Top Quark Physics @ LHC

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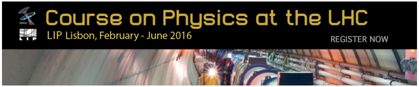
ATLAS



IST, April 11th, 2016

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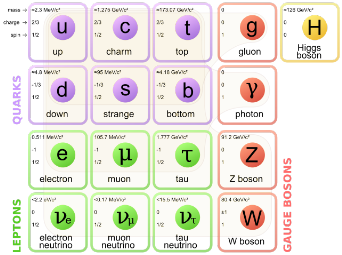
Topics covered in this lecture:

- Introduction
- The Wtb vertex structure (within and beyond the SM)
- Single Top quark (SM and beyond)
- Rare decays of top quarks and Flavor Changing Neutral Currents (FCNC)

The top quark

- **2015 is the top quark's 20th anniversary**
  it was discovered by CDF and D0 in 1995
  PRL**74** 2626-2631 (1995);
  PRL**74** 2632-2637 (1995).



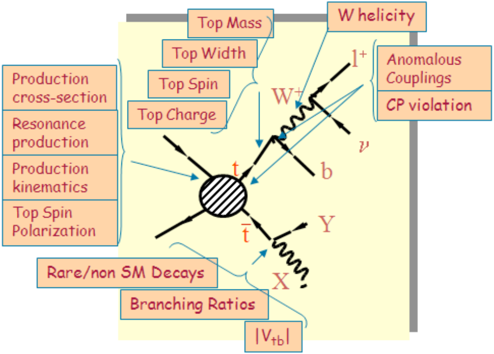
- It completes the 3 family structure of the SM
  - top is the weak-isospin partner of the b-quark
  - spin = $1/2$
  - charge = $+2/3\ |e|$
- Top quark is the heaviest known fundamental particle ($m_t = 173.34 \pm 0.76$ GeV, World comb.(2014), arXiv:1403.4427)
- Top decays (almost exclusively) through $t \to bW$
  $BR(t \to sW) \leq$0.18%, $BR(t \to dW) \leq$0.02%
- $\Gamma_t^{SM} = 1.42$ GeV (including m_b, m_W, α_s, EW corrections)
  - τ_t=$(3.29^{+0.90}_{-0.63})\ \times 10^{-25}$s (D0, PRD **85** 091104, 2012)
    $\ll \Lambda_{QCD}^{-1} \sim$(100 MeV)$^{-1} \sim 10^{-23}$s (hadronization time)
    $\Rightarrow$ 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, $t \to bW$ 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 $t \to W^+ b$
  - understanding the structure of the Wtb vertex helps revealling 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, theorectically equivalent, observables studied for $t\bar{t}$ production at LHC (not all explored yet @ LHC)
- Single top cross section usefull (sensitive to V_{tb} and anomalous couplings)
- Indirect limits from $b \to s\gamma$ 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 Wtb vertex structure

Effective *Wtb* vertex from dim-6 operators

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

$V_{\rm L} \equiv V_{tb} \sim 1$ (within SM)

$V_{\rm R}, g_{\rm R}, g_{\rm L} \Rightarrow$ 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 distibutions
- measurements of $t\bar{t}$ production: angular distributions of top quark decays

The Wtb vertex structure

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B-physics constraints to *Wtb* vertex

IFT-2/2008

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

Bohdan Grzadkowski and Mikołaj 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 $\bar{B} \to X_s \gamma$ 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.

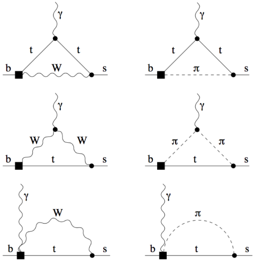


FIG. 1: Diagrams with non-SM $b \to t$ vertices that contribute to $f_7^{g_{L,R}}(x)$. The pseudogoldstone boson is denoted by π.

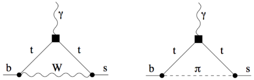


FIG. 2: Diagrams with non-SM $\bar{t}t\gamma$ vertices that contribute to $f_7^{g_R}(x)$.

't Hooft gauge. The relevant Feynman diagrams with non-SM $b \to t$ vertices are shown in Fig. 1. In addition, analogous six diagrams with non-SM $t \to s$ 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 $f_7^{g_L}$(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 $f_i^{g_{L,R}}(x)$ read:

[EPJC57 (2008) 183]

B-physics constraints to Wtb vertex

$$BR(\bar{B} \to X_s\gamma) = \left(3.55 \pm 0.24\,^{+0.09}_{-0.10} \pm 0.03\right) \times 10^{-4}$$

[hep-ex/0603003]

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

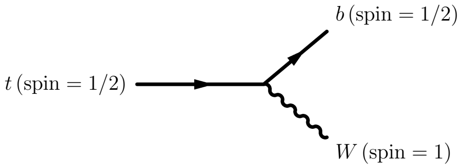
$$\mathcal{O}\left[(V_L - V_{tb}, V_R, \ldots)^2\right] \simeq 1.32(V_L - V_{tb})^2 - 262(V_L - V_{tb})V_R + 12970\,V_R^2 + \ldots$$

	$V_L - V_{tb}$	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

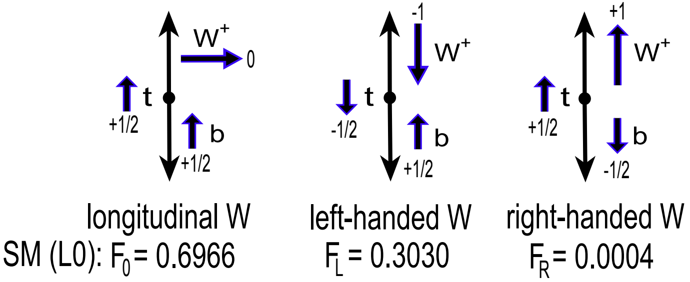
[EPJC57 (2008) 183]

The Wtb vertex structure

[PRD 45 (1992) 124]



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



The Wtb vertex structure

- [arXiv:hep-ph0605190v2 18 Mar 2007]

Probing anomalous Wtb couplings in top pair decays

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[c] *UCP, Rua Dr. Mendes Pinheiro 24, 3080 Figueira da Foz, Portugal*

Abstract

We investigate several quantities, defined in the decays of top quark pairs, which can be used to explore non-standard Wtb interactions. Two new angular asymmetries are introduced in the leptonic decay of top (anti)quarks. Both are very sensitive to anomalous Wtb couplings, and their measurement allows for a precise determination of the W helicity fractions. We also examine other angular and energy asymmetries, the W helicity fractions and their ratios, as well as spin correlation asymmetries, analysing their dependence on anomalous Wtb couplings and identifing the quantities which are most sensitive to them. It is explicitly shown that spin correlation asymmetries are less sensitive to new interactions in the decay of the top quark; therefore, when combined with the measurement of other observables, they can be used to determine the $t\bar{t}$ spin correlation even in the presence of anomalous Wtb couplings. We finally discuss some asymmetries which can be used to test CP violation in $t\bar{t}$ production and complex phases in the effective Wtb vertex.

The Wtb vertex structure

- [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 Γ_R, Γ_L, Γ_0, being $\Gamma \equiv \Gamma(t \to W^+ b) = \Gamma_R + \Gamma_L + \Gamma_0$. The Γ_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. (1), yielding

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

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

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

The Wtb vertex structure

- [arXiv:hep-ph0605190v2 18 Mar 2007]

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

The Wtb vertex structure

- [arXiv:hep-ph0605190v2 18 Mar 2007]

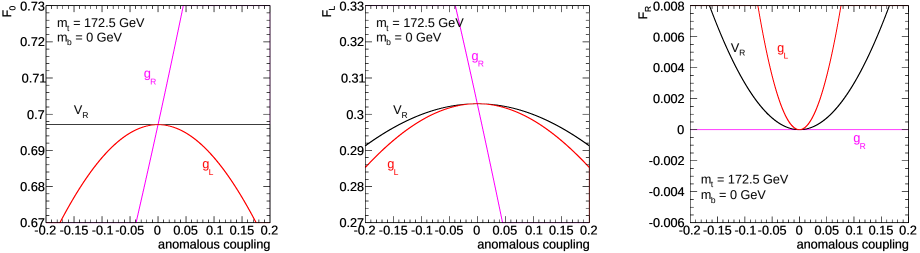
the modulus of the W boson three-momentum in the top quark rest frame. The total top width is

$$\begin{aligned}\Gamma \;=\; & \frac{g^2|\vec{q}|}{32\pi}\frac{m_t^2}{M_W^2}\left\{\left[|V_L|^2+|V_R|^2\right]\left(1+x_W^2-2x_b^2-2x_W^4+x_W^2x_b^2+x_b^4\right)\right. \\ & -12x_W^2x_b\,\mathrm{Re}\,V_LV_R^*+2\left[|g_L|^2+|g_R|^2\right]\left(1-\frac{x_W^2}{2}-2x_b^2-\frac{x_W^4}{2}-\frac{x_W^2x_b^2}{2}+x_b^4\right) \\ & -12x_W^2x_b\,\mathrm{Re}\,g_Lg_R^*-6x_W\,\mathrm{Re}\,\left[V_Lg_R^*+V_Rg_L^*\right]\left(1-x_W^2-x_b^2\right) \\ & \left.+6x_Wx_b\,\mathrm{Re}\,\left[V_Lg_L^*+V_Rg_R^*\right]\left(1+x_W^2-x_b^2\right)\right\}\,. \qquad (4)\end{aligned}$$

[EPJC50 (2007) 519]

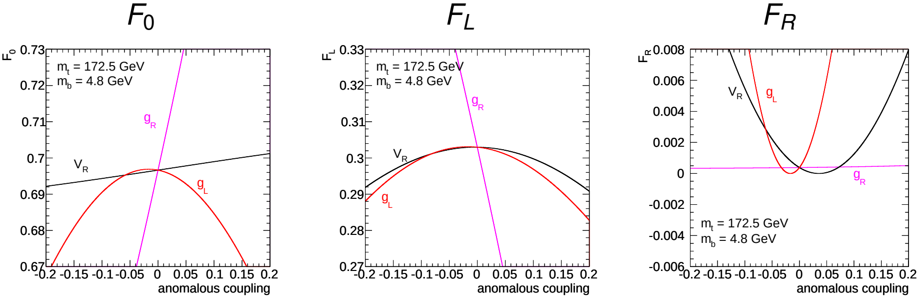
anomalous couplings ⇒ deviations in W helicity fractions

F_0 F_L F_R



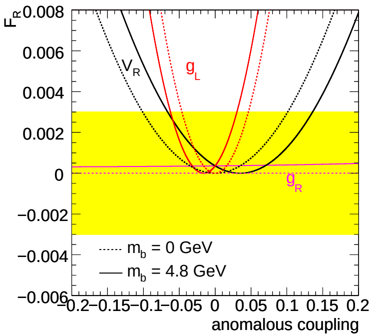
[EPJC50 (2007) 519]

anomalous couplings ⇒ deviations in *W* helicity fractions



☞ correct m_b has to be considered!

The Wtb vertex structure



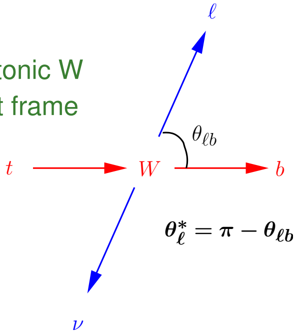
example: $|F_R| < 0.003$ can be converted into a V_R constraint using the intersection method:

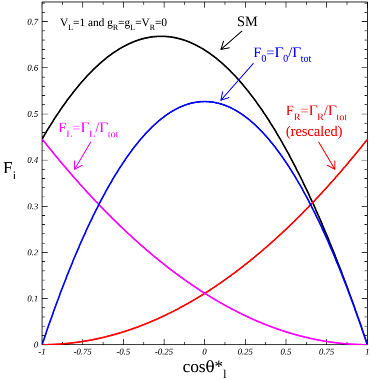
- ☞ $-0.101 < V_R < 0.101$ ($m_b = 0.0$ GeV)
- ☞ $-0.067 < V_R < 0.136$ ($m_b = 4.8$ GeV)

Measuring the W helicity states

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

leptonic W
rest frame





Measuring the W helicity states

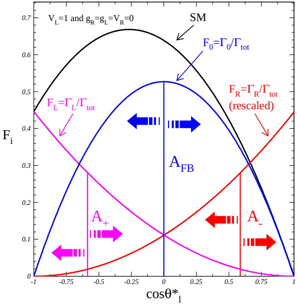
W polarisation can be measured by:

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: $A_t = \frac{N(\cos\theta^*_\ell > t) - N(\cos\theta^*_\ell < t)}{N(\cos\theta^*_\ell > t) + N(\cos\theta^*_\ell < t)}$

$$A_{FB} = 3/4[F_\mathrm{R} - F_\mathrm{L}]$$
$$= -0.2227 \text{ (SM, LO)}$$

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

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



$(\beta = 2^{1/3} - 1)$ [EPJC50 (2007) 519]

The Wtb vertex structure

- [arXiv:hep-ph0605190v2 18 Mar 2007]
- How do $\rho_{L,R}$ behave?

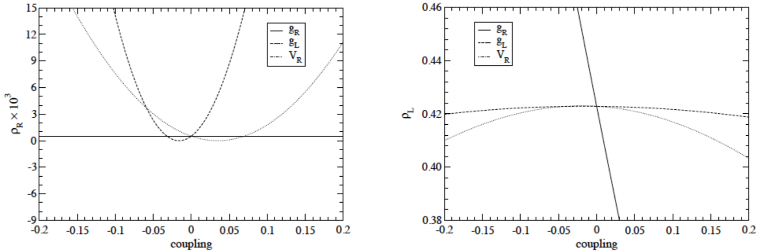


Figure 3: Dependence of the helicity ratios $\rho_{R,L} = \Gamma_{R,L}/\Gamma_0$ on the anomalous couplings in Eq. (1), in the CP-conserving case.

The Wtb vertex structure

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

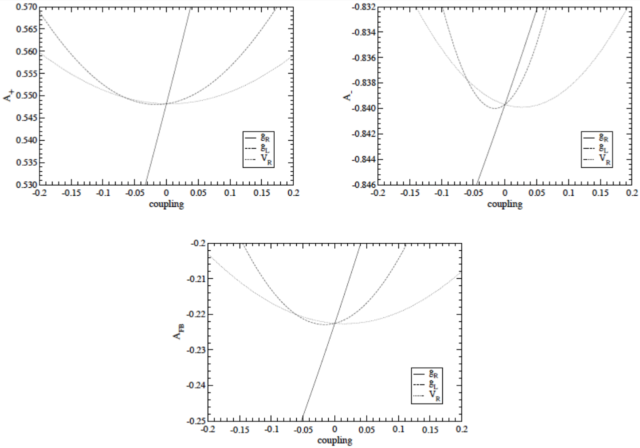


Figure 4: Dependence of the asymmetries A_+, A_- and $A_{\rm FB}$ on the couplings g_L, g_L and V_R, for the CP-conserving case.

The Wtb vertex structure

- [arXiv:hep-ph0605190v2 18 Mar 2007]
- A rough comparison between results

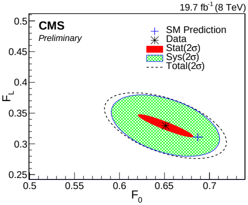
	F_i	ρ_i
V_R	$[-0.062, 0.13]$	$[-0.029, 0.099]$
g_L	$[-0.060, 0.028]$	$[-0.046, 0.013]$
g_R	$[-0.023, 0.021]$	$[-0.025, 0.026]$

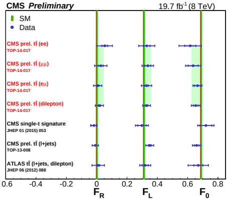
Table 1: 1σ bounds of anomalous couplings obtained from the measurement of helicity fractions F_i and ratios ρ_i.

	A_+	A_-	$A_{\rm FB}$
V_R	$[-0.15, 0.15]$	$[-0.056, 0.11]$	$[-0.12, 0.15]$
g_L	$[-0.12, 0.082]$	$[-0.057, 0.026]$	$[-0.092, 0.062]$
g_R	$[-0.019, 0.018]$	$[-0.024, 0.022]$	$[-0.027, 0.025]$

Table 2: 1σ bounds on anomalous couplings obtained from the measurement of angular asymmetries.

W Helicity from CMS (19.7 fb^{-1}@ 8 TeV): [CMS PAS TOP-14-017]





Systematic Uncertainties (3D Fit):

F_0: Fac./Renorm. scales, jet-parton matching top p_T reweight

F_L: Fac./Renorm. scales, jet-parton matching

$F_0 = 0.653 \pm 0.016(\text{stat}) \pm 0.024(\text{syst})$

$F_L = 0.329 \pm 0.009(\text{stat}) \pm 0.025(\text{syst})$

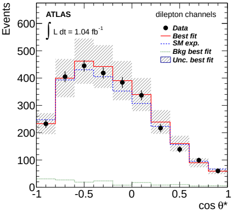
$F_R = 0.018 \pm 0.008(\text{stat}) \pm 0.026(\text{syst})$

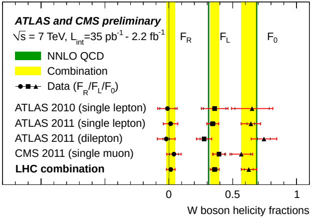
☞ single top important: JHEP**01** 053 (2015)

stringent limits on anomalous couplings!!

$\Delta F_0/F_0 = 4\%, \quad \Delta F_L/F_L = 8\%$

W Helicity from ATLAS (1.04 fb^{-1}) : [JHEP 1206 (2012) 088]





Combined (ATLAS+CMS):

[ATLAS-CONF-2013-033, CMS PAS TOP-12-025]

$F_0 = 0.626 \pm 0.034(\text{stat}) \pm 0.048(\text{syst})$

$F_L = 0.359 \pm 0.021(\text{stat}) \pm 0.028(\text{syst})$

$F_R = 0.015 \pm 0.034(\text{stat+syst})$

General Wtb vertex

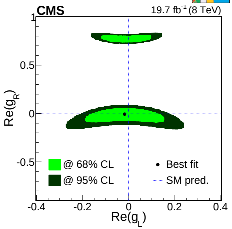
Eur.Phys.J. C50 (2007) 519-533

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

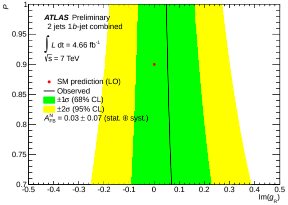
Vector (V_R) and Tensor like couplings (g_L, g_R) zero @ tree level in SM

- 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-2013-032



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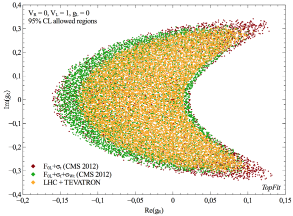
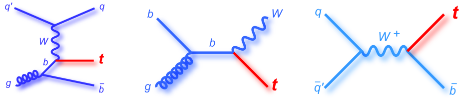


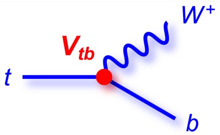
- What next? ☞ extract the spin properties of the mensagers of new physics from data arXiv:1508.04592v2 [hep-ph] 21 Aug 2015
- **Assuming V_L=1 (V_R=0)** ☞ **What is the current LHC status of V_{tb} in the SM? What about the top quark couplings to other bosons?**

Single top quark production

Single top quark

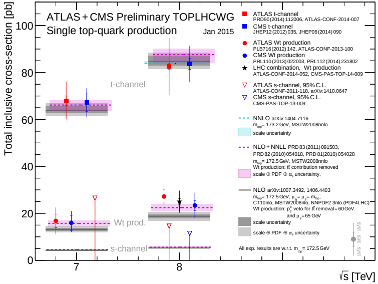
- Single top quark production cross section @ LHC:

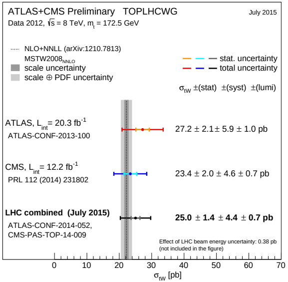




t-channel	(*Wt*-prod.)	(*s*-channel)	
$64.57^{+2.63}_{-1.74}$ pb	$15.74^{+1.17}_{-1.21}$ pb	$4.63^{+0.20}_{-0.18}$ pb	$\Longleftarrow$ @ 7TeV
$87.76^{+3.44}_{-1.91}$ pb	$22.37^{+1.52}_{-1.52}$ pb	$5.61^{+0.22}_{-0.22}$ pb	$\Longleftarrow$ @ 8TeV

- Powerfull probe of V_{tb} ($\delta V_{tb}/V_{tb}$ few % @ LHC) and Test of physics BSM (FCNC in *t*-channel; *W'* in *s*-channel)
- CMS and ATLAS results within SM expectations:





$\Delta\sigma_t/\sigma_t \sim 10\%$

$\Delta\sigma_{Wt}/\sigma_{Wt} \sim 20\%$

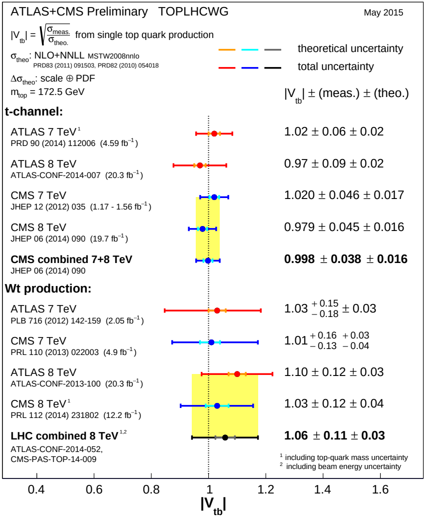
ATLAS@8 TeV:

$\sigma_s(95\%) < 14.6$ pb

CMS@8 TeV:

$\sigma_s(95\%) < 11.5$ pb

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 (γ, W, Z, H)?

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

Single top quark production

- [arXiv:hep-ph0605190v2 18 Mar 2007]

Single top quark production at LHC with anomalous Wtb couplings

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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 γ^μ 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

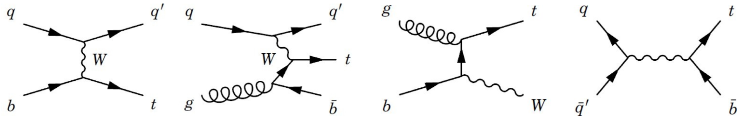
- [arXiv:hep-ph0605190v2 18 Mar 2007]

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]

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

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^{μ} 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 ϵ_{μ} is the polarisation vector of the W boson, so that terms proportional to q^{μ} 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 γ^{μ} 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



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

- the κ factors determine the dependence on anomalous couplings
- the κ 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

- **t-channel**
- [arXiv:hep-ph0605190v2 18 Mar 2007]

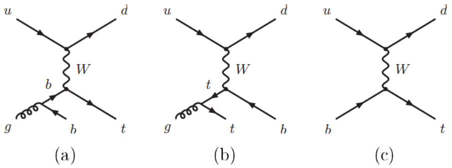


Figure 2: Sample Feynman diagrams for single top production in the t-channel process. Additional diagrams are obtained by crossing the light quark fermion line, and/or replacing (u, d) by (c, s). The diagrams for antitop production are the charge conjugate ones.

- **t-channel** [arXiv:hep-ph0605190v2 18 Mar 2007]

	tj				$\bar{t}j$			
	κ	ΔQ	Δm_t	Δm_b	κ	ΔQ	Δm_t	Δm_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	$^{+0.042}_{-0.033}$	$^{+0.014}_{-0.034}$	$^{+0.}_{-0.022}$	$1.75 - 1.77$	$^{+0.042}_{-0.033}$	$^{+0.007}_{-0.033}$	$^{+0.}_{-0.025}$
$V_L g_R$	$-(0.348 - 0.365)$	$^{+0.007}_{-0.011}$	$^{+0.}_{-0.}$	$^{+0.}_{-0.}$	$-(0.038 - 0.040)$	$^{+0.010}_{-0.009}$	$^{+0.}_{-0.}$	$^{+0.}_{-0.}$
$V_R g_L$	$-(0.006 - 0.008)$	$^{+0.006}_{-0.005}$	$^{+0.}_{-0.}$	$^{+0.}_{-0.}$	$-(0.399 - 0.408)$	$^{+0.}_{-0.008}$	$^{+0.}_{-0.}$	$^{+0.}_{-0.}$

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

	$t\bar{b}j$				$\bar{t}bj$			
	κ	ΔQ	Δm_t	Δm_b	κ	ΔQ	Δm_t	Δm_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 κ factors for the $t\bar{b}j$ and $\bar{t}bj$ 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 $R(\bar{t}/t) = \sigma(\bar{t})/\sigma(t)$ more sensitive to a V_R component than the total cross section itself. A purely left-handed interaction yields

- **tW associated production**
- [arXiv:hep-ph0605190v2 18 Mar 2007]

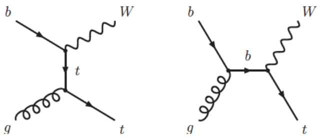


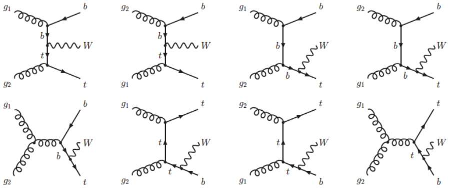
Figure 5: Feynman diagrams for single top production in the $gb \to tW^-$ process.

Single top quark production

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

	κ	ΔQ	Δm_t	Δm_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 κ factors for the tW^- and $\bar{t}W^+$ processes and their uncertainties, explained in the text. Errors smaller than 0.005 are omitted.

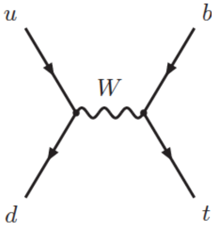


	κ	ΔQ	Δm_t	Δm_b
V_R^2	1	–	–	–
g_L^2, g_R^2	$4.51 - 4.73$	$^{+0.19}_{-0.04}$	$^{+0.009}_{-0.027}$	$^{+0.030}_{-0.}$
$V_L g_R, V_R g_L$	$1.21 - 1.23$	$^{+0.014}_{-0.003}$	$^{+0.005}_{-0.007}$	$^{+0.}_{-0.}$

Table 8: Representative κ 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.

Single top quark production

- **s-channel**



- **s-channel**

[arXiv:hep-ph0605190v2 18 Mar 2007]

	$t\bar{b}$				$\bar{t}b$			
	κ	ΔQ	Δm_t	Δm_b	κ	ΔQ	Δm_t	Δm_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: κ factors for the tb and $\bar{t}b$ processes and their uncertainties, explained in the text. Errors smaller than 0.005 are omitted.

(i) The κ 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_ν 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]

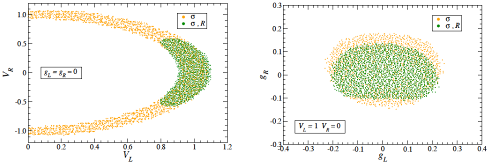


Figure 9: Estimated two-dimensional limits (with 68.3% CL) on (V_L, V_R) and (g_L, g_R), obtained from measurement of single top cross sections, with and without the ratio $R(\bar{t}/t)$ for the tj final state.

- **Using $t\bar{t}$ observables** [arXiv:hep-ph0605190v2 18 Mar 2007]

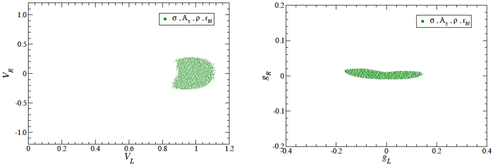


Figure 11: Combined limits on Wtb couplings from single top cross section measurements (excluding $R(\bar{t}/t)$) and top decay observables $A_\pm$, $\rho_{R,L}$, r_{bl}. The two graphs correspond to different projections of the 4-dimensional allowed region (with 68.3% CL).

Can we do better?.......

in preparation.

Constraining *Wtb* anomalous couplings: `TopFit`

- Constraints on *Wtb* vertex:
  - combine the information of the most sensitive observables (taking into account the correlations)
  - evaluate 95% CL allowed regions considering the dependence of these observables with V_R, g_L and g_R

☞ this is the purpose of TopFit

`http://www-ftae.ugr.es/topfit`

Observables from LHC

EXPERIMENTAL RESULTS

The t-channel single top quark production cross section has been measured with great precision at different center-of-mass energies, both at the LHC and Tevatron. CMS recently measured the t-channel single top-quark inclusive cross section using proton-proton collisions at 13 TeV [17], corresponding to an integrated luminosity of 42 pb^{-1}, with one muon in the final state:

$$\sigma_{t-ch}^{(13\text{ TeV})} = 274 \pm 98\ (\text{stat}) \pm 52\ (\text{sys}) \pm 33\ (\text{lum})\ \text{pb}\,. \tag{2}$$

The same measurement had already been performed by CMS at center-of-mass energy of 8 TeV, using a total integrated luminosity of 19.7 fb^{-1} [18],

$$\sigma_{t-chan}^{(8\text{ TeV})} = 83.6 \pm 2.3\ (\text{stat}) \pm 7.4\ (\text{syst})\ \text{pb}\,. \tag{3}$$

The cross section was measured inclusively, in final states with a muon or an electron. Previous results from CMS at 7 TeV were also taken into account, with the single top quark production cross section in the t-channel measured to be [19],

$$\sigma_{t-chan}^{(7\text{ TeV})} = 67.2 \pm 6.1\ \text{pb}\,. \tag{4}$$

Results from Tevatron were also used in this paper, in particular, the final combination of CDF and D0 measurements of cross sections for single-top-quark production in proton-antiproton collisions at a center-of-mass energy of 1.96 TeV. With a total integrated luminosity of up to 9.7 fb^{-1} per experiment, the measured t-channel cross section is [20],

$$\sigma_{t-chan}^{(1.96\text{ TeV})} = 2.25 \pm 0.29\ (\text{stat}) \pm 0.31\ (\text{sys})\ \text{pb}\,. \tag{5}$$

$$\begin{aligned} F_0 &= 0.659 \pm 0.015\ (\text{stat}) \pm 0.023\ (\text{syst})\,, \\ F_L &= 0.350 \pm 0.010\ (\text{stat}) \pm 0.024\ (\text{syst})\,, \\ F_R &= -0.009 \pm 0.006\ (\text{stat}) \pm 0.020\ (\text{syst})\,. \end{aligned} \tag{6}$$

Finally, the expected results for the t-channel single top quark production measurement in future LHC runs at 14 TeV and 33 TeV are also taken into account. In particular, in the single top t-channel final state with one lepton and a neutrino coming from the top quark decay, plus two jets (with one of them being tagged as a b-jet), the estimated cross-section precision is expected to reach 3.8% for 3000 fb^{-1} of 14 TeV pp collision data [28].

All measurements of single top quark production cross sections were assumed to be uncorrelated, and a correlation coefficient of $\rho = -0.95$ between F_0 and F_L was assumed [29].

LIMITS ON ANOMALOUS COUPLINGS

The dependences of the Wtb helicity fractions and single top quark production cross sections on the anomalous couplings were derived in [8] and [13], respectively. In this paper, these expressions were used to set limits on the anomalous contributions with the TopFit program, which provides a proper statistical treatment in establishing the allowed regions for these couplings, by taking into account different correlations between observables and systematic uncertainties. No consideration was given to four-fermion contributions to the t-channel single top quark production cross section [30, 31], and also no correlation was assumed between the helicities and the cross section measurements. The total uncertainty of each measurement is defined by adding in quadrature the corresponding statistical and systematic uncertainties.

The allowed regions of phase-space are presented in

Observables from LHC

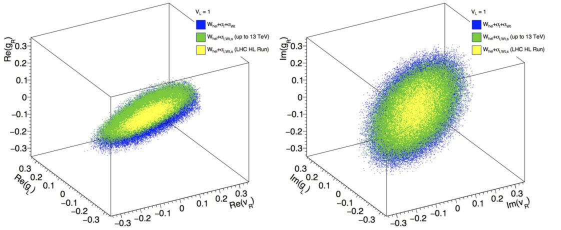
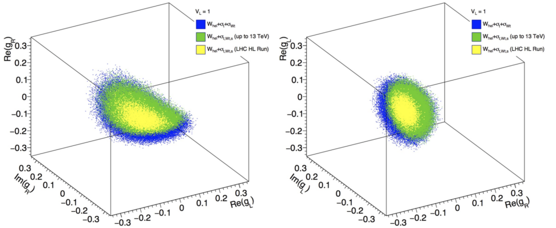
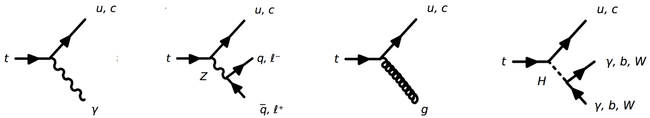


FIG. 1: Allowed region in $Re(g_R), Re(g_L)$ and $Re(V_R)$ at 95% CL (left). Allowed region in $Im(g_R), Im(g_L)$ and $Im(V_R)$ at 95% CL (right).



Top quarks and Flavor Changing Neutral Currents (FCNC)

- Several $t\bar{t}$ FCNC Decay Channels Studied @ LHC:



Theoretical predictions for the BR of FCNC top quark decays

Process	SM	QS	2HDM	FC 2HDM	MSSM	$\not{R}$ SUSY	RS
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	—	—	2×10^{-6}	3×10^{-5}	—
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	—	—	2×10^{-6}	1×10^{-6}	—
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	—	—	8×10^{-5}	2×10^{-4}	—
$t \to uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	—	10^{-5}	$\sim 10^{-6}$	—
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}	$\lesssim 10^{-5}$
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}	$\lesssim 10^{-9}$
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}	$\lesssim 10^{-10}$
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$	$\lesssim 10^{-4}$

Acta Phys.Polon.**B35**,2695(2004), arXiv:1311.2028

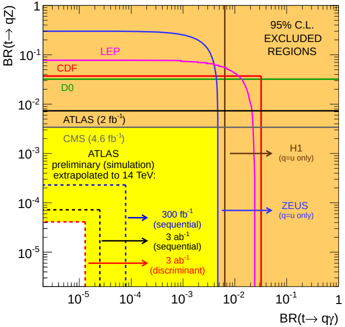
- In the SM flavour changing neutral currents (FCNC) are forbidden at tree level and much smaller than the dominant decay mode ($t \to bW$) at one loop level
- BSM models predict higher BR for top FCNC decays
  ☞ powerful probe for new physics

FCNC Direct Bounds RUN I (short) Summary:

Prospects:

Decay Channel	95% CL Limit	Data Set and Exp.
$B(t \to qg)$	4.0×10^{-5} $(q = u)$	ATLAS-TOPQ-2014-13-002
	1.70×10^{-4} $(q = c)$	(8 TeV, 20.3 fb^{-1})
	3.55×10^{-4} $(q = u)$	CMS-PAS-TOP-14-007
	3.44×10^{-3} $(q = c)$	(7TeV,5.0 fb^{-1})
$B(t \to qZ)$	7×10^{-4} $(q = u, c)$	arXiv:1508.05796 (8 TeV, 20.3 fb^{-1})
	5×10^{-4} $(q = u, c)$	PRL**112**,171802(2014) (7TeV,5.0 fb^{-1} $\oplus$ 8TeV,19.7 fb^{-1})
$B(t \to q\gamma)$	1.61×10^{-4} $(q = u)$	CMS-PAS-TOP-14-003
	1.82×10^{-3} $(q = c)$	(8 TeV, 19.1 fb^{-1})
$B(t \to qH)$	7.90×10^{-3} $(q = u, c)$	JHEP**1406**,008(2014) (7TeV,4.7 fb^{-1} $\oplus$ 8TeV,20.3 fb^{-1})
	4.20×10^{-3} $(q = u)$	CMS-PAS-TOP-14-019
	4.70×10^{-3} $(q = c)$	(8 TeV, 19.7 fb^{-1})

☞ Limits @ RUN 1 in the range 10^{-3} to 10^{-5}



☞ 95%Limits @ RUN 2 expected to improve ∼ 1 order of magnitude:

ATL-PHYS-PUB-2012-001
ATL-PHYS-PUB-2013-012

CMS-PAS-FTR-13-016

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!)
- Studies @ LHC of FCNC processes both at decay and production are promising (already best results in the world)

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