\varphi_{\ell\ell}$, is sensitive to ttbar spin correlations and can be measured precisely without reconstructing the full tt system.

-Discriminates between correlated and uncorrelated t and tbar spins

$$A_{\Delta\phi} = \frac{N(|\Delta\phi_{\ell^+\ell^-}| > \pi/2) - N(|\Delta\phi_{\ell^+\ell^-}| < \pi/2)}{N(|\Delta\phi_{\ell^+\ell^-}| > \pi/2) + N(|\Delta\phi_{\ell^+\ell^-}| < \pi/2)}$$

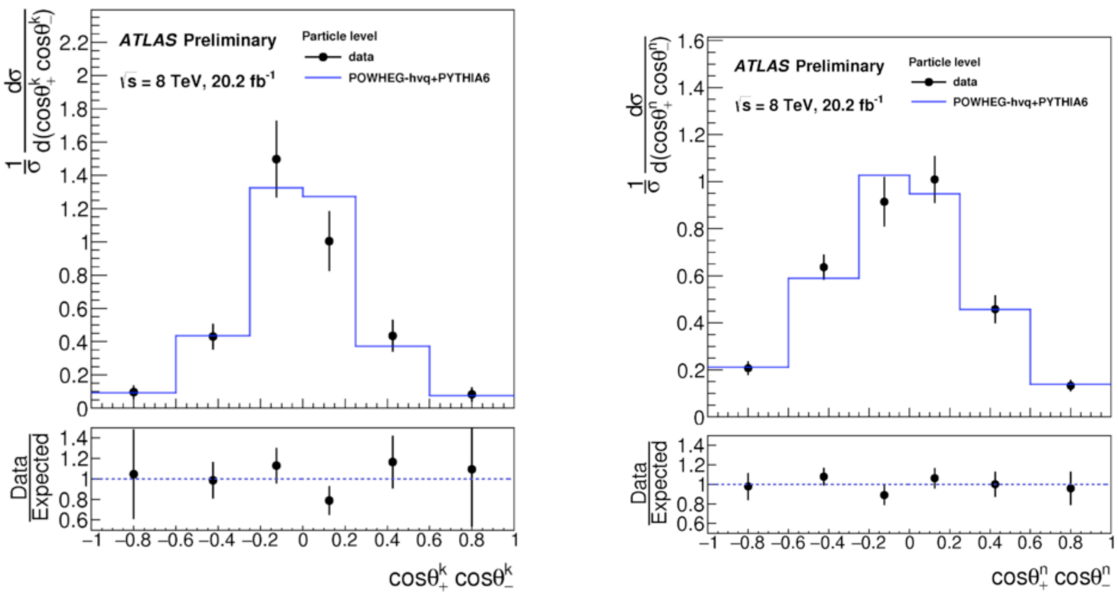
-Direct measure of the spin correlation coefficient C_{hel} through the relationship $C_{hel} = -4A_{c1c2}$

$$A_{c_1c_2} = \frac{N(c_1c_2 > 0) - N(c_1c_2 < 0)}{N(c_1c_2 > 0) + N(c_1c_2 < 0)},$$

Reconstructed asymmetry	Simulation	Data
$A_{\Delta\phi}$	0.188 ± 0.002	0.170 ± 0.005
$A_{\cos\varphi}$	0.114 ± 0.003	0.109 ± 0.005
$A_{c_1 c_2}$	-0.050 ± 0.003	-0.049 ± 0.005
A_{P+}	-0.026 ± 0.003	-0.032 ± 0.005
A_{P-}	-0.022 ± 0.003	-0.028 ± 0.005

CMS

Phys. Rev. D 93 (2016) 052007

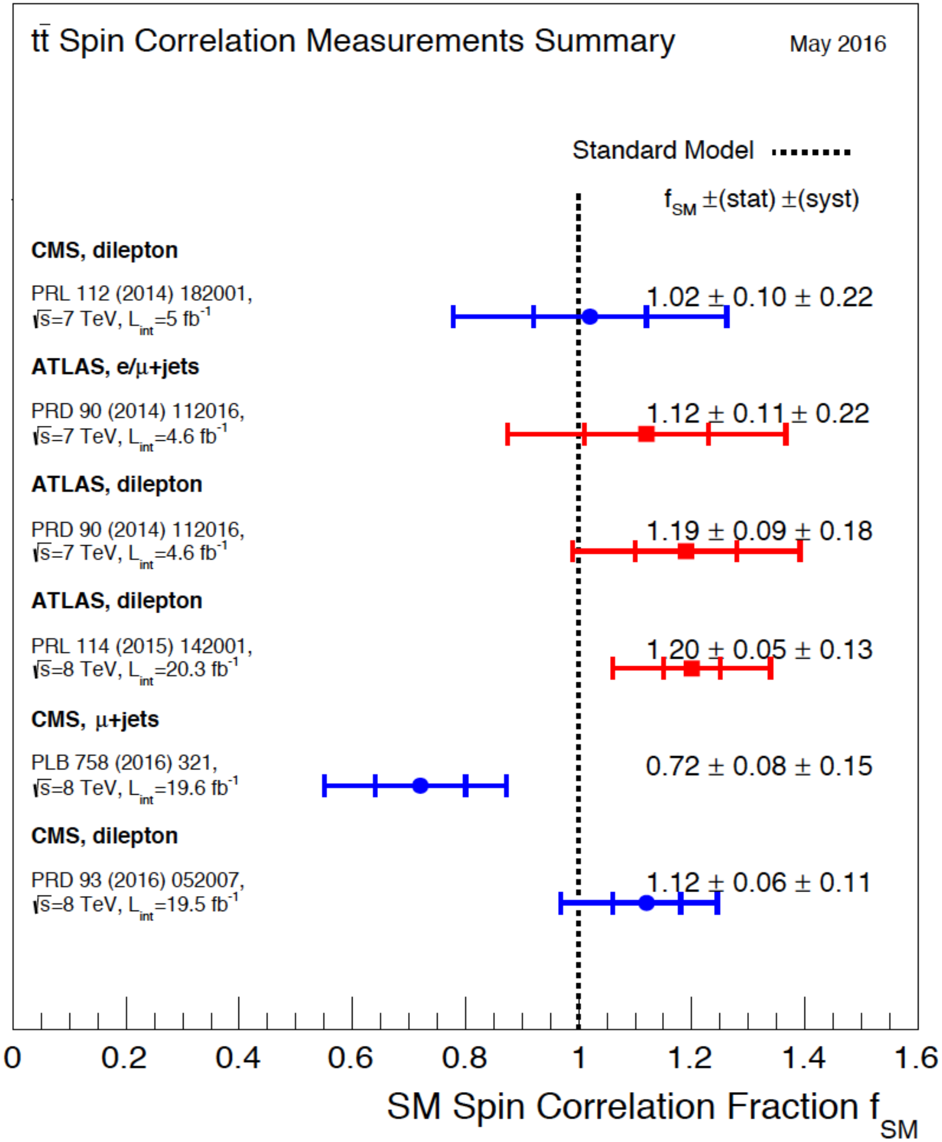


ATLAS-CONF-2016-099

Experiment	$\sqrt{s}$	Method	B^k_+	B^k_-	$C(k,k)$	B^n_+	B^n_-
ATLAS	8 TeV	Unfolding	-0.044 ± 0.038	-0.064 ± 0.040	0.296 ± 0.093	-0.018 ± 0.034	0.023 ± 0.042
CMS [16]	8 TeV	Unfolding	-0.022 ± 0.058		0.278 ± 0.084	-	-
ATLAS [11]	7 TeV	Template fit	-0.035 ± 0.040		-	-	-
ATLAS [10]	7 TeV	Template fit	-	-	0.23 ± 0.09	-	-
ATLAS [12]	7 TeV	Unfolding	-	-	0.315 ± 0.078	-	-
D0 [17]	1.96 TeV	Template fit	-0.102 ± 0.061		-	0.040 ± 0.034	

The strength of the spin correlations relative to the SM prediction, with f_{SM}= 1 corresponding to the SM and f_{SM} = 0 corresponding to uncorrelated events.

$$f_{SM} = \frac{N^{tt}_{SM}}{N^{tt}_{SM} + N^{tt}_{Uncor}}$$



-Measured spin correlations observables ($A_{\Delta\varphi}$, A_{c1c2} ..) are found to be in agreement with SM predictions→ exclusion limits can be set on new physics effects.

-The g-t-t interaction receives contributions from dimension six operators:

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

-The measured top quark spin observables ($A_{\Delta\varphi}$, A_{CPV}) are compared to theoretical predictions in order to search for hypothetical top quark anomalous couplings.

-No evidence of new physics is observed, and exclusion limits are obtained:

$$-0.053 < \text{Re}(\hat{\mu}_t) < 0.042 \qquad \hat{\mu}_t \equiv \frac{m_t}{g_s}\tilde{\mu}_t, \quad \hat{d}_t \equiv \frac{m_t}{g_s}\tilde{d}_t,$$

$$-0.068 < \text{Im}(\hat{d}_t) < 0.067$$

Phys. Rev. D 93 (2016) 052007

Summary and conclusions

-Precise measurements of top quark properties and its couplings provide the possibility for accurate tests of the SM, being at the same time sensitive to new physics.

-With the LHC data the top quark physics has entered in a precision era.

-Many of the top quark measurements performed at the LHC experiments at Run I are already dominated by systematics.

-Some rare processes also becoming available, and profit from the large amount of data in Run II.