

Top couplings

Rencontres du Vietnam 2014:
Physics at LHC and beyond, Quy-Nhon (Vietnam)

12/08/2014

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Outline

- **Top quark at LHC: production and decay**
- **Couplings studies in inclusive production**
 - tWb couplings in the production: single-top
 - top couplings to Z and photons: ttZ/W and tt γ
 - Searching for new physics: anomalous couplings and FCNC
 - Measurement of top to Wb branching ratio
- **Studies of couplings in the event properties**
 - W-helicity, and CP violation, top polarisation
- **Prospects for top couplings studies:**
 - At LHC 13-14TeV
 - With e+e- colliders

top-quark production in the standard model @LHC

Production mechanism...

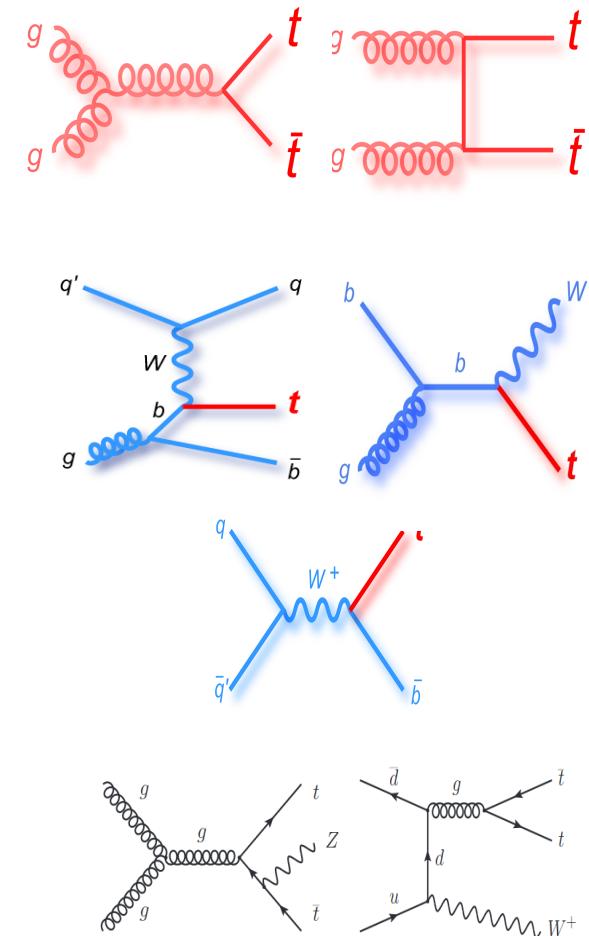
- **tt pairs** via strong interaction:
 - dominant at the LHC and Tevatron
 - depends on alpha strong
 - sensitive to pdf
- **single-tops:**
 - weak charged current interactions
 - t -, s -channel and W -associated
 - tWb vertex in production
 - Sensitive to V_{tb}
- **top + X :**
 - top pair and single top + W, Z, γ ...
 - way to probe neutral current vertices involving top quark

...cross section...

$$\text{LO} \propto (\alpha_s/m_{\text{top}})^2$$

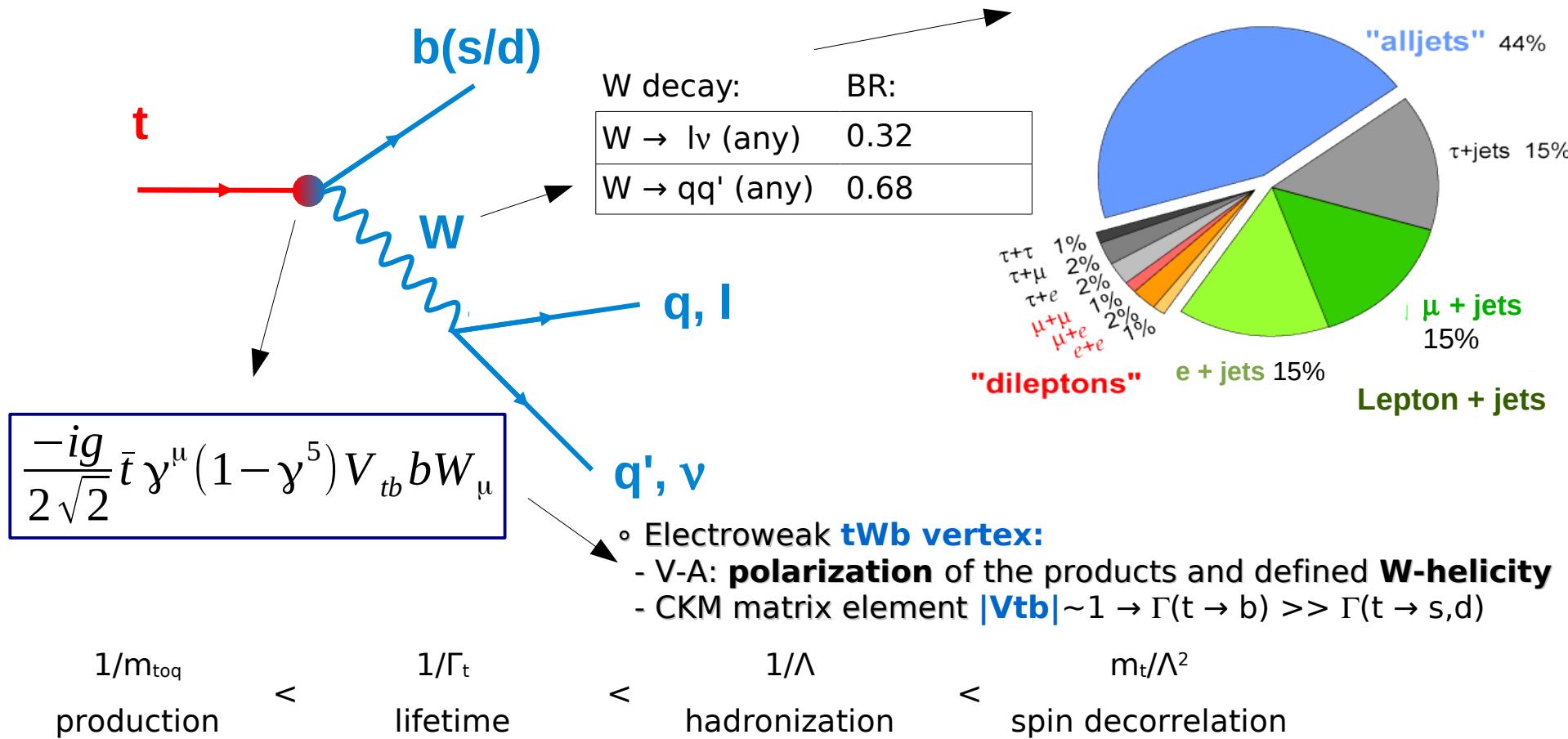
pp collisions @ 7/8/14 TeV:
 $\sim 172/246/950 \text{ pb}$

...LO diagrams



top-quark decays

- Main mechanism is electroweak: no hadronisation



Schema of the coupling measurements

What kind of measurement we do?



“Intensity”:
Incl. cross section, rates...

tt cross sections
single-top cross sections
top +Z/W/ γ associated production
FCNC in single-top production and decay
FCNC in tt top decays
top branching ratio to Wb

“Properties”:
angular distributions, diff xSecs...

Top quark polarisation in single-top and top pairs
tt spin correlations
W-helicity in top decays
CP violation in single-top

Schema of the coupling measurements

What kind of measurement we do?

Where do we probe the coupling more effectively?

@top interaction / production vertex

@top decay vertex

“Intensity”:
Incl. cross section, rates...

tt cross sections
single-top cross sections
top +Z/W/ γ associated production
FCNC in single-top production and decay

FCNC in tt top decays
top branching ratio to Wb

“Properties”:
angular distributions, diff xSecs...

Top quark polarisation in single-top and top pairs

tt spin correlations

W-helicity in top decays
CP violation in single-top

Couplings studies in inclusive production

The single-top quark processes: tWb vertex in the production

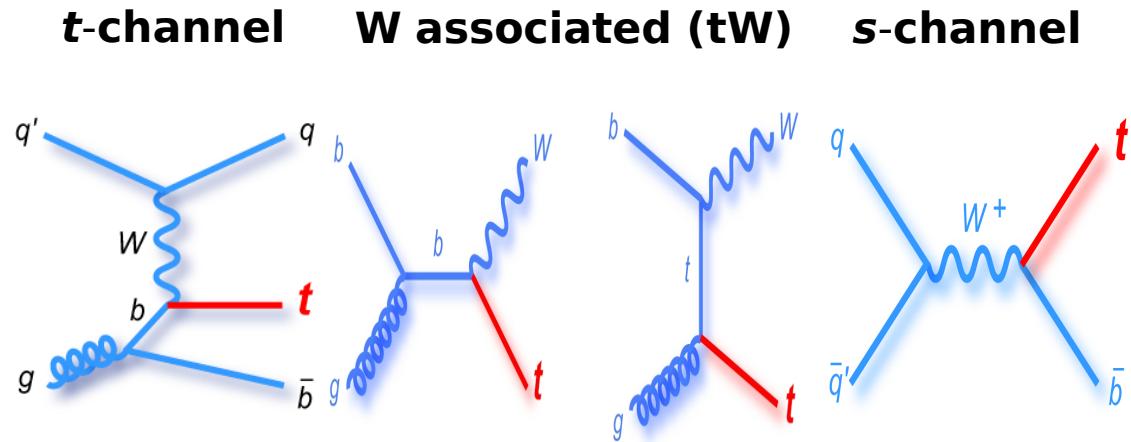
- **Single-top quark:**

- **tWb vertex in production**

- Top is produced polarised

- non SM couplings can appear in cross section and properties

- All channels cross sections: proportional to $|V_{tb}|^2$



LHC pp @7 TeV⁽¹⁾⁽²⁾

64.6±0.2.1 pb

15.6±1.2 pb

4.59±0.19 pb

LHC pp @8 TeV⁽¹⁾⁽²⁾

85.2±2.2 pb⁽³⁾

22.2±1.5 pb

5.55±0.22 pb

LHC pp @14 TeV⁽²⁾

248.1±6.8 pb

82.6±4.4 pb

11.86±0.51 pb

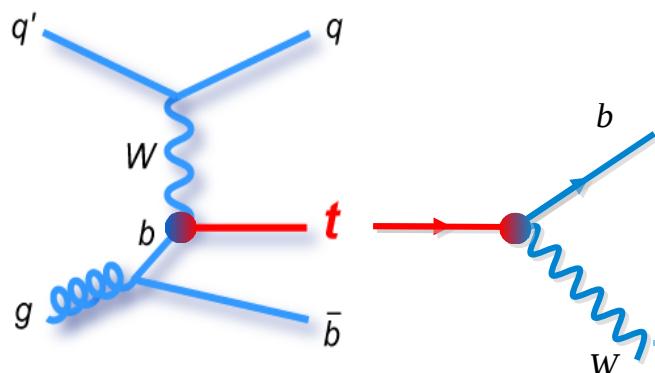
(1): N. Kidonakis Phys. Rev. D 82, 054018 (2010) and arxiv:0909.0037

(2): N. Kidonakis Phys. arXiv:1205.3453

(3): M. Burcherseifer, F.Caola, K. Melnikov: arXiv:1404.7116

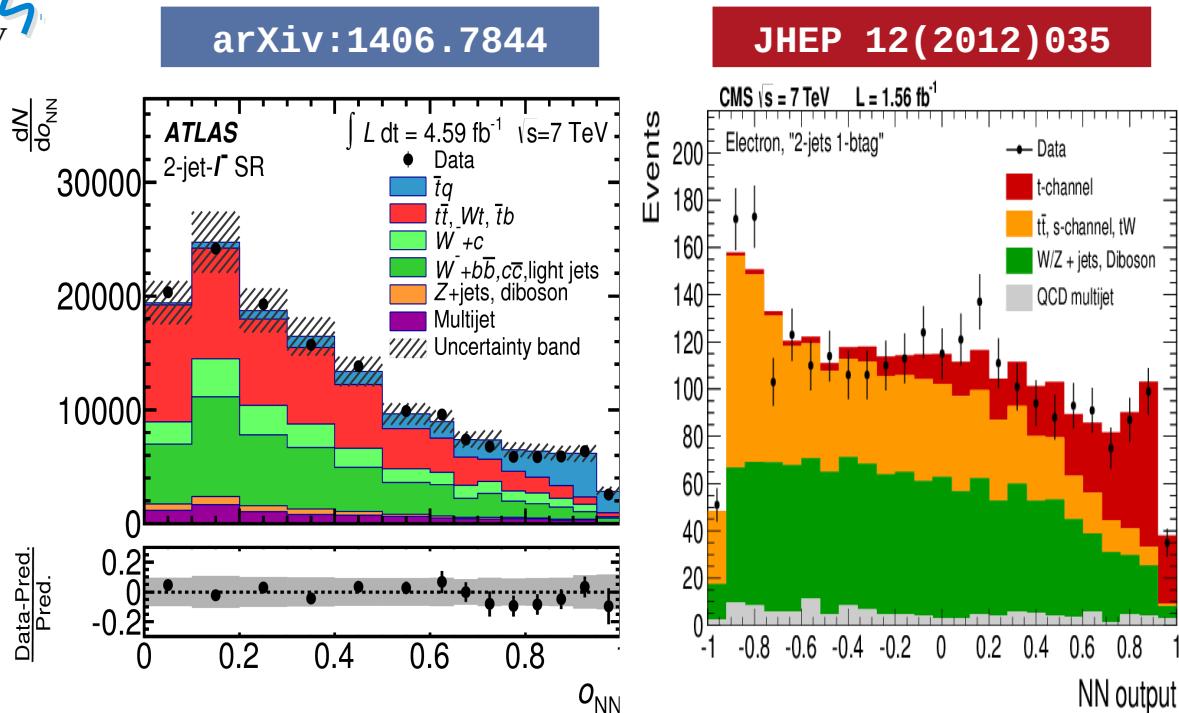
All with top mass = 172.5 GeV

The t -channel single-top



- **Inclusive cross sections:**
 - in leptonic only decay channels: precision of $\sim 10\%$ at LHC
 - Using MVAs to maximize background rejection
 - All measurements in the systematics dominated regime

- **Most abundant single-top ($\sigma \sim 1/3 \times \sigma(t\bar{t})$):**
 - **precision measurement of V_{tb} !**
 - Measurement of properties stemming from the coupling nature both in production and decay



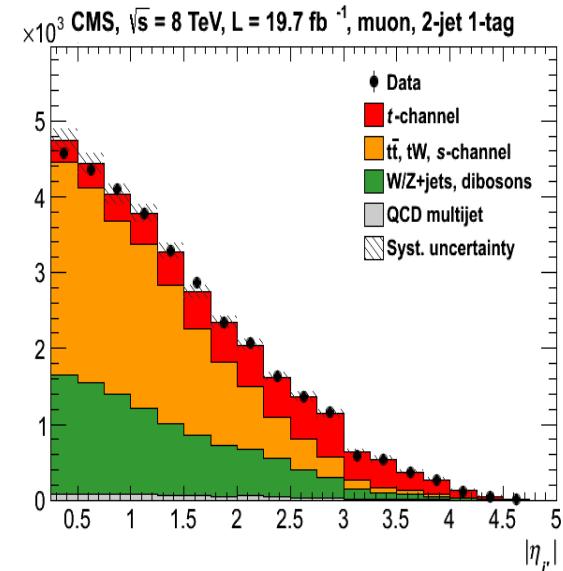
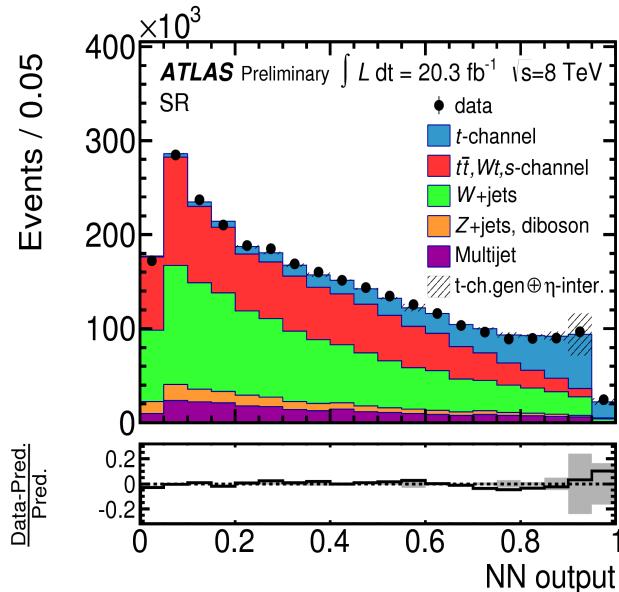
t -channel single-top: cross sections and $|V_{tb}|$

- Cross sections @7/8 TeV

	Atlas	CMS
$\sigma(7 \text{ TeV}) [\text{pb}]$	68 ± 8	67.2 ± 6.1
$\sigma(8 \text{ TeV}) [\text{pb}]$	82.6 ± 12.1	83.6 ± 7.8

- $|V_{tb}|$: Assuming $|V_{td}|, |V_{ts}| \ll |V_{tb}|$

$$|V_{tb}| = \sqrt{(\sigma_{t\text{-ch.}}^{\text{obs.}} / \sigma_{t\text{-ch.}}^{\text{theo.}})}$$



	Atlas	CMS
$V_{tb}(7 \text{ TeV}) / \text{limit @95%CL}$	$1.02 \pm 0.07 / > 0.88$	$1.02 \pm 0.05 / > 0.92$
$V_{tb}(8 \text{ TeV}) / \text{limit @95%CL}$	$0.97 \pm 0.09 / > 0.78$	$0.978 \pm 0.04 / > 0.89$

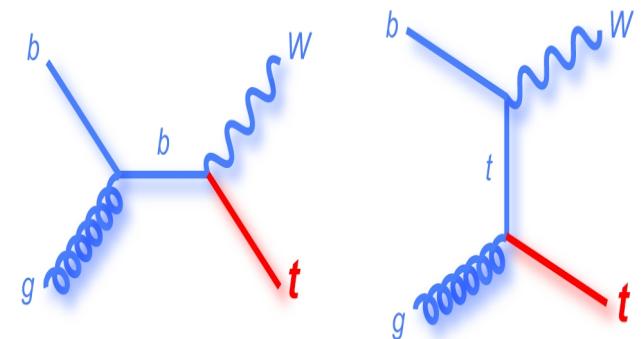
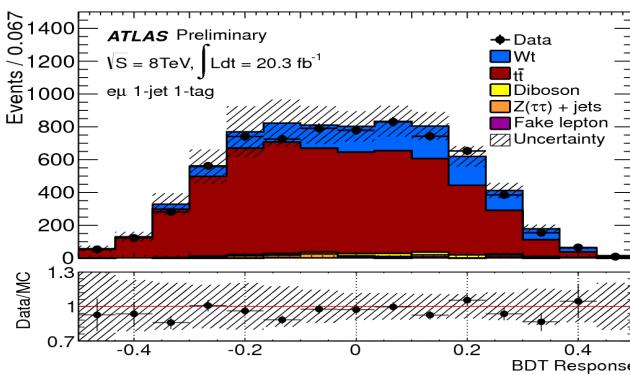
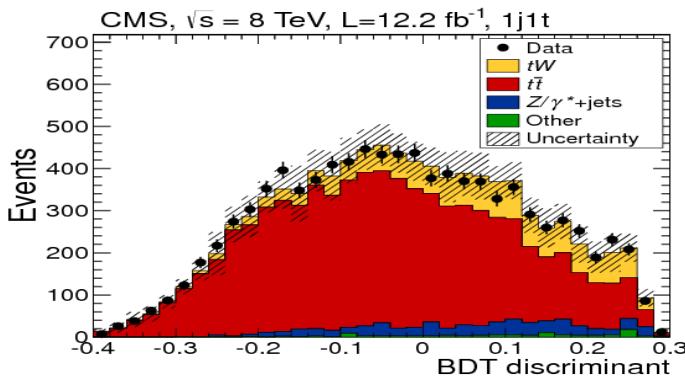
arXiv:1406.7844

JHEP 06(2014)090

The single-top quark W-associated production

- Entirely different production mechanism:

- complementary to t-channel route to measure tWb properties and Vtb



- Measurement at LHC with 8 TeV datasets:

- Measured in channels where both t and W decay leptonically: 2 opposite sign isolated leptons in the final state
- V_{tb} extracted in the same way as t -channel:

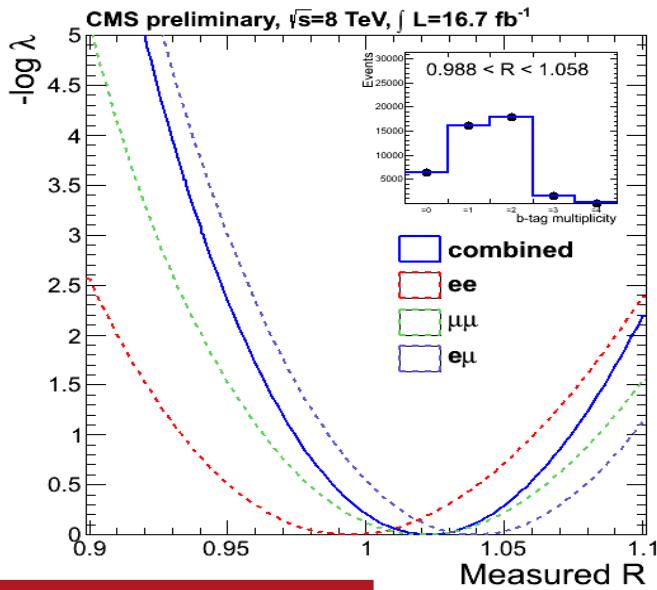
	Atlas	CMS
$\sigma(8 \text{ TeV}) [\text{pb}]$	27.2 ± 5.8	23.4 ± 5.4
$V_{tb}(8 \text{ TeV}) / \text{limit}$ @95%CL	$1.10 \pm 0.12 / >0.72$	$1.03 \pm 0.12 / >0.78$

ATLAS-CONF-2013-100

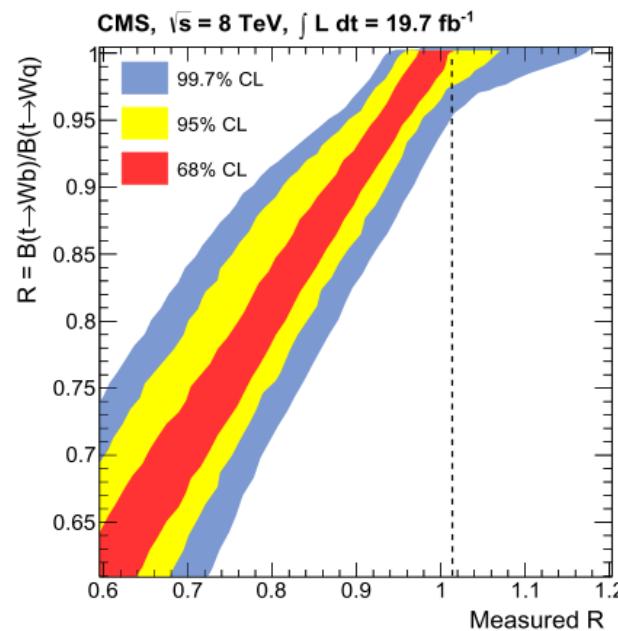
PRL 112, 231802

The R measurement

- Fraction $R = BR(t \rightarrow Wb)/BR(t \rightarrow Wq)$
- allows measurement of $|V_{tb}|$
- Unitarity limit foresees $|V_{tb}| = 0.999146$
- Likelihood fit to jet multiplicity spectrum



PLB 736(2014)33



- Most precise measurement up to date:

$R = 1.014 \pm 0.032 \rightarrow |V_{tb}| = 1.007 \pm 0.016$;
Assuming $R < 1$: $|V_{tb}| > 0.975$ @ 95%CL

- combined with single-top cross section measurement allows to measure top width:

$$\Gamma_t = \frac{\sigma_{t-ch}^{obs.}}{B(t \rightarrow Wb)} \frac{\Gamma(t \rightarrow Wb)}{\sigma_{t-ch}^{theo.}} = 1.36_{-0.11}^{+0.14}$$

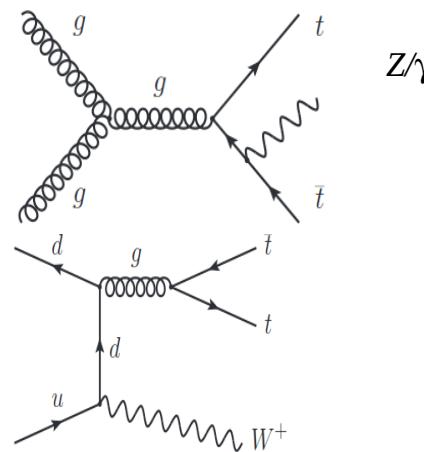
The top pair vector boson/gamma associated production

- **tt + W/Z:**

-Measurements with 3-4 leptons (CMS)
or 2-3 leptons (Atlas)

- **tt + gamma:**

- together with ttZ, probes ewk
Neutral Currents



$$\sigma(t\bar{t}Z) = \textcolor{blue}{150 \text{ (Atlas)}} \pm 56 / \textcolor{red}{200 \pm 80 \text{ (CMS)}} \text{ fb}$$

VS $\sim 197 \pm 24$ (theo, (1)) fb

$$\sigma(t\bar{t}W) = \textcolor{blue}{300 \pm 130 \text{ (Atlas)}} / \textcolor{red}{170 \pm 110 \text{ (CMS)}} \text{ fb}$$

VS 206 ± 22 (theo, (1)) fb

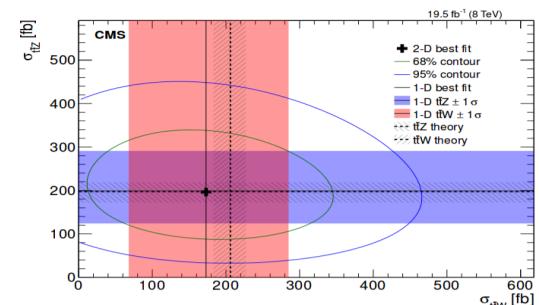
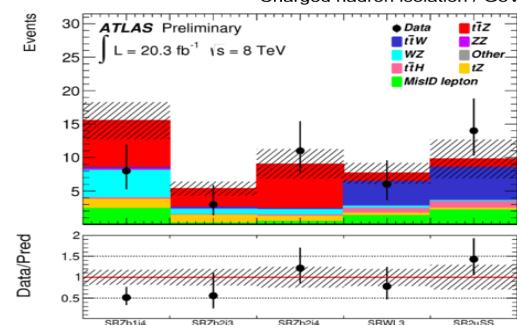
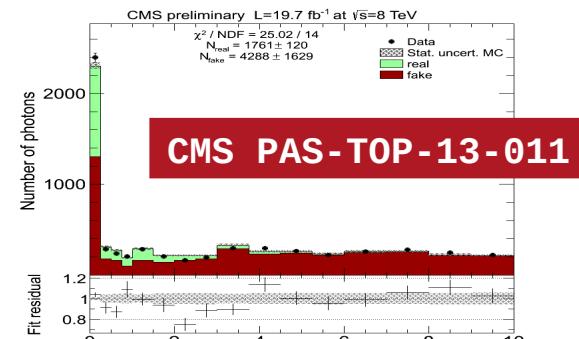
$$\sigma(t\bar{t}\gamma) = \textcolor{red}{2.4 \pm 0.6 \text{ (CMS)}} \text{ pb VS } 1.8 \pm 0.5 \text{ (theo. (2)) pb}$$

[arXiv:1406.7830](https://arxiv.org/abs/1406.7830)

ATLAS-CONF-2014-038

(1): automatic computation with aMC@NLO, J.Alwall et al., arXiv:1405.0301

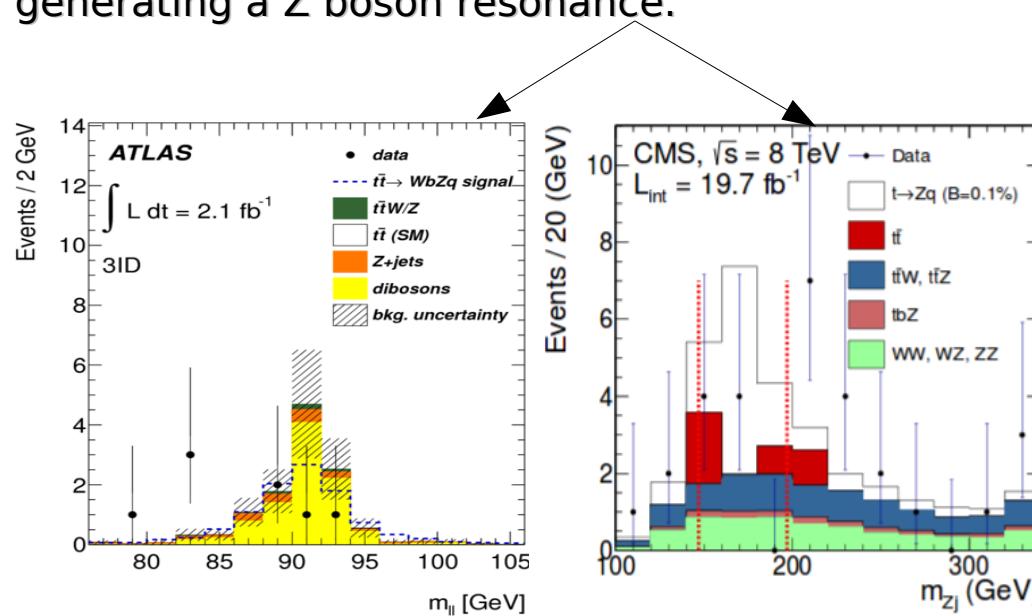
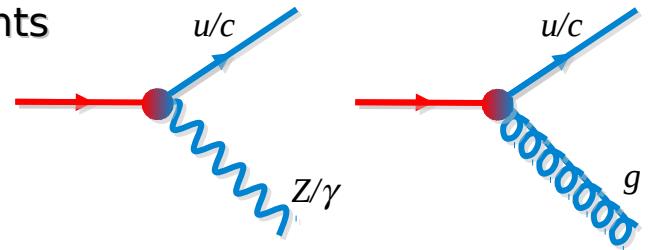
(2): M. Melnikov et al., PRD83 (2011) 074013



Search for non-SM couplings tt and FCNC in decays

- **top decays:**

- FCNC can give $t \rightarrow u/c + g/z/\gamma$: Can be searched for in events with 2 tops
- Several BSM theories can be parametrised through similar dimension-6 operators.
- CMS and Atlas look for events with 3 leptons, 2 of which generating a Z boson resonance.



**BR($t \rightarrow Zq$) < 0.73% (Atlas) /
< 0.05% (CMS)**

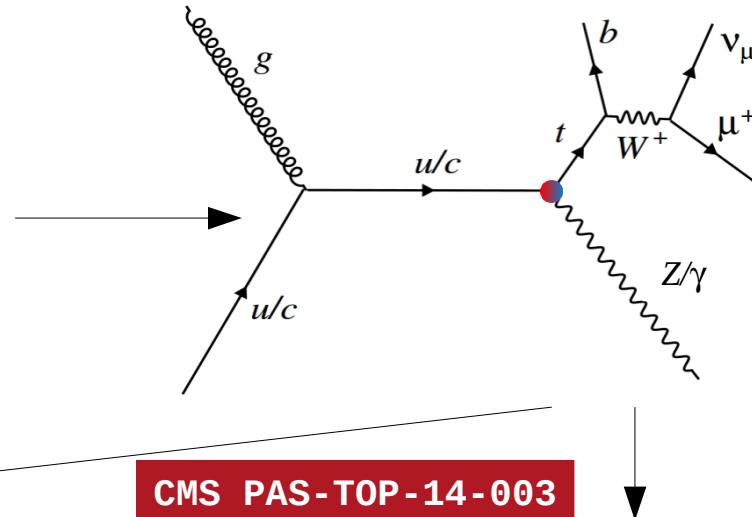
PLB 716(2012)142-159

PRL 112(2014)171802

Search for non-SM couplings top associated production

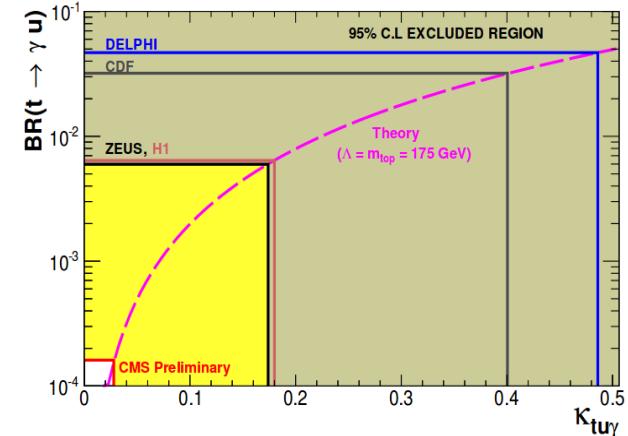
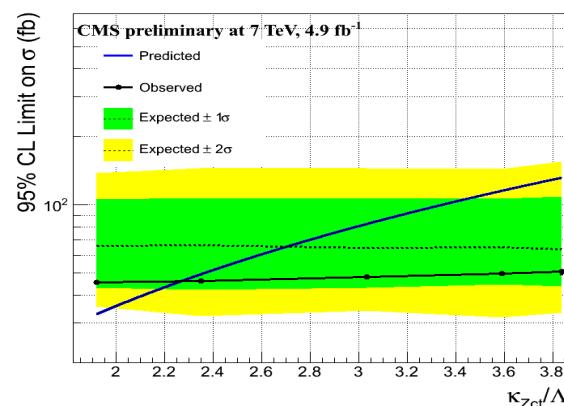
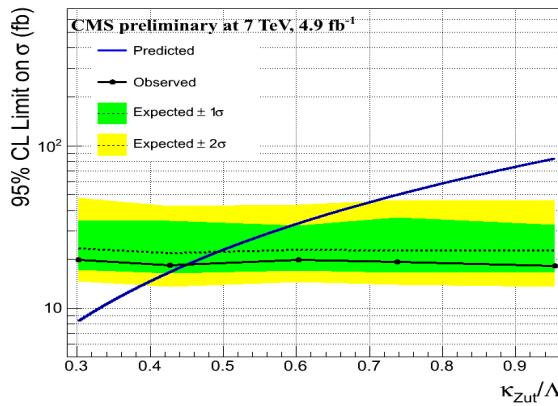
- **single-top + Z/gamma production:**

- Low cross section at LHC in the standard model (~ 0.2 pb).
- Susceptible to enhancement from BSM FCNC
- analyses exploiting trilepton / 1 lepton + 1 photon selections



CMS PAS-TOP-12-021

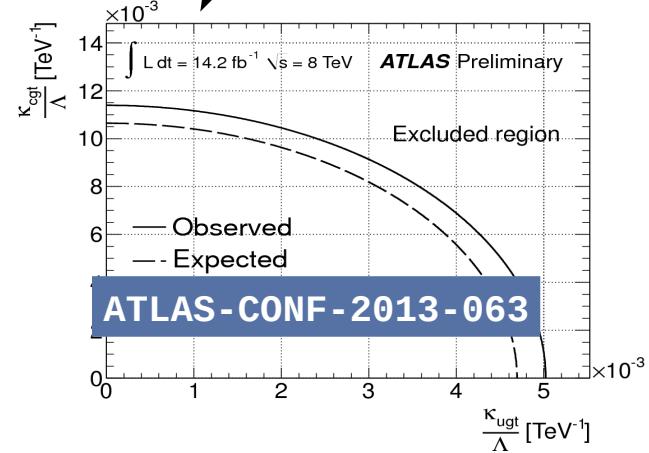
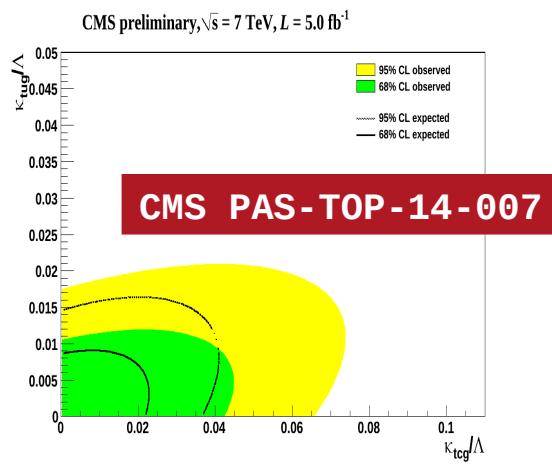
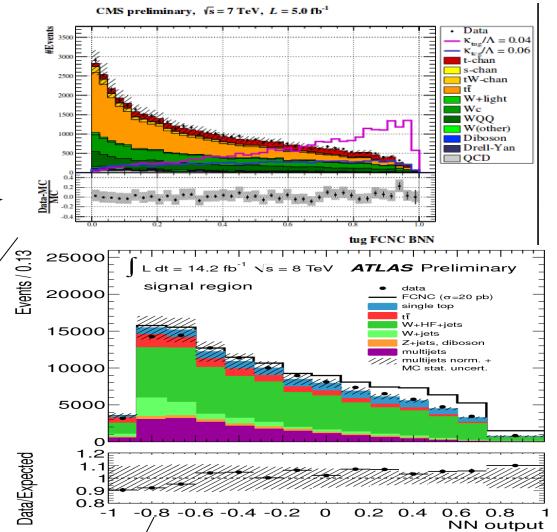
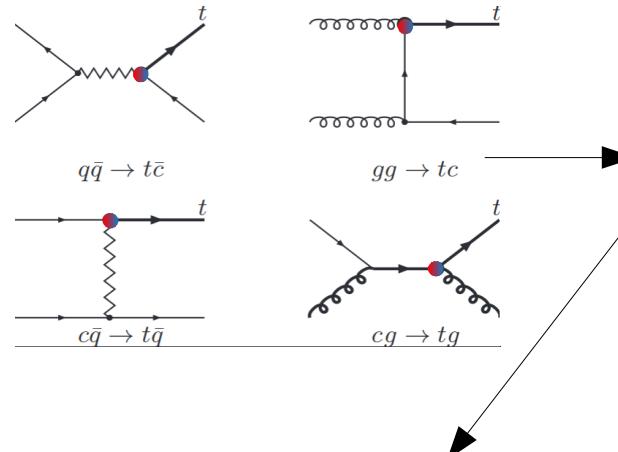
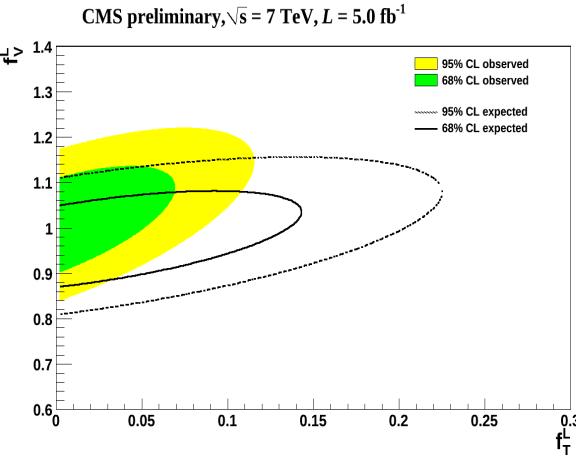
CMS PAS-TOP-14-003



Search for non-SM couplings single-top production

- **Single-top quarks:**

- Can be produced via FCNCs together with u/q/g
- Searched for at 7/8 TeV
- Also, possible to search for right-handed vector components



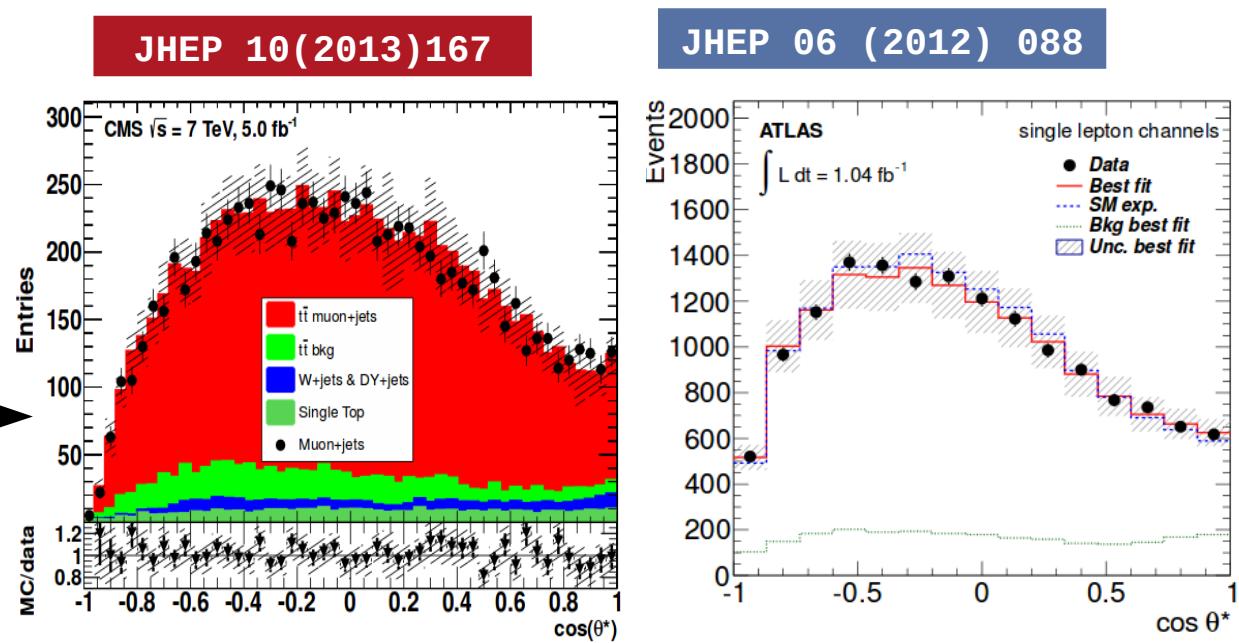
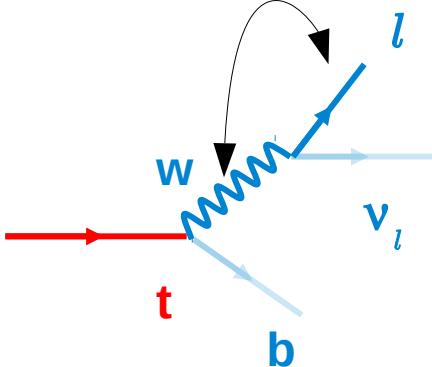
Couplings studies through event properties

W-helicity in top-quark decays

- **W-helicity:** fraction of left (F_L), right (F_R) and longitudinally (F_0) polarized Ws is predicted by the SM and it's sensitive to anomalous tWb couplings
- **Reflects on the angular distribution** of the lepton and the W-boson in the W rest frame

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

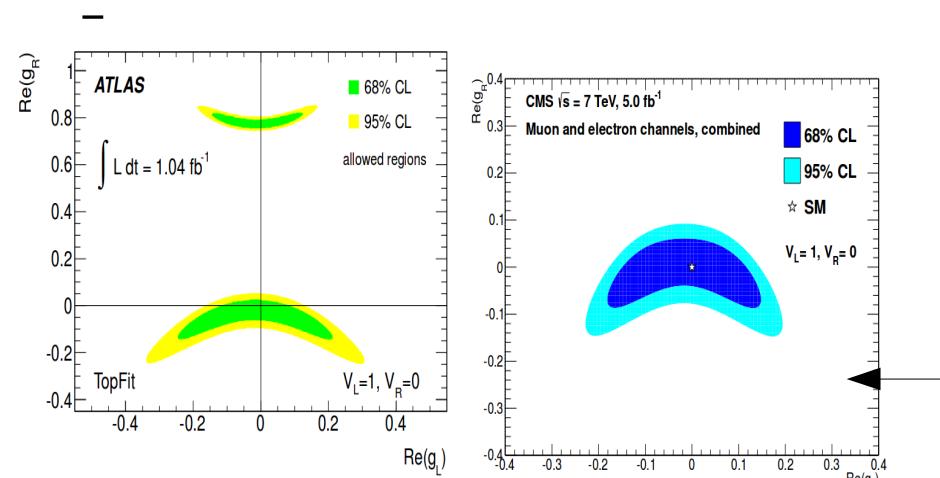
θ_l^* (note: use lepton in the W rest frame, W in top rest frame)



W-helicity in top-quark decays

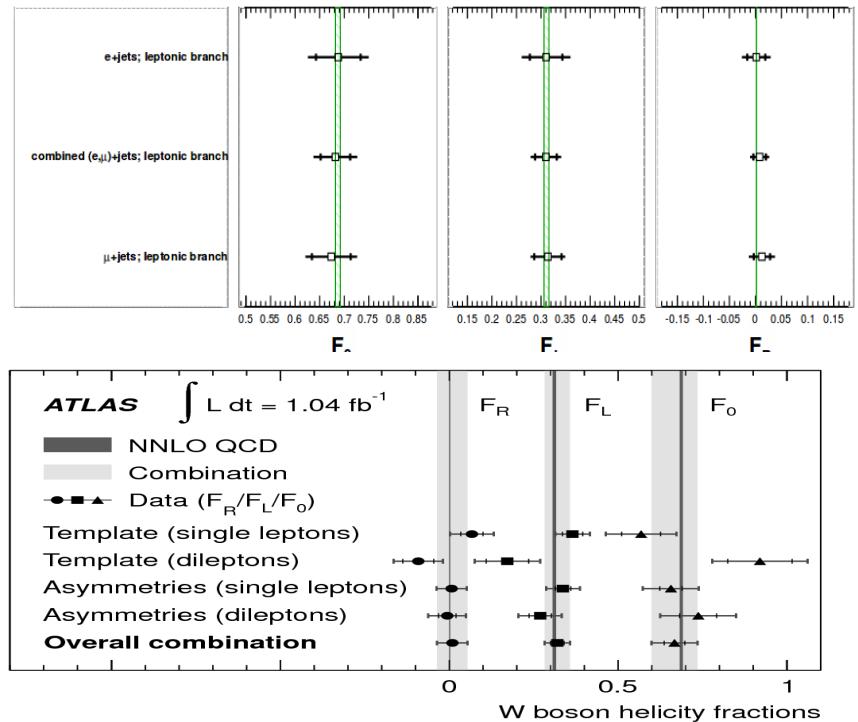
- From the $\cos\theta^*$ distribution:

- (F_L) , (F_0) values can be obtained in decays of tops from all production modes
- this is done mostly in $t\bar{t}$ but also can be done in single-top events



JHEP 06 (2012) 088

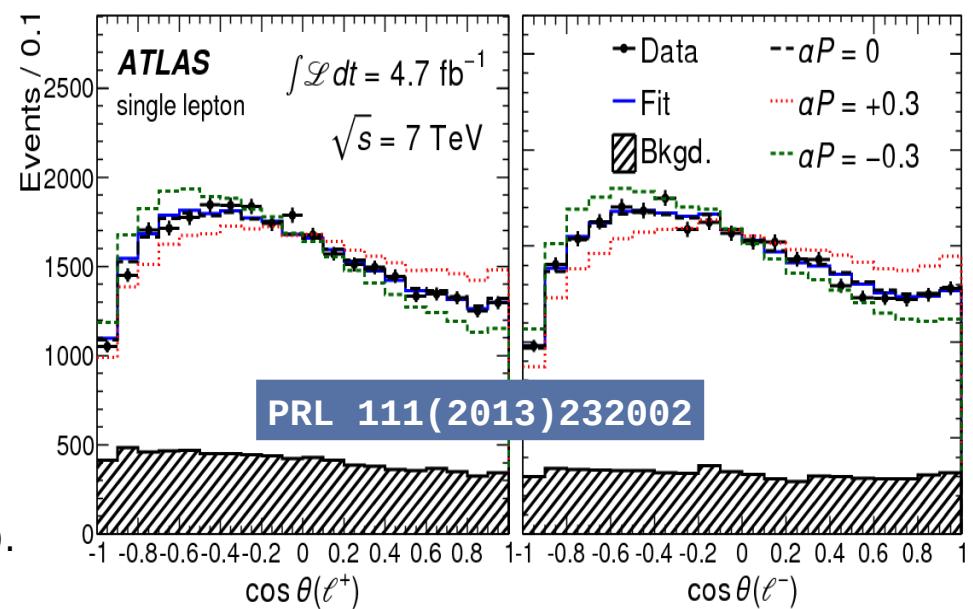
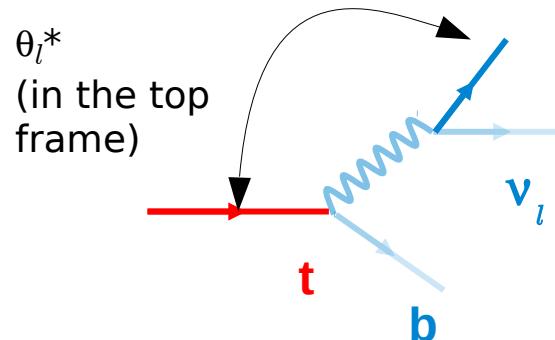
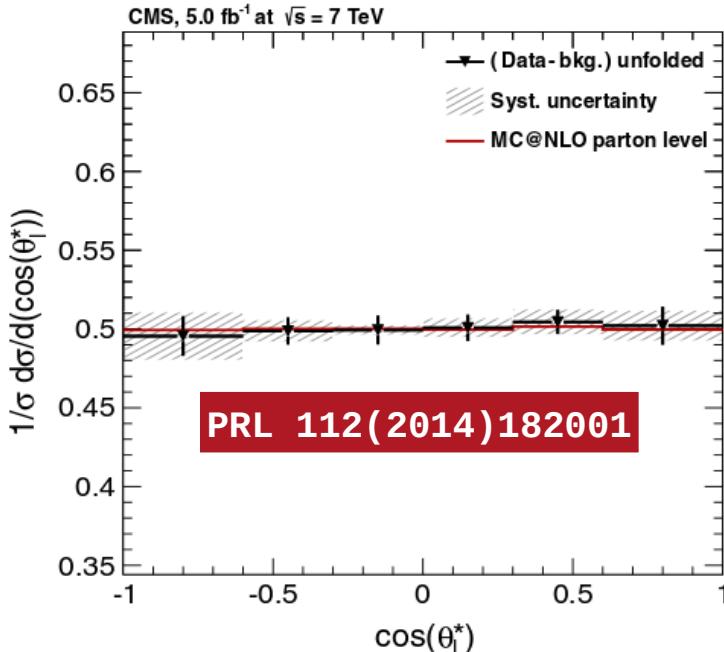
JHEP 10(2013)167



- Constraints to anomalous couplings:

- Extracted limits on BSM anom. couplings (G_L, G_R) from the measurement of (F_L, F_0)

Top polarisation in top quark pair production



◦ Top quarks in strong production:

- produced unpolarized: reflects into Decay products distribution
- Studied in both CMS (semileptonic) and Atlas (dileptonic and semileptonic channels).

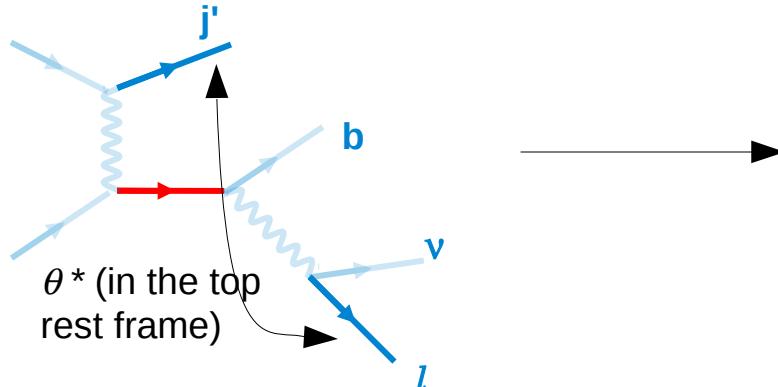
top-quark polarisation in t -channel events

- Top quark decay products distributions stems from the **V-A nature of the coupling:**

$$\frac{d\Gamma}{d \cos \theta_X} = \frac{\Gamma}{2} (1 + P_t \alpha_X \cos \theta_X) \equiv \Gamma \left(\frac{1}{2} + A_X \cos \theta_X \right)$$

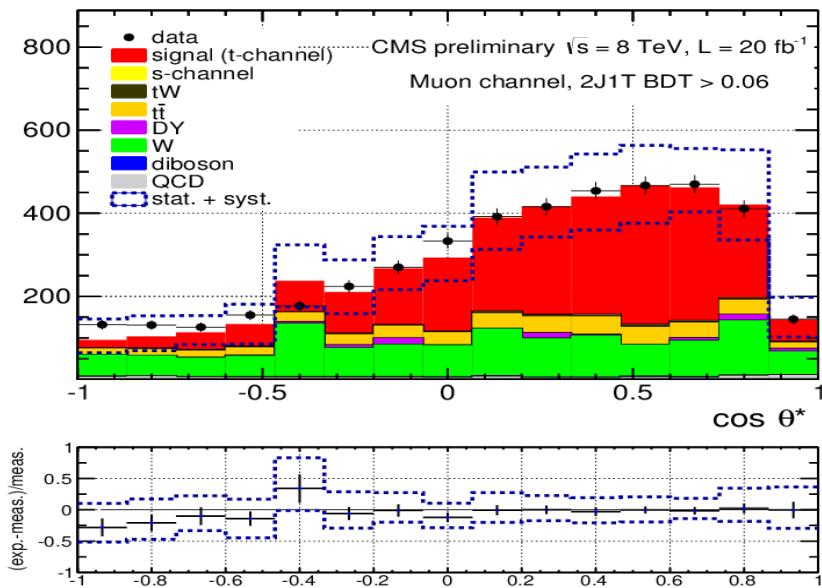
- θ_X = angle between the top decay product X and the top spin axis
- A_X = spin asymmetry, depends on the top polarisation
- We measure:** θ^* in leptonic top decays:

CMS-PAS-TOP-13-001



- Obtaining the **top polarisation:**

$$P_t = 0.82 \pm 0.12(\text{stat.}) \pm 0.32(\text{syst.})$$



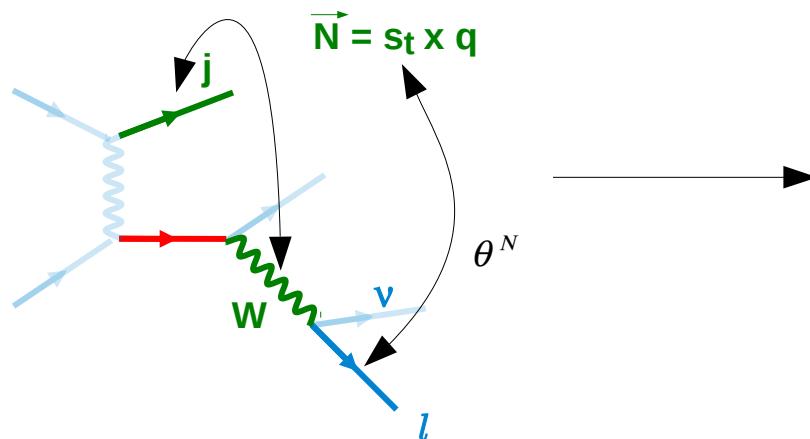
CP violation in single-top *t*-channel events

- Using top polarisation axis s_t , taken from the recoil jet j , and with q , one can define:

$$A_{FB}^N = \frac{N(\cos \theta^N > 0) - N(\cos \theta^N < 0)}{N(\cos \theta^N > 0) + N(\cos \theta^N < 0)} = 0.64 P \Im(gr)$$

where the latter is a CP violating component of the tWb lagrangian.

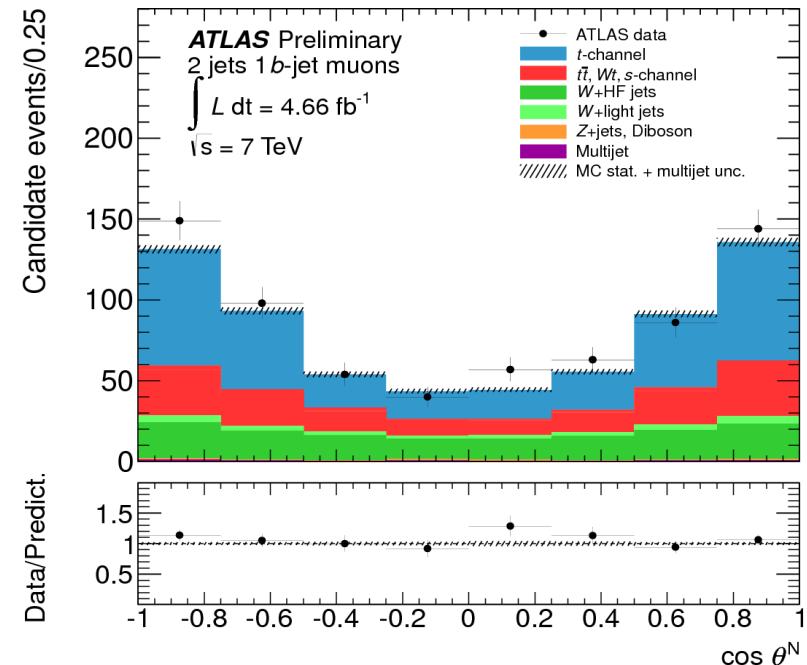
- Measuring:** θ^N in leptonic top decays:



- Obtaining 95% CL constraints on $\Im(gr)$

$$\Im(gr) \in [-0.20, 0.30]$$

ATLAS CONF-2013-132



Prospects for the future

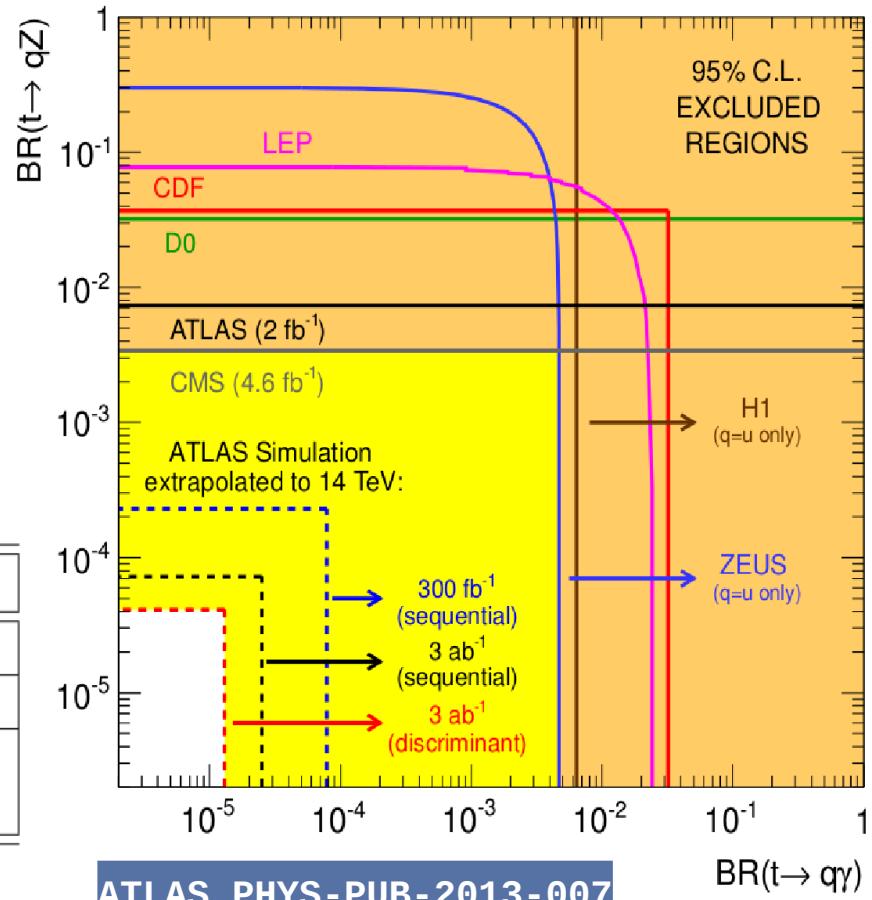
Run 2 top couplings: FCNC studies @14 TeV LHC

- **FCNC in top decays:**

- will greatly benefit from the increase of statistics
- signal/background ratio will become far more convenient
- Will become crucial to improve or keep same performances for JES and b-tagging

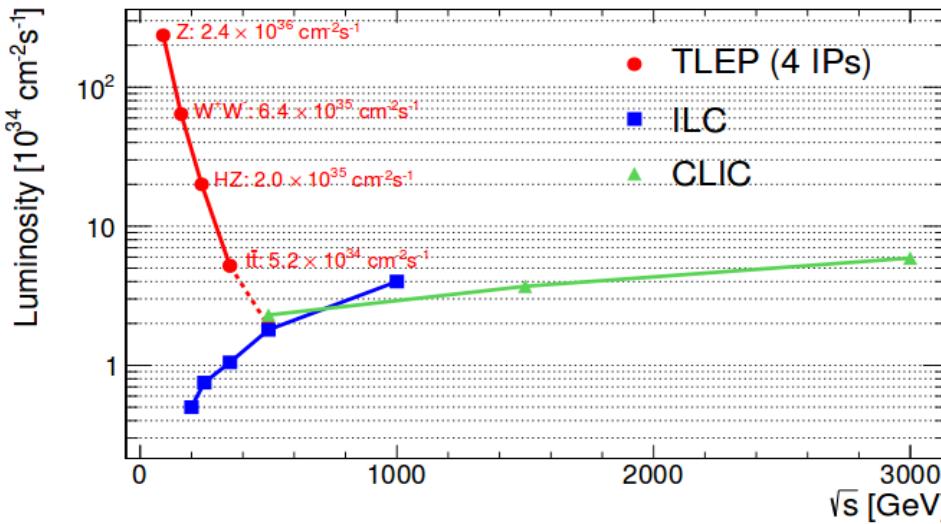
$\mathcal{B}(t \rightarrow Zq)$	300 fb^{-1} @ 14 TeV	3000 fb^{-1} @ 14 TeV
Exp. bkg. yield	26.8	268
Expected limit	$< 0.027\%$	$< 0.010\%$
1σ range	0.018 – 0.038%	0.007 – 0.014%
2σ range	0.013 – 0.051%	0.005 – 0.020%

CMS PAS-FRT-13-016



Note: the plot doesn't include all results presented in this talk

What are the perspectives @e+e- colliders?

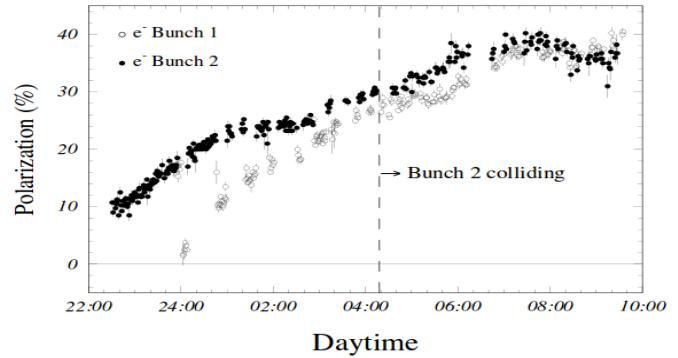


- **Production of tt pairs:**

- Production with e+e- beams at 350 GeV: pure ewk process
- will need precise measurement of the beam energy

[arXiv:1308.6176](https://arxiv.org/abs/1308.6176)

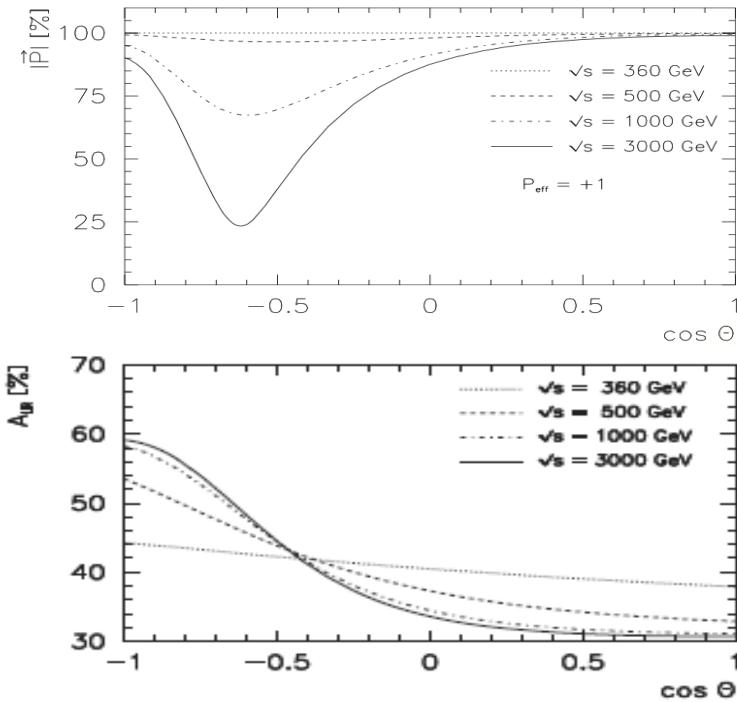
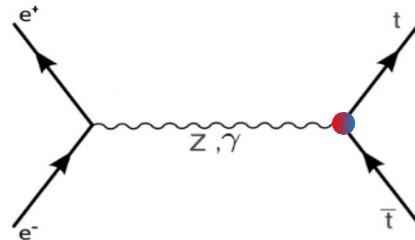
- Transverse polarisation of the beam: will allow energy calibration through spin depolarization in circular e+e-.
- Longitudinal beam polarization can be exploited for asymmetry measurements



@e+e- colliders: studies with polarised beams

◦ Top ewk production with polarized e+e-:

- Allow to probe features of the ewk vertex ttZ
- Anomalous form factors might be visible at the vertex



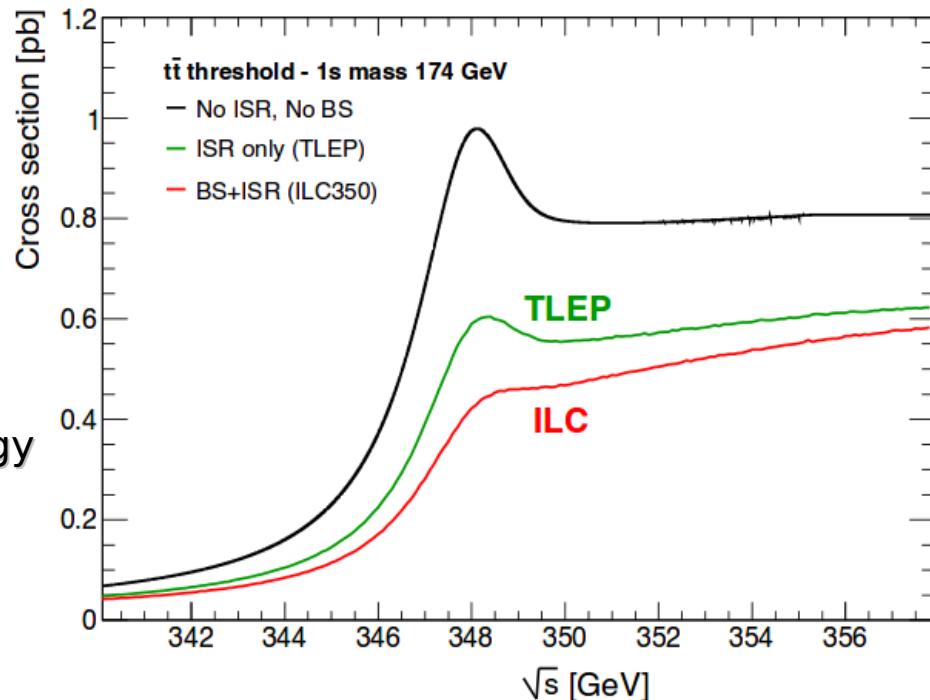
Measurements of top couplings and FCNC:

- top polarisation and forward-Backward asymmetry in production can be measured
- They are directly sensitive to newphysics, probing scalar and tensor- like anomalous couplings, see also for instance PRD 83(2011)016010
- FCNC can be studied in top decays and production as for LHC
- both improve by increasing beam polarisation

@e+e- colliders: precision ewk tt threshold scan

- **tt ewk production threshold:**

- High precision measurements will allow to constrain SM parameters
- top mass, decay width, and yukawa coupling to the Higgs will be measured with an unconceivable precision for LHC
- Main uncertainties: $\alpha_s(m_Z)$ and beam energy
- Experimental effort will be needed in tandem with a specific effort to reduce theoretical uncertainties on electroweak top production



arXiv:1308.6176

	m_{top}	Γ_{top}	λ_{top}
TLEP	10 MeV	11 MeV	13%
ILC	31 MeV	34 MeV	40%

Summary

- **Top quark couplings study at 7-8 TeV:**

- Showed to be an exciting field to check the standard model predictions and look for deviations due to new physics
- tWb vertex could be studied both in production, thanks to single-top, and decay, mostly in ttbar decays
- FCNC could be probed extensively, although it has space for improvement
- Still open for new ideas and creative ways to exploit at best our knowledge of the SM

- **In the future:**

- With the LHC run 2: all analyses will greatly benefit from higher statistics as well as improved signal-to-background ratio
- tt electroweak production at e+e- colliders could allow steps forward by orders of magnitude on the knowledge of crucial parameters of the standard model

Thanks!

Backup

Perspectives for SM measurements: ttZ and single-top

- **Signal and background cross section variation, 8 vs 13 TeV:**

Single top t-channel	8TeV	13 TeV	Ratio 13/8
t-channel(signal)	85	210	2.4
tt(background)	246	810	3.2
W+Jets (backg.)	~ 34k	~63k	~1.8
Single top W-assoc.	8TeV	13 TeV	Ratio 13/8
tW (signal)	22	71	3.2
tt(background)	246	810	3.3
Z+Jets (backg.)(1)	1.2k	~2k	1.7
top pair + Z	8TeV	13 TeV	Ratio 13/8
ttZ (signal)	0.2	~0.7(3)	3.2
ttW (signal/bkg to ttZ)	0.2	~0.6(3)	3
WZ (background)(2)	34	66	2.0

(1): Computation with FEWZ 3.1

(2): Computation with MCFM 6.6

(3): MCFM, Campbell, Ellis:
arXiv:1204.5678v1f

- **Main uncertainties:**

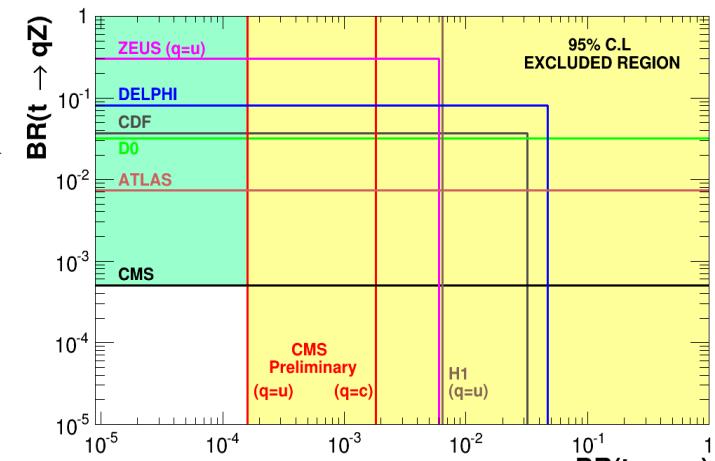
- t-channel single top: theory modeling --> NLO matching procedure + flavour scheme
- tW : signal and background modeling
- For ttZ / ttW : statistics, lepton mis-id, background control

Perspectives for FCNC and anom. couplings: broader picture including e+e- colliders

- We can add:

- Measured single-top + gamma FCNC @LHC
- Anom. Couplings in the Z vertex
- Possible FCNC in tt decay and single-top decay+production at e+e- colliders

	unpolarized beams $ P_{e^-} = 80\% \quad (P_{e^-} , P_{e^+}) = (80\%, 45\%)$		
	$\sqrt{s} = 500 \text{ GeV}$		
$BR(t \rightarrow Zq)(\gamma_\mu)$	6.1×10^{-4}	3.9×10^{-4}	2.2×10^{-4}
$BR(t \rightarrow Zq)(\sigma_{\mu\nu})$	4.8×10^{-5}	3.1×10^{-5}	1.7×10^{-5}
$BR(t \rightarrow \gamma q)$	3.0×10^{-5}	1.7×10^{-5}	9.3×10^{-6}
	$\sqrt{s} = 800 \text{ GeV}$		
$BR(t \rightarrow Zq)(\gamma_\mu)$	5.9×10^{-4}	4.3×10^{-4}	2.3×10^{-4}
$BR(t \rightarrow Zq)(\sigma_{\mu\nu})$	1.7×10^{-5}	1.3×10^{-5}	7.0×10^{-6}
$BR(t \rightarrow \gamma q)$	1.0×10^{-5}	6.7×10^{-6}	3.6×10^{-6}



\sqrt{s}	Case	Coupling	Individual limit from asymmetries			
			$A_1(\theta_0)$	$A_2(\theta_0)$	$A_1^{FB}(\theta_0)$	$A_2^{FB}(\theta_0)$
500GeV	+-	ReS			$2.3 \times 10^{-3} \text{ TeV}^{-2}$	
		ReT				$5.2 \times 10^{-3} \text{ TeV}^{-2}$
	++	ImT	$1.2 \times 10^{-3} \text{ TeV}^{-2}$		$1.0 \times 10^{-2} \text{ TeV}^{-2}$	
		ImS	$2.3 \times 10^{-3} \text{ TeV}^{-2}$			$1.0 \times 10^{-2} \text{ TeV}^{-2}$
		ReT		$1.2 \times 10^{-3} \text{ TeV}^{-2}$		$5.2 \times 10^{-3} \text{ TeV}^{-2}$
		ImT			$5.2 \times 10^{-3} \text{ TeV}^{-2}$	

Top lagrangians for anom. couplings @different vertices

- **tWb vertex:**

See also J. Aguilar-Saavedra,
Nucl.Phys. B812(2009)181-204

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

- **Anomalous couplings giving tZq and tGq FCNC:**

$$\begin{aligned} \mathcal{L} = & \sum_{q=u,c} \left[\sqrt{2} g_s \frac{\kappa_{gqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} T_a (f_q^L P_L + f_q^R P_R) q G_{\mu\nu}^a \right. \\ & \left. + \frac{g}{\sqrt{2} c_W} \frac{\kappa_{Zqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} (\hat{f}_q^L P_L + \hat{f}_q^R P_R) q Z_{\mu\nu} \right] + \text{h.c.} \end{aligned}$$

Some BSM models reviews:
 - J. Aguilar-Saavedra, Acta Phys. Polon. B35(2004) 2695-2710
 - F.Larios et al., Int. J. Mod. Phys. A21(2006) 3473-3494

- **tZt vertex:**

$$\mathcal{L}^{4F} = \sum_{i,j=L,R} \left[S_{ij} (\bar{e} P_i e) (\bar{t} P_j t) + T_{ij} (\bar{e} \frac{\sigma_{\mu\nu}}{\sqrt{2}} P_i e) (\bar{t} \frac{\sigma^{\mu\nu}}{\sqrt{2}} P_j t) \right]$$