Top Quark Physics @ LHC

António Onofre

(antonio.onofre@cern.ch)

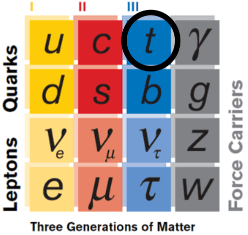
IST, May 8^{th}, 2013

Outline

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)

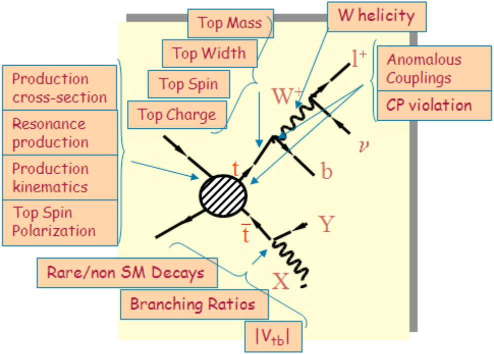
- Top quark completes the 3 family structure of the SM
  - top is the weak-isospin partner of the *b*-quark
  - spin = 1/2
  - charge = $+2/3\ |e|$



- Top quark is the heaviest known quark ($m_t = 173.2 \pm 0.9$ GeV, CDF+D0, arXiv:1107.5255)
- 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)
  - Λ_{QCD}^{-1}=(100 MeV)$^{-1}$=10^{-23}s (hadronization time)
  - $\tau_t \ll 10^{-23}$ s
    $\Rightarrow$ top decays before hadronization

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 $t \longrightarrow W^+b$
  - 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

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

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

$V_R, g_R, g_L \Rightarrow$ 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

Effective *Wtb* vertex from dim-6 operators

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

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

$V_R, g_R, g_L \Rightarrow$ 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

Effective *Wtb* vertex from dim-6 operators

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

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

$V_R, g_R, g_L \Rightarrow$ 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

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]

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

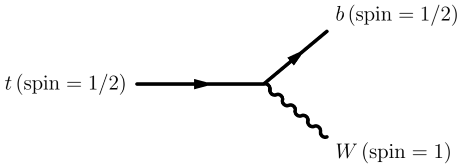
$$\mathcal{O}\left[(V_L - V_{tb}, V_R, \ldots)^2\right] \simeq 1.32(V_L - V_{tb})^2 - 262(V_L - V_{tb})V_R + 12970\, V_R^2 + \ldots$$

	$V_L - V_{tb}$	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

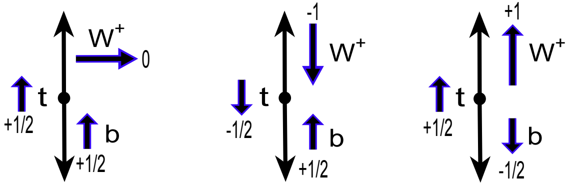
[EPJC57 (2008) 183]

The Wtb vertex structure

[PRD 45 (1992) 124]



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



longitudinal W	left-handed W	right-handed W
SM (LO): $F_0 = 0.6966$	$F_L = 0.3030$	$F_R = 0.0004$

The Wtb vertex structure

- [arXiv:hep-ph0605190v2 18 Mar 2007]

Probing anomalous Wtb couplings in top pair decays

J. A. Aguilar–Saavedra[a], J. Carvalho[b], N. Castro[b], A. Onofre[b,c], F. Veloso[b]

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

[b] *LIP - Departamento de Física, Universidade de Coimbra, 3004-516 Coimbra, Portugal*

[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

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

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]

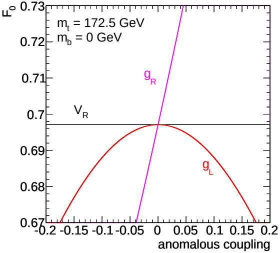
the modulus of the W boson three-momentum in the top quark rest frame. The total top width is

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

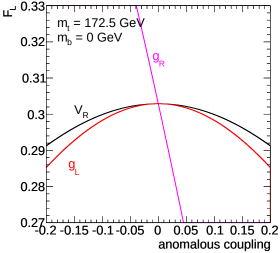
[EPJC50 (2007) 519]

anomalous couplings ⇒ deviations in W helicity fractions

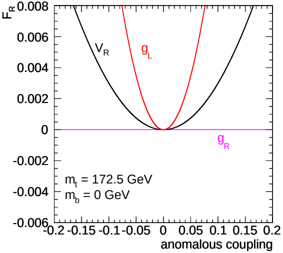
F_0



F_L



F_R

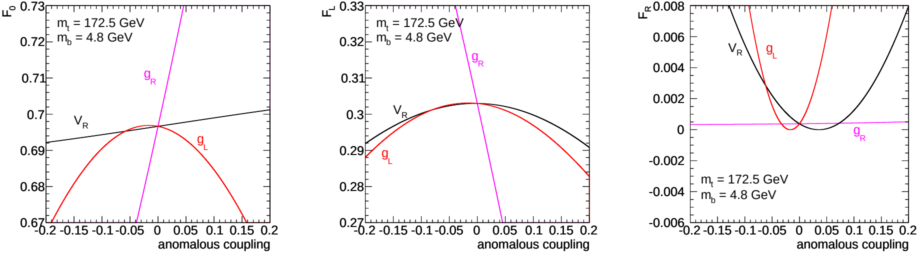


The Wtb vertex structure

[EPJC50 (2007) 519]

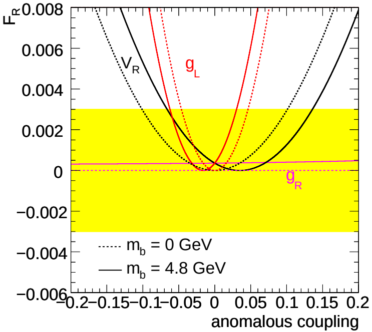
anomalous couplings ⇒ deviations in W helicity fractions

F_0 F_L F_R



☞ correct m_b has to be considered!

The Wtb vertex structure



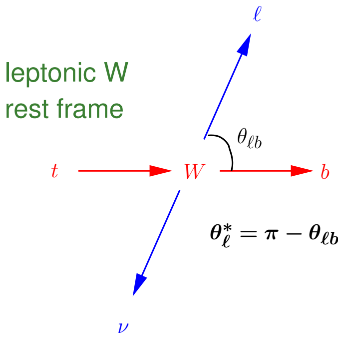
example: $|F_R| < 0.003$ can be converted into a V_R constraint using the intersection method:

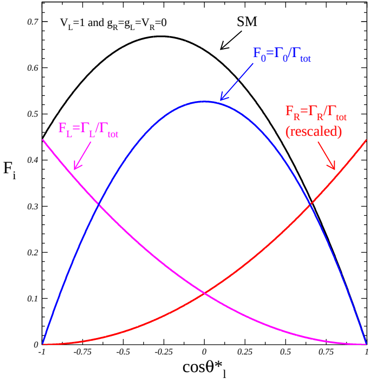
☞ $-0.101 < V_R < 0.101$ ($m_b = 0.0$ GeV)

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

Measuring the W helicity states

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





Measuring the W helicity states

W polarisation can be measured by:

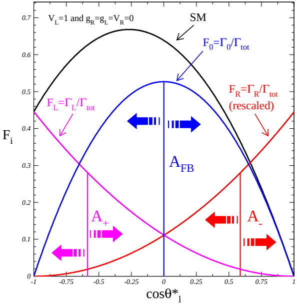
1. Fitting $\cos\theta^*_\ell$ to obtain the W helicity fractions (F_0, F_L, F_R)
2. Fitting $\cos\theta^*_\ell$ to obtain the W helicity ratios:
   - ☞ $\rho_L = F_L/F_0 = 0.435$ (SM, LO)
   - ☞ $\rho_R = F_R/F_0 = 5.5 \times 10^{-4}$ (SM, LO)
3. Computing angular asymmetries: $A_t = \frac{N(\cos\theta^*_\ell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

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

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

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

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



[EPJC50 (2007) 519]

The Wtb vertex structure

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

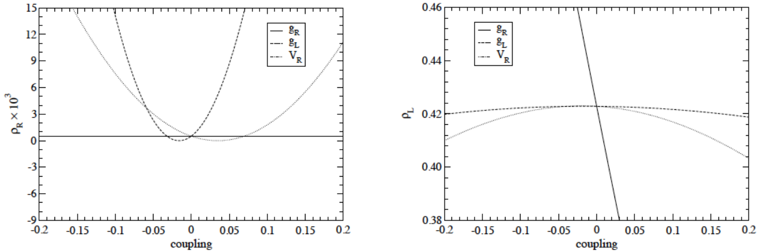


Figure 3: Dependence of the helicity ratios $\rho_{R,L} = \Gamma_{R,L}/\Gamma_0$ on the anomalous couplings in Eq. (1), in the CP-conserving case.

The Wtb vertex structure

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

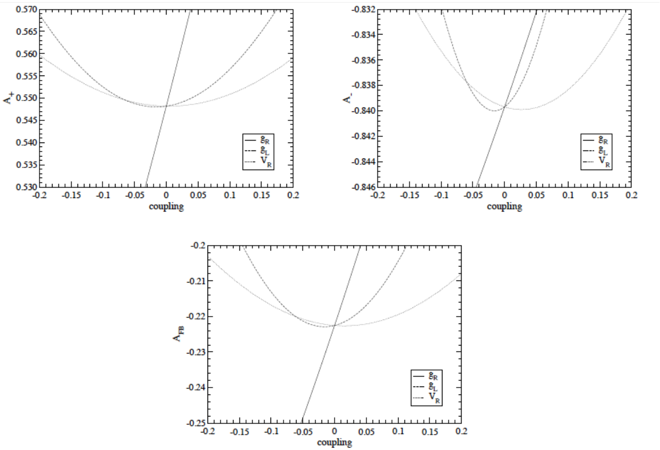


Figure 4: Dependence of the asymmetries A_+, A_- and $A_{\rm FB}$ on the couplings g_L, g_L and V_R, for the CP-conserving case.

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_{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	$[-0.019, 0.018]$	$[-0.024, 0.022]$	$[-0.027, 0.025]$

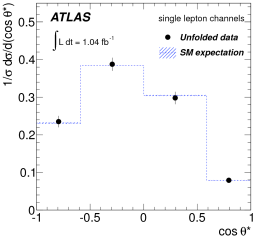
Table 2: 1σ bounds on anomalous couplings obtained from the measurement of angular asymmetries.

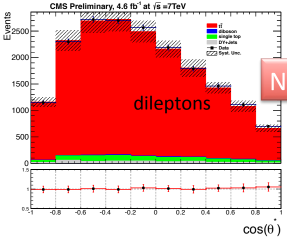
The Wtb vertex structure

- The LHC Current Status (Moriond 2013)

W Boson Polarization from tt~ Events

- Dilepton channel [CMS-PAS-TOP-12-015, ATLAS: JHEP1206 (2012) 088]
  - Analytical solution for the tt~ system.
- Lepton+jets [CMS-PAS-TOP-11-020, ATLAS: JHEP1206 (2012) 088]
  - Kinematic fit with m_t and m_W constraints.
- CMS:
  - Fit based on event-by-event reweighting for resolution and efficiencies.
- ATLAS:
  - Asymmetry and template methods
    - Protos for templates





NEW

$$A_{\pm} = \frac{N(\cos\theta^{*} > z) - N(\cos\theta^{*} < z)}{N(\cos\theta^{*} > z) + N(\cos\theta^{*} < z)}, \quad z = \pm\left(1 - 2^{2/3}\right)$$

PRD67(2003), EPJC50(2007)

All results consistent with each other and SM predictions.

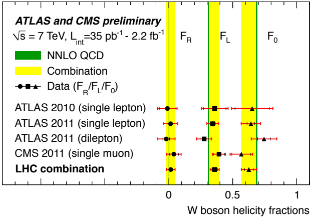
The Wtb vertex structure

- LHC limits on anomalous couplings (Moriond 2013)

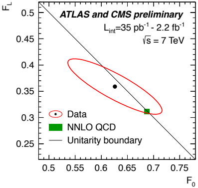
W Boson Polarization - LHC Combination

ATLAS-CONF-2013-033 & CMS-PAS-TOP-12-025

NEW



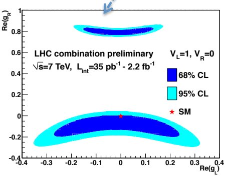
- All measurements utilize cos(θ*)
- Unitarity constraint: $F_L+F_R+F_0=1$ in each measurement and the combination



- BLUE method for the combination
  - Results stable against wrong correlation hypotheses.

$$F_0 = 0.626 \pm 0.034(stat) \pm 0.048(syst)$$
$$F_L = 0.359 \pm 0.021(stat) \pm 0.028(syst)$$
$$F_R = 0.015 \pm 0.034(stat + syst)$$

Strongly constrained by the single-top cross section measurements.

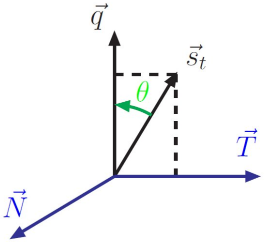


contours from profile likelihood method

SM prediction: F_0 = 0.687(5), F_R = 0.0017(1), and F_L = 0.311(5) [assuming m_t: 172.8+/-1.3 GeV]

W polarisation beyond helicity fractions

- New idea to study top decays: [NPB840 (2010) 349]
  ☞ consider transverse and normal directions



$\vec{q}$	→	W mom in t rest frame
$\vec{s}_t$	→	top spin

$$\vec{N} = \vec{s}_t \times \vec{q}$$

$$\vec{T} = \vec{q} \times \vec{N}$$

meaningful for polarised t decays

(e.g. in single top production)

θ_ℓ^* → angle between ℓ, $\vec{q}$

determine F_+, F_0, F_-

θ_ℓ^T → angle between ℓ, $\vec{T}$

determine F_+^T, F_0^T, F_-^T

θ_ℓ^N → angle between ℓ, $\vec{N}$

determine F_+^N, F_0^N, F_-^N

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell^X} = \frac{3}{8}(1+\cos\theta_\ell^X)^2\, F_+^X + \frac{3}{8}(1-\cos\theta_\ell^X)^2\, F_-^X + \frac{3}{4}\sin^2\theta_\ell^X\, F_0^X$$

$$A_{\mathrm{FB}}^N = \frac{3}{4}\left[F_+^N - F_-^N\right]$$

$$A_{\mathrm{FB}}^N \simeq 0.64\, P\, \mathrm{Im}\, g_R$$

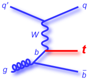
Single top quark production

Single top quark production

- Production Cross section (several channels)

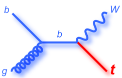
V_{tb} @ LHC

- Single top quark cross section @ LHC:



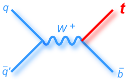
t-channel

64.6 ± 2.4 pb
87.8 ± 3.4 pb



(*Wt*-prod.)

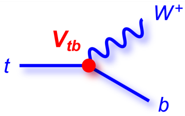
15.7 ± 1.1 pb
22.4 ± 1.5 pb



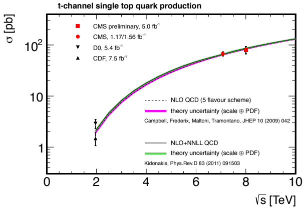
(*s*-channel)

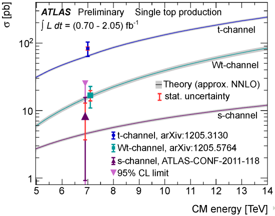
4.6 ± 0.2 pb
5.6 ± 0.3 pb

$\Longleftarrow$ @ 7TeV
$\Longleftarrow$ @ 8TeV



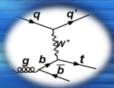
- Powerfull probe of V_{tb} ($\delta V_{tb}/V_{tb}$ few % @ LHC) and Test of physics BSM (FCNC in *t*-channel; W' in *s*-channel)
- CMS and ATLAS results within SM expectations:





- Dominant production @ LHC

CMS PAS TOP-12-011, ATLAS-CONF-2012-132

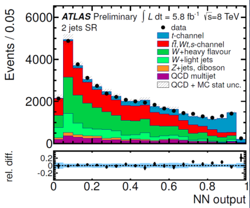


t-channel single top @8 TeV

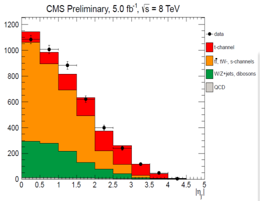
- Final state: one lepton + E_T^{miss} + one b-jet + one recoil jet
- Signal extracted by a fitting with

ATLAS: NN discriminant

CMS: η distribution of recoil jet



$\Delta\sigma/\sigma$=19%
- 9%: I/FSR
- 9%: b-tag
- 8%: JES
- 7%: Gen.

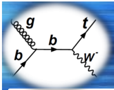


$\Delta\sigma/\sigma$=16%
- 8%: JES
- 6%: Gen.
- 5%: Muon
- 5%: b-tag
- 5%: PDF

* 11 input variables

	L[fb^{-1}]	t-channel cross section [pb]	$\lvert V_{tb}\rvert$
ATLAS	5.8	$95.1 \pm 2.4(\text{stat.}) \pm 18.0(\text{syst.})$	$1.04^{+0.10}_{-0.11}$
CMS	5.0	$80.1 \pm 5.7(\text{stat.}) \pm 11.0(\text{syst.}) \pm 4.0(\text{lumi.})$	$0.96 \pm 0.08(\text{exp.}) \pm 0.02(\text{th.})$

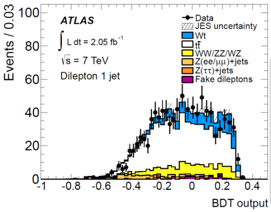
- The tW associated production @ LHC



Phys. Lett. B 716 (2012) 142–159, Phys. Rev. Lett. 110 (2013) 022003

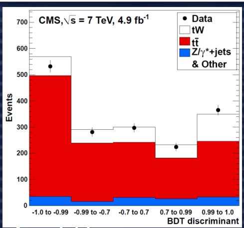
Wt associated production @7 TeV

- Final state: two leptons + E_T^{miss} + one b–jet
- Simultaneous fit of BDT outputs in different jet–bin regions
  – (1–jet bin: signal region, 2>=jet bin: background control region)
- First evidence from ATLAS using 2fb^{-1}, and confirmation by CMS with more stats.



$\Delta\sigma/\sigma$=34%
- 16%: JES
- 15%: PS
- 10%: Gen.
- 10% Pile-up

22 variables



$\Delta\sigma/\sigma$=31%
- 20%: Stat.
- 15%: JES
- 10%: PS

4 variables

	L [fb^{-1}]	Wt cross section [pb]	Significance	$\|V_{tb}\|$
ATLAS	2.05	$16.8 \pm 2.9(\text{stat.}) \pm 4.9(\text{syst.})$	3.3σ	$1.03^{+0.16}_{-0.19}$
CMS	4.9	16^{+5}_{-4}	$4.0\,\sigma$	$1.01^{+0.16}_{-0.13}(\text{exp.})^{+0.03}_{-0.04}(\text{th.})$

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

V_{tb} @ LHC

Summary of V_{tb} Measurements @ LHC

- $|V_{tb}|^2$ extracted by dividing the observed single top-quark cross section by the SM expectation

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

- $|V_{tb}| \gg |V_{ts}|,|V_{td}|$ (single top production through $|V_{ts}|,|V_{td}|$ is small)

ATLAS	Measurement (SM)
t-channel (@ 7TeV) (PLB 717 (2012) 330)	$|V_{tb}| = 1.13^{+0.14}_{-0.13}$ $|V_{tb}|>0.75$ @ 95% CL ($|V_{tb}$ in [0,1])
t-channel (@ 8TeV,5.8 fb^{-1}) (ATLAS-CONF-2012-132)	$|V_{tb}| = 1.04^{+0.10}_{-0.11}$ $|V_{tb}|>0.80$ @ 95% CL ($|V_{tb}$ in [0,1])
Wt-prod. (PLB 716 (2012) 142)	$|V_{tb}| = 1.03^{+0.16}_{-0.19}$

CMS	Measurement (SM)
t-channel (@ 7TeV) (arXiv:1209.4533)	$|V_{tb}|=1.02\pm0.046(\text{exp})\pm0.017(\text{th.})$ $|V_{tb}|>0.92$ @ 95% CL ($|V_{tb}$ in [0,1])
t-channel (@ 8TeV,5. fb^{-1}) (CMS PAS TOP-12-011)	$|V_{tb}|=0.96\pm0.08(\text{exp})\pm0.02(\text{th.})$ $|V_{tb}|>0.81$ @ 95% CL ($|V_{tb}$ in [0,1])
Wt-prod. (@ 7TeV) (arXiv:1209.3489)	$|V_{tb}| = 1.01^{+0.16}_{-0.13}(\text{exp.})^{+0.03}_{-0.04}(\text{th.})$ $|V_{tb}|>0.79$ @ 95% CL ($|V_{tb}$ in [0,1])

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

☞ What about top quark couplings to other bosons?

Single top quark production

- [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 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

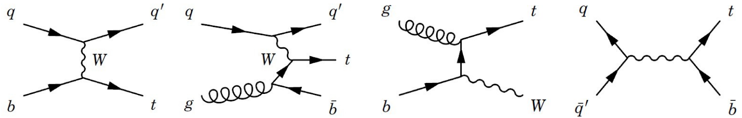
- [arXiv:hep-ph0605190v2 18 Mar 2007]

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]

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

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



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

- 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]

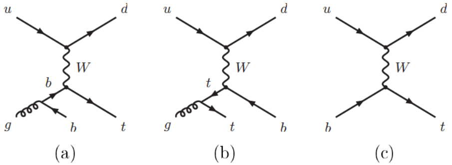


Figure 2: Sample Feynman diagrams for single top production in the t-channel process. Additional diagrams are obtained by crossing the light quark fermion line, and/or replacing (u, d) by (c, s). The diagrams for antitop production are the charge conjugate ones.

Single top quark production

- **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]

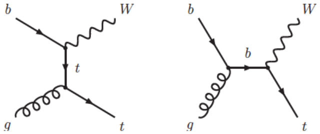
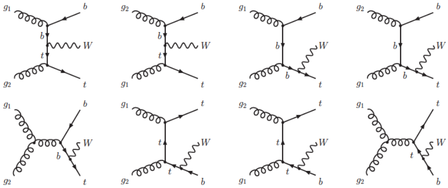


Figure 5: Feynman diagrams for single top production in the $gb \to tW^-$ process.

- **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	–	–	–

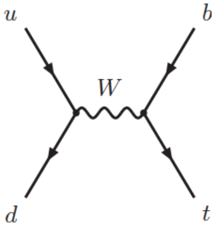
Table 7: Representative κ factors for the tW^- and $\bar{t}W^+$ processes and their uncertainties, explained in the text. Errors smaller than 0.005 are omitted.



	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.

- **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]

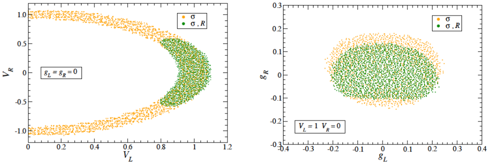


Figure 9: Estimated two-dimensional limits (with 68.3% CL) on (V_L, V_R) and (g_L, g_R), obtained from measurement of single top cross sections, with and without the ratio $R(\bar{t}/t)$ for the tj final state.

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

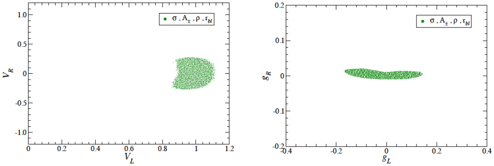


Figure 11: Combined limits on Wtb couplings from single top cross section measurements (excluding $R(\bar{t}/t)$) and top decay observables $A_\pm$, $\rho_{R,L}$, r_{bl}. The two graphs correspond to different projections of the 4-dimensional allowed region (with 68.3% CL).

W Helicity in Single Top Topologies

NEW

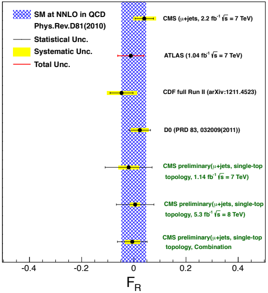
CMS-PAS-TOP-12-020

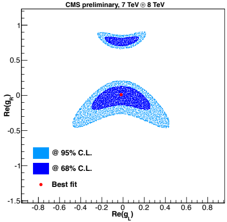
7+8 TeV combined results

$$F_L = 0.293 \pm 0.069(stat.) \pm 0.030(syst.)$$
$$F_0 = 0.713 \pm 0.114(stat.) \pm 0.023(syst.)$$
$$F_R = -0.006 \pm 0.057(stat.) \pm 0.027(syst.)$$

Results consistent with the SM and measurements in tt~ channels.

- Dominant systematic uncertainties
  - MET uncertainty from the fluctuations in un-clustered energy, JES/JER
  - Q2 and simulation
  - W+jet shape





A first publication to show what happens...

Phys. Rev. D 83, 117301 (2011)

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

- Top decay (in $t\bar{t}$ events): angular asymmetries
  - ☞ ATLAS Collaboration [ATLAS-CONF-2011-037]:

$$A_+ = 0.50 \pm 0.10 \text{ (stat)} \pm 0.06 \text{ (syst)} \qquad (e)$$
$$A_- = -0.85 \pm 0.07 \text{ (stat)} \pm 0.05 \text{ (syst)} \qquad (e)$$
$$A_+ = 0.50 \pm 0.08 \text{ (stat)} \pm 0.04 \text{ (syst)} \qquad (\mu)$$
$$A_- = -0.87 \pm 0.04 \text{ (stat)} \pm 0.03 \text{ (syst)} \qquad (\mu)$$

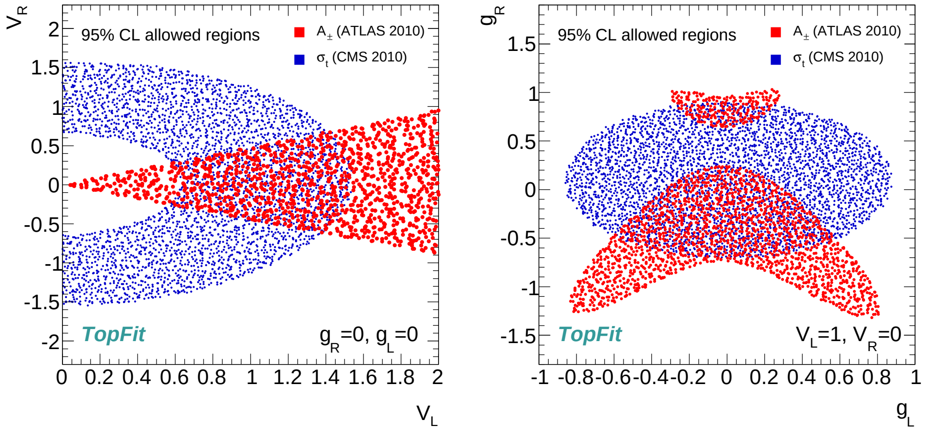
with $\rho(A_+, A_-) = 0.16$, assuming $m_t = 172.5$ GeV

- Single top production [CMS-PAS-TOP-10-008]:
  - ☞ CMS Collaboration:

$$\sigma_t = 83.6 \pm 30.0 \text{ pb}$$

assuming $m_t = 172.5$ GeV

Constraints on the *Wtb* vertex from early LHC data



(anomalous couplings assumed to be real)

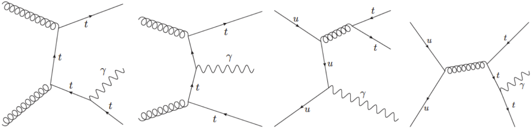
What about couplings to other bosons?

Couplings to other bosons

Top Couplings to Bosons ttV ($V = \gamma, Z, W, H$)

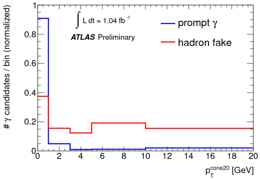
$t\bar{t}\gamma$

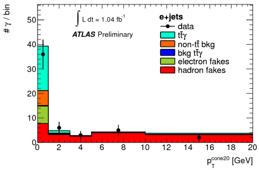
ATLAS-CONF-2011-153



LHC (7TeV) $\sigma_{t\bar{t}\gamma}$=2.1$\pm$0.4 pb ($p_{T,\gamma}$>8 GeV @ generator)

- $\sigma(t\bar{t}\gamma)$ ☞ direct measurement of the top quark EW couplings to γ ($\propto Q_t$)
- Event Selection = Lepton+jets channel $\bigoplus$ γ with $p_T > 15$ GeV
- γ isolation used to discriminate prompt from fake γ ☞ Template Fit to $p_{T,\gamma}$





$$\sigma(t\bar{t}\gamma) = 2.0 \pm 0.5\ (\mathrm{stat}) \pm 0.7\ (\mathrm{syst}) \pm 0.08\ (\mathrm{lumi.})\ \text{pb}$$

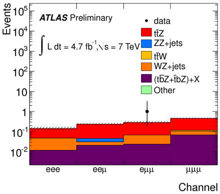
N_{Sig} = 46$\pm$12, N_{Back}: 78$\pm$14 Syst.: $\gamma_{id-eff.}$, ISR/FSR, JES

Couplings to other bosons

Top Couplings to Bosons ttV ($V = \gamma, Z, W, H$)

$t\bar{t}V$, $V = Z, W$

Trileptons (4.7 fb^{-1}) : [ATLAS-CONF-2012-126]



Event selection ($t\bar{t}Z$):

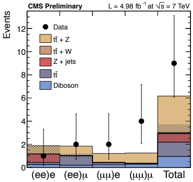
- $t\bar{t}$ Lepton+jets topology $\oplus$ $Z \rightarrow \ell^+\ell^-$ (≥ 1 b-jet)
- ≥ 1 $\ell^+\ell^-$ (OSSF) pair with $|m_{\ell\ell} - m_Z|$<10 GeV

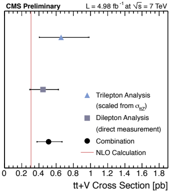
Results: $\sigma_{t\bar{t}Z}$ < 0.71 pb @ 95% CL $\sigma^{NLO,SM}_{t\bar{t}Z}$(7 TeV) = 0.14 pb

- Syst.: MC norm.(50%) for background

  JES (7%) and Renor. and Fac. (10%) for signal

Tri- and SS Dileptons (4.98 fb^{-1}) : [CMS PAS TOP-12-014]





Two analysis:

- Trilepton exclusive search ($t\bar{t}Z$):

  $\sigma(t\bar{t}Z) = 0.30^{+0.14}_{-0.11}(stat)^{+0.04}_{-0.02}(syst)$ pb
- SS dilepton inclusive search ($t\bar{t}V$):

  2 SS leptons, $\geq$3 jets, 1b-jet

  $\sigma(t\bar{t}W) = 0.28^{+0.14}_{-0.12}(stat) \pm 0.04(syst)$ pb

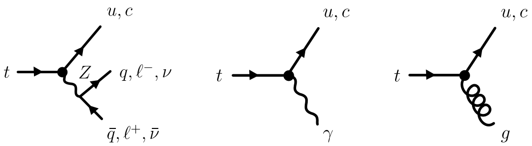
  ($\sigma^{SM}_{t\bar{t}W}$(7 TeV) = $0.169^{+0.029}_{-0.051}$ pb)

Combination (all) $\sigma(t\bar{t}V) = 0.51^{+0.15}_{-0.13}(stat)^{+0.05}_{-0.04}(syst)$ pb (4.67σ sig.)

Rare decays of top quarks and Flavor Changing Neutral Currents (FCNC)

FCNC decays ($t \rightarrow qX, X = \gamma, Z$)

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



Theoretical predictions for the BR of FCNC top quark decays

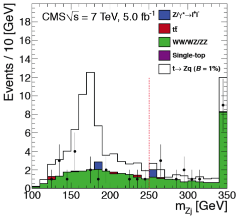
Process	SM	QS	2HDM	FC 2HDM	MSSM	$\not R$ SUSY	TC2	RS
$t \rightarrow u\gamma$	3.7×10^{-16}	7.5×10^{-9}	—	—	2×10^{-6}	1×10^{-6}	—	$\sim 10^{-11}$
$\boldsymbol{t \rightarrow uZ}$	8×10^{-17}	1.1×10^{-4}	—	—	2×10^{-6}	3×10^{-5}	—	$\sim 10^{-9}$
$t \rightarrow ug$	3.7×10^{-14}	1.5×10^{-7}	—	—	8×10^{-5}	2×10^{-4}	—	$\sim 10^{-11}$
$t \rightarrow c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}	$\sim 10^{-6}$	$\sim 10^{-9}$
$\boldsymbol{t \rightarrow cZ}$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}	$\sim 10^{-4}$	$\sim 10^{-5}$
$t \rightarrow cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}	$\sim 10^{-4}$	$\sim 10^{-9}$

Acta Phys. Polon. **B35** (2004) 2695

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

FCNC decays ($t \to qX, X = \gamma, Z$)

$t\bar{t} \to \ell\nu b + \ell\ell q$ (5.0) fb^{-1} : [arXiv:1208.0957] **t->qZ**



Trilepton selection:

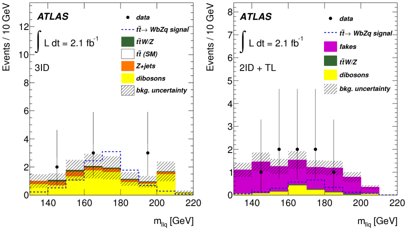
- 3 iso. leptons (e,μ) with 2 $\ell^+\ell^-$ with $|m_{\ell^+\ell^-} - m_Z|$<30 GeV
- $E_T^{\rm miss}$>30 GeV
- $\geq$ 2 jets, $S_T = \Sigma p_{T,\ell} + \Sigma p_{T,j} + E_T^{\rm miss}$>250 GeV
- m_{Zj}, m_{Wb} cuts

Results @ 7 TeV:

$Br(t \to qZ)$< **0.27% (obs.) 0.36% (exp.) @ 95% CL**

Syst.: JES, Cross-sections and E_T^{miss}

$t\bar{t} \to \ell\nu b + \ell\ell q$ (2.1) fb^{-1} : [arXiv:1206.0257]



Two (orthogonal) analysis:

- 3ID (3 isolated leptons)
- 2ID+TL (2 isolated leptons + track lepton)
- Dominant Syst.: JES, Di-boson shape
- **Results (3ID$\bigoplus$2ID+TL):**

  $Br(t \to qZ)$< **0.73% (obs.) 0.93% (exp.) @ 95% CL**

Summary

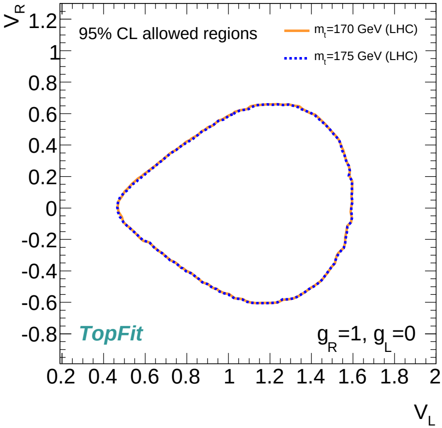
- Combination of production and decay observables is crucial to constrain the *Wtb* couplings
    - Should be done not only within a single experiment, but including all the available data from different experiments
- First publication done show limits improve significantly
    - Increase of collected 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!)
- Couplings to bosons (γ, Z, W, H) is the next thing to do
- Studies @ LHC of FCNC processes both at decay and production are promising (already best results in the world)

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR Portugal

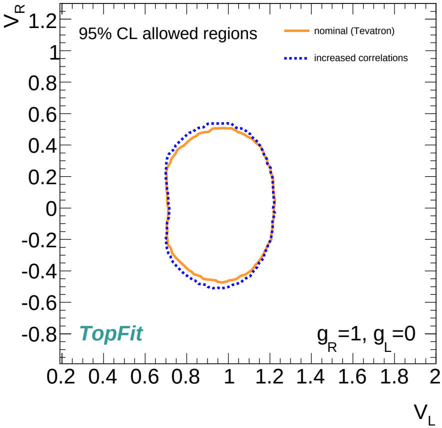
This work has been supported by FCT (project CERN/FP/116397/2010 and grant SFRH/BPD/63495/2009), CRUP (Acção integrada Ref. E 2/09), MICINN (FPA2010-17915 and HP2008-0039) and Junta de Andalucía (FQM 101 and FQM 437).

Backup Slides

Constraints on the *Wtb* vertex: effect of m_t and correlations



different m_t were considered



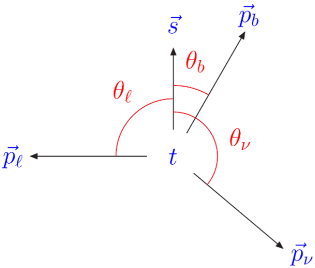
(increased correlations between *W* helicity fractions were introduced)

Probing the *Wtb* vertex: spin asymmetries

- polarised top decays

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_X} = \frac{1 + \alpha_X \cos\theta_X}{2}$$

☞ α_X depends on the anomalous couplings



X = top decay product ➞ $\vec{p}_X$ = momentum in t rest frame

$\vec{p}_j$ = jet momentum in t rest frame

$Q = \cos(\vec{p}_X, \vec{p}_j)$ ➞

$$A_X \equiv \frac{N(Q>0) - N(Q<0)}{N(Q>0) + N(Q<0)} = \frac{1}{2} P \alpha_X \quad [P = 0.95\ (t)\ \ P = -0.93\ (\bar{t})]$$

[PLB 476 (2000) 323]