Lecture 7: Top Quark Physics @ LHC

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ATLAS

Course
IDPASC Physics at the LHC
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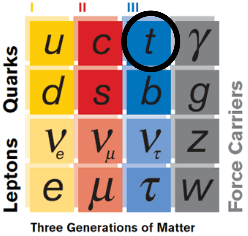
Outline

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)

Introduction

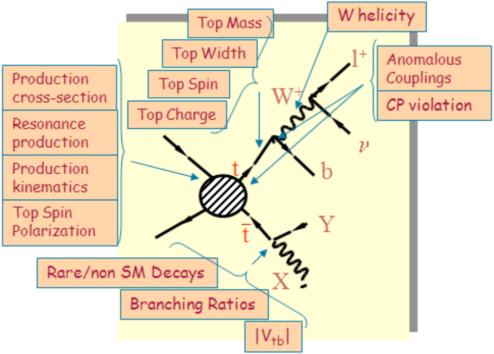
- Top quark completes the 3 family structure of the SM
  - top is the weak-isospin partner of the *b*-quark
  - spin = $1/2$
  - charge = $+2/3\ |e|$



- 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, $t \to bW$ decay and anomalous couplings)
  - FCNC
  - Charge Asymmetry
- Single top production
  - cross section
  - FCNC



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

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

$V_L \equiv V_{tb} \sim 1$ (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

The Wtb vertex structure

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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]

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

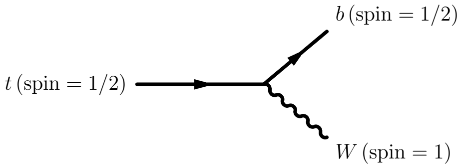
$$\mathcal{O}\left[(V_L - V_{tb}, V_R, \ldots)^2\right] \simeq 1.32(V_L - V_{tb})^2 - 262(V_L - V_{tb})V_R + 12970\, V_R^2 + \ldots$$

	$V_L - V_{tb}$	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

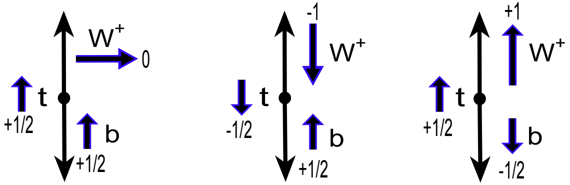
[EPJC57 (2008) 183]

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

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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.

- [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]

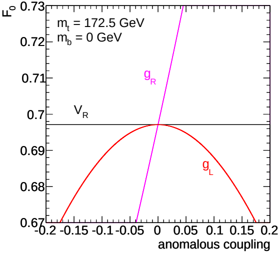
the modulus of the W boson three-momentum in the top quark rest frame. The total top width is

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

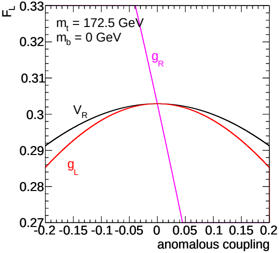
[EPJC50 (2007) 519]

anomalous couplings ⇒ deviations in W helicity fractions

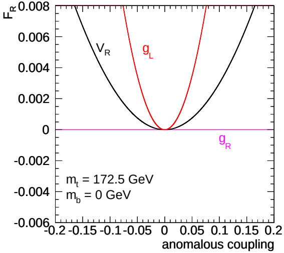
F_0



F_L



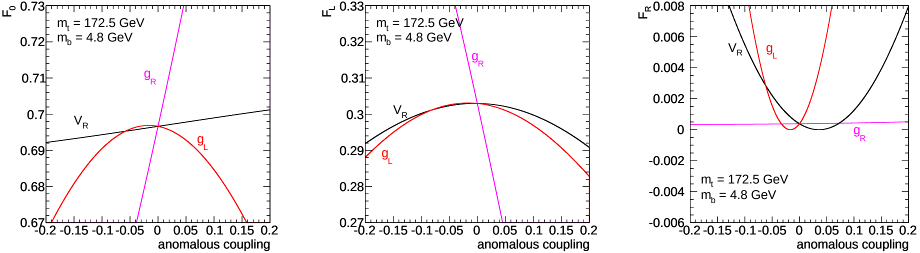
F_R



[EPJC50 (2007) 519]

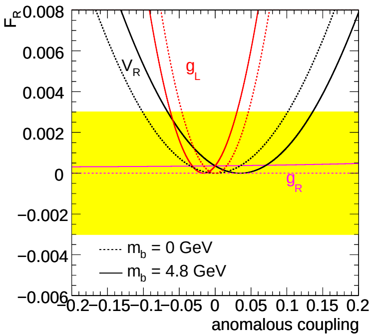
anomalous couplings ⇒ deviations in *W* helicity fractions

F_0 F_L F_R



☞ correct m_b has to be considered!

The Wtb vertex structure



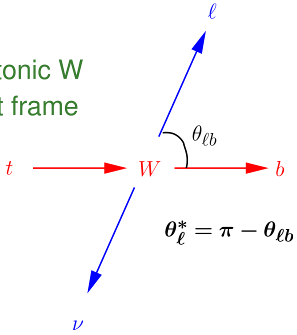
example: $|F_R| < 0.003$ can be converted into a V_R constraint using the intersection method:

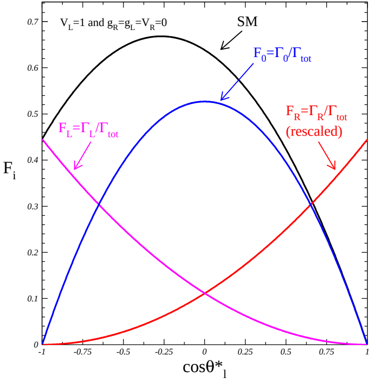
- ☞ $-0.101 < V_R < 0.101$ ($m_b = 0.0$ GeV)
- ☞ $-0.067 < V_R < 0.136$ ($m_b = 4.8$ GeV)

Measuring the W helicity states

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

leptonic W rest frame





Measuring the W helicity states

W polarisation can be measured by:

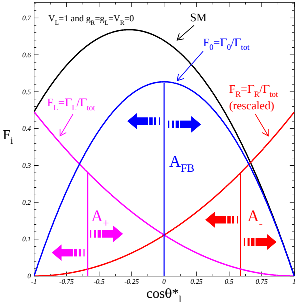
1. Fitting $\cos\theta^*_\ell$ to obtain the W helicity fractions (F_0, F_L, F_R)
2. Fitting $\cos\theta^*_\ell$ to obtain the W helicity ratios:
   ☞ $\rho_L = F_L/F_0 = 0.435$ (SM, LO)
   ☞ $\rho_R = F_R/F_0 = 5.5 \times 10^{-4}$ (SM, LO)
3. Computing angular asymmetries: $A_t = \frac{N(\cos\theta^*_\ell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

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

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

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

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



The Wtb vertex structure

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

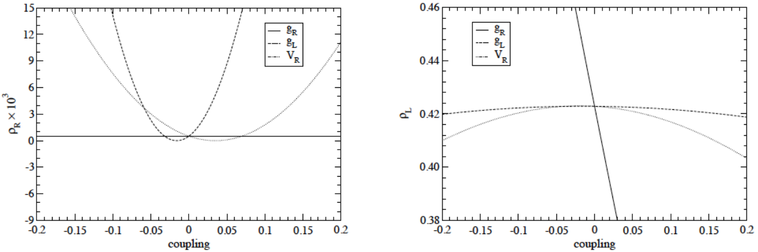


Figure 3: Dependence of the helicity ratios $\rho_{R,L} = \Gamma_{R,L}/\Gamma_0$ on the anomalous couplings in Eq. (1), in the CP-conserving case.

The Wtb vertex structure

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

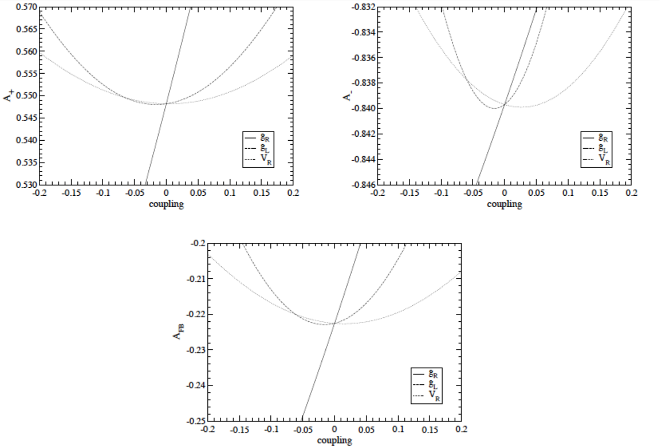


Figure 4: Dependence of the asymmetries A_+, A_- and A_{FB} on the couplings g_L, g_L and V_R, for the CP-conserving case.

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

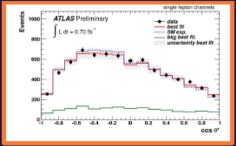
Table 2: 1σ bounds on anomalous couplings obtained from the measurement of angular asymmetries.

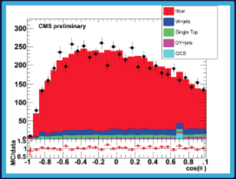
The Wtb vertex structure

- The LHC Current Status (Moriond 2012)

W-BOSON POLARIZATION

0.7 fb^{-1} ATLAS 2.2 fb^{-1} CMS





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

How

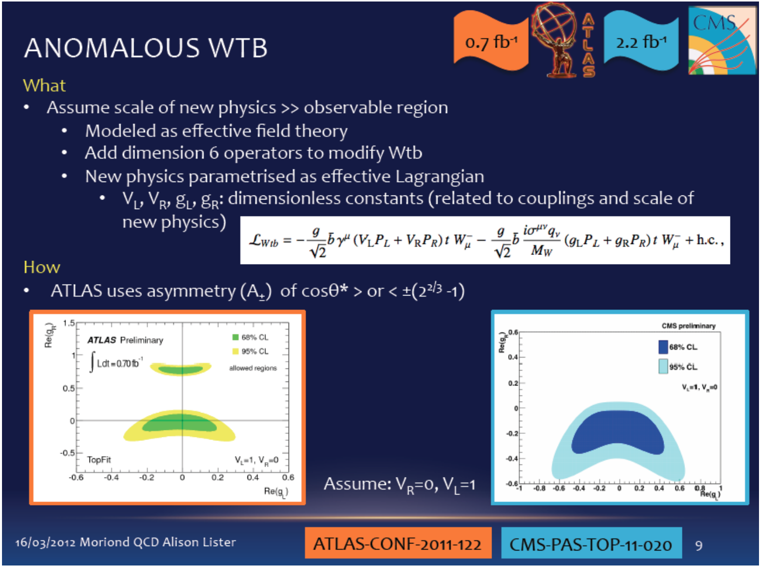
- θ*: Angle between $\vec{p}$(lep) in W rest-frame and $\vec{p}$(W) in top rest-frame
- Kinematic fit to event
- Remove background
- Unfold to particle-level

Polarisation	Predicted NNLO	Measured ATLAS	Measured CMS
F_R	0.0017 ± 0.0001	$0.09 \pm 0.04(\mathrm{stat}) \pm 0.09(\mathrm{syst})$	$0.040 \pm 0.035(\mathrm{stat}) \pm 0.044(\mathrm{syst})$
F_L	0.311 ± 0.005	$0.35 \pm 0.04(\mathrm{stat}) \pm 0.04(\mathrm{syst})$	$0.393 \pm 0.045(\mathrm{stat}) \pm 0.029(\mathrm{syst})$
F_0	0.687 ± 0.005	$0.57 \pm 0.07(\mathrm{stat}) \pm 0.09(\mathrm{syst})$	$0.567 \pm 0.074(\mathrm{stat}) \pm 0.047(\mathrm{syst})$

16/03/2012 Moriond QCD Alison Lister ATLAS-CONF-2011-122 CMS-PAS-TOP-11-020 8

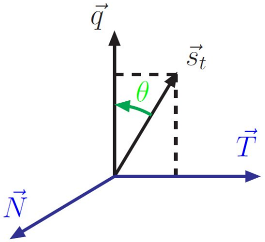
The Wtb vertex structure

- LHC limits on anomalous couplings (Moriond 2012)



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

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

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

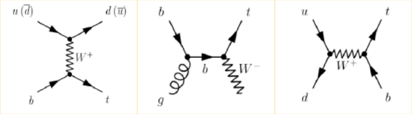
$$A_{\rm FB}^N \simeq 0.64\, P\, {\rm Im}\, g_R$$

Single top quark production

Single top quark production

- Production Cross section (several channels)

- Top quarks (Tevatron, 1995) in hadron colliders are mostly produced in pairs, via **strong interaction**
- Alternative production: via the **weak interaction**, involving a **Wtb vertex**, leading to a **single top quark final state**:



t-channel	Associated tW production	s-channel
σ = 64.6 +3.3 −2.6 (pb)	σ = 15.7 +1.3 −1.4 (pb)	σ = 4.6 ± 0.3 (pb)

Cross-sections by N. Kidonakis approximate NNLO, $\sqrt{s}$ = 7 TeV ($\sigma_{t\bar{t}}$ = 164.6 pb)

- First observed at the Tevatron (2009), in a combination of t/s-channel
- Already observed by the LHC experiments with 2010-2011 data
- Single top-quark processes:
  - are sensitive to many models of **new physics**
  - allow for a measure of $\mathbf{V_{tb}}$ without **assumptions about the number of quark generations**
  - can be used to measure the b-quark parton distribution function (**PDF**)

Single top quark production

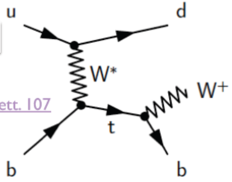
- Dominant production @ LHC

t-channel

- Dominating process with the highest cross section at the Tevatron and the LHC
- **ATLAS** and **CMS** have public results with 2011 data:

ATLAS-CONF-2011-101 July 2011; L = 0.7fb^{-1}	CMS PAS TOP-11-021 New! March 2012; L = 1.1/1.5fb^{-1}

Updates previous result with 36pb^{-1} Phys. Rev. Lett. 107 (2011) 091802 arxiv:1106.305



- The final state studied is a **lepton + jets signature**
- Signal events are characterized by:
  - One isolated **muon or electron** and missing transverse energy (**E_T^{miss}**) (leptonic decay of the W)
  - A central **b-jet** and an additional light-quark jet from the hard scattering process (often forward)
  - Additionally, a second b-jet produced in association to the top quark can be present as well (softer p_T spectrum with respect to the b-jet from top decay)

Single top quark production

- Dominant production @ LHC

Selection criteria

- CMS:
  - Exactly 1 isolated lepton (e,μ)
  - 2 jets in the event, 1 b-tagged
  - Muon channel: $m_T(W) > 40$ GeV
  - Electron channel: $E_T^{miss} > 35$ GeV
  - Invariant mass of the reconstructed top quark within (130,220) GeV

- ATLAS:
  - Exactly 1 isolated lepton (e,μ)
  - 2 or 3 jets in the event (NN only 2), 1 b-tagged
  - $E_T^{miss} > 25$ GeV
  - m_T (W) > 60 GeV − E_T^{miss}

Other jet (1-2-3 jets) and b-tagging multiplicities (0-1-2) used in background estimations and control regions

Main backgrounds:

- **W boson production in association with jets** (W+jets)
- **top pair** ($t\bar{t}$) production
- **Multijets** (QCD) events

$t\bar{t}$ and smaller backgrounds from Z+jets, other single-top processes, and diboson production are estimated from simulation and normalized to their theoretical cross-sections.

- Dominant production @ LHC

Results

- **ATLAS:** As the cut-based method uses both 2- and 3-jet channels, and has a slightly smaller overall expected uncertainty, it is chosen as the baseline result.

$$\text{(2-jet) } \sigma_t = 102^{+12}_{-11}(stat.)^{+38}_{-27}(syst.) = 102^{+40}_{-30}\text{pb}$$

$$\text{(3-jet) } \sigma_t = 50^{+15}_{-14}(stat.)^{+30}_{-22}(syst.) = 50^{+34}_{-27}\text{pb}$$

$$\text{(NN) } \sigma_t = 105 \pm 7(stat)^{+36}_{-30}(syst) = 105^{+37}_{-31}\text{pb}$$

$$\sigma_t = 90^{+9}_{-9}(stat.)^{+31}_{-20}(syst.) = 90^{+32}_{-22}\text{pb}$$

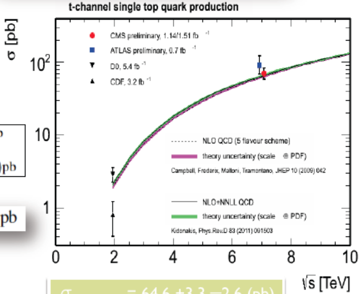
- **CMS:** Results for muon and electron channels and combination

$$\text{(muons) } \sigma_t = 76.9 \pm 6.6(stat.) \pm 11.4(syst.) \pm 3.7(lumi.)\text{pb}$$

$$\text{(electrons) } \sigma_t = 59.3 \pm 8.2(stat.) \pm 11.9(syst.) \pm 2.8(lumi.)\text{pb}$$

$$\sigma_t = 70.2 \pm 5.2(stat.) \pm 10.4(syst.) \pm 3.4(lumi.)\text{pb}$$

$$|V_{tb}| = \sqrt{\frac{\sigma_{t-\text{ch.}}}{\sigma^{\text{th}}_{t-\text{ch.}}}} = 1.04 \pm 0.09\,(\text{exp.}) \pm 0.02\,(\text{th.}),$$



$$\sigma_{\text{theoretical}} = 64.6\ {+3.3}\ {-2.6}\ \text{(pb)}$$

8 Rebeca Gonzalez Suarez (VUB), March 2012 Moriond QCD

Single top quark production

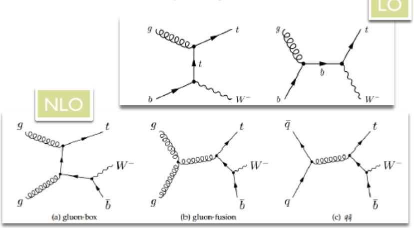
- The next biggest contribution @ LHC

tW associated production

- Interesting topology (background to H → WW searches), not yet observed
- Mixes at NLO with tt production
- Public results with 2011 data:

ATLAS-CONF-2011-104
July 2011; L = 0.7 fb^{-1}

CMS PAS-TOP-11-022
September 2011; L = 2.1 fb^{-1}



- Dilepton final states:
  - 2 leptons, E_T^{miss} and a jet from a b-decay
- Main backgrounds:
  - tt production
  - Z+jets
  - Small contributions from dibosons, other single top channels, W+jets and QCD

- The tW associated production @ LHC

Results

- Main sources of **systematics**:
  - **CMS:** B-tagging (10%) and Q^2 (~10%)
  - **ATLAS:** JES (35%), JER(32%), and background normalization

Tables in the backup slides

ATLAS:

95% CL observed limit on tW production: σ_{tW} < 39.1(40.6) pb obs. (exp.)
Observed significance of 1.2 σ
With a value of the cross-section:
σ_{tW} = 14 +5.3-5.1(stat.) +9.7-9.4(syst.) pb

CMS:

Observed (expected) significance of
2.7 σ (1.8±0.9 σ)
Measured value of the cross-section and 68% CL interval:
σ_{tW} = 22 +9-7 (stat+sys) pb

Single top quark production

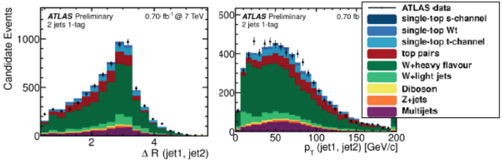
- The most difficult channel @ LHC

ATLAS-CONF-2011-118
August 2011; L = 0.7 fb^{-1}

s-channel

- Sensitive to several models of new physics, like W' bosons or charged Higgs bosons
- Not yet observed
- Signal signature: lepton + jets
  - A lepton (e,μ) and E_T^{miss} from the leptonic decay of a W boson
  - two hadronic jets with high transverse momentum, at least one of which is required to originate from a b-quark
- Backgrounds: tt, W+jets , Multijet + small contributions from other processes
- **Very Challenging**

Same objects and pre-selection as t-channel
Also same background estimations for Multijets and W+jets



Cut-based analysis

After the final selection: signal purity of 6%
Upper limit on the observed production cross-section

$$\sigma_t < 26.5(20.5)\ \text{pb obs.(exp.)}, 95\%\text{CL}$$

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

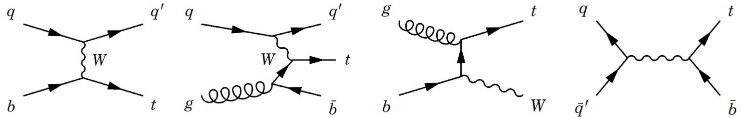
- [arXiv:hep-ph0605190v2 18 Mar 2007]

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]

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

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



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

- 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

Single top quark production

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

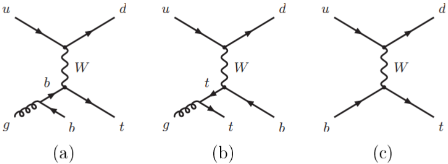


Figure 2: Sample Feynman diagrams for single top production in the t-channel process. Additional diagrams are obtained by crossing the light quark fermion line, and/or replacing (u, d) by (c, s). The diagrams for antitop production are the charge conjugate ones.

- **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]

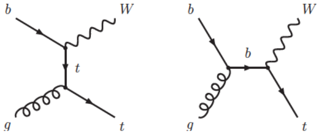


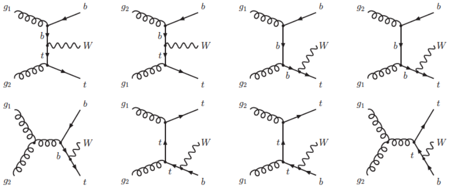
Figure 5: Feynman diagrams for single top production in the $gb \to tW^-$ process.

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.

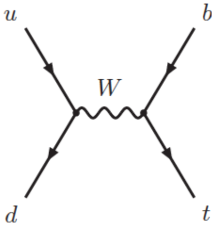


	κ	ΔQ	Δm_t	Δm_b
V_R^2	1	–	–	–
g_L^2, g_R^2	$4.51 - 4.73$	$^{+0.19}_{-0.04}$	$^{+0.009}_{-0.027}$	$^{+0.030}_{-0.}$
$V_L g_R, V_R g_L$	$1.21 - 1.23$	$^{+0.014}_{-0.003}$	$^{+0.005}_{-0.007}$	$^{+0.}_{-0.}$

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]

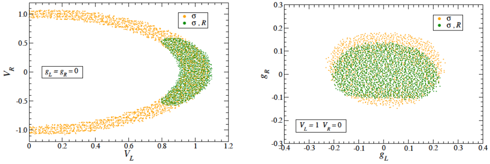


Figure 9: Estimated two-dimensional limits (with 68.3% CL) on (V_L, V_R) and (g_L, g_R), obtained from measurement of single top cross sections, with and without the ratio $R(\bar{t}/t)$ for the tj final state.

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

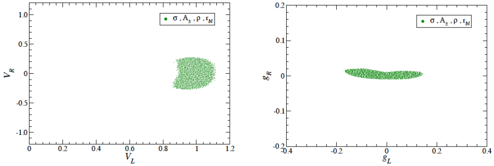


Figure 11: Combined limits on Wtb couplings from single top cross section measurements (excluding $R(\bar{t}/t)$) and top decay observables $A_\pm$, $\rho_{R,L}$, r_{bl}. The two graphs correspond to different projections of the 4-dimensional allowed region (with 68.3% CL).

Just a first try to see what happens...

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]:

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

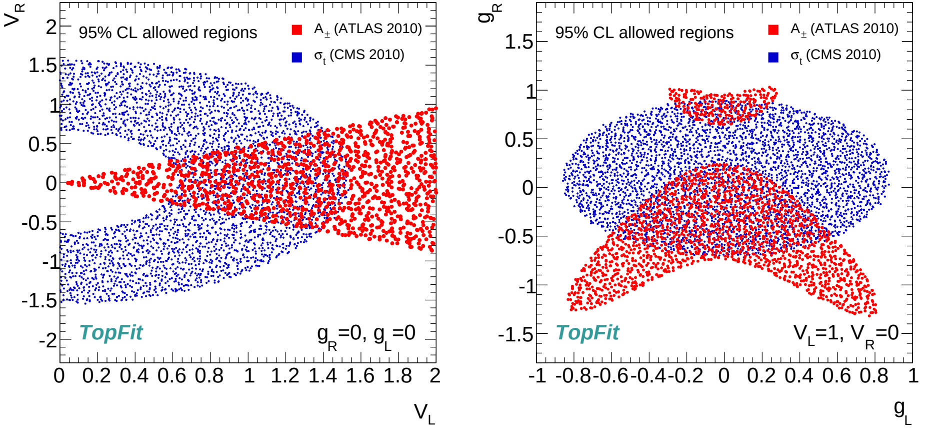
with $\rho(A_+, A_-) = 0.16$, assuming $m_t = 172.5$ GeV

- 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)

Observables from Tevatron

- Top decay (in $t\bar{t}$ events)
  - *W* **helicity fractions**

☞ CDF Collaboration [PRL 105 (2010) 042002]:

$$F_0 = 0.88 \pm 0.11\ \text{(stat)} \pm 0.06\ \text{(syst)}\,,$$
$$F_R = -0.15 \pm 0.07\ \text{(stat)} \pm 0.06\ \text{(syst)}\,,$$

with $\rho = -0.59$, assuming $m_t = 175$ GeV

☞ D0 Collaboration [PRD 83 (2011) 032009]:

$$F_0 = 0.669 \pm 0.078\ \text{(stat)} \pm 0.065\ \text{(syst)}\,,$$
$$F_R = 0.023 \pm 0.041\ \text{(stat)} \pm 0.034\ \text{(syst)}\,,$$

with $\rho = -0.83$, assuming $m_t = 172.5$ GeV

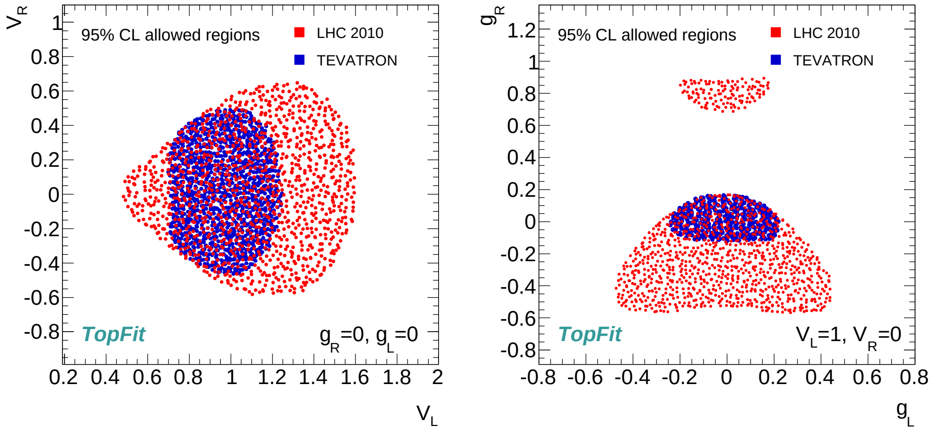
- Single top production [arXiv:0908.2171]:

☞ CDF and D0 Collaborations:

$$\sigma_{s+t} = 2.76^{+0.58}_{-0.47}\ \text{pb}$$

assuming $m_t = 170$ GeV

Constraints on the *Wtb* vertex: LHC and Tevatron



(anomalous couplings assumed to be real)

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

FCNC @ decay

• Several channels @ decay

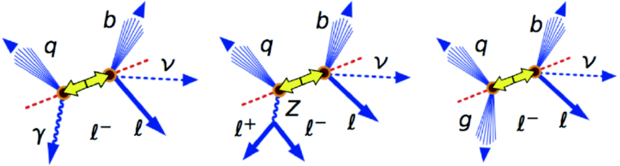


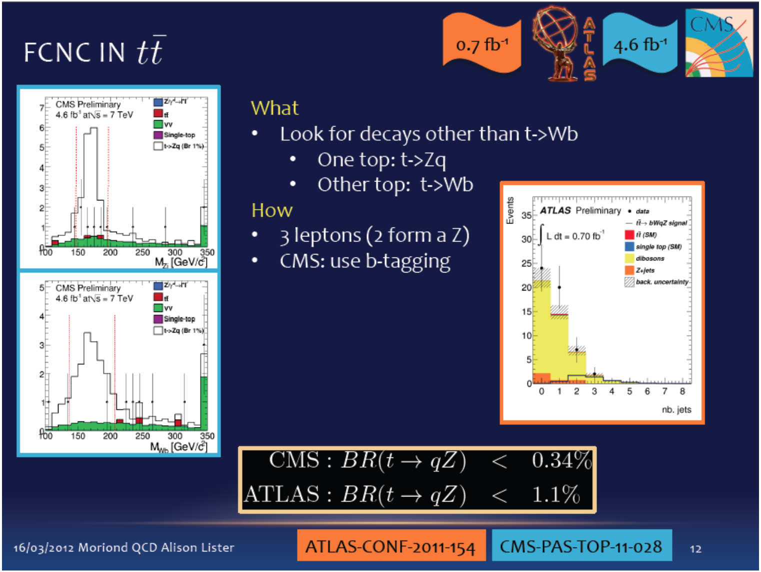
Table 1: The maximum values for the branching ratios of the FCNC top quark decays, predicted by the Standard Model (SM), the quark-singlet model (QS), the two-Higgs doublet model (2HDM), the flavour-conserving two-Higgs doublet model (FC 2HDM), the minimal supersymmetric model (MSSM), SUSY with R-parity violation and Topcolour-assisted Technicolour model (TC2) are shown. (See text for references)

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

[Acta Phys. Polon. B 35 (2004) 2695]

FCNC @ decay

- The LHC Current Status (Moriond 2012)



Production @ LHC

Effective Lagrangian

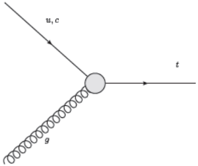
$$\mathcal{L}_{Total} = \mathcal{L}_{SM} + \frac{1}{\Lambda^5}\mathcal{L}^{(5)} + \frac{1}{\Lambda^6}\mathcal{L}^{(6)}$$

- FCNC can be studied through an effective Lagrangian
- This extra Lagrangian terms will be composed by effective operators that obey SM symmetries
- Buchmuller and Wyler calculated all possible operators of dimension 6 that respect the SM symmetries (Nucl. Phys. B 268 (1986) 621.)
- Now reduced by B. Grzadkowski, M. Iskrzynski, M. Misiak, J. Rosiek (arXiv:1008.4884v2)

$$\frac{ico_1 g_s}{\Lambda}\bar{u}\lambda^a\sigma^{\mu\nu}(f_u + h_u\gamma_5)tG^a_{\mu\nu} + H.C.$$

Production @ LHC

LO event generation



- Generate phase-space for $2 \to 1$ process
- Weight with $|M|^2 \times PDF_1 \times PDF_2$
- Write the events within "Les Houches Accord"
- Shower and Hadronization (PYTHIA or HERWIG)
- Simulate the detector (DELPHES)

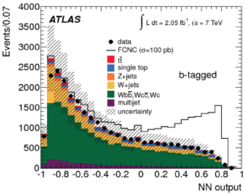
- The LHC Current Status (Moriond 2012)

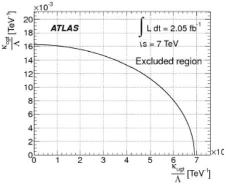
FCNC single top quark production

New!

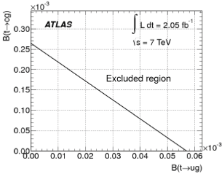
Submitted to Phys. Lett. B
arXiv:1203.0529
Mar 2012; 2.05fb^{-1}

- Analysis strategy:
  - use leptonic decays, 1 jet bin
  - classify events using a neural network
  - most signicant variables: W boson p_T, $\Delta R_{(b\text{-jet,lepton})}$ and lepton charge





Upper limit on the coupling constants κ_{ugt}/Λ and κ_{cgt}/Λ.



Upper limit on the branching fractions t → ug and t → cg

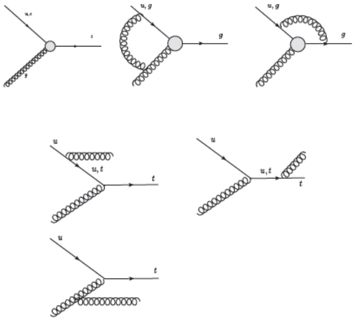
- Results: no observed excess over SM, limits set:

$\sigma(qg \to t) \cdot B(t \to Wb) < 3.9$ pb (95% CL), $B(t \to ug) < 5.7 \cdot 10^{-5}$, $B(t \to cg) < 2.7 \cdot 10^{-4}$

14 Rebeca Gonzalez Suarez (VUB), March 2012 Moriond QCD

- Production @ LHC

Next to Leading order



$$\sigma_{NLO} = \int_m d\sigma^{Born} + \int_m d\sigma^{virtual} + \int_{m+1} d\sigma^{Real}$$

- Production @ LHC

Inclusive NLO Direct top cross sections

FCNC Direct top cross sections ($\frac{k^g_{tq}}{\Lambda} = 0.01\,Tev^{-1}$) (pb) (PRD 72 074018 (2005))				
Subprocess	LHC (LO)	LHC (NLO)	Tevatron Run2 (LO)	Tevatron Run2 (NLO)
$gu \to t$	11.068	16.818	0.259	0.413
$gc \to t$	1.817	2.537	0.0176	0.0283

- The NLO cross section highly enhanced
- About 60% for Tevatron and 40%-50% for LHC
- FCNC BR limits improvements of the same order
- It is desirable to generate NLO Direct top events

- MEtop Code is ready to be used
- (contact Miguel Won: miguel.won@coimbra.lip.pt)

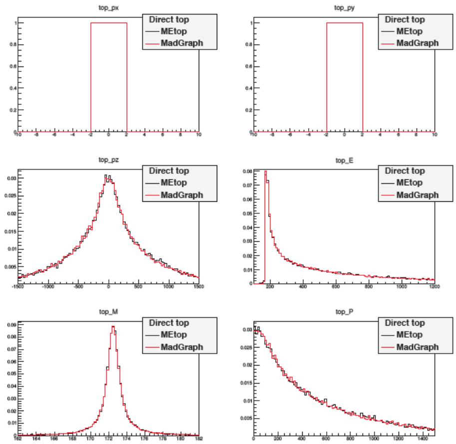
A few generator properties

- W and top widths taken into account
- Spin correlactions are included
- In addition to the Strong FCNC it is included electroweak and 4f FCNC
- New interactions can be included

FCNC @ Production

- MEtop Cross-checks

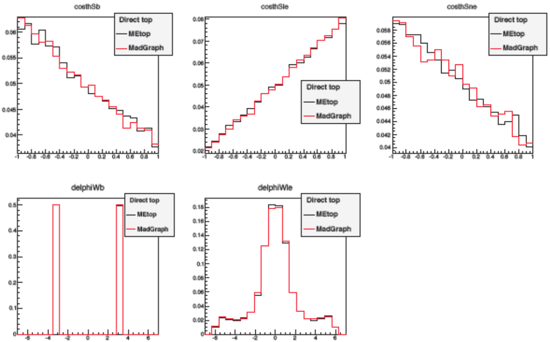
Direct top



FCNC @ Production

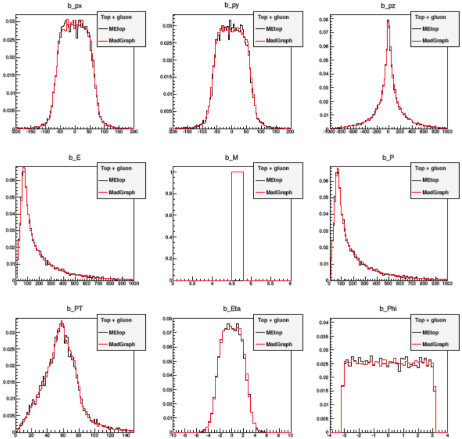
- MEtop Cross-checks

Direct top



- MEtop Cross-checks

top+gluon



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
- Obtained early LHC limits are not too far away from the Tevatron ones
  - Rapid increase of collected luminosity at the LHC should allow to have stringent bounds on the *Wtb* vertex soon
- 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)
- A new FCNC NLO generator is already available (MEtop) $\Rightarrow$ use it!

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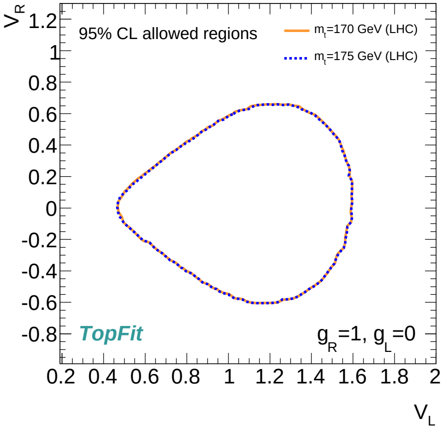
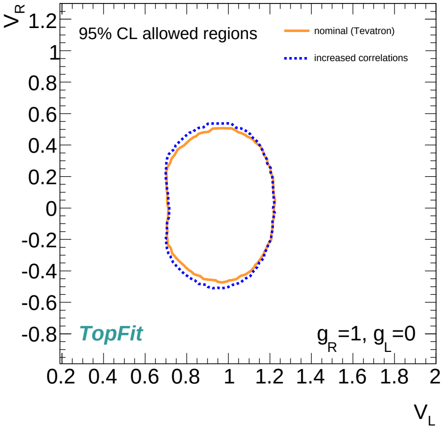
Backup Slides

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



different m_t were considered



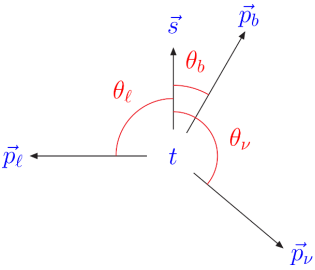
(increased correlations between *W* helicity fractions were introduced)

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

$Q = \cos(\vec{p}_X, \vec{p}_j)$ ➙

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

[PLB 476 (2000) 323]