

# Top Quark Physics @ LHC

António Onofre

(antonio.onofre@cern.ch)



Universidade do Minho



IST, March 26<sup>th</sup>, 2018



CERN/FP/123619/2011

## Topics covered in this lecture:

- ▶ Introduction
- ▶ The  $Wtb$  vertex structure (within and beyond the SM)
- ▶ Single Top quark (SM and beyond)
- ▶ TopFit

# The top quark

- **2015 was the top quark's 20<sup>th</sup> anniversary**

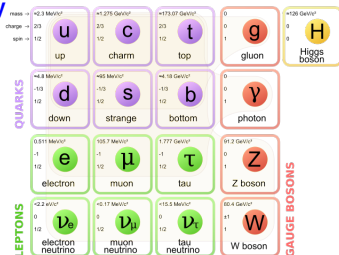
it was discovered by CDF and D0 in 1995

PRL74 2626-2631 (1995);

PRL74 2632-2637 (1995).

- It completes the 3 family structure of the SM

- top is the weak-isospin partner of the  $b$ -quark
- spin = 1/2
- charge =  $+2/3 |e|$



- Top quark is the heaviest known fundamental particle

( $m_t = 173.34 \pm 0.76$  GeV, World comb.(2014), arXiv:1403.4427)

- Top decays (almost exclusively) through  $t \rightarrow bW$

$BR(t \rightarrow sW) \leq 0.18\%$ ,  $BR(t \rightarrow dW) \leq 0.02\%$

- $\Gamma_t^{SM} = 1.42$  GeV (including  $m_b$ ,  $m_W$ ,  $\alpha_s$ , EW corrections)

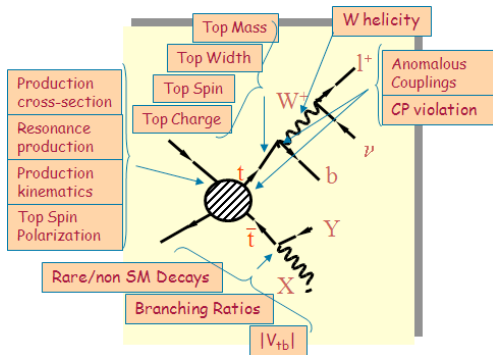
- $\tau_t = (3.29^{+0.90}_{-0.63}) \times 10^{-25}$  s (D0, PRD **85** 091104, 2012)
- $\ll \Lambda_{QCD}^{-1} \sim (100 \text{ MeV})^{-1} \sim 10^{-23}$  s (hadronization time)
- ⇒ top decays before hadronization takes place

# Introduction

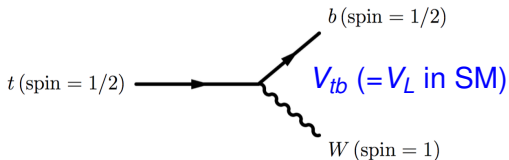
The phenomenology of Top Quark Physics is too Rich  
☞ impossible to cover everything here

## Top quark @ LHC

- $t\bar{t}$  production
  - $\sigma_{t\bar{t}}$
  - Mass
  - the  $Wtb$  vertex struct. (W polarization,  $t \rightarrow bW$  decay and anomalous couplings)
  - FCNC
  - Charge Asymmetry
- Single top production
  - cross section



# The $Wtb$ vertex structure



## Why is it necessary a precise **model-independent** measurement of the $Wtb$ vertex structure?

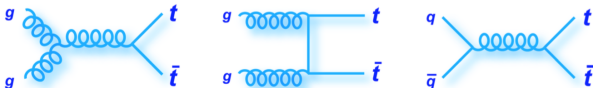
- It may reveal physics beyond the Standard Model
  - $V_{tb}$  could be different from the Standard Model value
  - Anomalous couplings may appear at the vertex
- It may help understand possible other new physics beyond the Standard Model
  - top quarks decay almost exclusively to  $t \rightarrow W^+b$
  - understanding the structure of the  $Wtb$  vertex helps revealing possible non-standard  $t\bar{t}$  production at LHC,  $Zt\bar{t}/\gamma t\bar{t}$  couplings at ILC, etc.
  - important for  $B$  and  $K$  physics (indirect limits on anomalous couplings, see later)

## The $Wtb$ vertex must be determined by a global fit to several observables:

- Several, theoretically equivalent, observables studied for  $t\bar{t}$  production at LHC (not all explored yet @ LHC)
- Single top cross section useful (sensitive to  $V_{tb}$  and anomalous couplings)
- Indirect limits from  $b \rightarrow s\gamma$  available (not used)
- The most general CP-conserving vertex for top quarks on-shell is used
- All couplings are allowed to vary freely in TopFit to find the allowed regions for a given CL

# The $W$ b vertex structure

- Production at the LHC:

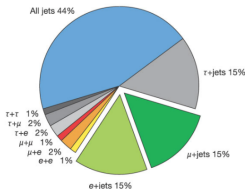


$\sigma(t\bar{t})=177.3\pm 9.9^{+4.6}_{-6.0}$  pb @ 7 TeV,  $\sigma(t\bar{t})=252.9\pm 11.7^{+6.4}_{-8.6}$  pb @ 8 TeV,  $\sigma(t\bar{t})=832^{+40}_{-46}$  pb @ 13 TeV  
 NNLO+NNLL,  $m_t = 172.5$  GeV PLB **710** 612 (2012), PRL **109** 132001(2012),  
 JHEP **1212** 054(2012), JHEP **1301** 080(2013), PRL**110** 252004 (2013).

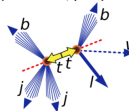
Top pair decay channels

$c\bar{s}$	electron-jets			all-hadronic	
$\bar{u}d$	muon-jets			all-hadronic	
$\tau$	$e\tau$	$\mu\tau$	$\tau\tau$	tau-jets	
$\mu$	$e\mu$	$\mu\mu$	$\mu\tau$	muon-jets	
$e$	$ee$	$e\mu$	$e\tau$	electron-jets	
$W$ decay	$e^+$	$\mu^+$	$\tau^+$	$u\bar{d}$	$c\bar{s}$

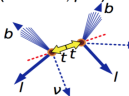
Top pair branching fractions



$\Rightarrow$  Lepton+jets ( $\sim 30\%$ ):  
 $(\ell = e^\pm, \mu^\pm)$



$\Rightarrow$  Dilepton ( $\sim 5\%$ ):  
 $(\ell = e^\pm, \mu^\pm)$





# The $Wtb$ vertex structure

## Effective $Wtb$ vertex from dim-6 operators

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

$$V_L \equiv V_{tb} \sim 1 \text{ (within SM)}$$

$$V_R, g_R, g_L \Rightarrow \text{anomalous couplings}$$

[EPJC50 (2007) 519, NPB804 (2008) 160, NPB812 (2009) 181]

## How to probe anomalous couplings in the $Wtb$ vertex?

- indirect limits from  $B$ -physics
- measurements of single top quark production: cross-section and angular distributions
- measurements of  $t\bar{t}$  production: angular distributions of top quark decays

# The $Wtb$ vertex structure

## Effective $Wtb$ vertex from dim-6 operators

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

$$V_L \equiv V_{tb} \sim 1 \text{ (within SM)}$$

$$V_R, g_R, g_L \Rightarrow \text{anomalous couplings}$$

[EPJC50 (2007) 519, NPB804 (2008) 160, NPB812 (2009) 181]

## How to probe anomalous couplings in the $Wtb$ vertex?

- indirect limits from  $B$ -physics
- measurements of single top quark production: cross-section and angular distributions
- measurements of  $t\bar{t}$  production: angular distributions of top quark decays

# The $Wtb$ vertex structure

## Effective $Wtb$ vertex from dim-6 operators

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

$$V_L \equiv V_{tb} \sim 1 \text{ (within SM)}$$

$$V_R, g_R, g_L \Rightarrow \text{anomalous couplings}$$

[EPJC50 (2007) 519, NPB804 (2008) 160, NPB812 (2009) 181]

## How to probe anomalous couplings in the $Wtb$ vertex?

- indirect limits from  $B$ -physics
- measurements of single top quark production: cross-section and angular distributions
- measurements of  $t\bar{t}$  production: angular distributions of top quark decays

## Anomalous $Wtb$ coupling effects in the weak radiative $B$ -meson decay

Bohdan Grzadkowski and Mikolaj Misiak  
 Institute of Theoretical Physics, University of Warsaw, PL-00-681 Warsaw, Poland and  
 Theoretical Physics Division, CERN, CH-1211 Geneva 23, Switzerland  
 (Dated: February 7, 2008)

We study the effect of anomalous  $Wtb$  couplings on the  $\bar{B} \rightarrow X_s \gamma$  branching ratio. The considered couplings are introduced as parts of gauge-invariant dimension-six operators that are built out of the Standard Model fields only. One-loop contributions from the charged-current vertices are assumed to be of the same order as the tree-level flavour-changing neutral current ones. Bounds on the corresponding Wilson coefficients are derived.

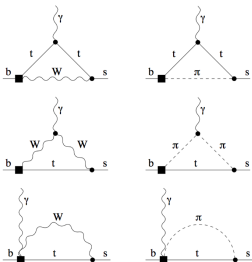


FIG. 1: Diagrams with non-SM  $b \rightarrow t$  vertices that contribute to  $f_7^{g^{L,R}}(x)$ . The pseudogoldstone boson is denoted by  $\pi$ .

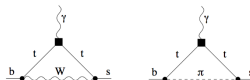


FIG. 2: Diagrams with non-SM  $\bar{t}t\gamma$  vertices that contribute to  $f_7^{g^R}(x)$ .

't Hooft gauge. The relevant Feynman diagrams with non-SM  $b \rightarrow t$  vertices are shown in Fig. 1. In addition, analogous six diagrams with non-SM  $t \rightarrow s$  vertices and two diagrams with non-SM  $\bar{t}t\gamma$  vertices (Fig. 2) occur in the case of  $f_7^{g^R}(x)$ . In the case of  $f_8^{g^{L,R}}(x)$ , there are also diagrams where the intermediate  $t$ -quark gets replaced by  $u$  or  $c$ . The functions  $f_8^{g^{L,R}}(x)$  have been found by replacing the external photon by the gluon in the diagrams like the ones in the first row of Fig. 1.

Our final results for  $f_4^{g^{L,R}}(x)$  read:

# B-physics constraints to $Wtb$ vertex

$$BR(\bar{B} \rightarrow X_s \gamma) = \left( 3.55 \pm 0.24 \begin{matrix} +0.09 \\ -0.10 \end{matrix} \pm 0.03 \right) \times 10^{-4}$$

[hep-ex/0603003]

$$\begin{aligned} BR(B \rightarrow X_s \gamma) \times 10^4 &= (3.15 \pm 0.23) - 4.14 (V_L - V_{tb}) + 411 V_R \\ &- 53.9 g_L - 2.12 g_R - 8.03 C_7^{(p)}(\mu_0) \\ &+ \mathcal{O} \left[ \left( V_L - V_{tb}, V_R, g_L, g_R, C_7^{(p)} \right)^2 \right] \end{aligned}$$

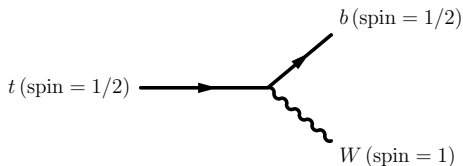
$$\mathcal{O} \left[ \left( V_L - V_{tb}, V_R, \dots \right)^2 \right] \simeq 1.32 (V_L - V_{tb})^2 - 262 (V_L - V_{tb}) V_R + 12970 V_R^2 + \dots$$

	$V_L - V_{tb}$	$V_R$	$g_L$	$g_R$	$C_7^{(p)}(\mu_0)$
upper bound	0.04	0.0024	0.003	0.08	0.02
lower bound	-0.24	-0.0004	-0.018	-0.46	-0.12

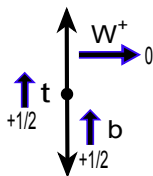
[EPJC57 (2008) 183]

# The $Wtb$ vertex structure

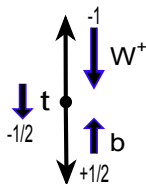
[PRD 45 (1992) 124]



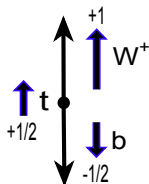
$W$  helicity fractions ( $F_0 = \Gamma_0/\Gamma$ ,  $F_L = \Gamma_L/\Gamma$ ,  $F_R = \Gamma_R/\Gamma$ ):



longitudinal  $W$   
SM (LO):  $F_0 = 0.6966$



left-handed  $W$   
 $F_L = 0.3030$



right-handed  $W$   
 $F_R = 0.0004$

- [arXiv:hep-ph0605190v2 18 Mar 2007]

## 2 $W$ helicity fractions and ratios

The polarisation of the  $W$  bosons emitted in the top decay is sensitive to non-standard couplings [17]. The  $W$  bosons can be produced with positive (right-handed), negative (left-handed) or zero helicity, with corresponding partial widths  $\Gamma_R$ ,  $\Gamma_L$ ,  $\Gamma_0$ , being  $\Gamma \equiv \Gamma(t \rightarrow W^+b) = \Gamma_R + \Gamma_L + \Gamma_0$ . The  $\Gamma_R$  component vanishes in the  $m_b = 0$  limit because the  $b$  quarks produced in top decays have left-handed chirality, and for vanishing  $m_b$  the helicity and the chirality states coincide. The three partial widths can be calculated for a general  $Wtb$  vertex as parameterised in Eq. (II), yielding

$$\begin{aligned} \Gamma_0 = & \frac{g^2|\bar{q}|}{32\pi} \left\{ \frac{m_t^2}{M_W^2} [ |V_L|^2 + |V_R|^2 ] (1 - x_W^2 - 2x_b^2 - x_W^2x_b^2 + x_b^4) - 4x_b \operatorname{Re} V_L V_R^* \right. \\ & + [ |g_L|^2 + |g_R|^2 ] (1 - x_W^2 + x_b^2) - 4x_b \operatorname{Re} g_L g_R^* \\ & - 2 \frac{m_t}{M_W} \operatorname{Re} [ V_L g_R^* + V_R g_L^* ] (1 - x_W^2 - x_b^2) \\ & \left. + 2 \frac{m_t}{M_W} x_b \operatorname{Re} [ V_L g_L^* + V_R g_R^* ] (1 + x_W^2 - x_b^2) \right\}, \end{aligned}$$

being  $x_W = M_W/m_t$ ,  $x_b = m_b/m_t$  and

$$|\bar{q}| = \frac{1}{2m_t} (m_t^4 + M_W^4 + m_b^4 - 2m_t^2 M_W^2 - 2m_t^2 m_b^2 - 2M_W^2 m_b^2)^{1/2}$$

# The $Wtb$ vertex structure

- [arXiv:hep-ph0605190v2 18 Mar 2007]

$$\begin{aligned}\Gamma_{R,L} = & \frac{g^2 |\vec{q}|}{32\pi} \left\{ [ |V_L|^2 + |V_R|^2 ] (1 - x_W^2 + x_b^2) - 4x_b \operatorname{Re} V_L V_R^* \right. \\ & + \frac{m_t^2}{M_W^2} [ |g_L|^2 + |g_R|^2 ] (1 - x_W^2 - 2x_b^2 - x_W^2 x_b^2 + x_b^4) - 4x_b \operatorname{Re} g_L g_R^* \\ & - 2 \frac{m_t}{M_W} \operatorname{Re} [ V_L g_R^* + V_R g_L^* ] (1 - x_W^2 - x_b^2) \\ & \left. + 2 \frac{m_t}{M_W} x_b \operatorname{Re} [ V_L g_L^* + V_R g_R^* ] (1 + x_W^2 - x_b^2) \right\} \\ & \pm \frac{g^2}{64\pi} \frac{m_t^3}{M_W^2} \left\{ -x_W^2 [ |V_L|^2 - |V_R|^2 ] + [ |g_L|^2 - |g_R|^2 ] (1 - x_b^2) \right. \\ & \left. + 2x_W \operatorname{Re} [ V_L g_R^* - V_R g_L^* ] + 2x_W x_b \operatorname{Re} [ V_L g_L^* - V_R g_R^* ] \right\} \\ & \times (1 - 2x_W^2 - 2x_b^2 + x_W^4 - 2x_W^2 x_b^2 + x_b^4),\end{aligned}\tag{2}$$



# The $Wtb$ vertex structure

- [arXiv:hep-ph0605190v2 18 Mar 2007]

the modulus of the  $W$  boson three-momentum in the top quark rest frame. The total top width is

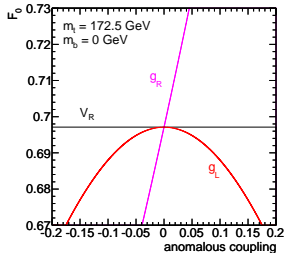
$$\begin{aligned} \Gamma = & \frac{g^2 |\vec{q}|}{32\pi} \frac{m_t^2}{M_W^2} \left\{ [|V_L|^2 + |V_R|^2] (1 + x_W^2 - 2x_b^2 - 2x_W^4 + x_W^2 x_b^2 + x_b^4) \right. \\ & - 12x_W^2 x_b \operatorname{Re} V_L V_R^* + 2 [|g_L|^2 + |g_R|^2] \left( 1 - \frac{x_W^2}{2} - 2x_b^2 - \frac{x_W^4}{2} - \frac{x_W^2 x_b^2}{2} + x_b^4 \right) \\ & - 12x_W^2 x_b \operatorname{Re} g_L g_R^* - 6x_W \operatorname{Re} [V_L g_R^* + V_R g_L^*] (1 - x_W^2 - x_b^2) \\ & \left. + 6x_W x_b \operatorname{Re} [V_L g_L^* + V_R g_R^*] (1 + x_W^2 - x_b^2) \right\} . \end{aligned} \quad (4)$$

# The $Wtb$ vertex structure

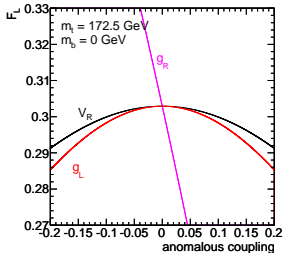
[EPJC50 (2007) 519]

**anomalous couplings  $\Rightarrow$  deviations in  $W$  helicity fractions**

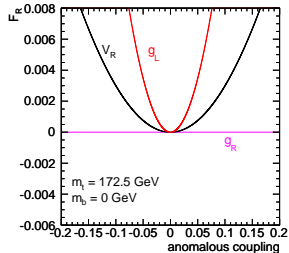
$F_0$



$F_L$



$F_R$

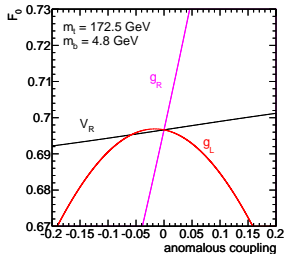


# The $Wtb$ vertex structure

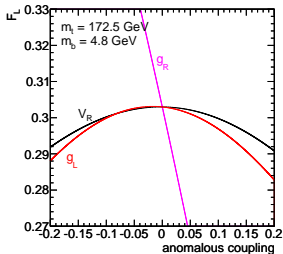
[EPJC50 (2007) 519]

**anomalous couplings  $\Rightarrow$  deviations in  $W$  helicity fractions**

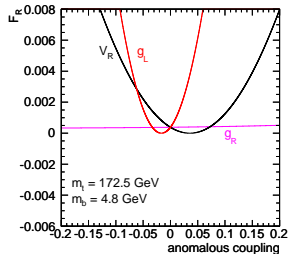
$F_0$



$F_L$

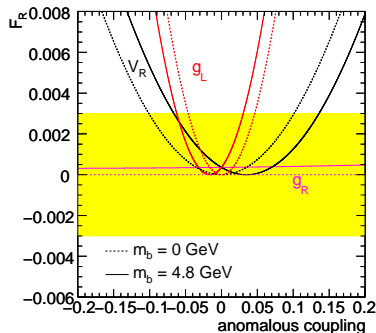


$F_R$



**👉 correct  $m_b$  has to be considered!**

# The $Wtb$ vertex structure



example:  $|F_R| < 0.003$  can be converted into a  $V_R$  constraint using the intersection method:

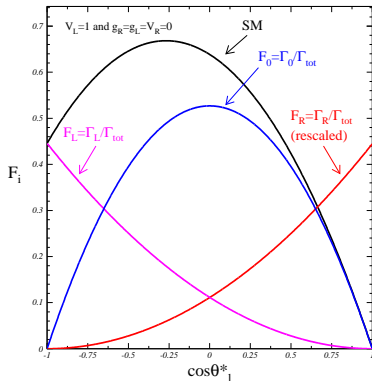
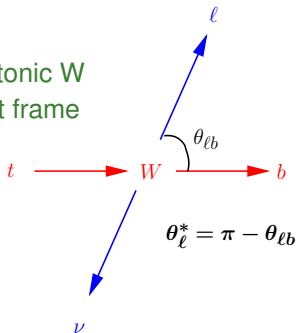
☞  $-0.101 < V_R < 0.101$  ( $m_b = 0.0$  GeV)

☞  $-0.067 < V_R < 0.136$  ( $m_b = 4.8$  GeV)

# Measuring the $W$ helicity states

$$\frac{1}{N} \frac{dN}{d \cos \theta_{\ell}^*} = \frac{3}{2} \left[ F_0 \left( \frac{\sin \theta_{\ell}^*}{\sqrt{2}} \right)^2 + F_L \left( \frac{1 - \cos \theta_{\ell}^*}{2} \right)^2 + F_R \left( \frac{1 + \cos \theta_{\ell}^*}{2} \right)^2 \right]$$

leptonic  $W$   
rest frame



# Measuring the $W$ helicity states

$W$  polarisation can be measured by:

- 1 Fitting  $\cos \theta_\ell^*$  to obtain the  $W$  helicity fractions ( $F_0, F_L, F_R$ )
- 2 Fitting  $\cos \theta_\ell^*$  to obtain the  $W$  helicity ratios:
  - ☞  $\rho_L = F_L/F_0 = 0.435$  (SM, LO)
  - ☞  $\rho_R = F_R/F_0 = 5.5 \times 10^{-4}$  (SM, LO)
- 3 Computing angular asymmetries:  $A_t = \frac{N(\cos \theta_\ell^* > t) - N(\cos \theta_\ell^* < t)}{N(\cos \theta_\ell^* > t) + N(\cos \theta_\ell^* < t)}$

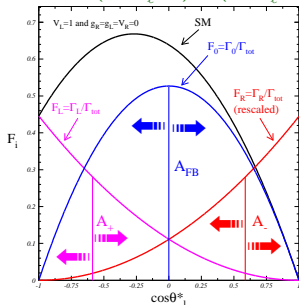
$$A_{FB} = 3/4[F_R - F_L] \\ = -0.2227 \text{ (SM, LO)}$$

$$A_+ = 3\beta[F_0 + (1 + \beta)F_R] \\ = 0.5436 \text{ (SM, LO)}$$

$$A_- = -3\beta[F_0 + (1 + \beta)F_L] \\ = -0.8409 \text{ (SM, LO)}$$

$$(\beta = 2^{1/3} - 1)$$

[EPJC50 (2007) 519]



# The $Wtb$ vertex structure

- [arXiv:hep-ph0605190v2 18 Mar 2007]
- How do  $A_{FB}$ ,  $A_+$  and  $A_-$  behave?

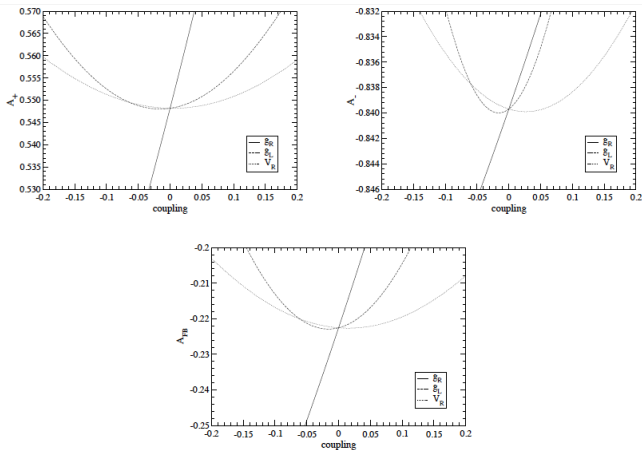
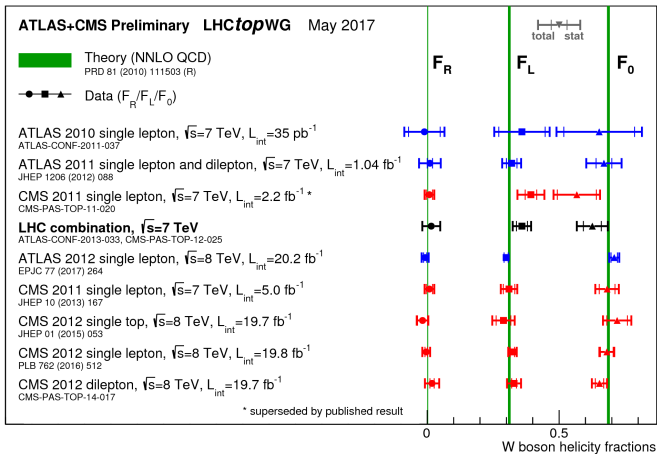


Figure 4: Dependence of the asymmetries  $A_+$ ,  $A_-$  and  $A_{FB}$  on the couplings  $g_L$ ,  $g_R$  and  $V_R$ , for the CP-conserving case.

# The $Wtb$ vertex structure in $t\bar{t}$ events

## Summary of $W$ -boson helicity meas. @ LHC



$$\Delta F_0/F_0=3\%, \quad \Delta F_L/F_L=5\% \quad F_R=-0.008\pm 0.014$$



# The $t \rightarrow bW$ decay in $t\bar{t}$ events

## General $Wtb$ vertex

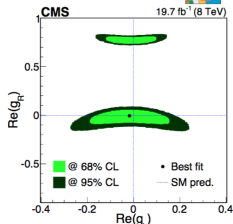
Eur.Phys.J. C50 (2007) 519-533

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

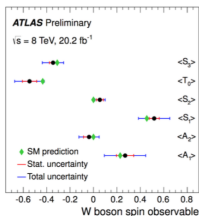
Vector ( $V_R$ ) and Tensor like couplings ( $g_L, g_R$ ) zero @ tree level in SM

- Angular distributions of the top decay products (and asymmetries) can be used to probe anomalous couplings at the  $Wtb$  vertex **Combinations is the game!**

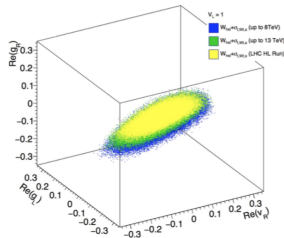
JHEP01 053 (2015)



ATLAS CONF-2016-097



PRD 93 (2016) 11, 113021

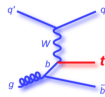


- What next? **extract the spin properties of the messengers of new physics from data Phys. Rev. D 93 (2016) 011301 (ATLAS-CONF-2016-097)**
- Assuming  $V_L=1$  ( $V_R=0$ ) What is the current LHC status of  $V_{tb}$  in the SM? What about the top quark couplings to other bosons?**

# Single top quark production

# The $Wtb$ vertex structure

## • Single top quark production cross section @ LHC:

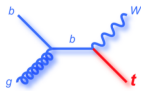


t-channel

$64.57^{+2.63}_{-1.74}$  pb

$87.76^{+3.44}_{-1.91}$  pb

$217 \pm 10$  pb

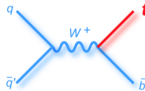


( $Wt$ -prod.)

$15.74^{+1.17}_{-1.21}$  pb

$22.37^{+1.52}_{-1.52}$  pb

$71.7 \pm 1.8 \pm 3.4$  pb



(s-channel)

$4.63^{+0.20}_{-0.18}$  pb

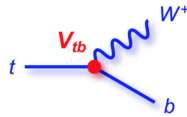
$5.61^{+0.22}_{-0.22}$  pb

$11.92 \pm 0.40$  pb

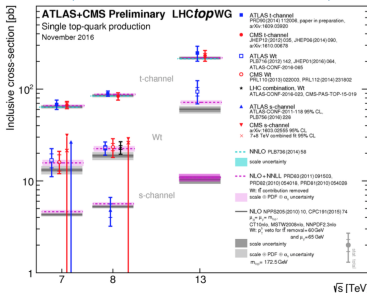
⇐ @ 7TeV

⇐ @ 8TeV

⇐ @ 13,14TeV



## • Powerful probe of $V_{tb}$ ( $\delta V_{tb}/V_{tb}$ few % @ LHC) and Test of physics BSM (FCNC in t-channel; $W'$ in s-channel)



$\Delta\sigma_t/\sigma_t \sim 10\% @ 7-8\text{TeV}, 20\% @ 13\text{TeV}$

$\Delta\sigma_{Wt}/\sigma_{Wt} \sim 20\% @ 7-8\text{TeV}, 30\% @ 13\text{TeV}$

ATLAS@8 TeV:

$\sigma_s = 4.8 \pm 0.8(\text{stat.})_{1.3}^{+1.6}(\text{syst.})$  pb (3.2 $\sigma$  sign.)

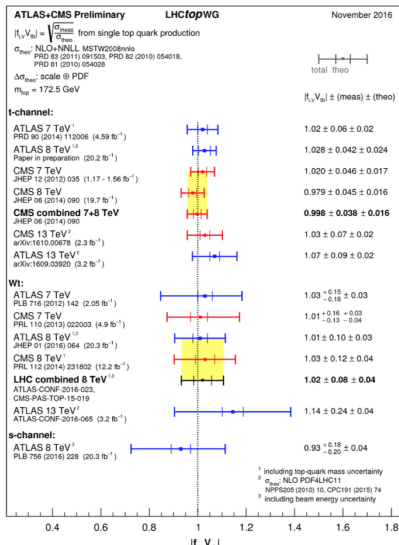
CMS@8 TeV:

$\sigma_s(95\%) < 28.8$  pb



# Single Top Quark

## Summary of $V_{tb}$ Measurements @ LHC



👉  $|V_{tb}|^2$  extracted with:

$$|V_{tb,obs.}|^2 = \frac{\sigma_{t,obs.}}{\sigma_{t,SM}} \times |V_{tb,SM}|^2$$

$\delta|V_{tb}|/|V_{tb}| @ 5-10\%$

👉 What about the top quark couplings to the known gauge bosons ( $\gamma, W, Z, H$ )?



# What can single top production say about the $Wtb$ vertex structure beyond $V_{tb}$ ?

● [arXiv:hep-ph0605190v2 18 Mar 2007]

## Single top quark production at LHC with anomalous $Wtb$ couplings

J. A. Aguilar-Saavedra

*Departamento de Física Teórica y del Cosmos and CAFPE,  
Universidad de Granada, E-18071 Granada, Spain*

### Abstract

We investigate single top production in the presence of anomalous  $Wtb$  couplings. We explicitly show that, if these couplings arise from gauge invariant effective operators, the only relevant couplings for single top production and decay are the usual  $\gamma^\mu$  and  $\sigma^{\mu\nu}q_\nu$  terms, where  $q$  is the  $W$  boson momentum. This happens even in the single top production processes where the  $Wtb$  interaction involves off-shell top and/or bottom quarks. With this parameterisation for the  $Wtb$  vertex, we obtain expressions for the dependence on anomalous couplings of the single top cross sections, for (i) the  $t$ -channel process, performing a matching between  $tj$  and  $t\bar{b}j$  production, where  $j$  is a light jet; (ii)  $s$ -channel  $t\bar{b}$  production; (iii) associated  $tW^-$  production, including the correction from  $tW^-\bar{b}$ . We use these expressions to estimate, with a fast detector simulation, the simultaneous limits which the measurement of single top cross sections at LHC will set on  $V_{tb}$  and possible anomalous couplings. Finally, a combination with top decay asymmetries and angular distributions is performed, showing how the limits can be improved when the latter are included in a global fit to  $Wtb$  couplings.

# Single top quark production

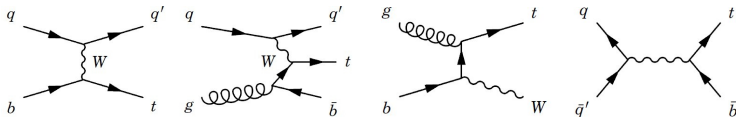
- [arXiv:hep-ph0605190v2 18 Mar 2007]

New physics beyond the Standard Model (SM) is expected to affect especially the top quark, and, in particular, it may modify its charged current interaction with its  $SU(2)_L$  partner the bottom quark. For on-shell  $t$ ,  $b$  and  $W$ , the most general  $Wtb$  vertex involving terms up to dimension five can be written as [5]

$$\begin{aligned}\mathcal{L}_{Wtb}^{\text{OS}} = & -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu(V_L P_L + V_R P_R)t W_\mu^- \\ & -\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}(g_L P_L + g_R P_R)t W_\mu^- + \text{H.c.},\end{aligned}\quad (1)$$

with  $q \equiv p_t - p_b$  (being  $p_t$  and  $p_b$  the momenta of the top and  $b$  quark, respectively, following the fermion flow), which equals the  $W$  boson momentum. Additional  $\sigma^{\mu\nu}k_\nu$  and  $k^\mu$  terms, where  $k \equiv p_t + p_b$ , can be absorbed into this Lagrangian using Gordon identities. If the  $W$  boson is on its mass shell or it couples to massless external fermions we have  $q^\mu \epsilon_\mu = 0$ , where  $\epsilon_\mu$  is the polarisation vector of the  $W$  boson, so that terms proportional to  $q^\mu$  can be dropped from the effective vertex. Within the SM, the only  $Wtb$  interaction term at the tree level is given by the left-handed  $\gamma^\mu$  term, with  $V_L \equiv V_{tb} \simeq 1$ . The rest of couplings are called “anomalous” and vanish at the tree level, although they can be generated by radiative corrections. They are not necessarily constants but rather “form factors”, usually approximated by the constant term (as we will do in this work). If we assume that CP is conserved in the  $Wtb$  interaction then  $V_{L,R}$  and  $g_{L,R}$  are real, and  $V_L$  can be taken to be positive without loss of generality.

# Single top quark production



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

- the  $\kappa$  factors determine the dependence on anomalous couplings
- the  $\kappa$  factors are, in general, different for  $t$  and  $\bar{t}$  production
- the measurement of the single top production cross-section allows to obtain a measurement of  $V_L$  ( $\equiv V_{tb}$ ) and bounds on anomalous couplings



# Single top quark production

- **t-channel**

- [arXiv:hep-ph0605190v2 18 Mar 2007]

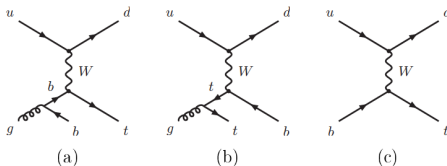


Figure 2: Sample Feynman diagrams for single top production in the  $t$ -channel process. Additional diagrams are obtained by crossing the light quark fermion line, and/or replacing  $(u, d)$  by  $(c, s)$ . The diagrams for antitop production are the charge conjugate ones.

# Single top quark production

## • t-channel

[arXiv:hep-ph0605190v2 18 Mar 2007]

	$tj$				$\bar{t}j$			
	$\kappa$	$\Delta Q$	$\Delta m_t$	$\Delta m_b$	$\kappa$	$\Delta Q$	$\Delta m_t$	$\Delta m_b$
$V_R^2$	0.916 – 0.923	+0. -0.	+0. -0.	+0. -0.	1.082 – 1.084	+0. -0.	+0. -0.	+0. -0.
$g_L^2$	1.75 – 1.79	+0.044 -0.038	+0.007 -0.035	+0 -0.027	2.16 – 2.17	+0.035 -0.022	+0.014 -0.032	+0. -0.
$g_R^2$	2.18	+0.042 -0.033	+0.014 -0.034	+0. -0.022	1.75 – 1.77	+0.042 -0.033	+0.007 -0.033	+0. -0.025
$V_L g_R$	-(0.348 – 0.365)	+0.007 -0.011	+0. -0.	+0. -0.	-(0.038 – 0.040)	+0.010 -0.009	+0. -0.	+0. -0.
$V_R g_L$	-(0.006 – 0.008)	+0.006 -0.005	+0. -0.	+0. -0.	-(0.399 – 0.408)	+0.010 -0.008	+0. -0.	+0. -0.

Table 1: Representative  $\kappa$  factors for the  $tj$  and  $\bar{t}j$  processes and their uncertainties, explained in the text. Errors smaller than 0.005 are omitted.

	$\bar{t}\bar{b}j$				$t\bar{b}j$			
	$\kappa$	$\Delta Q$	$\Delta m_t$	$\Delta m_b$	$\kappa$	$\Delta Q$	$\Delta m_t$	$\Delta m_b$
$V_R^2$	0.927 – 0.932	+0.005 -0.	+0. -0.	+0. -0.	1.068 – 1.069	+0. -0.005	+0. -0.	+0. -0.
$V_L V_R$	-0.117	+0. -0.	+0. -0.	+0.005 -0.005	-0.126	+0. -0.	+0. -0.	+0.006 -0.006
$g_L^2$	1.96 – 2.01	+0.070 -0.056	+0.005 -0.005	+0. -0.	2.98 – 3.00	+0.040 -0.040	+0.014 -0.014	+0. -0.
$g_R^2$	2.97 – 2.98	+0.056 -0.043	+0.013 -0.013	+0. -0.	2.08 – 2.11	+0.056 -0.045	+0.006 -0.007	+0. -0.
$V_L g_R$	-(0.539 – 0.550)	+0.012 -0.010	+0. -0.	+0. -0.	-(0.169 – 0.172)	+0.010 -0.010	+0.014 -0.013	+0. -0.
$V_R g_L$	-(0.121 – 0.134)	+0.009 -0.011	+0. -0.	+0. -0.	-(0.567 – 0.571)	+0.014 -0.013	+0. -0.	+0. -0.

Table 2: Representative  $\kappa$  factors for the  $\bar{t}\bar{b}j$  and  $t\bar{b}j$  processes and their uncertainties, explained in the text. Errors smaller than 0.005 are omitted.

- (ii) The coefficient of the  $V_R^2$  term is different for single top and single antitop production, but the differences cancel to a large extent in the total cross section. This property makes the ratio  $R(\bar{t})/\sigma(t)$  more sensitive to a  $V_R$  component than the total cross section itself. A purely left-handed interaction yields

- **$tW$  associated production**

- [arXiv:hep-ph/0605190v2 18 Mar 2007]

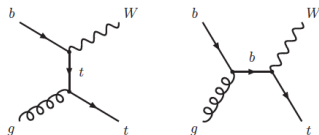


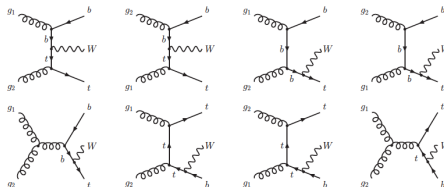
Figure 5: Feynman diagrams for single top production in the  $gb \rightarrow tW^-$  process.

# Single top quark production

## • $tW$ associated prod. [arXiv:hep-ph0605190v2 18 Mar 2007]

	$\kappa$	$\Delta Q$	$\Delta m_t$	$\Delta m_b$
$V_R^2$	1	-	-	-
$g_L^2, g_R^2$	3.46 – 3.57	+0.23 -0.11	+0.015 -0.015	+0.009 -0.008
$V_L g_R, V_R g_L$	1	-	-	-

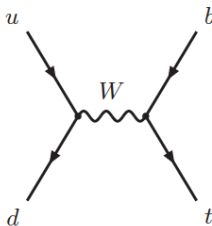
Table 7: Representative  $\kappa$  factors for the  $tW^-$  and  $\bar{t}W^+$  processes and their uncertainties, explained in the text. Errors smaller than 0.005 are omitted.



	$\kappa$	$\Delta Q$	$\Delta m_t$	$\Delta m_b$
$V_R^2$	1	-	-	-
$g_L^2, g_R^2$	4.51 – 4.73	+0.19 -0.04	+0.009 -0.027	+0.030 -0.
$V_L g_R, V_R g_L$	1.21 – 1.23	+0.014 -0.003	+0.005 -0.007	+0. -0.

Table 8: Representative  $\kappa$  factors for the  $tW^- \bar{b}$  and  $\bar{t}W^+ b$  processes and their uncertainties, explained in the text. Errors smaller than 0.005 are omitted.

- **s-channel**



# Single top quark production

## ● s-channel

[arXiv:hep-ph0605190v2 18 Mar 2007]

	$t\bar{b}$				$\bar{t}b$			
	$\kappa$	$\Delta Q$	$\Delta m_t$	$\Delta m_b$	$\kappa$	$\Delta Q$	$\Delta m_t$	$\Delta m_b$
$V_R^2$	1	-	-	-	1	-	-	-
$V_L V_R$	0.121	+0. -0.	+0. -0.	+0.005 -0.005	0.127	+0. -0.	+0. -0.	+0.006 -0.006
$g_L^2, g_R^2$	13.06 – 13.10	+0.25 -0.21	+0.26 -0.26	+0. -0.	12.22 – 12.28	+0.21 -0.18	+0.25 -0.24	+0. -0.
$g_L g_R$	1.23	+0.007 -0.008	+0.012 -0.012	+0.055 -0.055	1.25	+0.008 -0.009	+0.013 -0.013	+0.056 -0.056
$V_L g_L, V_R g_R$	-0.415	+0. -0.	+0. -0.	+0.018 -0.018	-0.426	+0. -0.	+0. -0.	+0.019 -0.019
$V_L g_R, V_R g_L$	-5.51	+0.009 -0.010	+0.057 -0.057	+0. -0.	-5.48	+0.008 -0.010	+0.057 -0.056	+0. -0.

Table 5:  $\kappa$  factors for the  $t\bar{b}$  and  $\bar{t}b$  processes and their uncertainties, explained in the text. Errors smaller than 0.005 are omitted.

- (i) The  $\kappa$  factors of  $g_L^2$  and  $g_R^2$  are a factor of four larger than for the  $t$ -channel process, because in  $t\bar{b}$  production the  $s$ -channel  $W$  boson carries a larger momentum, and so the  $q_\nu$  factor in the  $\sigma^{\mu\nu}$  vertex gives a larger enhancement.
- (ii) For  $t\bar{b}$  and  $\bar{t}b$  production the factors are very similar, although not equal (the difference is not due to Monte Carlo statistics, which is very high). Then, the measurement of the ratio  $\sigma(\bar{t}b)/\sigma(t\bar{b})$  is not as useful as in the  $t$ -channel process.
- (iii) Interferences among couplings are again important, in particular between  $V_L$  and  $g_R$ , and between  $V_R$  and  $g_L$ .

# Constraints on anomalous couplings

## ● Limits from single top

[arXiv:hep-ph0605190v2 18 Mar 2007]

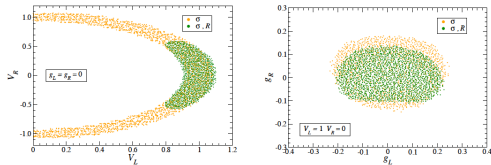


Figure 9: Estimated two-dimensional limits (with 68.3% CL) on  $(V_L, V_R)$  and  $(g_L, g_R)$ , obtained from measurement of single top cross sections, with and without the ratio  $R(\bar{t}/t)$  for the  $tj$  final state.

## ● Using $t\bar{t}$ observables

[arXiv:hep-ph0605190v2 18 Mar 2007]

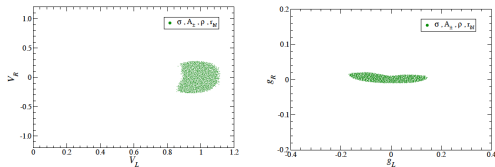


Figure 11: Combined limits on  $Wtb$  couplings from single top cross section measurements (excluding  $R(\bar{t}/t)$ ) and top decay observables  $A_{\pm}$ ,  $\rho_{R,L}$ ,  $\tau_M$ . The two graphs correspond to different projections of the 4-dimensional allowed region (with 68.3% CL).

**Can we do better?.....Yes, still  
in preparation.**



- Constraints on  $Wtb$  vertex:
  - combine the information of the most sensitive observables (taking into account the correlations)
  - Use new asymmetries  $A_{FB}^T$ ,  $A_{FB}^N$ ,  $A_{FB}^\ell$
  - evaluate 95% CL allowed regions considering the dependence of these observables with  $V_R$ ,  $g_L$  and  $g_R$

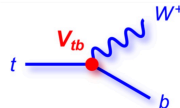
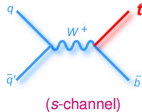
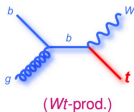
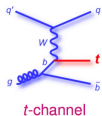
☞ this is the purpose of



<http://www-ftae.ugr.es/topfit>

# Combination of Observables

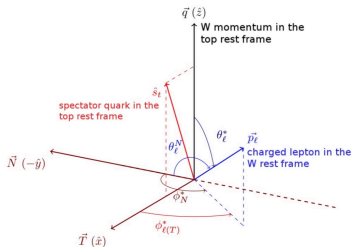
- All single top quark production cross sections used @ LHC:



- Angular distributions in  $t$ -channel exploited helicity formalism, PRD **93** (2016) 011301
  - full spin-density matrix for  $W$  helicity fractions



JHEP04 (2017) 124



Asymmetry	Angular observable	Polarisation observable	SM prediction
$A_{FB}^\ell$	$\cos \theta_\ell$	$\frac{1}{2} \alpha_\ell P$	0.45
$A_{FB}^{\ell W}$	$\cos \theta_W \cos \theta_\ell^*$	$\frac{3}{8} P (F_R + F_L)$	0.10
$A_{FB}$	$\cos \theta_\ell^*$	$\frac{3}{4} \langle S_3 \rangle = \frac{3}{4} (F_R - F_L)$	-0.23
$A_{EC}$	$\cos \theta_\ell^*$	$\frac{3}{8} \sqrt{\frac{2}{3}} \langle T_0 \rangle = \frac{3}{16} (1 - 3F_0)$	-0.20
$A_{FB}^T$	$\cos \theta_\ell^T$	$\frac{3}{4} \langle S_1 \rangle$	0.34
$A_{FB}^N$	$\cos \theta_\ell^N$	$-\frac{3}{4} \langle S_2 \rangle$	0
$A_{FB}^{T,\phi}$	$\cos \theta_\ell^* \cos \phi_\ell^*$	$-\frac{2}{3} \langle A_1 \rangle$	-0.14
$A_{FB}^{N,\phi}$	$\cos \theta_\ell^* \cos \phi_\ell^N$	$\frac{2}{3} \langle A_2 \rangle$	0


# Combination of Observables

General  $Wtb$  vertex

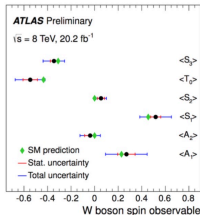
Eur.Phys.J. C50 (2007) 519-533

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

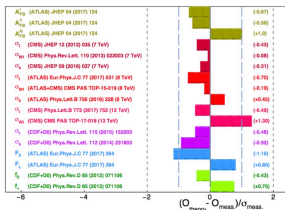
Vector ( $V_R$ ) and Tensor like couplings ( $g_L, g_R$ ) zero @ tree level in SM

- Angular distributions of the top decay products (and asymmetries) can be used to probe anomalous couplings at the  $Wtb$  vertex  **Combination is the game!**

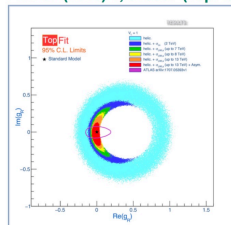
JHEP 04 (2017) 124



PRD 97 (2018) no.1, 013007



PRD 97 (2018) 1, 013007 (TopFit)




- All couplings allowed to vary (Real and Imaginary parts)

 Still significant room for improvement?

- We expect to perform the same type of combination @ HL-LHC and HE-LHC

## Summary

- Combination of production and decay observables is crucial to constrain the  $Wtb$  couplings
  - Should be done not only within a single experiment, but including all the available data from different experiments
- Several studies show limits improve significantly on ALL couplings
  - Increase of collected luminosity at the LHC should allow to have stringent bounds on the  $Wtb$  vertex  rapidly become a precision physics field
- Global fit to the general complex  $Wtb$  vertex requires not only more data but also a complete set of observables (TopFit available to experiments  $\Rightarrow$  use it!)



**FCT** Fundação para a Ciência e a Tecnologia

MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR Portugal

This work has been supported by FCT (project CERN/FP/116397/2010 and grant SFRH/BPD/63495/2009), CRUP (Acção integrada Ref. E 2/09), MICINN (FPA2010-17915 and HP2008-0039) and Junta de Andalucía (FQM 101 and FQM 437).