Wtb anomalous couplings as a probe of new physics beyond the Standard Model

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Plan de la présentation

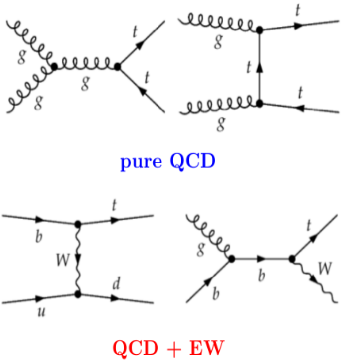
1. Introduction
2. Anomalous *Wtb* couplings in the 2HDM: Abdesslam Arhrib and A.J (JHEP 1608)
3. Probing *Wtb* anomalous couplings at the LHC in *t*-channel: A. Arhrib, F. Boudjema, R. M. Godbole and A.J (to appear).
4. Conclusions and Outlook

Introduction

- $m_t \simeq \Lambda_{SM} \Rightarrow$ very sensitive to new physics effects ?
- Important rôle in EWSB dynamical symmetry breaking ?
- $\Gamma_t \gg \Lambda^2_{QCD}/m_t \Rightarrow$properties could be studied perturbatively: spin-spin correlations, polarisation, width..
- top quark channels are important background to new physics processes (SUSY, Extended Higgs sector, Extra dimensions...)
- Very important for Electroweak Precision Tests (EWPT)
- Very important effect on the properties of the vacuum: stability, metastability and non-stability beyond the electroweak scale Λ_{SM}

We should know the properties of top quark with a very high precision

Introduction



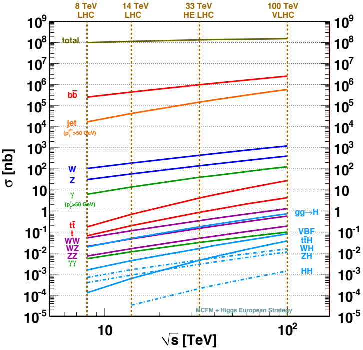


Figure: Examples of Feynman diagrams for Top production at the LHC (left), Cross sections at the LHC @7, 8 TeV and future colliders @33 and 100 TeV (WGR: QCD, arXiv:1310.5189.) (right)

tbW Anomalous Couplings

- In the SM, at tree level, Top quark couplings to $W^{\pm} + b$ has a $V - A$ structure.
- new physics effects and/or one-loop corrections might induce non-trivial right chiral and tensorial couplings.

$$\mathcal{M}(t \to bW^{+}) = \frac{-e}{\sqrt{2}s_W}\bar{u}_b\left[(\mathbf{V_L}P_L + \mathbf{V_R}P_R)\gamma^{\mu} - \frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(\mathbf{g_L}P_L + \mathbf{g_R}P_R)\right]u_t\epsilon^{*}_{\mu}$$

- In the SM, the corrections at the one-loop order are very small and dominated by the QCD contribution.

Coupling	Value in the SM
g_L	$-(1.247 + 0.002747i) \times 10^{-3}$
g_R	$-(8.6 + 2.05i) \times 10^{-3}$
V_R	$(2.911 + 0.9) \times 10^{-3}$
V_L	$-0.0296 + 0.0119i$

Constraints

- The strongest constraint comes from BR$[b \to s\gamma]$,

$$
\begin{aligned}
-0.15 < Re(g_R) < 0.57, \\
-7 \times 10^{-4} \leq V_R \leq 2.5 \times 10^{-3}, \\
-1.3 \times 10^{-3} \leq g_L \leq 4 \times 10^{-4}.
\end{aligned}
$$

- Tevatron has reported 95% CL limit on anomalous couplings,

$$
|V_R|^2 < 0.30, \qquad |g_L|^2 < 0.05 \quad \text{and} \quad |g_R|^2 < 0.12
$$

- A global fit from the existing data on single top production cross section and $W^{\pm}$ helicity fractions gives:

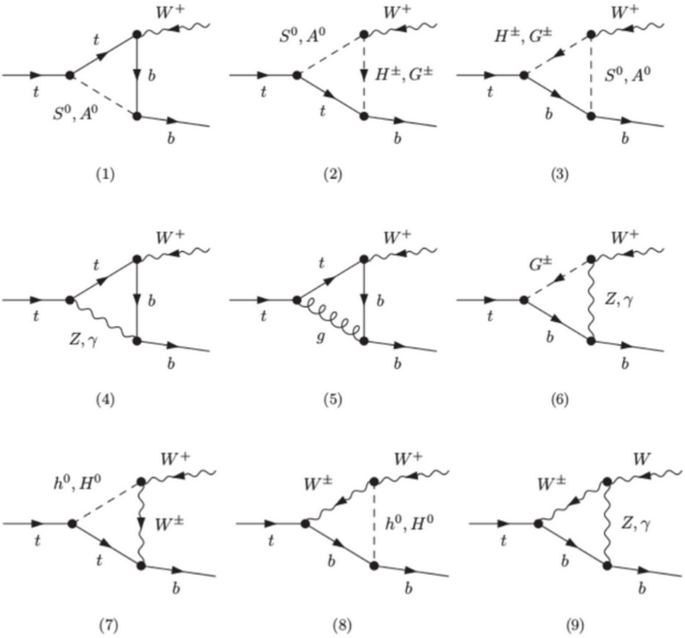
$$
\begin{aligned}
-0.142 \leq g_R \leq 0.023 \quad , \quad -0.081 \leq g_L \leq 0.049, \\
0.902 \leq V_L \leq 1.081 \quad \text{and} \quad -0.112 \leq V_R \leq 0.162.
\end{aligned}
$$

- Constraints from ATLAS and CMS measurements of the $W^{\pm}$ helicity fractions in $t\bar{t}$ production.
- There also other constraints from oblique parameters, electron and neutron electric dipole moments on anomalous *Wtb* anomalous couplings.

the Two-Higgs-Doublet Model (2HDM)

- Two Higgs Doublet Model is an extension of the SM where two doublets H_1 and H_2 participate to the mechanism of EWSB.
- To avoid Flavor Changing Neutral Currents (FCNC), a discrete Z_2 symmetry is imposed. Under this symmetry, there are four possible combinations of the fermion and scalar fields from which four types of 2HDM arise: I, II, X and Y.
- In type-I 2HDM, only the second doublet H_2 interacts with all the fermions while in type-II model the doublet H_2 interacts with up-type quarks and H_1 interacts with the charged leptons and down-type quarks.
- After EWSB, we have four additional scalar particles : CP even H^0, CP odd A^0 and pair of charged scalars $H^{\pm}$. Additionaly a new parameter $\tan\beta$ which is the ratio of the two vacuum expecation values.

Feynman diagrams



Setup

We calculate the anomalous couplings in the Two-Higgs-Doublet Model type-I and type-II. Computation of the V_R and $g_{L;R}$ does not require a renormalization prescription while a renormalization is needed to compute the one-loop corrections to V_L. We define the fields and parameters as follows

$$\begin{aligned} e &\to (1+\delta Z_e)e, \\ \psi \to Z_\psi^{1/2}\psi = (1+\frac{1}{2}\delta Z_\psi)\psi, \qquad \psi &= b_L, t_L \\ W^\mu &\to (1+\delta Z_W)W^\mu, \\ s_W &\to s_W + \delta s_W. \end{aligned}$$

δZ_i are counterterms fixed by suitable renormalization conditions in the on-shell scheme. We find the counter-term for the *Wtb* vertex

$$\delta V_{Wtb} = \frac{1}{\sqrt{2}s_W}\left(\delta Z_e - \frac{\delta s_W}{s_W} + \frac{1}{2}\delta Z_W + \frac{1}{2}(\delta Z^{t,L\dagger} + \delta Z^{b,L})\right)$$

The one-loop corrected form factor plus the counter-term gives a UV finite result which was checked both analytically and numerically.
There are also IR divergences of the one-loop integrals due to soft gluon/photon loops. This was regularized in the mass-regularization scheme and then completely removed by adding $t \to bW^+ g/\gamma$ tree level amplitudes.

We made a scan over the parameter space of the 2HDM respecting all the possible theoretical and experimental constraints

- Vacuum stability of the scalar potential.
- Tree-level perturbative unitarity.
- We imposed constraints on the ρ parameter.
- We imposed constraints from the ATLAS measurement of the signal strength μ_{XX}.
- We used the results of indirect constraints on the charged Higgs boson mass from processes at the one-loop order, e.g $b \to s\gamma$ and R_b In our analysis, we assume that $m_{H\pm} \geq 480$ GeV in 2HDM type-II.
- Constraints from direct searches of charged Higgs bosons at LEP and the LHC are used.

For numerical analysis, we have defined the ratio $\Delta\mathcal{O}_i$ by :

$$\Delta\mathcal{O}_i = \frac{\mathcal{O}_i^{2HDM} - \mathcal{O}_i^{SM}}{\mathcal{O}_i^{SM}}$$

where $\mathcal{O}_i = \mathrm{Re}(g_L), \mathrm{Re}(g_R), \mathrm{Re}(V_R), V_{tb} + \mathrm{Re}(V_L)$.

Warning! $\Delta\mathcal{O}$ gives only the contribution of the extra particles in the THDM

Numerical Results : tensorial left coupling g_L

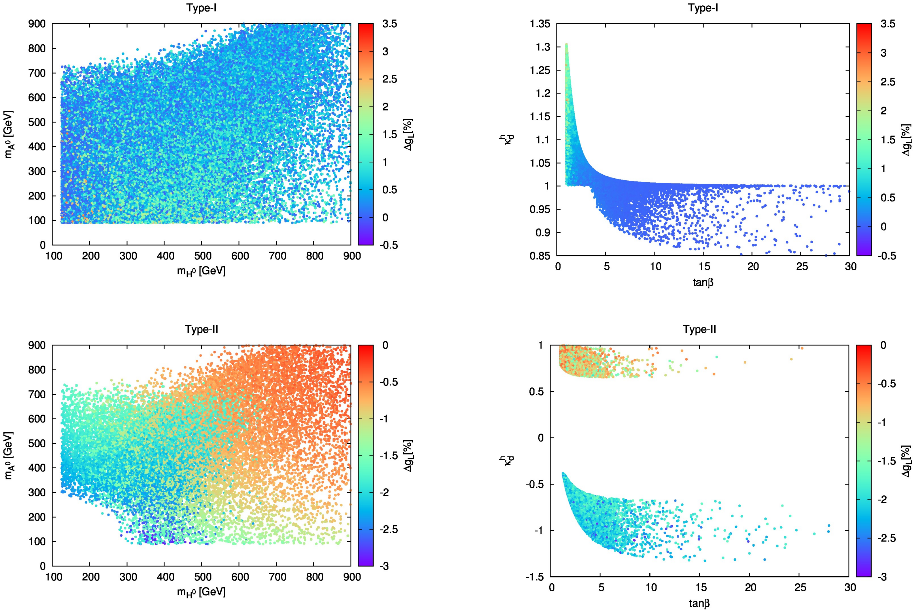


Figure: Relative contribution to the *tbW* left anomalous tensorial coupling g_L in type-I and type-II THDM

Numerical Results : tensorial right coupling g_R

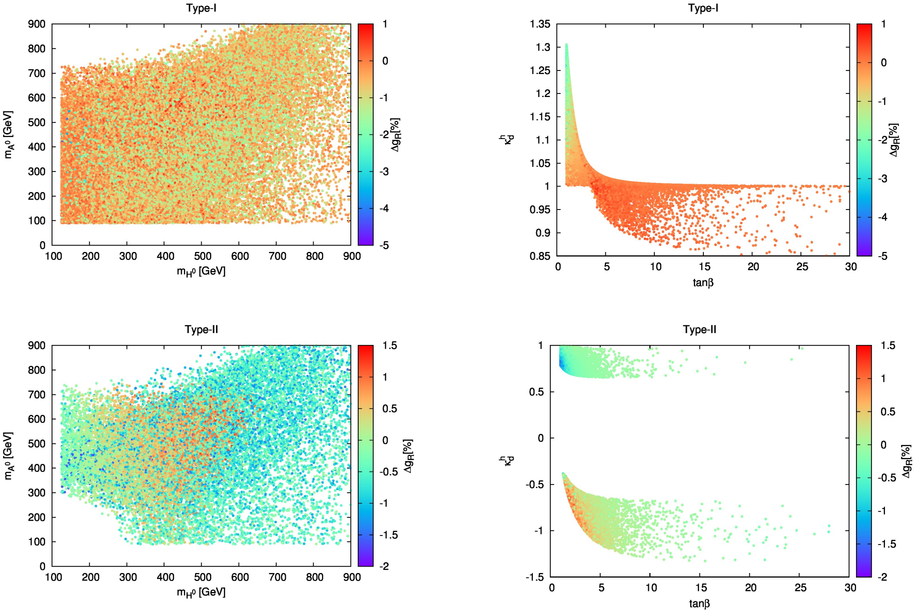


Figure: Relative contribution to the *tbW* right anomalous tensorial coupling g_R in type-I and type-II models

Numerical Results : right chiral coupling V_R

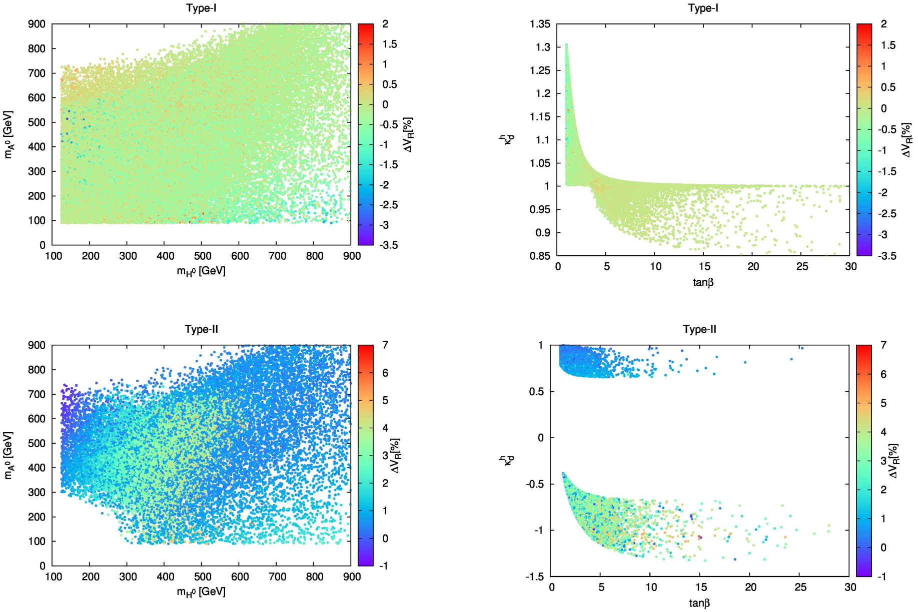


Figure: Relative contribution to the *tbW* right chiral coupling V_R in type-I and type-II

Numerical Results : left chiral coupling V_L

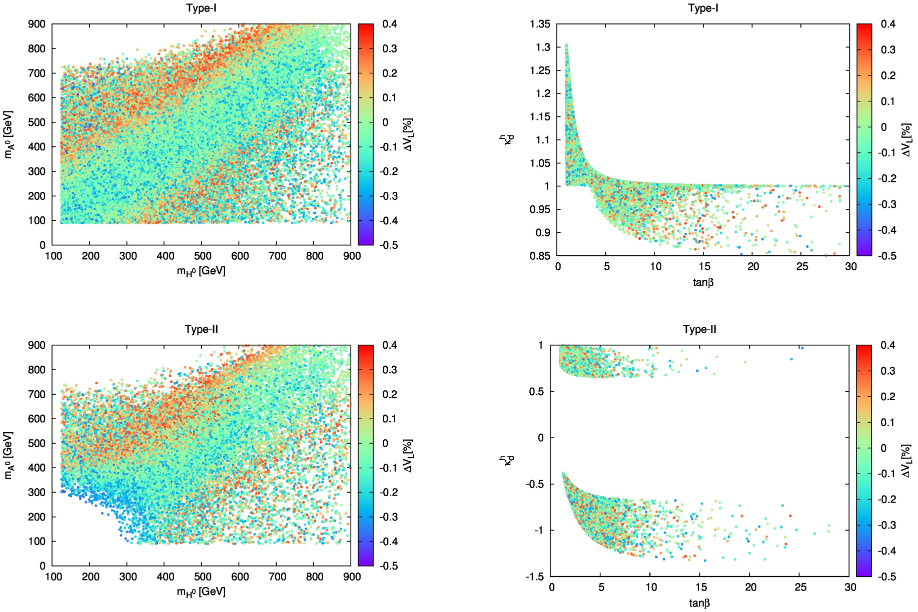


Figure: Relative contribution to the *tbW* left chiral coupling V_L in type-I and type-II

Introduction

The top quark is singly produced in association with a lighter particle; three major single top production processes exist:

- s-channel single top production

$$u\bar{d} \to t\bar{b}$$

- t-channel

$$bq \to tq' \qquad q = u, c \text{ and } q' = d, s$$

- $tW^{\pm}$ associated production

$$bg \to tW^{-}$$

- There are also associated production with a Higgs boson or a Z-boson.

Observables

- Measurement of the anomalous *Wtb* couplings is made by using a set of sensitive observables.
- These observables consist of the single top quark production cross section and $W^{\pm}$ helicity fractions.
- In addition to those observables, we propose a new set of asymmetries and combine them to improve the sensitivity to anomalous *Wtb* couplings.
- The angular polar distribution of the charged lepton in $t \to bW^{+} \to b\ell^{+}\nu_{\ell}$ is a good probe of top quark polarisation. No sensitivity to anomalous *Wtb* couplings provided that they are small.

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_k} = \frac{1}{2}(1 + \alpha_k P_t \cos\theta_k)$$

  P_t is the top quark polarisation and α_k is the spin analyzing power.
- at LO, $\alpha_\ell = \alpha_{\bar{d}} = 1$, $\alpha_b = \alpha_W = -0.41$.

  $\boxed{\text{Charged leptons are the best analyzers of the top quark spin}}$

Observables

We propose four new observables to probe the anomalous *Wtb* coupling g_R

- The scaled charged lepton energy distribution (in the lab and top quark rest frame),

$$x_\ell = \frac{2E_\ell}{m_t}$$

- the energy ratio of the charged lepton to the total visible energy:

$$u = \frac{E_\ell}{E_\ell + E_b}$$

- the z variable, which measures the fraction of the top quark energy taken by the b-quark in the Lab frame

$$z = \frac{E_b}{E_t}$$

The last two observables are very useful to measure simultaneously the top polarisation and anomalous *Wtb* couplings.

single top production cross sections

Presence of anomalous *Wtb* couplings modify the top quark production cross sections. Cross sections of single top producton in *pp* collisions can be expressed as function of anomalous *Wtb* couplings as

$$\sigma_{\text{t-ch}} = \sigma_{\text{t-ch}}^{\text{SM}}\left(1 + \kappa_1^{\text{t-ch}} g_R + \kappa_2^{\text{t-ch}} |g_R|^2\right),$$

$$\sigma_{\text{s-ch}} = \sigma_{\text{s-ch}}^{\text{SM}}\left(1 + \kappa_1^{\text{s-ch}} g_R + \kappa_2^{\text{s-ch}} |g_R|^2\right),$$

$$\sigma_{\text{tW}} = \sigma_{\text{tW}}^{\text{SM}}\left(1 + \kappa_1^{\text{tW}} g_R + \kappa_2^{\text{tW}} |g_R|^2\right).$$

single top prodution cross sections

Process		σ [pb]	$\delta\sigma_\mu$ [%]	$\delta\sigma_{\mathrm{PDF}}$ [%]	K	κ_1	κ_2
s-channel	LO	4.377	${}^{+3.12}_{-3.9}$	$\pm$6.38	–	5.44465	13.0895
	NLO	6.205	$\pm$3.8	$\pm$1.6	1.42	–	–
t-channel	LO	123.82	${}^{+9.24}_{-11.3}$	$\pm$8.88	–	0.45485	2.05348
	NLO	141.8	${}^{+2.8}_{-2.5}$	$\pm$1.2	1.15	–	–
tW-channel	LO	26.42	${}^{+16.1}_{-15.7}$	$\pm$13.9	–	$-$1.0028	3.32153
	NLO	35.92	${}^{+6.9}_{-8.1}$	$\pm$2.0	1.36	–	–

Table: LO, NLO cross sections of *s*-, *t*-channel and *tW* associated production in the SM.

t-channel single top production

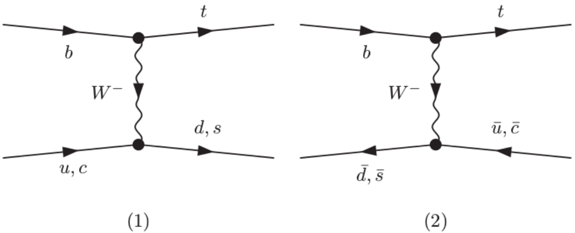


Figure: Feynman diagrams contributing to t-channel process at LO in the SM.

t-channel single top production

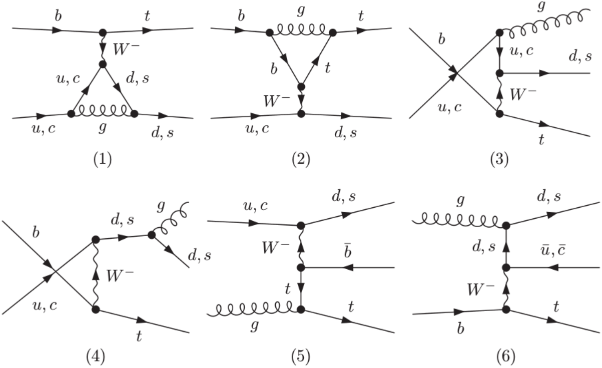


Figure: Feynman diagrams contributing to $bq \to tq'$ subprocess at NLO in the SM where $q = u, c$ and $q' = d, s$.

Order	σ [pb]	$\delta\sigma_{\mu}$ [%]	$\delta\sigma_{\mathrm{PDF}}$ [%]	$\delta\sigma_{m_t}$ [%]	$\delta\sigma_{\mathrm{PDF}+\alpha_s}$ [%
LO	123.8	$^{+9.12}_{-11.3}$	± 8.88	$^{+2.18}_{-1.94}$	$-$
NLO	141.8	$^{+2.8}_{-2.5}$	± 1.2	$^{+1.27}_{-3.67}$	$^{+1.19}_{-2.75}$

Table: t-channel production cross section at LO and NLO at $\sqrt{s} = 13$ TeV. Uncertainties due to scale variations, PDF, top mass and PDF+α_s are shown.

In order to take into account the contribution of the anomalous coupling g_R in the production and improve the sensitivity of the asymmetries on g_R, three different samples will be generated. The transition amplitude for the process

$$pp \to t + X \to b\ell^{+}\nu_{\ell} + X,$$

can be written as

$$\mathcal{M}(\lambda) = \mathcal{P}(\lambda)\mathcal{D}(\lambda).$$

$\mathcal{P}(\lambda)$ ($\mathcal{D}(\lambda)$) is the transition amplitude corresponding to the production (decay) of the top quark with helicity state λ. The production matrix element can have the following decomposition

$$\mathcal{P}(\lambda) = \mathcal{P}_1(\lambda) + \delta\mathcal{P}_1(\lambda),$$

The transition amplitude can be squared to give

$$
\begin{aligned}
|\mathcal{M}(\lambda,\lambda')|^2 &= \Big(\mathcal{P}(\lambda)\mathcal{P}^*(\lambda')\Big)\Big(\mathcal{D}(\lambda)\mathcal{D}^*(\lambda')\Big) \\
&= \Big[(\mathcal{P}_1(\lambda)+\delta\mathcal{P}_1(\lambda))(\mathcal{P}_1^*(\lambda')+\delta\mathcal{P}_1^*(\lambda'))\Big] \times \Big[\mathcal{D}(\lambda)\mathcal{D}^*(\lambda')\Big] \\
&= \Big[\mathcal{P}_1(\lambda)\mathcal{P}_1^*(\lambda')+\delta\mathcal{P}_1(\lambda)\delta\mathcal{P}_1^*(\lambda')+2\{\mathcal{P}_1(\lambda)\delta\mathcal{P}_1^*(\lambda')\}\Big] \times \Big[\mathcal{D}(\lambda)\mathcal{D}^*(\lambda')\Big] \\
&= \Big[\mathcal{P}_1(\lambda)\mathcal{P}_1^*(\lambda')+(\mathcal{P}_{\text{anom.}}(\lambda)-\mathcal{P}_2(\lambda))(\mathcal{P}*_{\text{anom.}}(\lambda')-\mathcal{P}*_2(\lambda'))\Big] \times \Big[\mathcal{D}(\lambda)\mathcal{D}^*(\lambda')\Big] \\
&= \Big[\mathcal{P}_1(\lambda)\mathcal{P}_1^*(\lambda')+\mathcal{P}_{\text{anom.}}(\lambda)\mathcal{P}_{\text{anom.}}^*(\lambda')-\mathcal{P}_2(\lambda)\mathcal{P}_2^*(\lambda')\Big] \times \Big[\mathcal{D}(\lambda)\mathcal{D}^*(\lambda')\Big].
\end{aligned}
$$

$$\delta\mathcal{P}_1(\lambda) = \mathcal{P}_{\text{anom.}(\lambda)-\mathcal{P}_2(\lambda)},$$

with $\mathcal{P}_{\text{anom.}(\lambda)}$ is the full LO transition amplitude (containing anomalous coupling) and $\mathcal{P}_2(\lambda)$ is the SM transition amplitude at LO.

Setup and event selection

- Events generated with `Madgraph5_aMC@NLO` at NLO and decayed with `MadSpin`.
- The decayed events are passed to `Pythia8` for hadronization and showering.
- Events are selected if they contain a charged lepton (electron or muon), missing $E_{\mathrm{T}}^{\mathrm{miss}}$ and at least two jets where one of them is b-tagged.
- First, we require exactly one isolated charged lepton with transverse momentum $p_\perp(\text{lepton}) > 10$ GeV and pseudorapidity $|\eta| < 2.5$. We require at least two jets where one of them is tagged with $|\eta| < 2.5$ and $p_\perp(\text{jet}) \geq 25$ GeV. Further isolation requirements are applied to jets, i.e the angular separation should be always $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} > 0.5$ for two jets and $\Delta R(\text{jet}, \text{lepton}) > 0.4$.

Results for t-channel

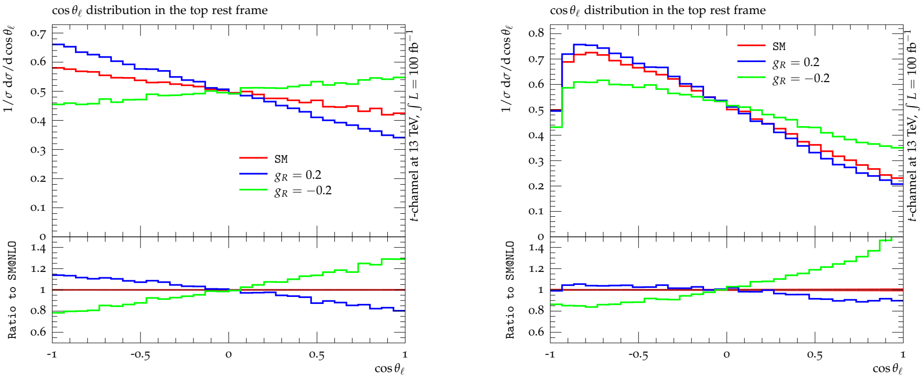


Figure: $\cos\theta_\ell$ distribution in the top quark rest frame without cuts (left panel) and with cuts (right panel).

Results for t-channel

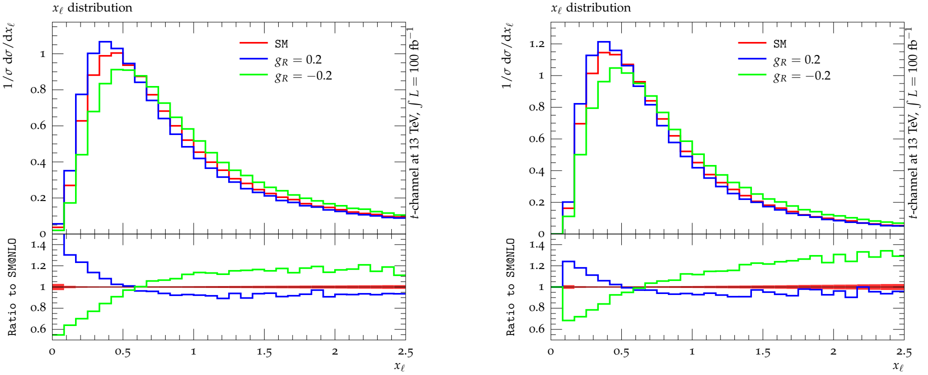


Figure: x_ℓ distribution in the lab frame without cuts (left panel) and with cuts (right panel).

Results for t-channel

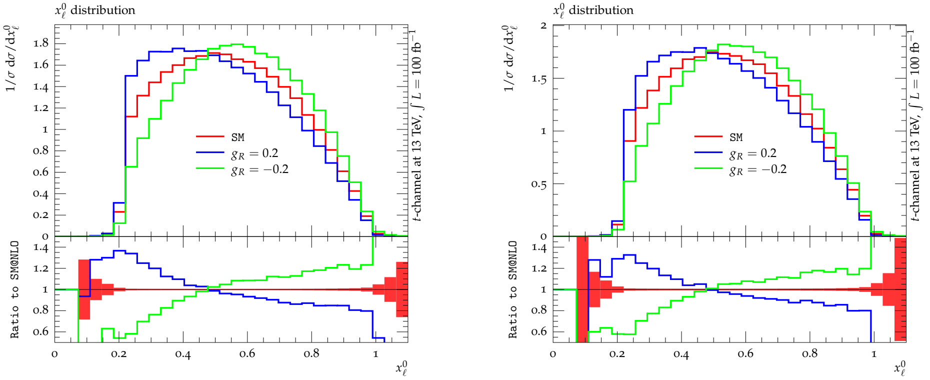


Figure: x_ℓ distribution in the top quark rest frame without cuts (left panel) and with cuts (right panel).

Results for t-channel

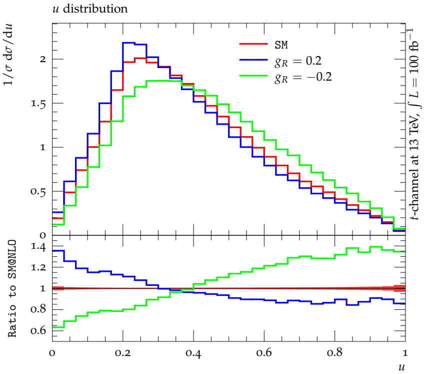
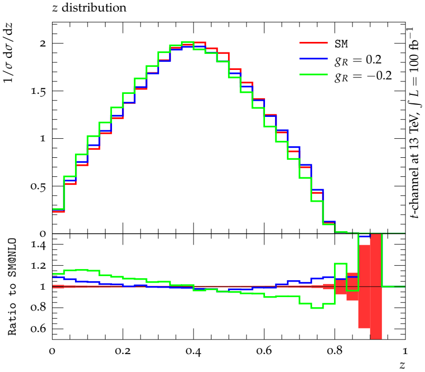


Figure: u distribution in the lab frame without cuts (left panel) and with cuts (right panel).

Results for t-channel



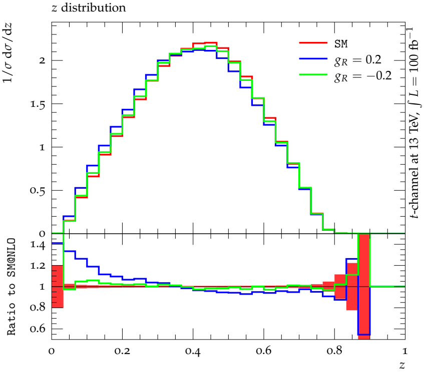


Figure: z distribution in the lab frame without cuts (left panel) and with cuts (right panel).

Asymmetries

From these observables, we define appropriate asymmetries

$$A_{\mathcal{O}} = \frac{\sigma(\mathcal{O} < \mathcal{O}_c) - \sigma(\mathcal{O} > \mathcal{O}_c)}{\sigma(\mathcal{O} < \mathcal{O}_c) + \sigma(\mathcal{O} > \mathcal{O}_c)}$$

where $\mathcal{O} = u, x_\ell, \cos\theta_\ell, z$ and x_ℓ^0 and $\mathcal{O}_c$ is a reference point for the asymmetry.

Asymmetry $A_{\mathcal{O}}$	A_{θ_ℓ}	A_u	A_z	A_{x_ℓ}
Reference point $\mathcal{O}_c$	0	0.4	0.4	0.5

We have generated MC samples for each value of the anomalous coupling g_R corresponding to an integrated luminosity of 100 fb^{-1}. The asymmetries were computed for each value of the anomalous coupling

$$g_R \in \{-0.2, -0.15, -0.1, 0.0, 0.1, 0.15, 0.2\}.$$

An interpolation to the the computed asymmetries was performed. We have adopted a 6th order polynomial defined as

$$A_{\mathcal{O}} = \sum_{i=0}^{6} \zeta_i^{\mathcal{O}} g_R^i,$$

where $\zeta_i^{\mathcal{O}}, i = 0, \cdots, 7$ are set of coefficients determined from the fit and corresponding to the observable $\mathcal{O}$ such that $\zeta_0^{\mathcal{O}} = A_{\mathcal{O}}(\mathrm{SM})$.

Angular based asymmetries

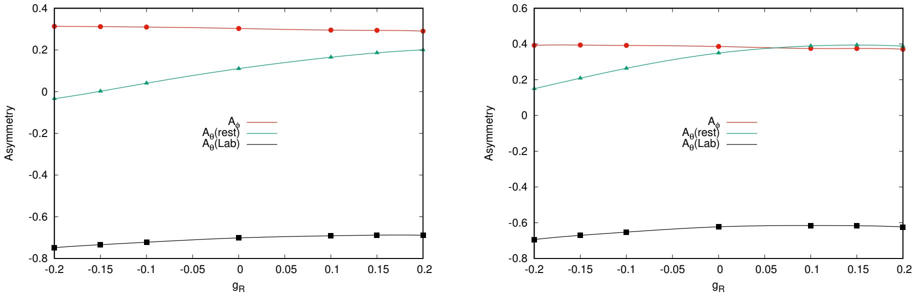


Figure: Angular based asymmetries as function of the anomalous coupling without (left panel) and with (right panel) cuts. The red curves show the azimuthal asymmetry A_ϕ, the green (black) ones show the polar asymmetry in the top rest (laboratory) frame.

Energy based asymmetries

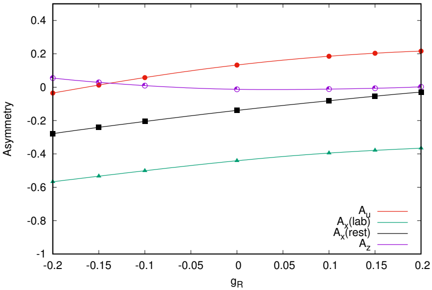


Figure: Energy based asymmetries as function of the anomalous coupling without (left panel) and with (right panel) cuts. The red curves show the A_u asymmetry, A_{x_ℓ} is represented by the green lines, $A_{x_\ell^0}$ by the black lines and A_z by the lines in purple.

Conclusion and Outlook

- Anomalous couplings computed from one-loop corrections to $t \to bW^+$ cannot disteangle the SM from the 2HDM.
- With the high luminosity option of the Super-Belle II, new indirect constraints on the anomalous coupling from $b \to s\gamma$ can be used to give more constraints on the parameter space of the 2HDM.
- Energy and angular based asymmetries are very strong probe of the anomalous coupling.
- Our aim is to make new sensitivity projections on g_R using those asymmetries.
- Get the best combination of observables to probe anomalous *Wtb* couplings (asymmetries, $W^\pm$ helicity fraction and single top production cross section).