Top quark properties in the light of recent LHC data

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Why the top quark is so interesting?

- The top quark is the **heaviest known fundamental particle in the Standard Model.**
  → Large coupling with the Higgs boson
  → Strong implications on the stability of the electroweak vacuum

- The top quark is **a short lived particle:**
  $\tau \sim 10^{-25}$s < τ(hadronization) < τ(spin-decorrelation) << τ(quark b)
  → It decays before hadronization
  → Access to polarization and spin correlations

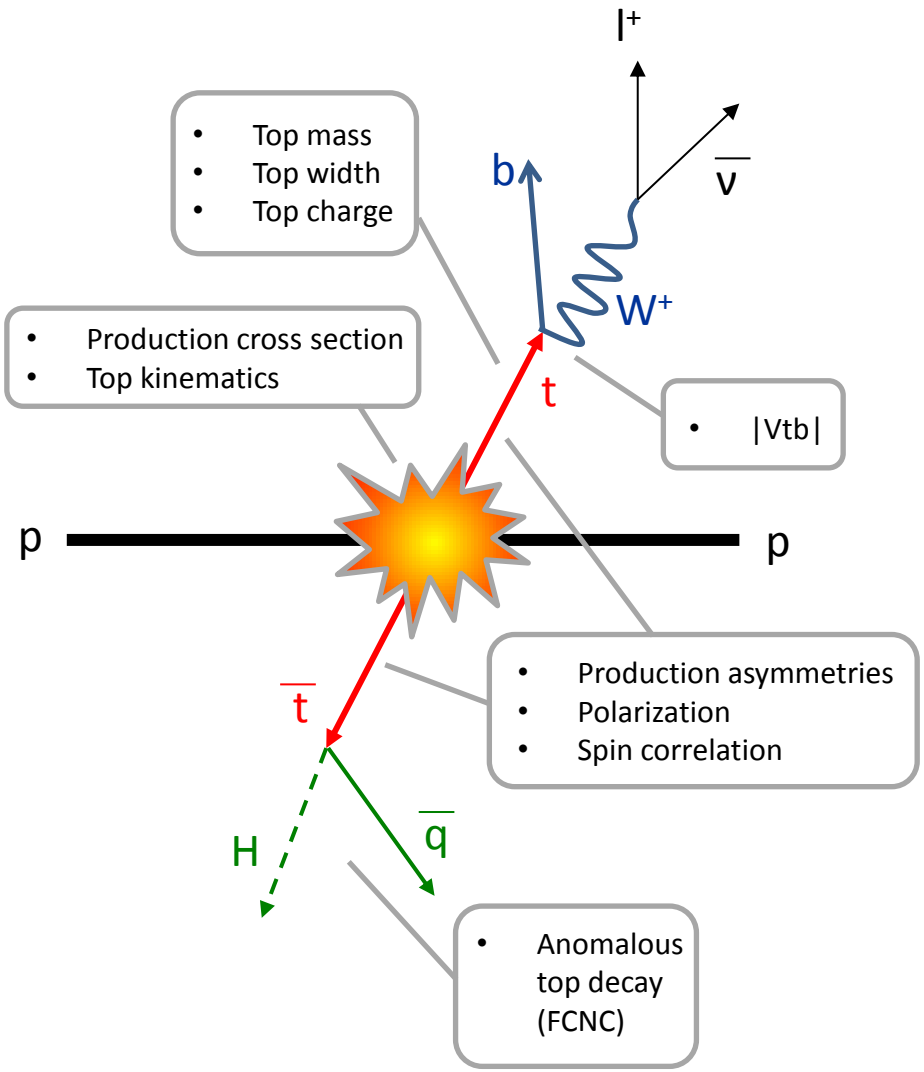
- The top quark has a **discriminating event signature** due to $V_{tb} \sim 1$

- Top events are **a source of background** for Higgs and new physics searches.

- **Probe of New Physics:**
  →Exotic particles could decay preferentially to top quarks.

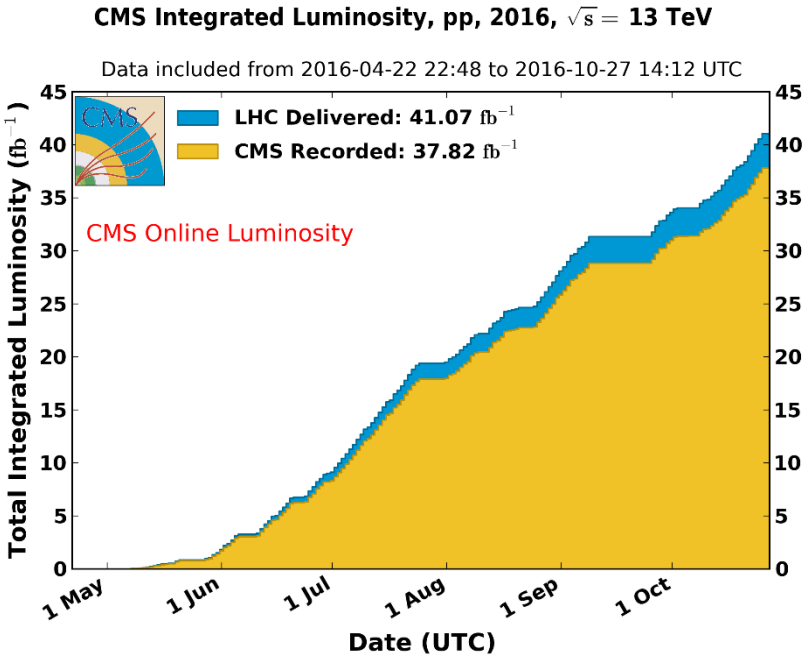
Measurements on the top quark @ the LHC

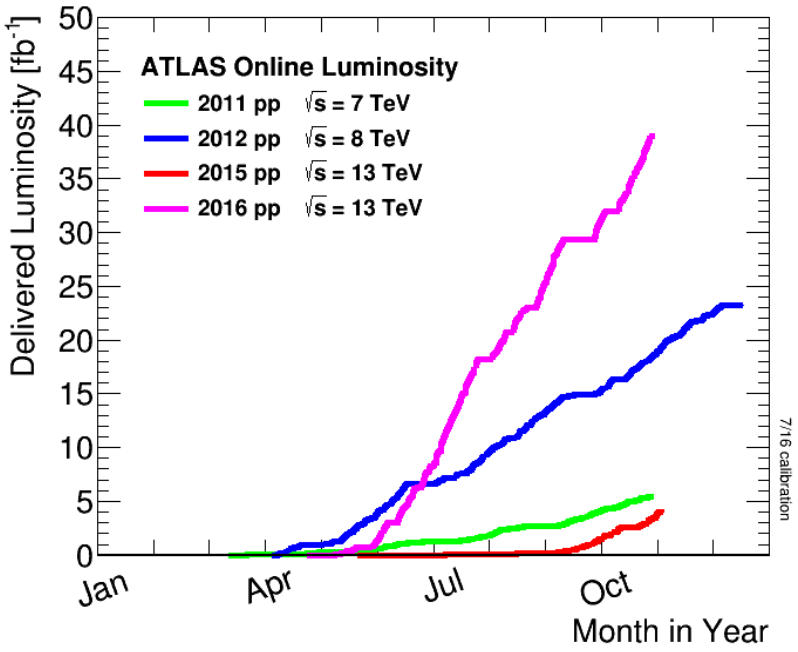
- Charge
- Mass (and top-antitop difference)
- Full total width
- Cross sections:
  - Single top and top pair production
  - Total and differential cross sections
- Spin and asymmetries:
  - Top polarization
  - Spin correlation
  - W-boson helicity in the top quark decay
  - Charge asymmetry in $t\bar{t}$ production
- Couplings:
  - CKM matrix element V_{tb}
  - Coupling Wtb, gtt
  - Associated production: $t\bar{t}Z$, $t\bar{t}\gamma$, $t\bar{t}W$, $t\bar{t}H$.
  - FCNC anomalous couplings in single top production and in top decay



In the recent data

2016 proton-proton data-taking is over. The p-pb run begins.





First results available with the 13 TeV data:

- Total cross sections of top pair and single top production.
- Differential cross-sections.
- Matrix element |Vtb|.
- Top-quark total width.
- Associated production: $t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}H$.

L^{int} used = until ~ 13 fb^{-1}

Topics covered by this talk

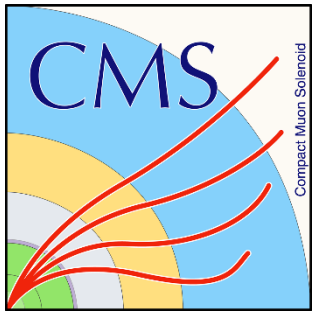
1. Short overview:
   - Top production cross-section [13 TeV data]
   - |Vtb| [13 TeV data]
   - Mass of the top quark [7+8 TeV data]

1. Width of the top quark [13/8TeV data]

2. Associated production ttX [13 TeV data]
   - ttZ and ttW
   - ttH

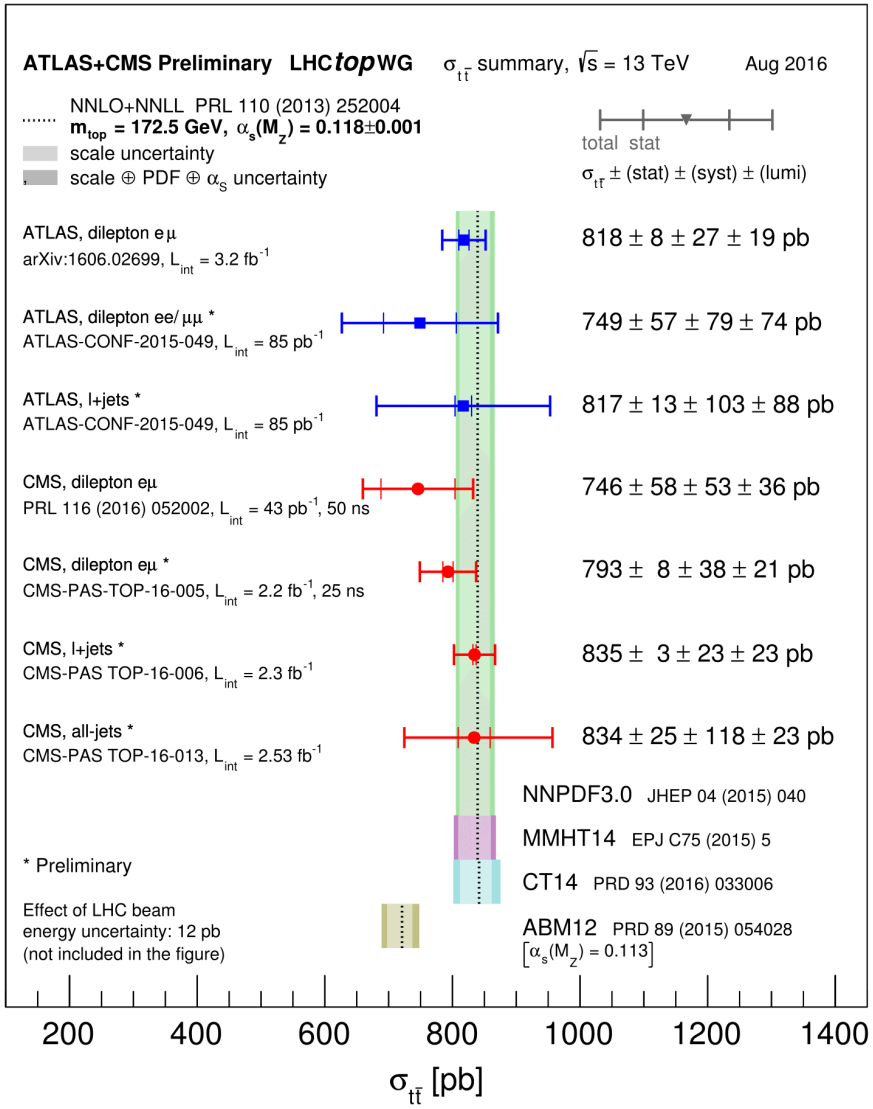
3. FCNC anomalous couplings [7/8 TeV data]
   - Coupling t-Z-q
   - Summary of all searches

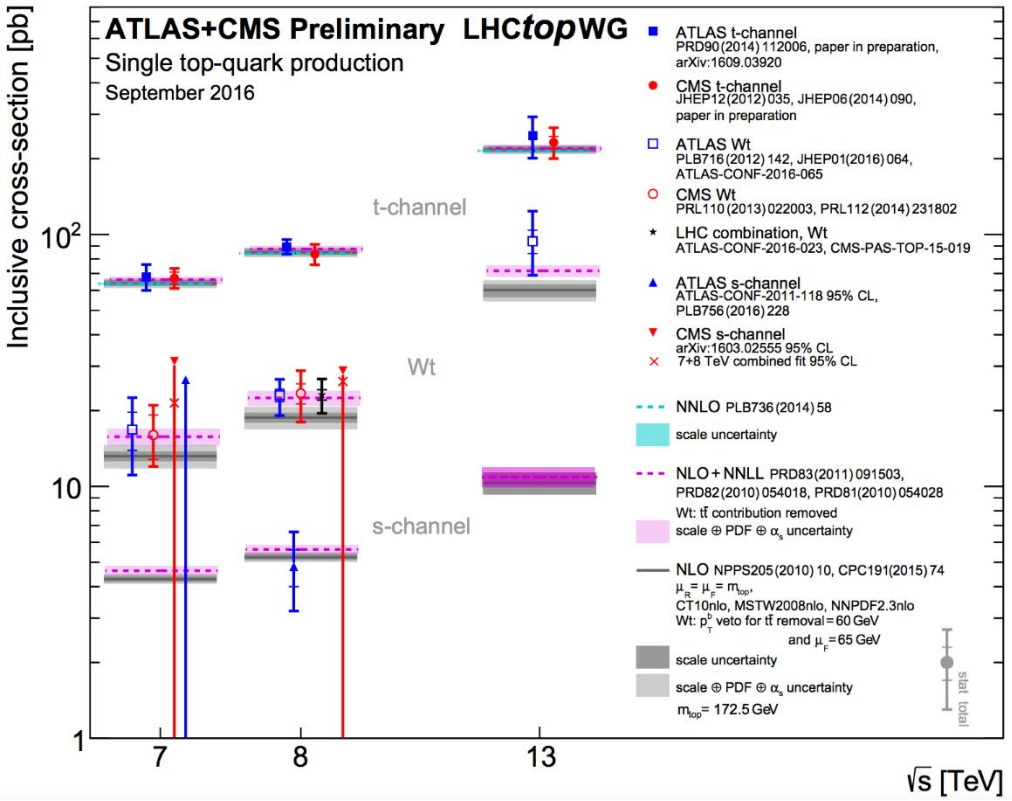
Results of both collaborations will be shown



LHC Top Combination Working Group

1. Short overview: cross-sections





1. Short overview: |Vtb|

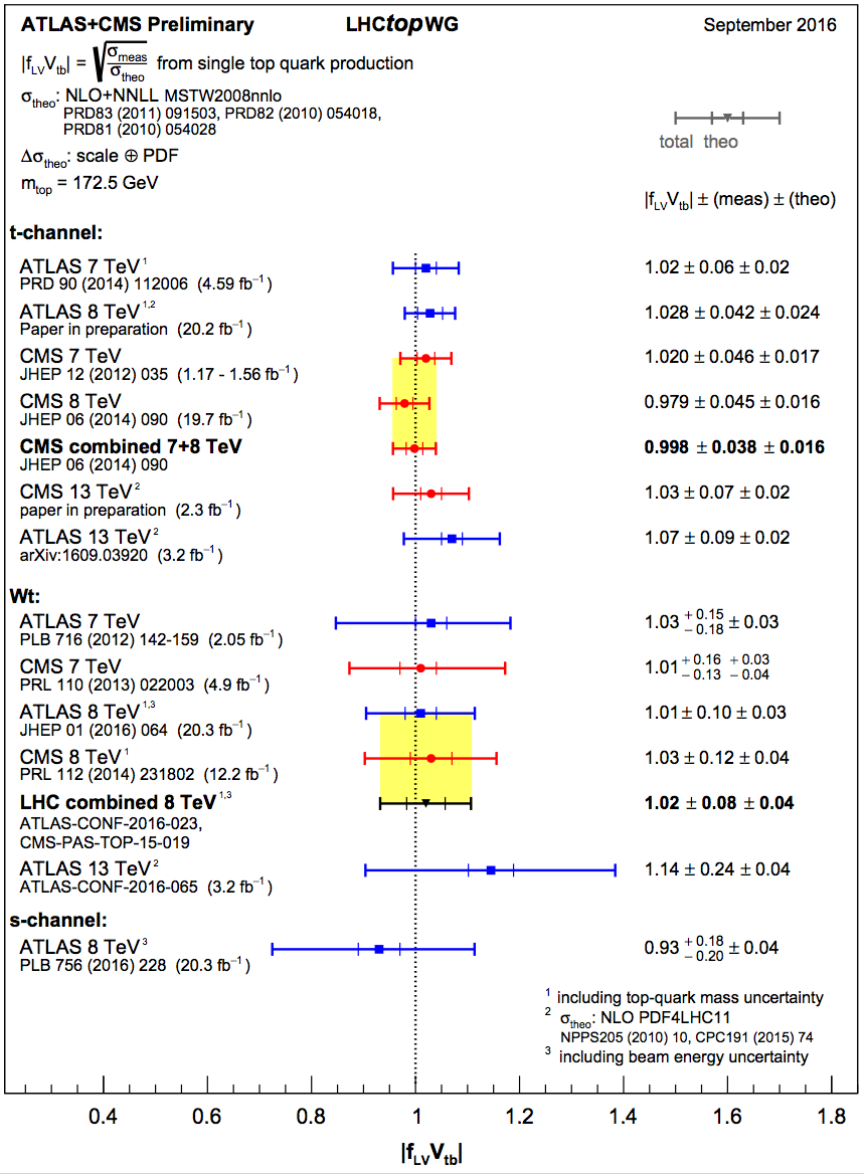
Single top production:
$\sigma \propto |f_{LV} V_{tb}|^2$

with f_{LV} encapsulates new physics
f_{LV} =1 in the Standard Model

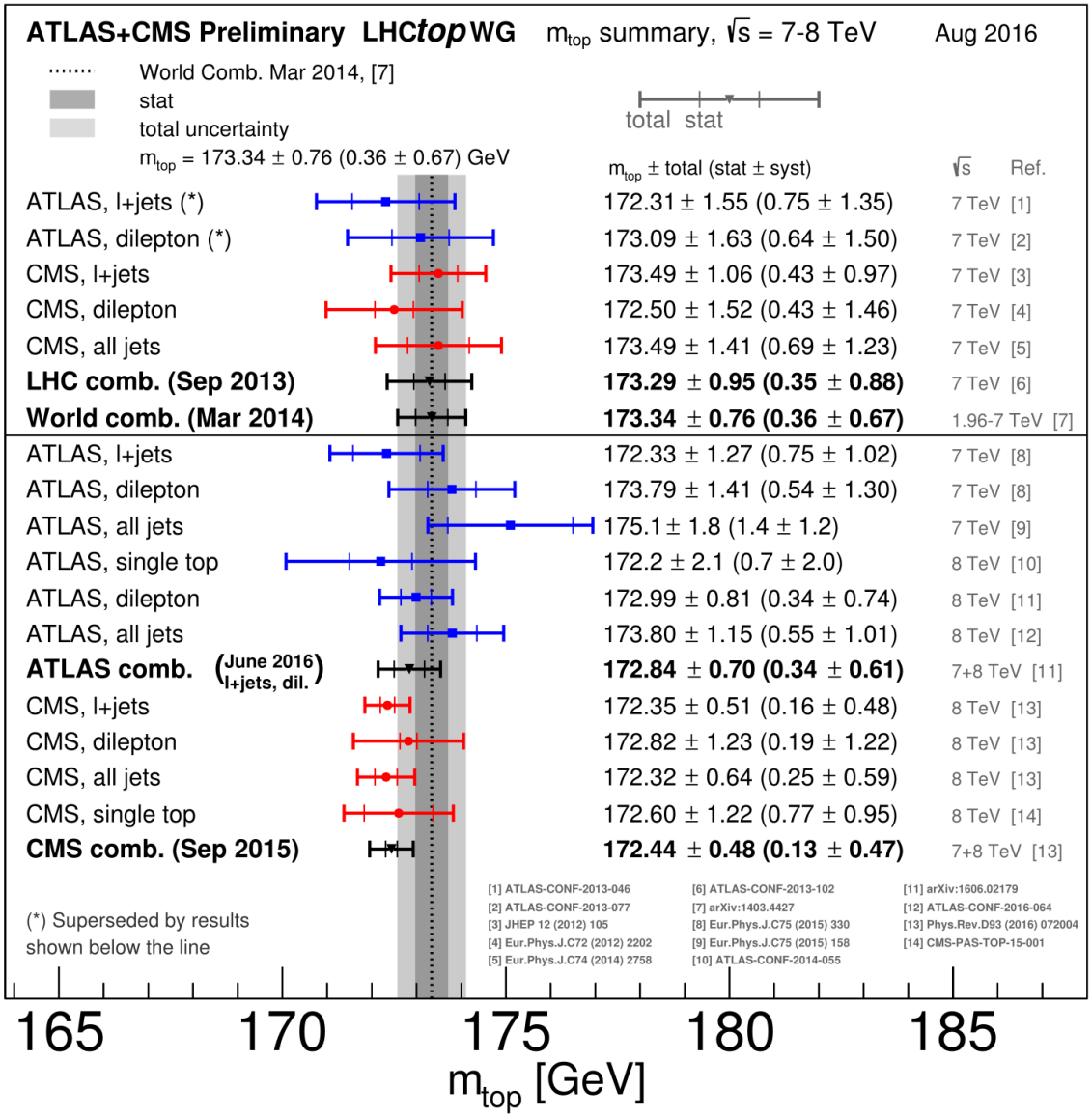
$$|f_{LV} V_{tb}| = \sqrt{\frac{\sigma_{measured}}{\sigma_{theoretical}}}$$

Comment:

- No CKM unitary assumption
- Assumption: $|V_{td}|$ & $|V_{ts}|$ negligible with respect to $|V_{tb}|$



1. Short overview: top-quark mass



2. Width of the quark top

- **Expected value in the Standard Model:** $\Gamma_t^{NLO} = 1.35$ GeV for m_t=173.3 GeV, α_S=0.118 ARXIV:1404.2292

- **Two available methods of measurement:**

  - **Indirect method** based on

$$R_b = \frac{BR(t \to Wb)}{BR(t \to Wq)}$$

$$\sigma(\text{single top t}-\text{channel})$$

Exp.	Value	
D0	$\Gamma_t = 2.00^{+0.47}_{-0.43}$GeV	ARXIV:1201.4156
CMS	$\Gamma_t = 1.36 \pm 0.02(\text{stat})^{+0.14}_{-0.11}(\text{syst})$ GeV	ARXIV:1404.2292
PDG average	$\Gamma_t = 1.41^{+0.19}_{-0.15}$GeV	

  - **Direct method** based on top-quark mass lineshape + comparison with MC

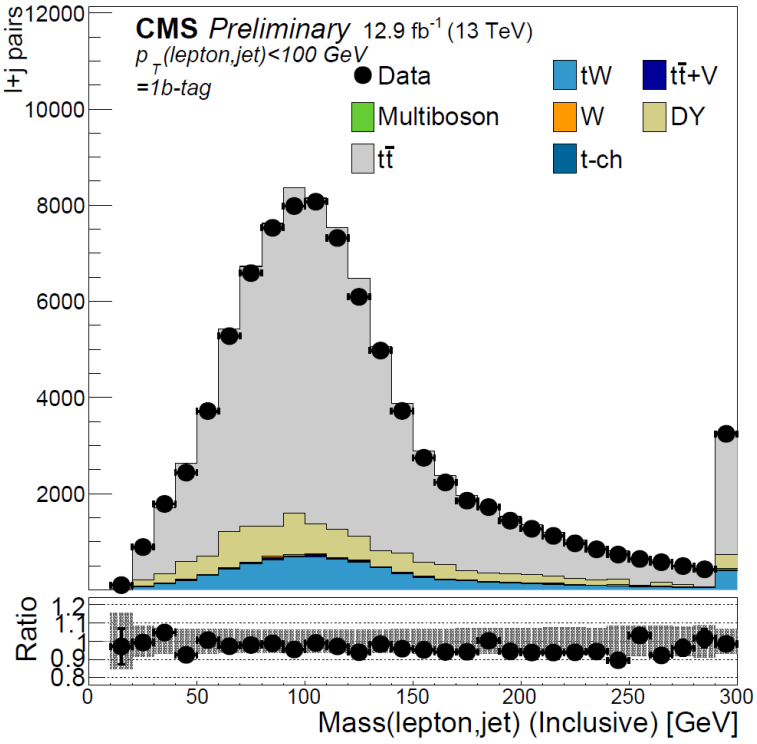
Exp.	Value	
CDF	$\Gamma_t < 6.38$ GeV	ARXIV:1308.4050

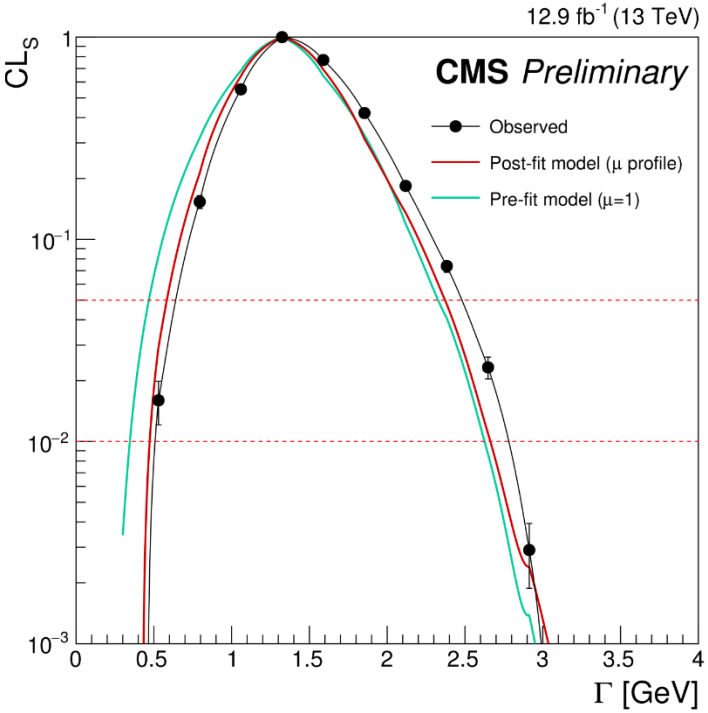
Limited by statistical uncertainties and jet energy scale resolution uncertainties

2. Width of the quark top

TOP-16-019

New result: direct measurement with L^{int}=12.9 fb^{-1}, 13 TeV





- Sensitive observable: M(l,b)
- Several categories:
  - Boosted or unboosted top
  - Only 1 or more b-tagged jets
- Comparison to the simulated expectations for different width scenarios using a likelihood ratios technique

The most precise direct bound of the top quark width

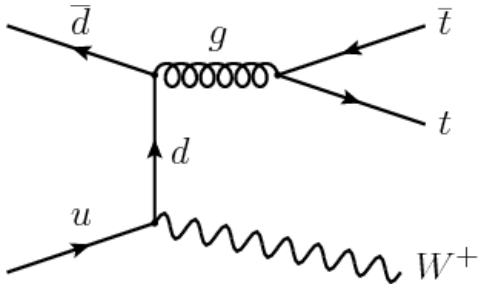
- $0.6 < \Gamma_t < 2.5$ GeV @ CL=95%
- $0.6 < \Gamma_t < 2.4$ GeV for m_t = 172.5 GeV

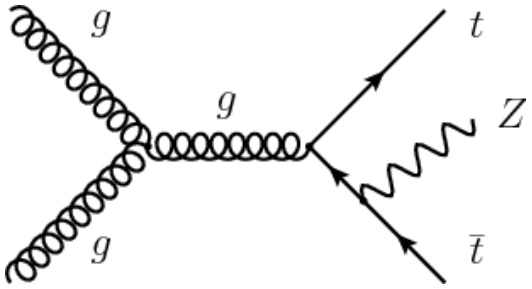
3. Associated production ttV

TOPQ-2015-22
TOP-16-017

Motivation for ttV cross section measurement:

- Probing ttW, ttγ and ttZ couplings
- Background sources for new physics or ttH





Expected cross section in the Standard Model @ 13 TeV:

$$\sigma^{NLO}(pp \to ttZ) = 839^{+80}_{-92}(\text{scale})^{+9}_{-9}(\text{pdf})^{+11}_{-11}(\alpha_S)\ \text{fb}$$ [ARXIV:1504.03446]

$$\sigma^{NLO}(pp \to ttW) = 601^{+56}_{-51}(\text{scale})^{+9}_{-9}(\text{pdf})^{+11}_{-11}(\alpha_S)\ \text{fb}$$ [ARXIV:1405.0301]

[LHCHXSWG-DRAFT-INT-2016-008]

Analysis strategy in ATLAS & CMS:

Several channels

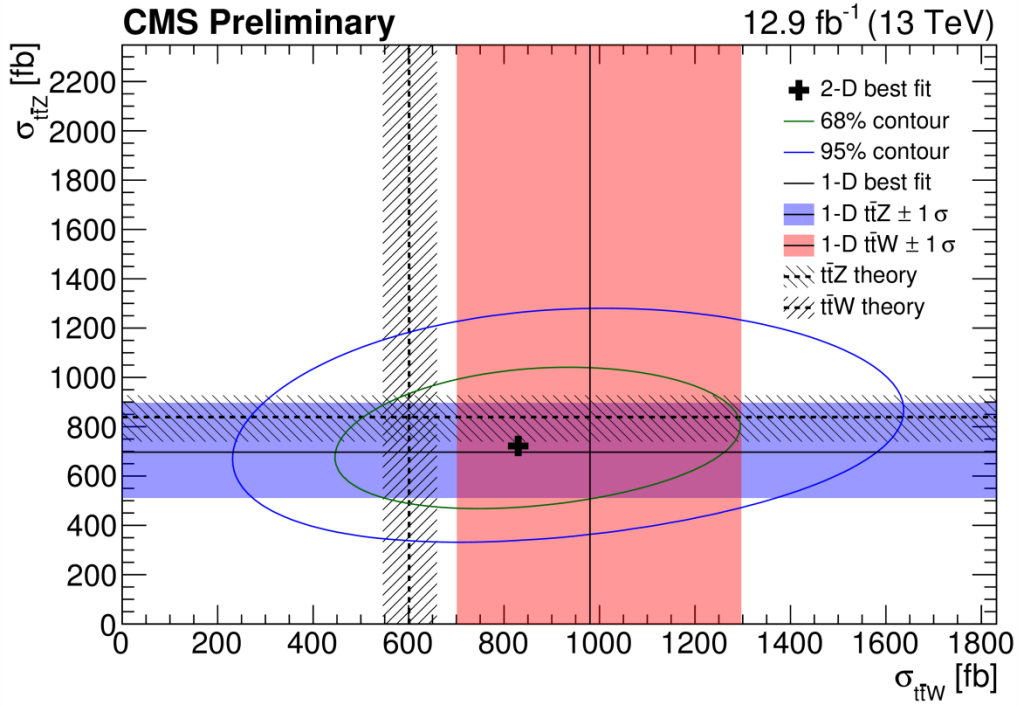
Process	$t\bar{t}$ decay	Boson decay	Channel
$t\bar{t}W^{\pm}$	$(\mu^{\pm}\nu b)(q\bar{q}b)$	$\mu^{\pm}\nu$	SS dimuon
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{\pm}\nu$	Trilepton
$t\bar{t}Z$	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	Trilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{+}\ell^{-}$	Tetralepton

The most sensible channels:
- 2 SS leptons for ttW
- 3 leptons for ttZ

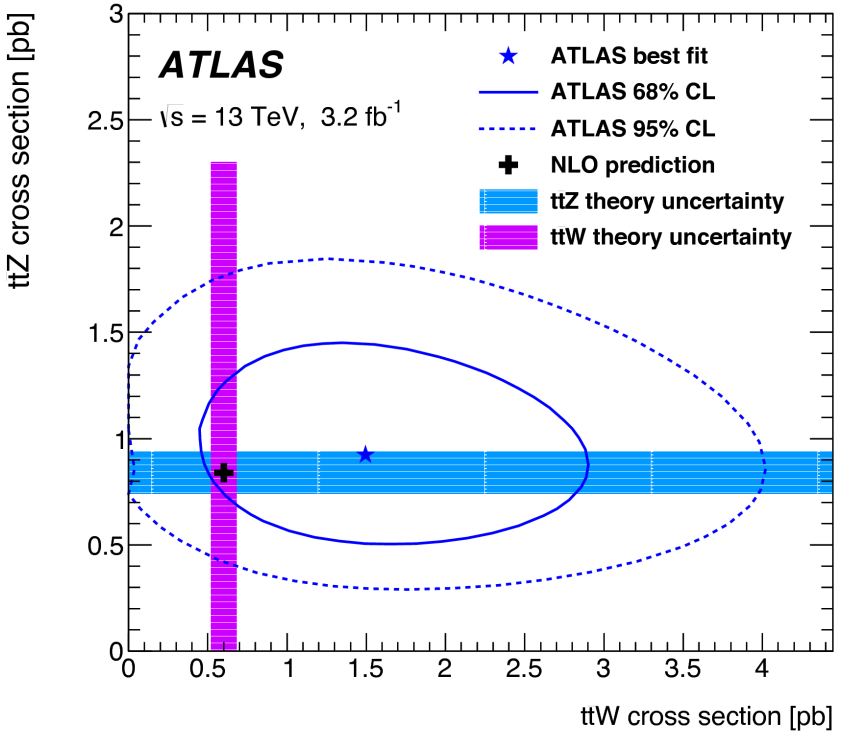
3. Associated production ttV

TOPQ-2015-22
TOP-16-017

2016 data



2015 data



$\sigma(pp \to ttZ) = 0.70^{+0.16}_{-0.15}(\text{stat})^{+0.14}_{-0.12}(sys)$ pb

$\sigma(pp \to ttW) = 0.98^{+0.23}_{-0.22}(\text{stat})^{+0.22}_{-0.18}(sys)$ pb

$\sigma(pp \to ttZ) = 0.92 \pm 0.29(stat) \pm 0.10(sys)$ pb

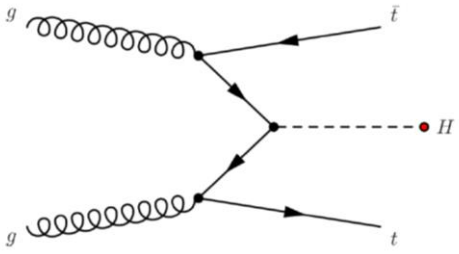
$\sigma(pp \to ttW) = 1.50 \pm 0.72(stat) \pm 0.33(sys)$ pb

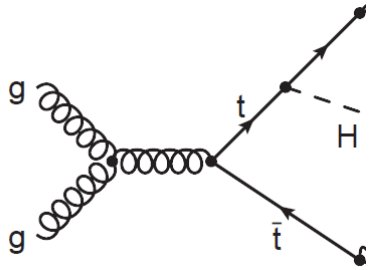
Agreement with the Standard Model predictions

3. Associated production ttH

CONF-16-080 HIG-16-004
CONF-16-058 HIG-16-022
CONF-16-067 HIG-16-020
CONF-16-068

ttH production at tree level :
direct probe of Top-Higgs Yukawa coupling (indirect through gluon fusion)





Expected cross section in the Standard Model @ 13 TeV: [LHCHXSWG-DRAFT-INT-2016-008]

$$\sigma^{NLO}(pp \to ttH) = 507.1 \text{ fb}\ {}^{+5.8\%}_{-9.2\%}(\text{scale})^{+3\%}_{-3\%}(\text{pdf})^{+2\%}_{-2\%}(\alpha_S)$$

- NLO QCD and NLO EW accuracies
- m_H=125 GeV

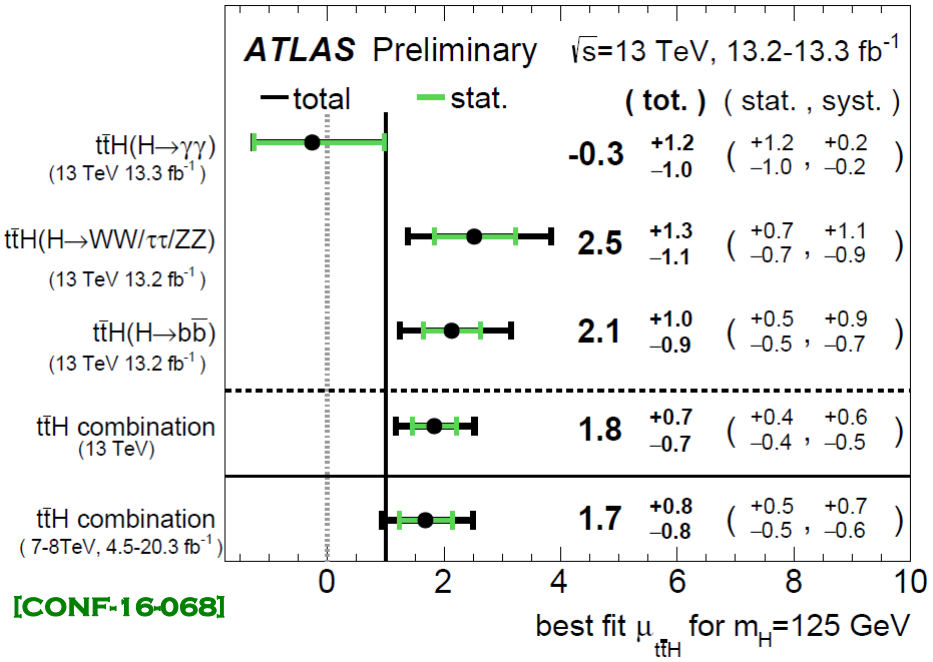
Search strategy in ATLAS & CMS: several analyses according to the Higgs boson decay

Channel	Branching ratio	Property	ATLAS	CMS
H→γγ	0.23%	Clean signature but small BR	[CONF-16-067]	[HIG-16-020]
H→WW/ττ/ZZ	21.5%/6.3%/2.6%	Multileptonic signature, low background final state wrt H→b	[CONF-16-058]	[HIG-16-022]
H→bb	58.1%	High statistic but multijet background	[CONF-16-080]	[HIG-16-004]

3. Associated production ttH

CONF-16-080 HIG-16-004
CONF-16-058 HIG-16-022
CONF-16-067 HIG-16-020
CONF-16-068

Focus only on the results. For details, see talks related to Higgs boson.



[CONF-16-068]

CMS results

Channel	Data	Results
ttH, H→γγ	2016	$\mu = 1.9^{+1.5}_{-1.2}$
ttH, H→WW/ττ/ZZ	2015 + 2016	$\mu = 2.0^{+0.8}_{-0.7}$
ttH, H→bb	2015	$\mu = -2.0^{+1.8}_{-1.8}$

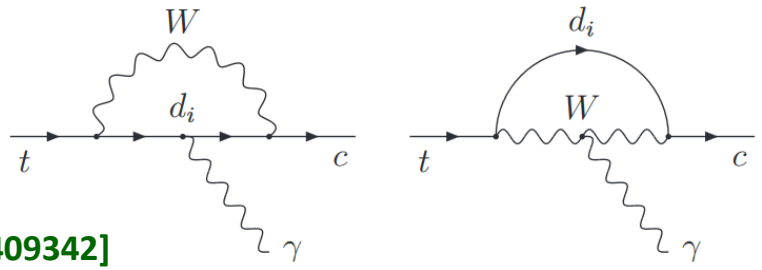
Results are expressed in terms of signal strength: $\mu = \sigma/\sigma_{SM}$.

4. FCNC anomalous couplings

- FCNC top couplings are highly suppressed in the SM due to GIM (Glashow-Iliopoulos-Maiani) mechanism

→Promising signatures of New Physics

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



[arXiv:0409342]

- Lagrangian in terms of FCNC anomalous top couplings derivated from LO EFT.

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

[arXiv:0803.3810, 0811.3842, 0904.2387]

Several conventions are used for the coupling definition.
→ Convention-independent way : Result = a limit on BR(t→Xq)

4. FCNC anomalous couplings

TOPQ-2014-08 TOPQ-2014-13 TOPQ-2014-14
TOP-14-007 TOP-14-003 TOP-12-039 TOP-14-020 TOP-13-017 TOP-14-019

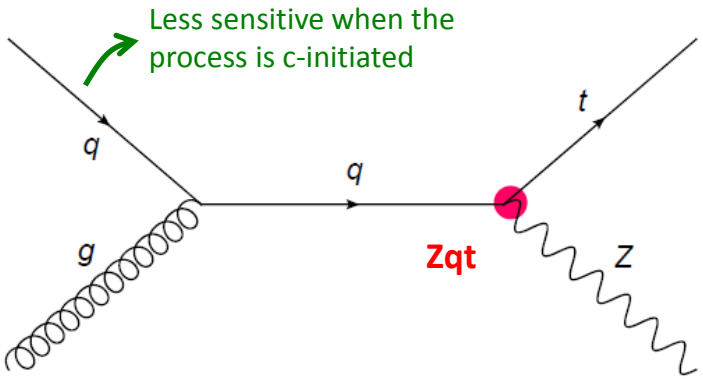
2 ways to look for FCNC anomalous couplings Xqt :

- In the top decay of tt processes : t → X q (not relevant for X = g or γ)
- In the associated single top production : pp → tX

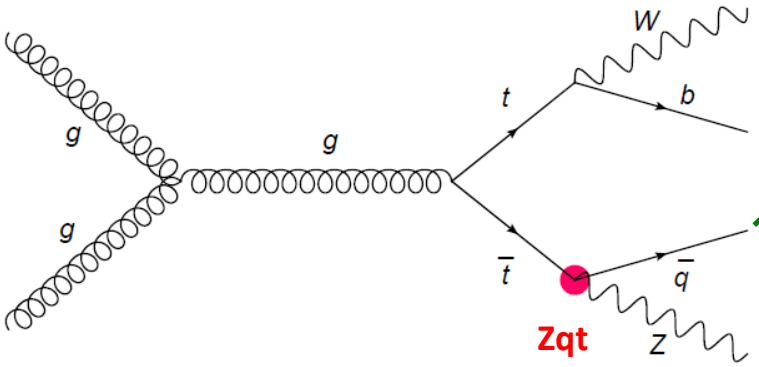
Ex: κ_{Zqt}/Λ coupling

For small coupling value, $cross\ section \propto |coupling|^2$

Single-top-like diagram



TT-like diagram



No c-tagger used in the analyses. Sensibility to Zqu or Zqc should be similar.

4. FCNC anomalous couplings

TOPQ-2014-08
TOPQ-2014-13
TOPQ-2014-14
TOP-14-007
TOP-14-003
TOP-12-039
TOP-14-020
TOP-13-017
TOP-14-019

Example: analyses dedicated to κ_{Zqt}/Λ coupling

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

TOPQ-2014-13

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

Only ttbar processes

Selection:

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

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

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

TOP-12-039

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

Both ttbar + single top processes

Selection:

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

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

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

4. FCNC anomalous couplings

TOPQ-2014-08
TOPQ-2014-13
TOPQ-2014-14
TOP-14-007
TOP-14-003
TOP-12-039
TOP-14-020
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TOP-14-019

Example: analyses dedicated to κ_{Zqt}/Λ coupling

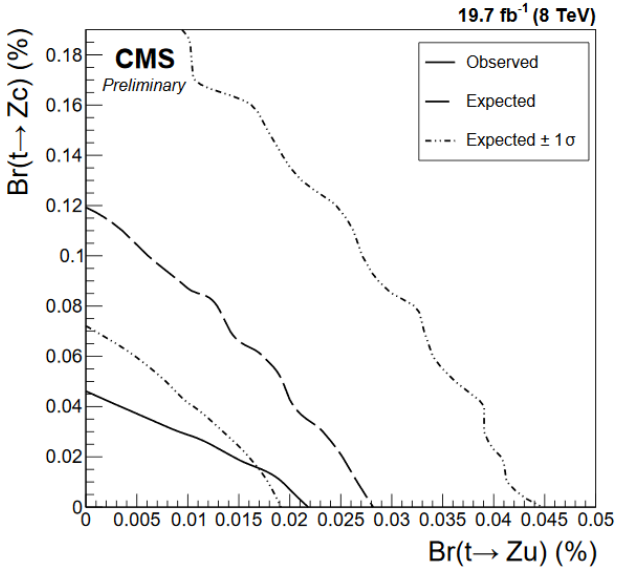
Signature = trileptonic final state
(leptonic decay for one top + Z>ll)

TOPQ-2014-13
8 TeV, L^{int}=20.3 fb^{-1}
Only ttbar processes

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

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

TOP-12-039
8 TeV, L^{int}=19.7 fb^{-1}
Both ttbar + single top processes



$$\boldsymbol{BR(t \to Zu) < 2.2\times10^{-4}}$$
$$\boldsymbol{BR(t \to Zc) < 4.9\times10^{-4}}$$

4. FCNC anomalous couplings

TOPQ-2014-08
TOPQ-2014-13
TOPQ-2014-14
TOP-14-007
TOP-14-003
TOP-12-039
TOP-14-020
TOP-13-017
TOP-14-019

Summary of the FCNC top searches

observed 95% CL upper limits

Coupling	CMS Results	ATLAS Results
κ_{gqt}/Λ [GeV^{-2}]	TOP-14-007 7 TeV, L^{int}=5 fb^{-1} $\boldsymbol{BR(t \to gu) < 3.5\times10^{-4}}$ $\boldsymbol{BR(t \to gc) < 34.4\times10^{-4}}$	TOPQ-2014-13 8 TeV, L^{int}=20.3 fb^{-1} $\boldsymbol{BR(t \to gu) < 0.4\times10^{-4}}$ $\boldsymbol{BR(t \to gc) < 2\times10^{-4}}$
$\kappa_{\gamma qt}/\Lambda$ [GeV^{-2}]	TOP-14-003 8 TeV, L^{int}=19.8 fb^{-1} $\boldsymbol{BR(t \to \gamma u) < 1.3 \times 10^{-4}}$ $\boldsymbol{BR(t \to \gamma c) < 17 \times 10^{-4}}$	
κ_{Zqt}/Λ [GeV^{-2}]	TOP-12-039 8 TeV, L^{int}=19.7 fb^{-1} Both ttbar + single top processes $\boldsymbol{BR(t \to Zu) < 2.2\times10^{-4}}$ $\boldsymbol{BR(t \to Zc) < 4.9\times10^{-4}}$	TOPQ-2014-08 8 TeV, L^{int}=20.3 fb^{-1} Only ttbar processes $\boldsymbol{BR(t \to Zq) < 7\times10^{-4}}$

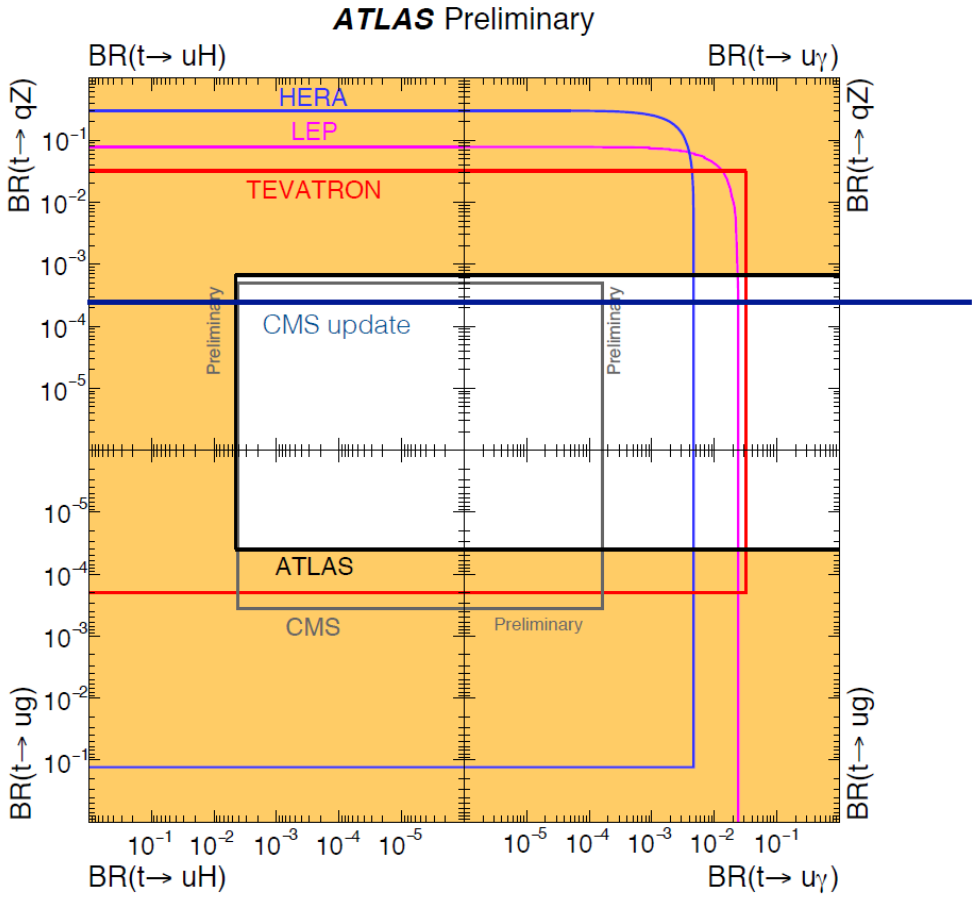
4. FCNC anomalous couplings

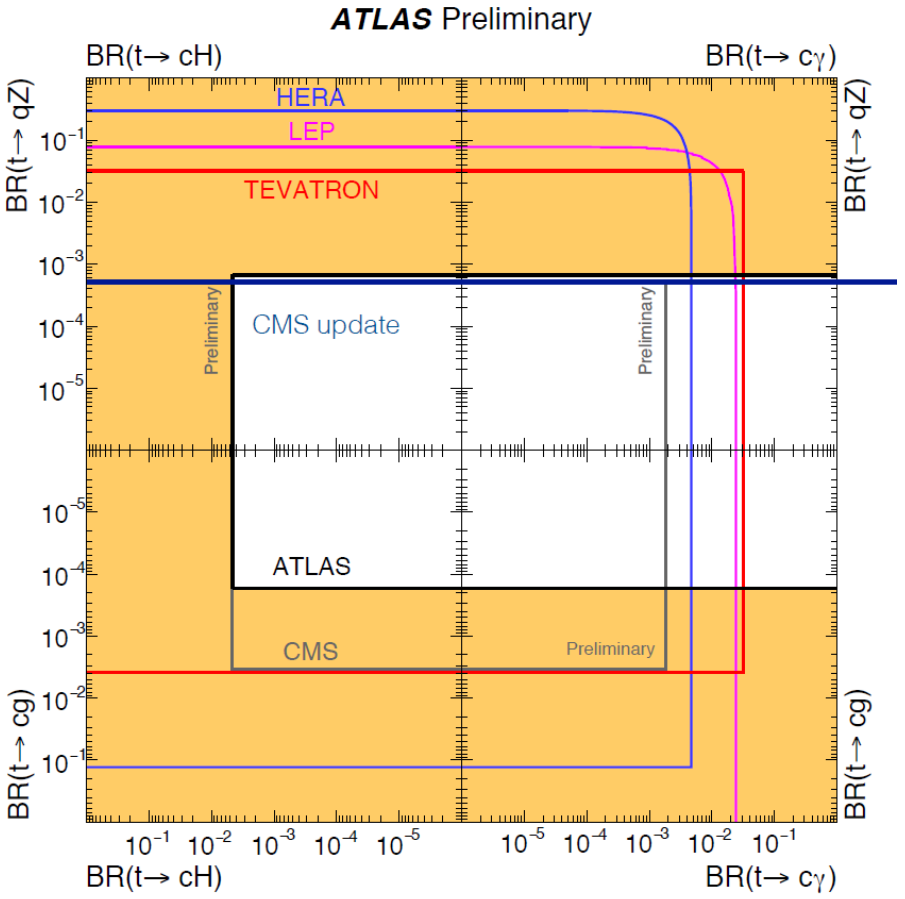
Coupling	Channel	CMS Results	ATLAS Results TOPQ-2014-14 8 TeV, L^{int}=20.3 fb^{-1}
η_{hqt} [no unit]	H→bb	TOP-14-020 8 TeV, L^{int}=19.8 fb^{-1} Only ttbar processes $BR(t \to Hu) < 192\times10^{-4}$ $BR(t \to Hc) < 116\times10^{-4}$	Only ttbar processes $BR(t \to Hu) < 61\times10^{-4}$ $BR(t \to Hc)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

4. FCNC anomalous couplings

TOPQ-2014-08
TOPQ-2014-13
TOPQ-2014-14

TOP-14-007
TOP-14-003
TOP-12-039
TOP-14-020
TOP-13-017
TOP-14-019





Summary

- Measurements of top quark properties are crucial for testing the Standard Model.

- Both ATLAS and CMS collaboration have analyzed intensively LHC data to extract quark top properties. The work is still on going with 2016 data.

- This talk was devoted to the first measurements done with 13 TeV data…
  - Cross-sections of single top and top pair production
  - CKM matrix element |Vtb|
  - Direct measurement of the quark-top total width
  - Cross-section of associated production ttX with X = Z, W or H

- … and discussed also some recent results:
  - Mass combination improvement [ATLAS]
  - Search of FCNC anomalous couplings: in particular the Zqt coupling

- Up to now, all the measures show a good agreement with the Standard Model predictions.

Results on other topics which are not covered by this talk can be found here:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults