

Studying the Wtb vertex structure using recent LHC results

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The Wtb vertex structure and the search for new anomalous couplings is studied using top quark measurements obtained at the LHC, for a centre-of-mass energy of 8 TeV. By combining the latest and most precise results on the single top quark production cross section and the measurements of the W -boson helicity fractions (F_0 and F_L), it is possible to set new limits, at 95% CL (confidence level), on the real and imaginary components of the new couplings. The combination of the LHC observables clearly improves the limits obtained when using the individual results alone. The updated measurements of the W -boson helicity fractions and the $s + t$ -channels electroweak single top quark production, at the Tevatron, improve the LHC limits, when a world combination of all observables (LHC+Tevatron) is performed.

I. INTRODUCTION

The discovery of the top quark at the Tevatron in 1995 [1, 2] was the starting point of a new era of precision studies for the Standard Model (SM). With the amount of data already collected by the LHC experiments (ATLAS and CMS), precision tests of the top quark properties have become more and more common. Nonetheless, the possibility of existence of physics, beyond the SM, hidden in the uncertainties of the experimental measurements, requires a criterious survey of the parameter space in the quest for signs of new contributions in the top quark sector. In the SM, the top quark decays almost exclusively to a W -boson and a b -quark and the decay vertex has the typical (V-A) structure. One way to probe the structure of the vertex and test the SM is to study the helicity fractions of the W -bosons produced in top quark decays, and/or the observables which depend on these helicity fractions [3, 4] *i.e.*, angular and spin asymmetries, ratios of fractions, etc. The Tevatron results on the helicity fractions, obtained by CDF and D0, have been combined [5], showing good agreement (within 10%) with the NNLO SM predictions [6]. At the LHC, both ATLAS [7] and CMS [8] have measured the W -boson helicity fractions in top quark decays. The production cross sections can play an important role, as well, in constraining the allowed phase space for the new couplings. The t -channel single top quark production is particularly relevant given its magnitude. Measurements of the t -channel cross section have been performed by both the ATLAS [9] and CMS [10] experiments at centre-of-mass energies of 7 and 8 TeV. Although smaller than the t -channel, the Wt associated production cross section is also important. In fact, as the Wt cross section is not affected by new physics contributions like, for instance, four-fermion contact interactions, it can probe

the Wtb vertex in a model independent way. ATLAS [11] and CMS [12] measured the Wt associated production at 7 and 8 TeV.

In this paper, the results of the most precise measurements of the single top quark production cross section at a centre-of-mass energy of 8 TeV at the LHC, are combined with the W -boson helicity fractions (F_0 and F_L), obtained by the CMS experiment to set limits on the real and imaginary parts of possible new anomalous couplings that could be present at the Wtb vertex. The TOPFIT [13] code is used to perform the combination of the observables, as well as to extract the corresponding anomalous couplings allowed regions at 95% confidence level (CL). The real and imaginary part of the couplings are considered. In order to describe the interaction, an effective field theory approach is used [14]. The most general vertex can be described by [15]

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

where V_L , V_R , g_L , g_R are dimensionless couplings that are, in general, complex. At tree level and in the SM, $V_L = V_{tb} \simeq 1$ and all the other couplings vanish. However, if new physics appear at the Wtb vertex, the new couplings V_R , g_L and g_R may acquire important corrections. These anomalous couplings can be tested in top quark decays by measuring the W -boson helicity states [3, 4, 16]. The results can be combined with the single top quark production measurements to improve the limits on the anomalous couplings [17–22]. It is interesting to recall the sensitivity to the new couplings at the LHC, in top quark decays, can be largely surpassed at a future Linear Collider (ILC) [23].

II. LHC OBSERVABLES AT 8 TEV

A. W -boson helicity fractions

The W -boson helicity fractions in this paper were measured by the CMS experiment at a centre-of-mass energy of 8 TeV using a sample of $t\bar{t}$ events which decayed to the muon+jets channel. The sample corresponds to an integrated luminosity of 19.6 fb^{-1} . The longitudinal and left handed helicity fractions are, respectively [8],

$$\begin{aligned} F_0 &= 0.659 \pm 0.015 \text{ (stat)} \pm 0.023 \text{ (syst)}, \\ F_L &= 0.350 \pm 0.010 \text{ (stat)} \pm 0.024 \text{ (syst)}, \end{aligned} \quad (2)$$

with a correlation coefficient $\rho = -0.95$ and assuming a top quark mass $m_t = 172.5 \text{ GeV}$. The measurement is clearly dominated by the systematic uncertainties.

B. Single top quark production cross sections

The most precise measurement of the t -channel single top quark production cross section used in this paper, was performed by the CMS experiment [10] at 8 TeV. Signal events were considered whenever top-quark decay products were accompanied with a high rapidity light quark together with a low p_T b -quark. Events were selected if they contained one isolated lepton (electron or muon). The value of the top quark mass assumed in all simulated Monte Carlo samples was $m_t = 172.5 \text{ GeV}$. The measurement, using a total integrated luminosity of 19.7 fb^{-1} is,

$$\sigma_{t\text{-chan}} = 83.6 \pm 2.3 \text{ (stat)} \pm 7.4 \text{ (syst) pb}. \quad (3)$$

The effect of the Wt associated production in the anomalous couplings fits, is also investigated. The measurement with smaller uncertainty, normalized to the SM cross section expectation, is [12],

$$\sigma_{Wt} = 23.4 \pm 5.4 \text{ pb}. \quad (4)$$

The measurements of the single top quark production cross sections are assumed to be uncorrelated.

III. 95% CL LIMITS AT THE LHC

By taking into account the analytic expressions introduced in [4] and [19] for the helicity fractions and single top quark production cross section as a function of the complex anomalous couplings, respectively, it is possible to determine, using TOPFIT, the allowed regions for the couplings, provided a minimal set of measurements is specified. In the current paper, the CMS results of the helicity fractions (F_0 and F_L) and the t -channel single top quark production cross section are, initially, used as input parameters to TOPFIT. It should be stressed that no four-fermion contributions to the t -channel single top

quark production cross section is considered [24, 25]. No correlations are assumed between the helicities and the cross section measurements. The total uncertainty associated to each measurement is defined by adding in quadrature the corresponding statistical and systematic uncertainties. The results are presented in terms of two dimensional plots of subsets of anomalous couplings (assuming the others vanishing) or individual limits (assuming all other anomalous couplings vanishing), as convenient, to illustrate each physics case. It should be stressed that the approach, although not fully general, is justified once different couplings indeed arise from different gauge invariant operators and the limited number of observables and their precision makes a global fit almost useless for the time being. Limits are set by TOPFIT, at 95% CL, for a top quark mass of $m_t = 172.5 \text{ GeV}$ (as for the LHC experiments), $M_W = 80.4 \text{ GeV}$ and $m_b = 4.8 \text{ GeV}$. Two different scenarios are considered:

- the couplings are assumed real (Re) and,
- the couplings may have a non vanishing imaginary (Im) part.

In both scenarios several combinations of couplings are considered in order to illustrate the potential of the physics case and give an idea of the order of magnitude of the 95% CL allowed regions for the anomalous couplings, given the current results at the LHC. The effect of the Wt associated production cross section at the LHC, as well as the recent results on the W -boson helicity fractions and the $s + t$ single top quark production cross section measured at the Tevatron, are finally combined with the previous measurements to set 95% CL limits on the anomalous couplings allowed regions.

A. Real anomalous couplings

In the following discussion, all couplings are assumed real. The W -boson helicity fractions (F_0 and F_L) and the t -channel single top quark production cross section at the LHC were used as input parameters to TOPFIT. In Fig. 1 the limits obtained with the 2012 CMS [8, 10] results are compared with the previous results obtained in 2010 [26]. In the left plot, limits at 95% CL are set in the $[Re(g_R), Re(g_L)]$ plane, assuming $V_R = 0$ and $V_L = 1$. In the right plot, limits in the plane $[Re(V_R), Re(V_L)]$ are shown, for $g_R = g_L = 0$. A clear improvement

LHC	g_R	g_L	V_R
Allowed Regions (Re)	[-0.15 , 0.01]	[-0.09 , 0.06]	[-0.13 , 0.18]

TABLE I. One dimension 95% CL limits on the anomalous couplings (assumed real) from W -boson helicities and t -channel cross section at the LHC.

with respect to the 2010 results can be observed. The

complementarity of the different measurements is clearly visible, as discussed in [26]: when allowed regions corresponding to different measurements overlap, either for 2010 or 2012, the combined measurements allowed region is indeed very much constrained, when compared to the results from the individual measurements alone. In Table I the 95% CL limits for the couplings, assuming $V_L = 1$ and all the other (real) couplings zero at a time, are shown.

B. Complex anomalous couplings

In this section the anomalous couplings g_R , g_L and V_R are assumed complex, with both real and imaginary components. By combining the helicity fractions with the t -channel single top quark production cross section results at the LHC, limits at 95% CL were set on the allowed regions of the Im versus the Re components of the couplings. In Fig. 2 the 95% CL allowed region

LHC	g_R	g_L	V_R
Allowed Regions (Re)	[-0.16 , 0.13]	[-0.11 , 0.08]	[-0.15 , 0.21]
Allowed Regions (Im)	[-0.34 , 0.34]	[-0.09 , 0.09]	[-0.18 , 0.18]
LHC+Tevatron	g_R	g_L	V_R
Allowed Regions (Re)	[-0.13 , 0.11]	[-0.10 , 0.07]	[-0.15 , 0.20]
Allowed Regions (Im)	[-0.31 , 0.31]	[-0.09 , 0.09]	[-0.17 , 0.17]

TABLE II. Two dimension 95% CL limits on the real and imaginary components of the anomalous couplings from W -boson helicities and t -channel cross section at the LHC (top), and from the combination of the LHC and Tevatron measurements (bottom).

LHC	g_R	g_L	V_R
Allowed Regions (Im)	[-0.29 , 0.29]	[-0.08 , 0.08]	[-0.16 , 0.16]
LHC+Tevatron	g_R	g_L	V_R
Allowed Regions (Im)	[-0.27 , 0.27]	[-0.07 , 0.07]	[-0.15 , 0.15]

TABLE III. One dimension 95% CL limits on pure imaginary anomalous couplings from W -boson helicities and t -channel cross section at the LHC (top) and from the combination of the LHC and Tevatron measurements (bottom).

for the V_R (left) and g_L (right) complex couplings is shown, assuming both the Re and the Im parts of the couplings non-vanishing. For the left (right) plot the allowed region is obtained by fixing $g_R = g_L = 0, V_L = 1$ ($V_R = g_R = 0, V_L = 1$). In Fig. 3 (left) the 95% CL allowed region for the g_R assuming $V_R = g_L = 0, V_L = 1$, is shown. The (two dimensional) LHC limits on the anomalous couplings from Fig. 2 and Fig. 3 (left) are shown in Table II (top). One particular case is considered when the anomalous couplings are pure imaginary only. In Table III (top), the 95% CL limits for the Im part of the

couplings, assuming $V_L = 1$ and all the other couplings vanishing at a time (as well as any Re part), are shown.

C. Impact of Wt associated production at LHC and measurements at the Tevatron

The effect of the LHC Wt associated production cross section was studied by including in the fit, as well, its most precise measurement at 8 TeV ($\sigma_{Wt} = 23.4 \pm 5.4$ pb [12]). The improvement seems limited, as can be noticed in Fig. 3 (right, green dots or lighter gray dots if printed in black and white). A more visible effect is observed, when the W -boson helicity fractions and the single top quark cross section measurements at the Tevatron are included, in addition to the LHC results. The combined Tevatron measurements of the W -boson helicity fractions ($F_0 = 0.722 \pm 0.081$, $F_R = -0.033 \pm 0.046$, with correlation -0.88 [27]) and the ($s + t$) single top quark cross section with smaller uncertainty at the Tevatron ($\sigma_{s+t} = 3.02^{+0.49}_{-0.48}$ pb [29]), were used. The (two dimensional) LHC limits on the anomalous couplings from Fig. 3 (right, yellow dots or darker dots if printed in black and white) are shown in Table II (bottom). In Table III (bottom), the 95% CL limits for the Im part of the couplings, assuming $V_L = 1$ and all the other couplings vanishing at a time (as well as any Re part), are shown. The Tevatron measurements can improve the LHC limits by as much as roughly 20%, specially for the g_R anomalous coupling.

IV. CONCLUSIONS

In this paper, 95% CL limits on new anomalous couplings at the Wtb vertex are revisited. Recent measurements at 8 TeV, of the W -boson helicity fractions (F_0 and F_L) and single top quark production cross sections (t -channel and Wt associated production) at the LHC, were used. It was shown, with simple case studies, that a proper combination of the LHC observables can provide useful information on anomalous couplings. This is true not only for the Re part of the couplings, but also for the Im part. Similar 95% CL limits for the Re and Im components of the anomalous couplings are observed. This suggests that, the data from the LHC can be used to constrain equally well, not only the real, but also the imaginary part of the couplings. Given the current precision of the measurements at the LHC and the Tevatron, it is still useful to combine the results from both colliders. Improvements as high as roughly 20% in the limits, in particular for the anomalous coupling g_R , are observed.

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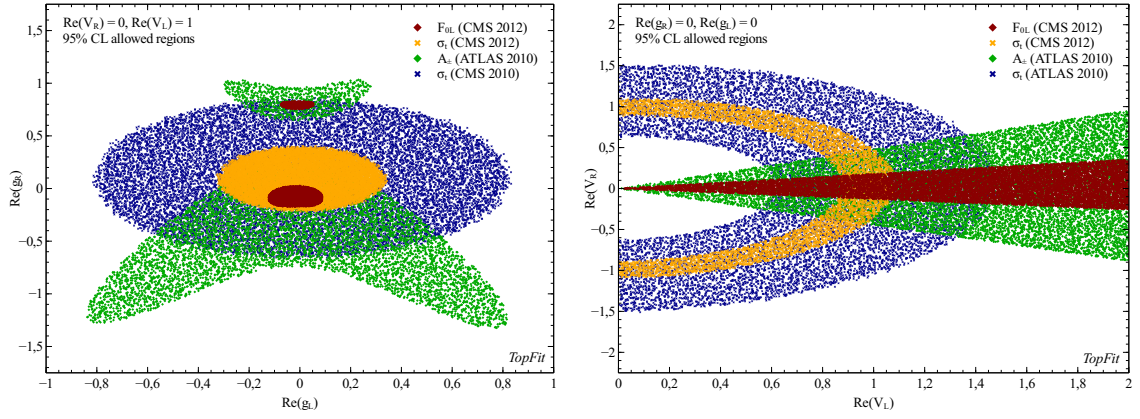


FIG. 1. LHC 95% CL allowed regions in the planes $[Re(g_R), Re(g_L)]$ (left) and $[Re(V_R), Re(V_L)]$ (right) from W -boson helicity and t -channel single top quark production at the LHC assuming couplings are real.

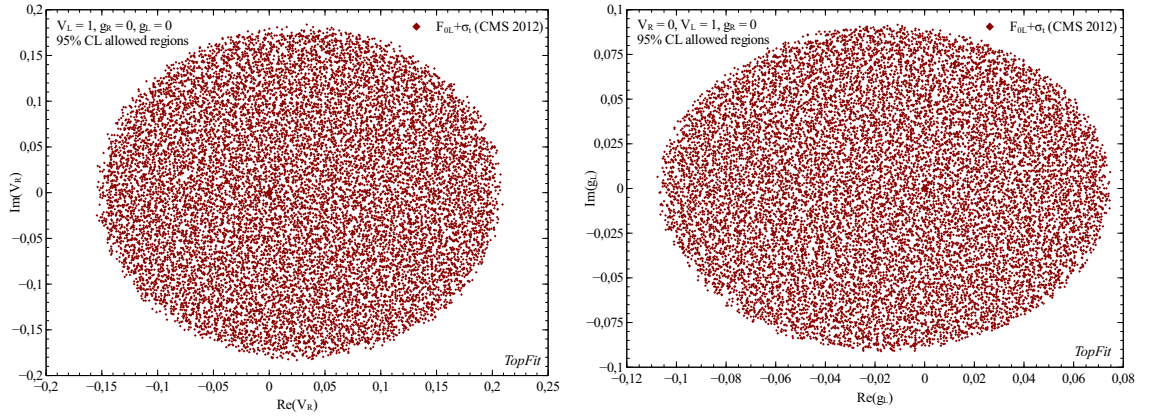


FIG. 2. 95% CL allowed regions for the V_R (left) and g_L (right) complex couplings from the combination of the W -boson helicity and t -channel single top quark production measurements at the LHC.

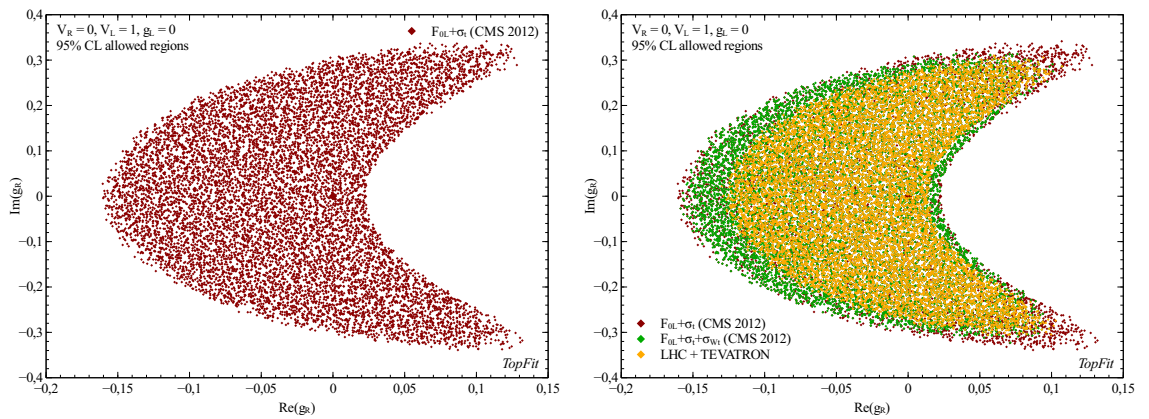


FIG. 3. 95% CL allowed regions for the g_R complex coupling from the combination of the W -boson helicity and t -channel single top production measurements at the LHC (left) and combining all LHC and Tevatron results (right).