

# BSM contribution to the off-shell electroweak top quark production

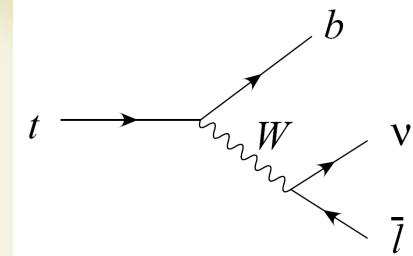


- ~ Possible BSM contribution to tWb interactions
- ~ Associated tW production
- ~ New approach to search for BSM in tWb production process

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QUARKS'18

# What we call anomalous Wtb couplings?



$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i$$

Operators that contribute to the Wtb vertex:

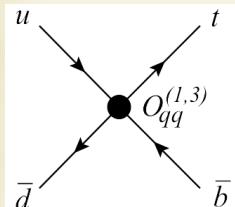
J. A. Aguilar-Saavedra, arXiv:1008.3225

$$O_{\phi q}^{(3,3+3)} = \frac{i}{2} \left[ \phi^\dagger (\tau^I D_\mu - \overleftarrow{D}_\mu \tau^I) \phi \right] (\bar{q}_{L3} \gamma^\mu \tau^I q_{L3}), \quad O_{\phi \phi}^{33} = i(\tilde{\phi}^\dagger D_\mu \phi)(\bar{t}_R \gamma^\mu b_R),$$

$$O_{dW}^{33} = (\bar{q}_{L3} \sigma^{\mu\nu} \tau^I b_R) \phi W_{\mu\nu}^I, \quad O_{uW}^{33} = (\bar{q}_{L3} \sigma^{\mu\nu} \tau^I t_R) \tilde{\phi} W_{\mu\nu}^I,$$

contact four-fermion interactions  
(not a part of Wtb vertex):

$$O_{qq}^{(1,3)} = (\bar{q}^i \gamma_\mu \tau^I q^j)(\bar{q} \gamma^\mu \tau^I q)$$



Cen Zhang,  
Scott Willenbrock,  
arXiv:1008.3869

one can derive vertices:

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W_\mu^-$$

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

order:

$V_L \equiv F_L^L \equiv F_{_1}^L$ ,	$1/\Lambda^2$	$1/\Lambda^4$
$V_R \equiv F_R^R \equiv F_{_1}^R$	$V_L$	$(V_L)^2$
$g_L \equiv F_L^L \equiv F_{_2}^L$ ,	-	$(V_R)^2$
$g_R \equiv F_R^R \equiv F_{_2}^R$	-	$(g_L)^2$
	$g_R$	$(g_R)^2$

Where corrections to SM coupling:

$$V_L = V_{tb} + C_{\phi q}^{(3,3+3)} \frac{v^2}{\Lambda^2},$$

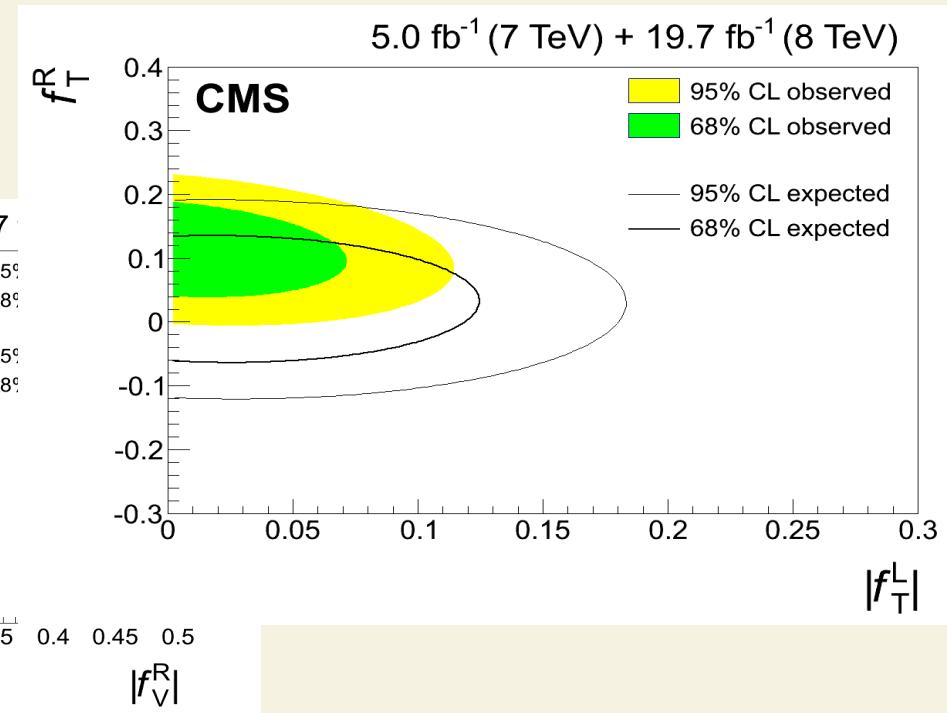
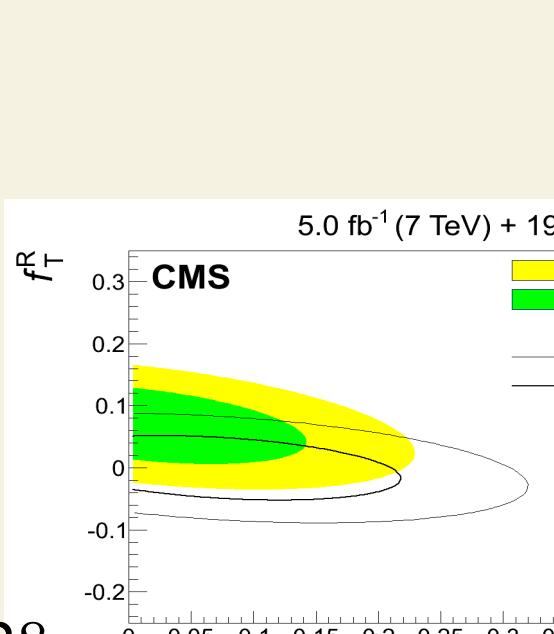
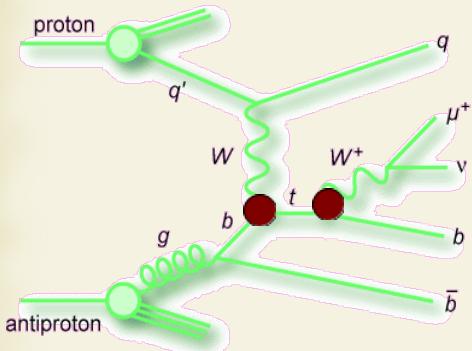
$$V_R = \frac{1}{2} C_{\phi \phi}^{33} \frac{v^2}{\Lambda^2},$$

$$g_L = \sqrt{2} C_{dW}^{33} \frac{v^2}{\Lambda^2},$$

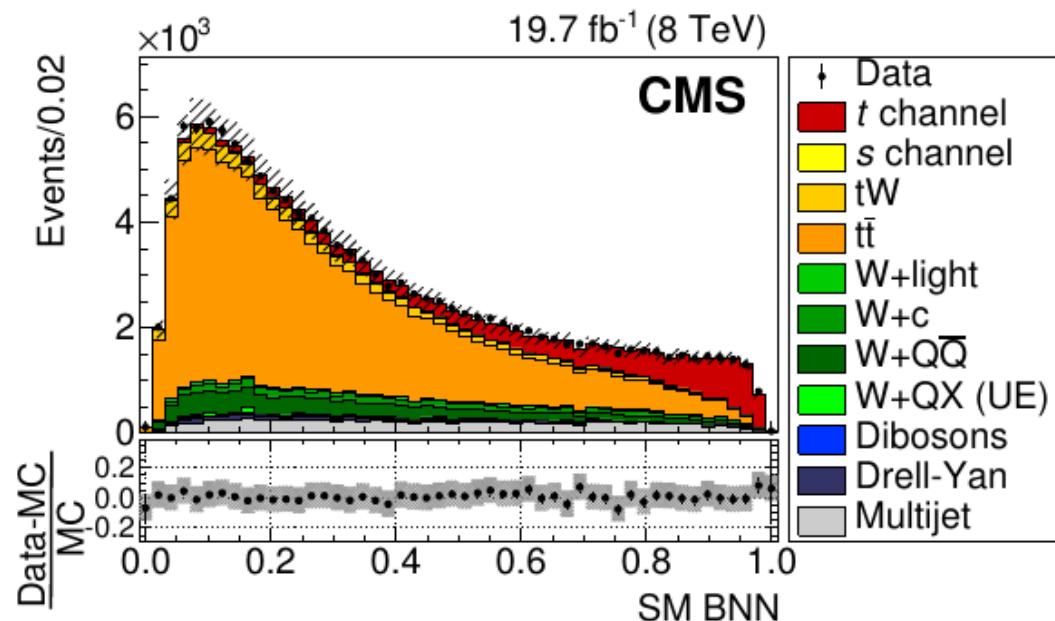
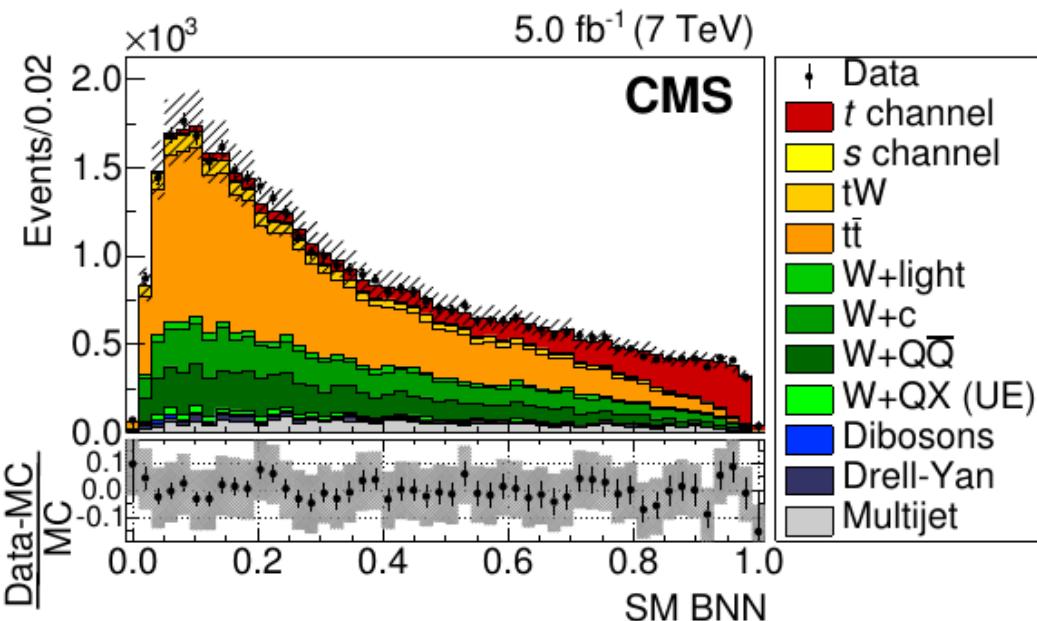
$$g_R = \sqrt{2} C_{uW}^{33} \frac{v^2}{\Lambda^2},$$

$$\sigma \propto A \cdot (f_1^L)^2 + B \cdot (f_1^R)^2 + C \cdot (f_1^L \cdot f_2^R) + D \cdot (f_1^R \cdot f_2^L) + E \cdot (f_2^L)^2 + G \cdot (f_2^R)^2 - 2$$

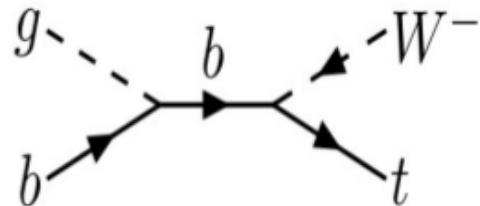
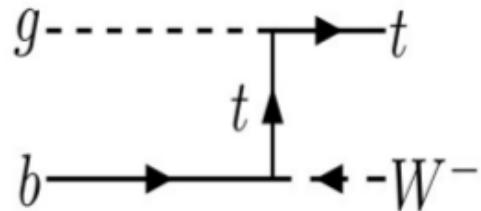
# Direct search in t-channel



JHEP 02 (2017) 028

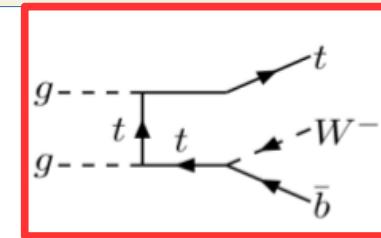
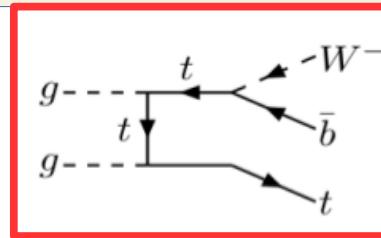
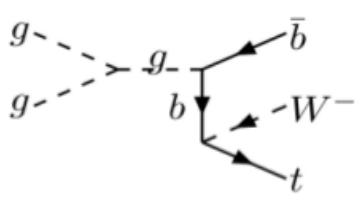
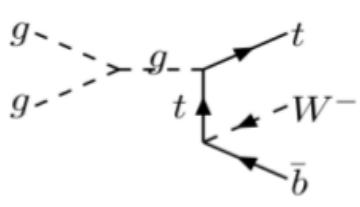


# What is the top pair and associated tW production?

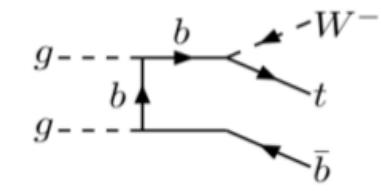
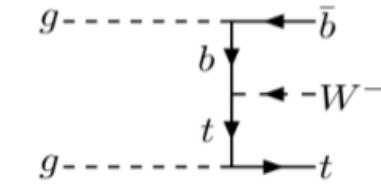
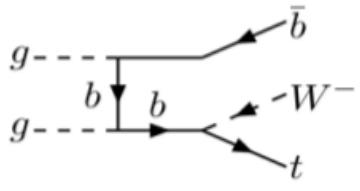
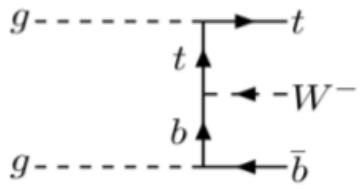


Leading order (**LO**)  
2->2 process  
**tW** production

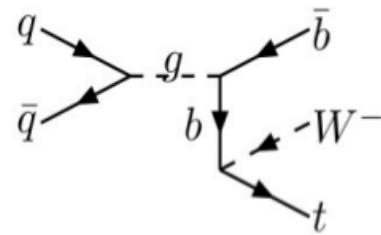
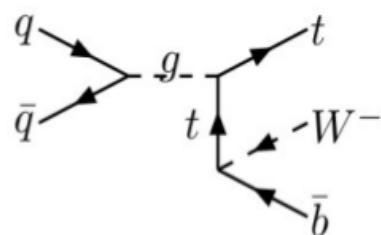
Next to leading order (**NLO**),  $O(1/\log(m_t/m_b))$ , 2->3 processes, **tWb**



**t tbar**  
production



gluon gluon  
processes



# How to simulate associative tW electroweak production?

Diagram removal scheme S. Frixione et al., arXiv:0805.3067.

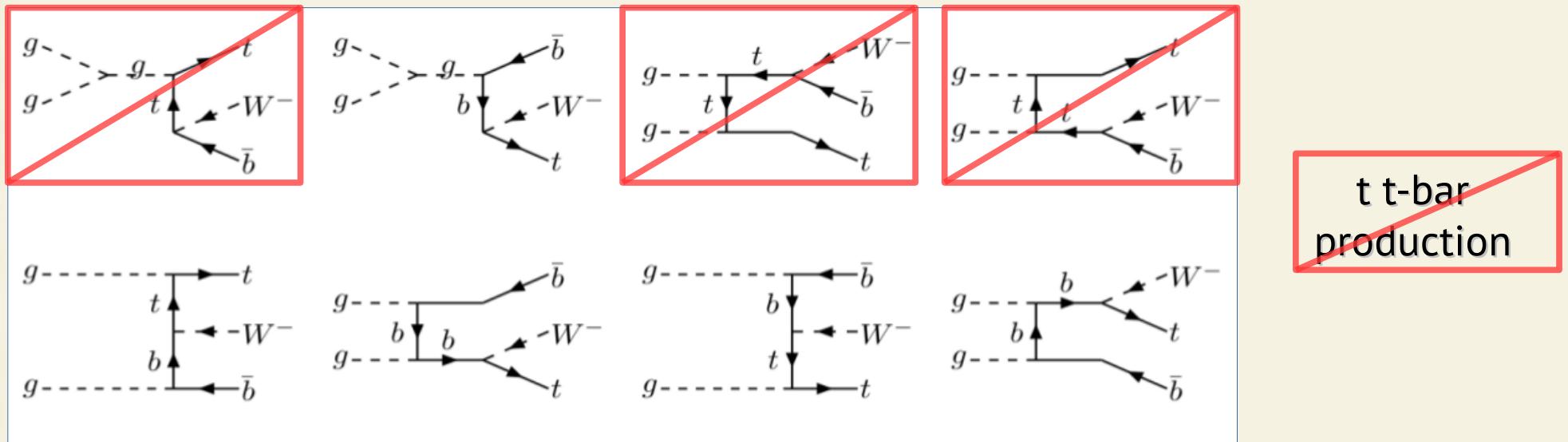
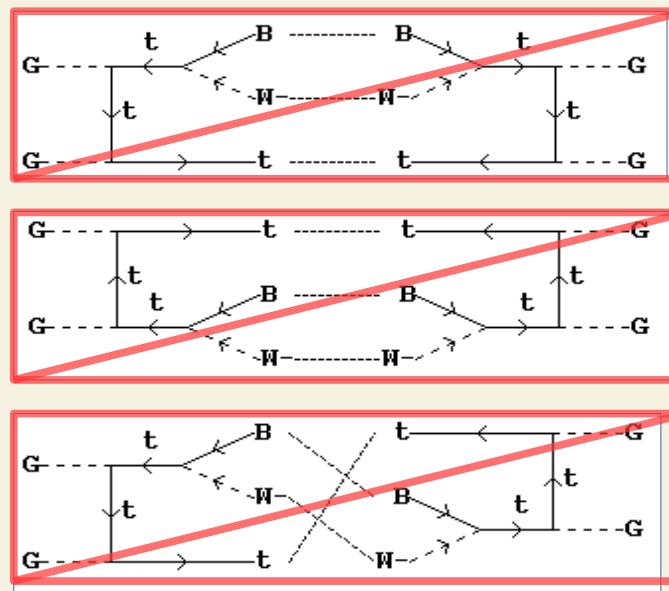


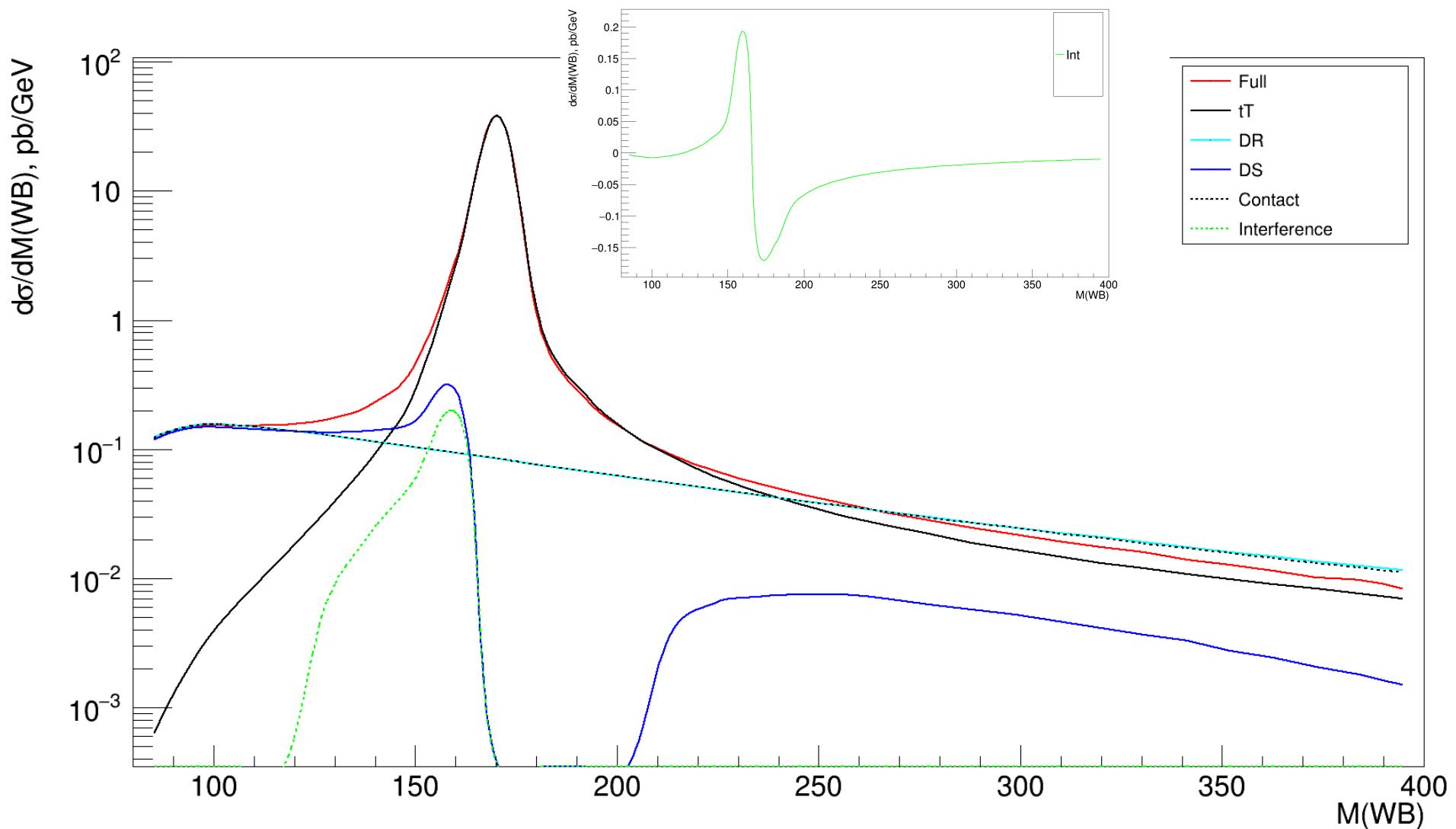
Diagram subtraction  
Scheme

T. M. P. Tait, arXiv:hep-ph/9909352



Kinematic separation  
A. Belyaev, E. Boos,  
arXiv:hep-ph/0003260

# How to simulate associative tWb production correctly?



# Simulation of tWb, additional plots

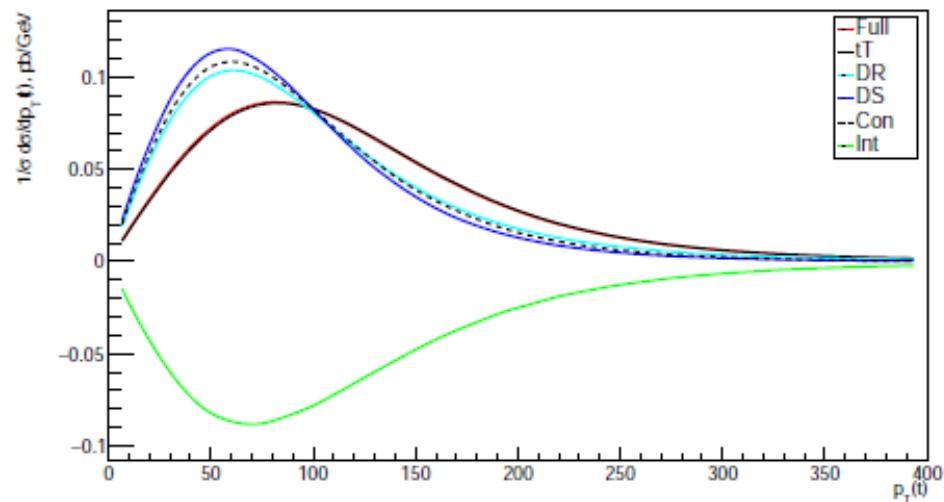


Figure 5: Transverse momentum of top

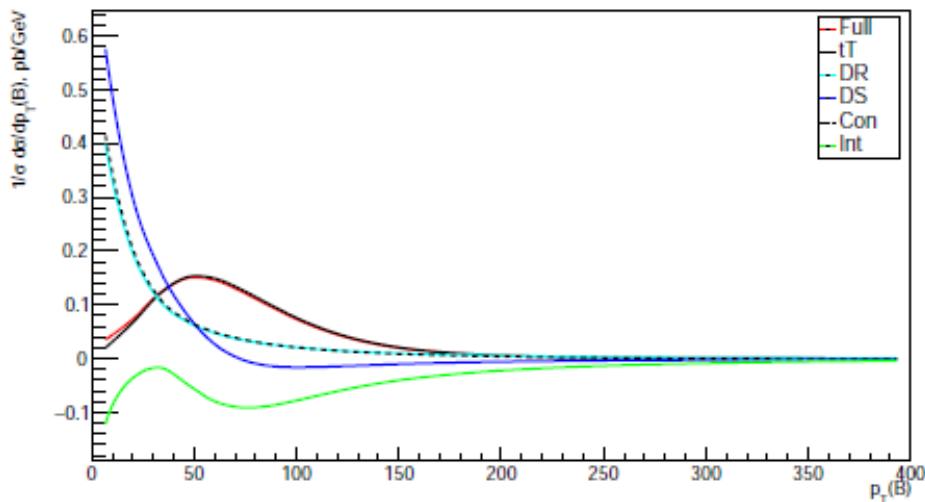


Figure 6: Transverse momentum of b

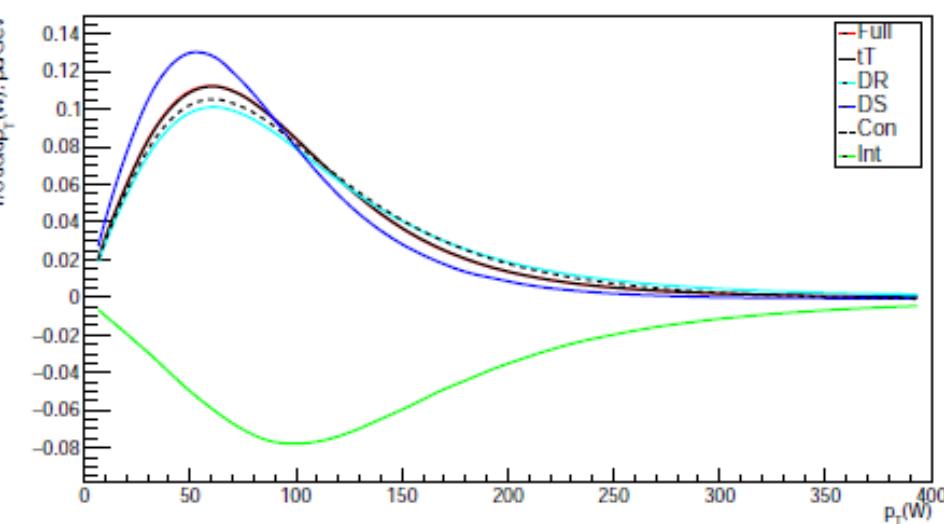


Figure 7: Transverse momentum of W boson

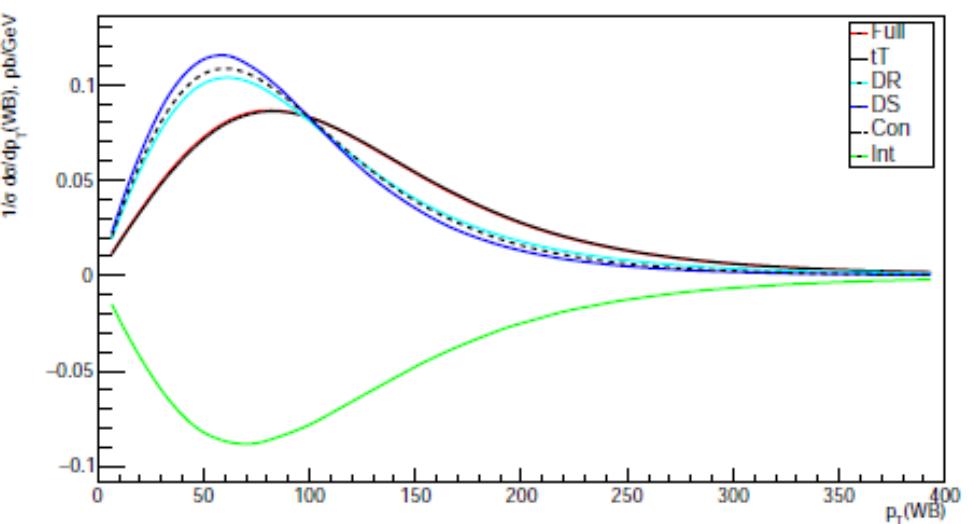


Figure 8: Transverse momentum of system of W boson and b quark.

# Simulation of tWb, angular variables

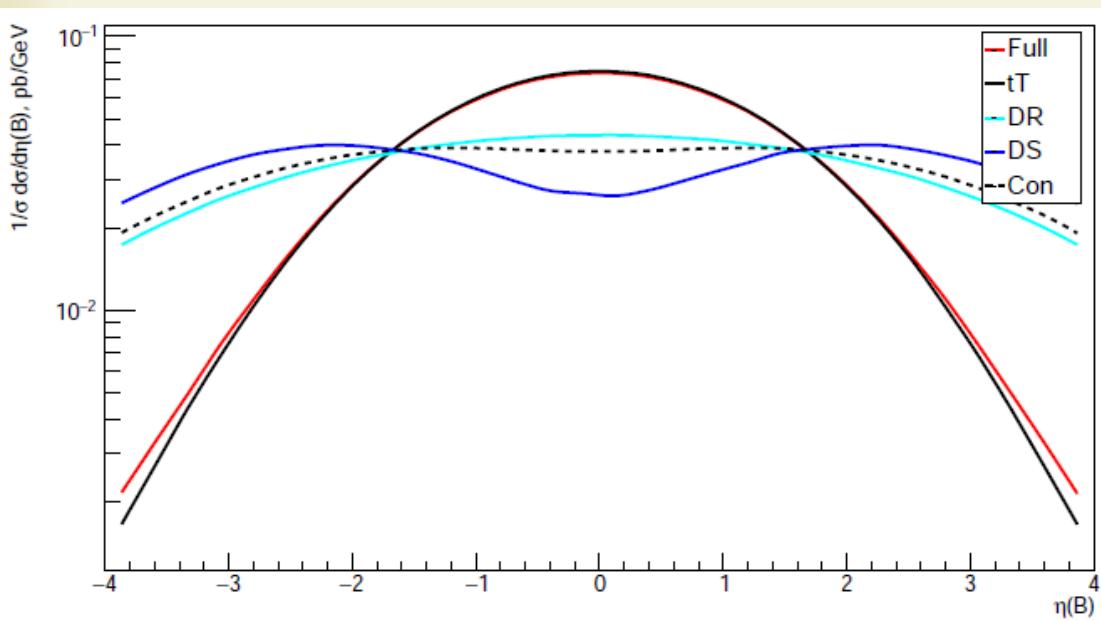


Figure 10: Pseudorapidity of b quark.

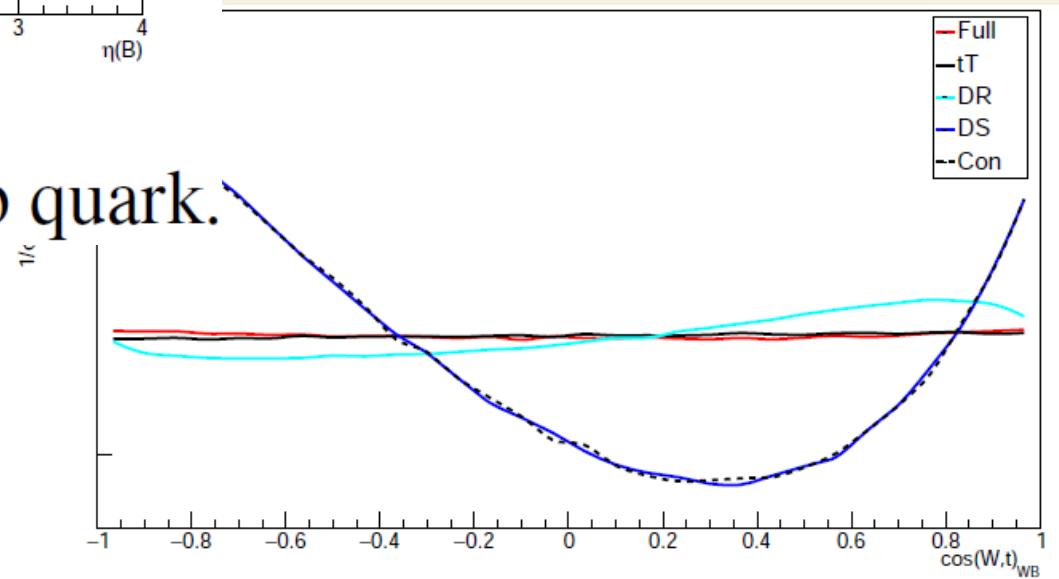
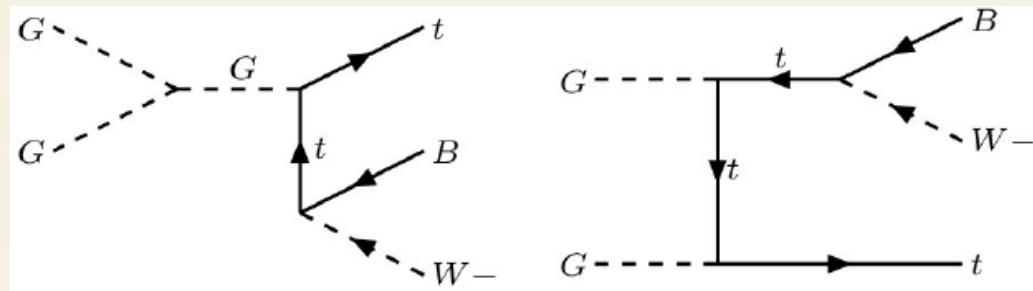


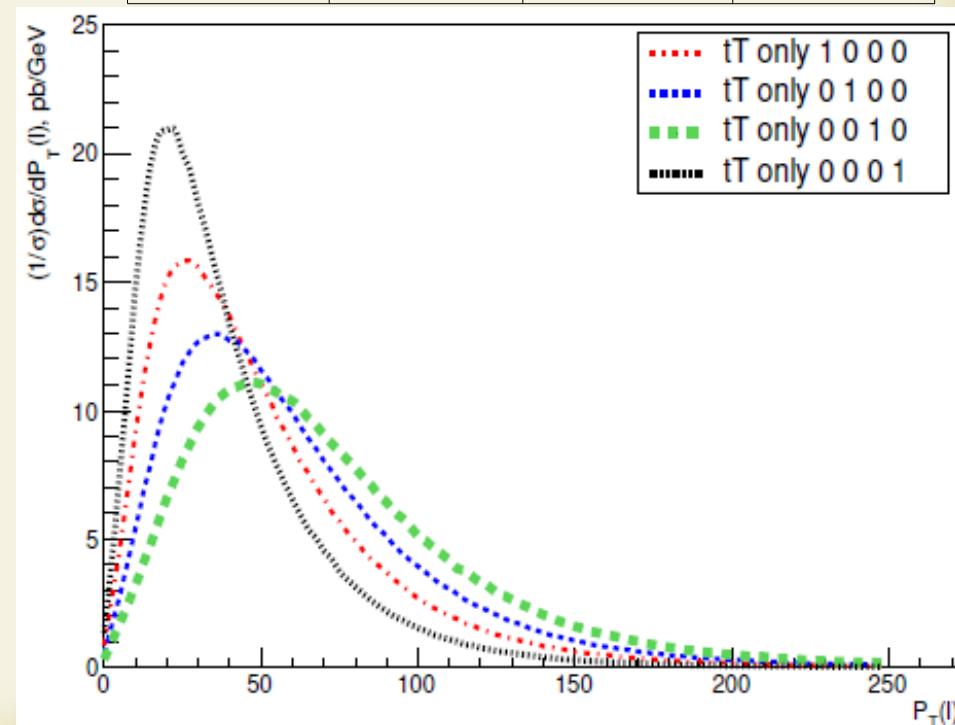
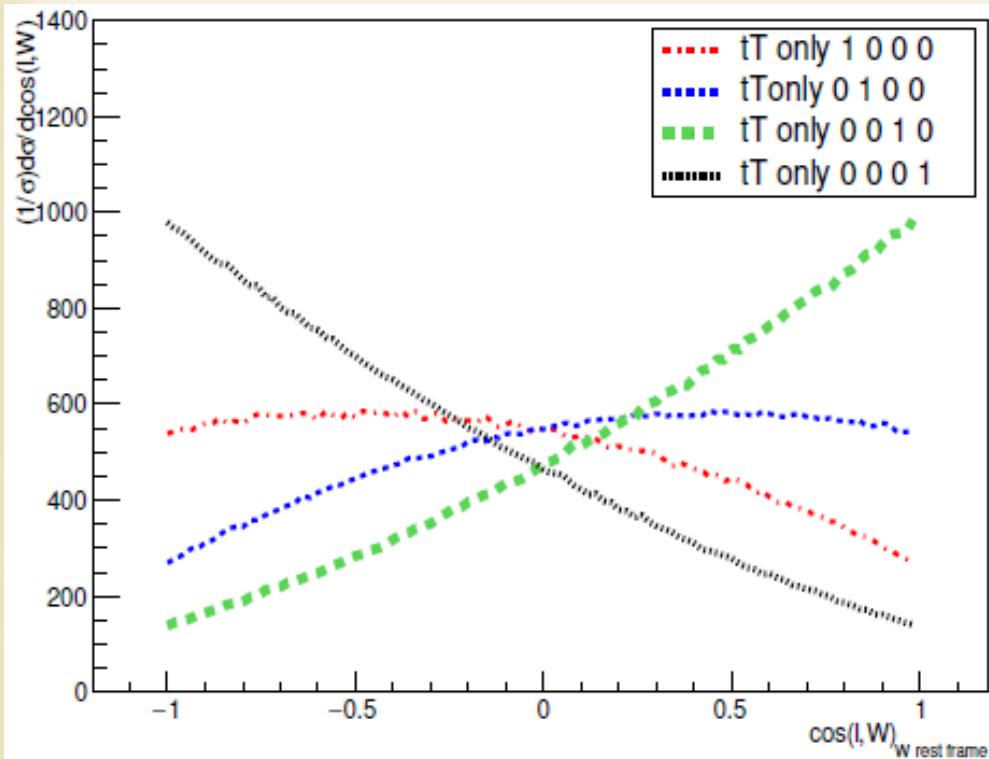
Figure 14: Cosine between W boson and top quark in rest frame of W and b

# Is ttbar sensitive to Wtb anomalous interactions?



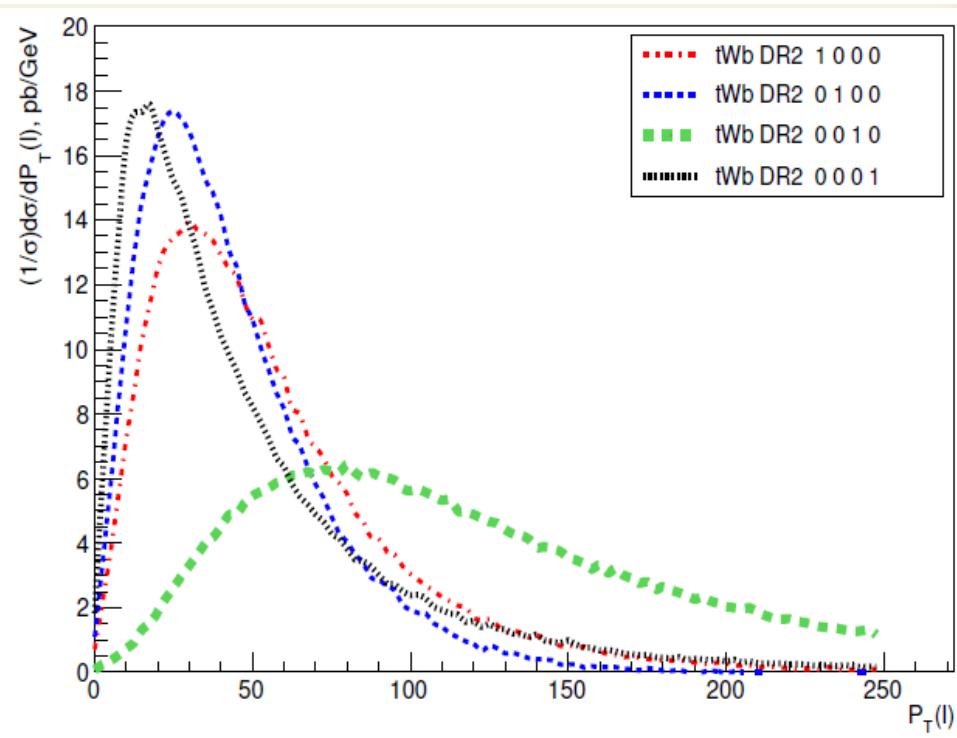
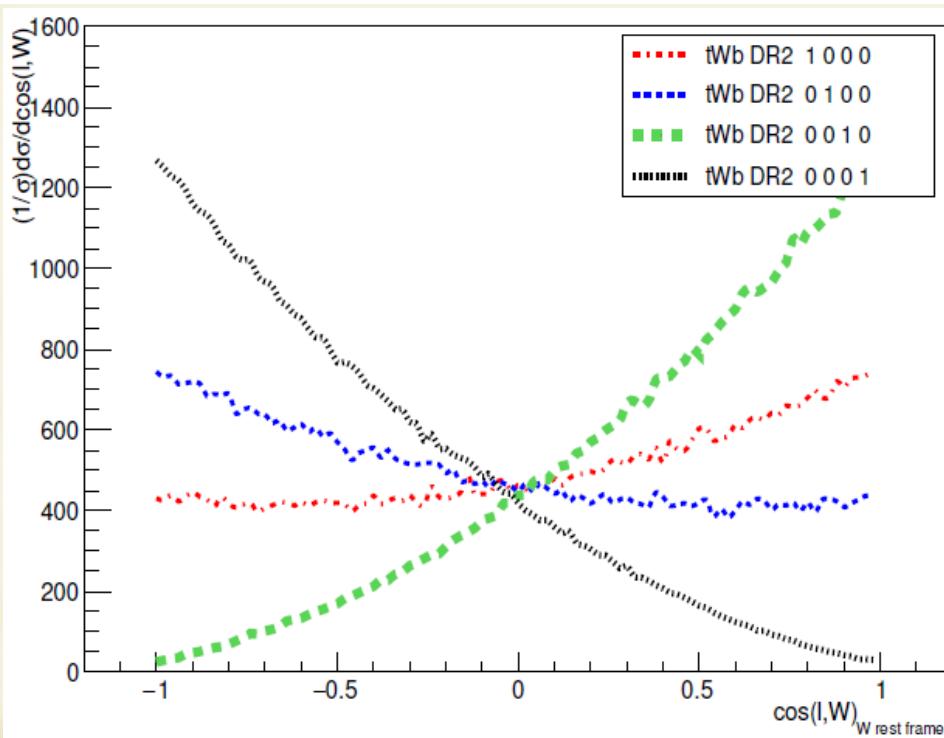
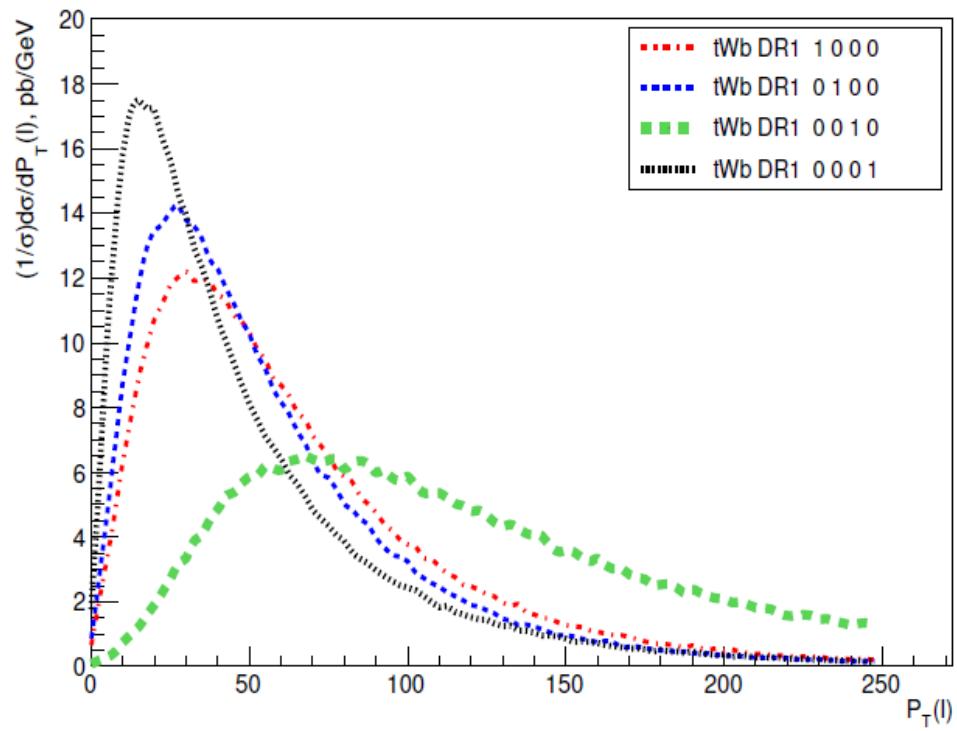
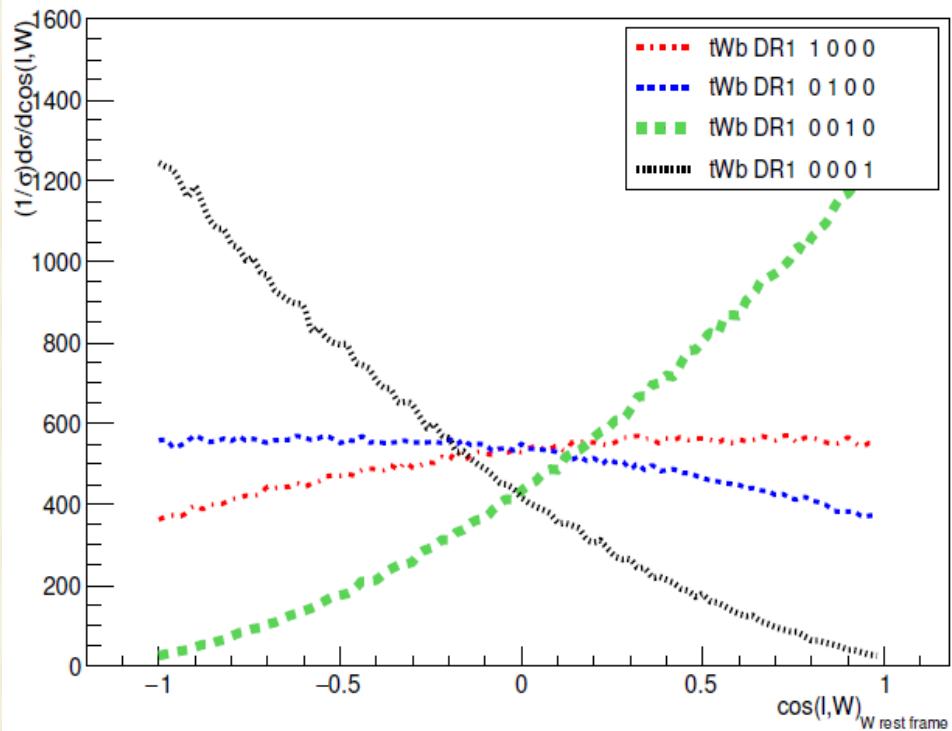
Anomalous Wtb vertex is only in the decay of top quark.

Yes, it is sensitive, but less and differently than tW, also ttbar is in about 20 times large than tW

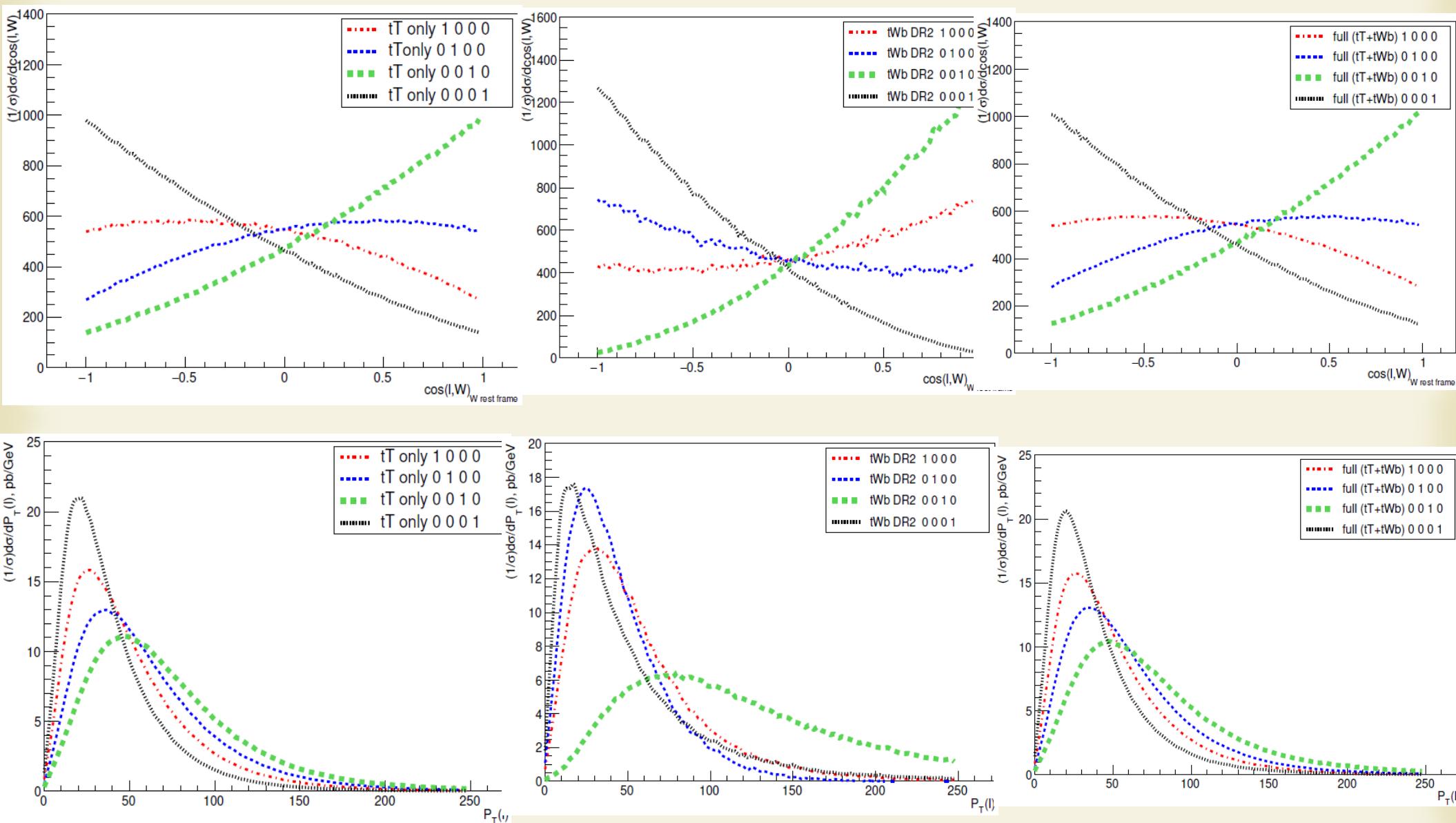


$L_V$	$R_V$	$L_T$	$R_T$
1	0	0	0
0	1	0	0
0	0	1	0
1	0	0	1

# Sensitivity of tW production to Wtb anomalous interactions

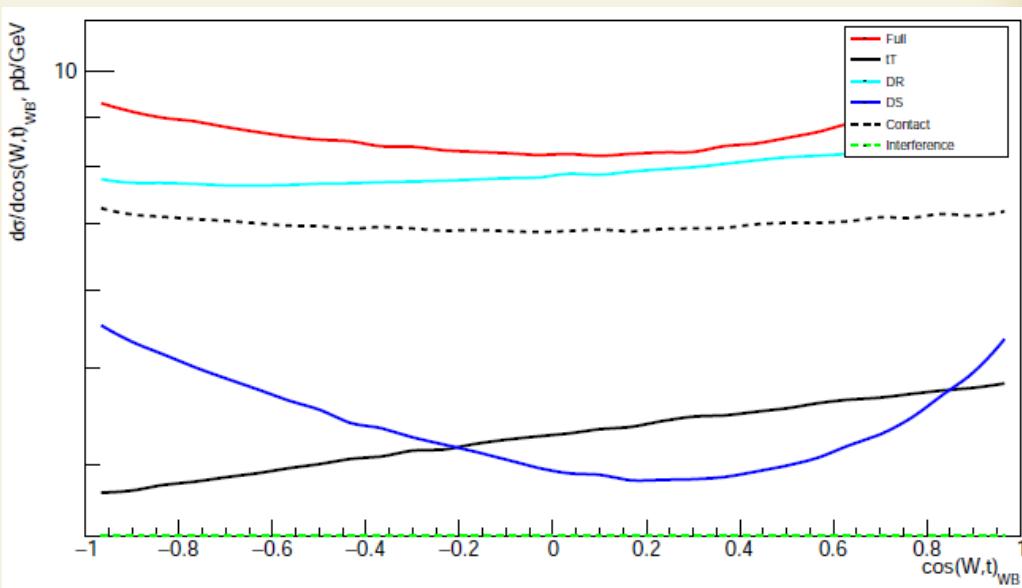
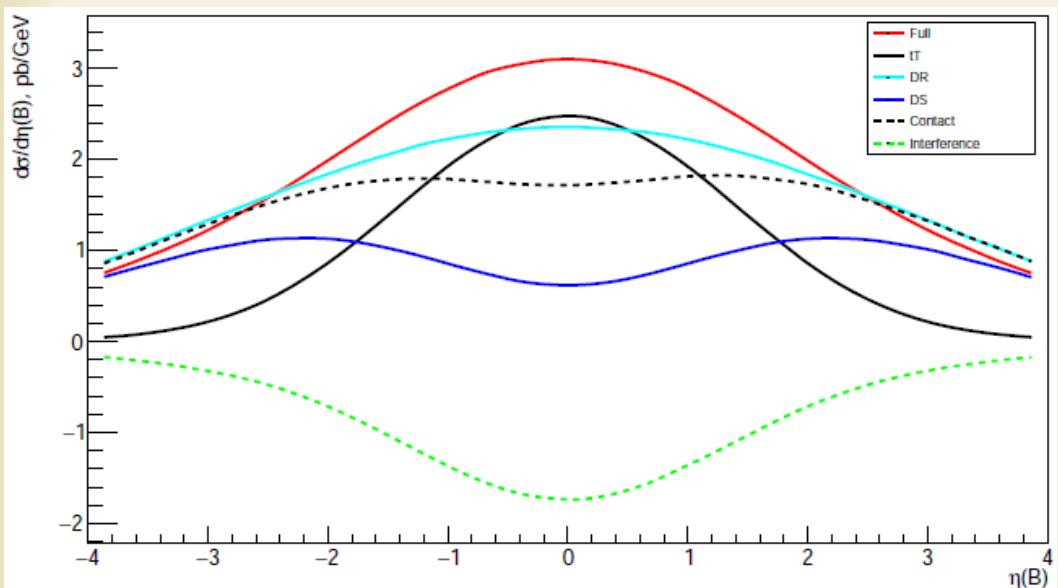
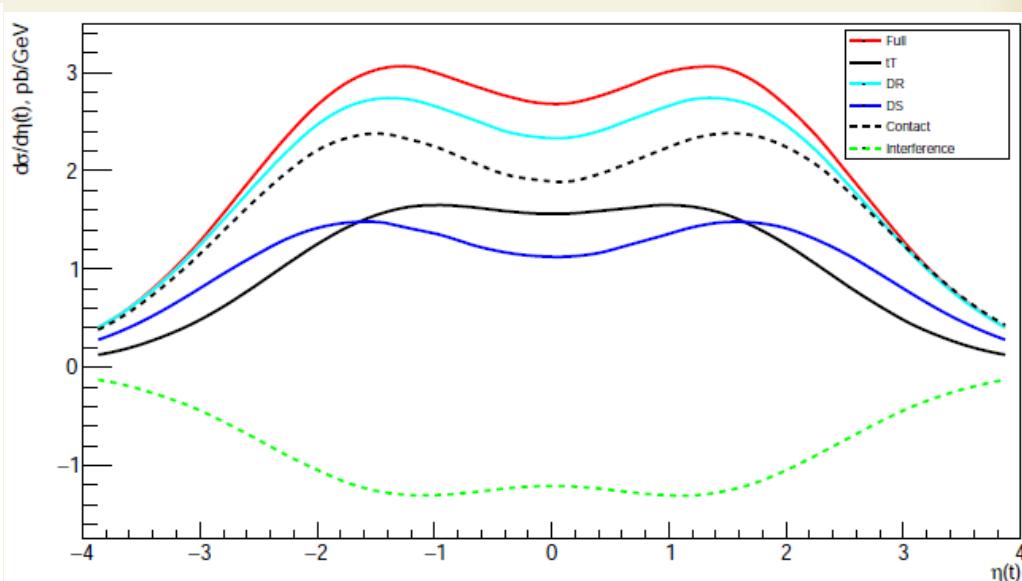
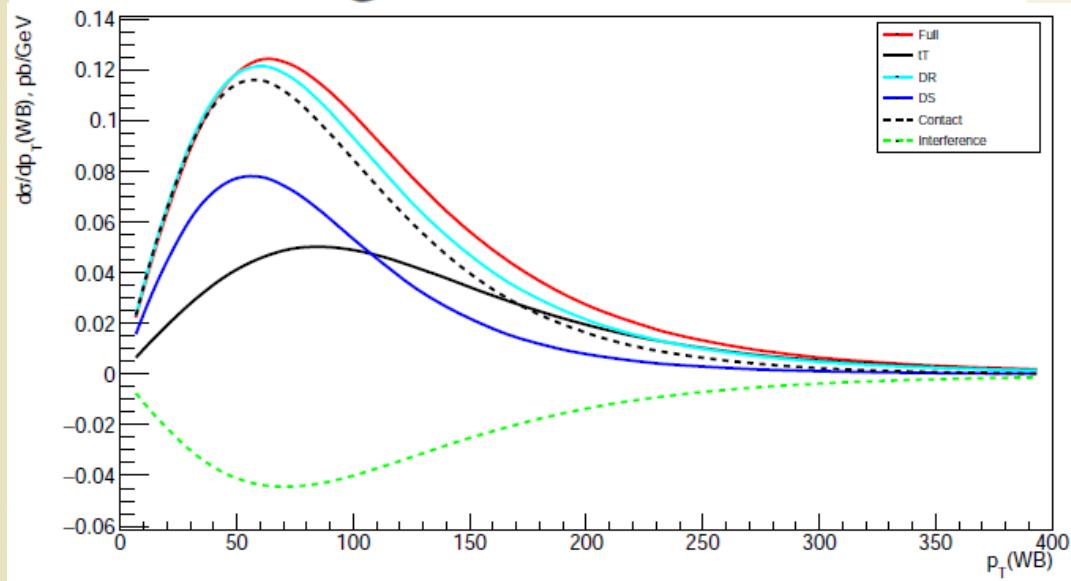


# Difference in ttbar, tW and full scheme sensitivity



# Kinematic separation of ttbar and tW contributions in full scheme simulation

excluded region  $145 < M_{Wb} < 200 \text{ GeV}$



# Prescription to search for anomalous Wtb interactions in tWb production processes

- ~ Simulate tWb SM and anomalous Wtb interactions in full scheme simulation (ttbar+interf+tW)
  - ~ Apply kinematic separation by efficient multivariate technique
    - prepare Deep Learning Neural Net (DNN) to separate ttbar and tW phase space regions DNN(ttbar-tW),
    - do not cut the output, but split regions (simulated events)
- ~ Prepare two additional DNNs sensitive to BSM:
  - DNN(ttbar\_region, SM/aWtb)
  - DNN(tW\_region, SM/aWtb)
- ~ Apply statistical analysis to 1 dimensional anomalous DNN discriminant (ttbar + tW regions), and set limits to the anomalous couplings

# Summary

- ~ It is impossible to search for anomalous Wtb interactions using approximate simulation schemes for tWb production
- ~ Need to simulate tWb process in full scheme ( $t\bar{t} + tW$ ) for SM and BSM contributions
- ~  $t\bar{t}$  and  $tW$  phase space regions of tWb are sensitive differently to BSM and require kinematic separation for the efficient search for BSM contribution
- ~ It is planned to implement the developed prescription in phenomenology analysis and in the search of CMS experiment (LHC)

# Back Up

# Production Cross Section

for  $s$ -channel:

$$\begin{aligned} \sigma(\hat{s})_{u\bar{d} \rightarrow t\bar{b}} = & \frac{\pi \cdot V_{ud}^2 \cdot \alpha^2}{24 \sin^4 \Theta_W} \cdot \frac{\beta^4 \cdot \hat{s}}{(\hat{s} - m_W^2)^2} \left[ (3 - \beta^2) \cdot (f_{LV}^2 + f_{RV}^2) \right. \\ & \left. + (3 - 2\beta^2) \cdot \frac{\hat{s}}{m_W^2} \cdot (f_{LT}^2 + f_{RT}^2) - \frac{6m_t}{m_W} \cdot (f_{LV} \cdot f_{RT} + f_{RV} \cdot f_{LT}) \right] \end{aligned}$$

for  $t$ -channel:

$$\begin{aligned} \sigma(\hat{s})_{ub \rightarrow td} = & \frac{\pi \cdot V_{ud}^2 \cdot \alpha^2}{4 \cdot \hat{s} \cdot \sin^4 \Theta_W} \left[ c_0 c_p \beta^4 \cdot f_{LV}^2 + ((-1 + c_1) \cdot \ln(a_1) + (2 + c_0) \cdot \beta^2) \cdot f_{RV}^2 \right. \\ & + ((2 + c_0) \cdot \ln(a_1) - (1 + c_1) \cdot c_0 c_p \beta^2) \cdot f_{RT}^2 + (c_1 \cdot \ln(a_1) - 2\beta^2) \cdot c_0 \beta^2 \cdot f_{LT}^2 \\ & \left. + \frac{2m_t}{m_W} \cdot ((-\ln(a_1) + c_p \beta^2) \cdot f_{LV} \cdot f_{RT}) + \frac{2m_t}{m_W} \cdot ((c_1 \cdot \ln(a_1) - 2\beta^2) \cdot f_{RV} \cdot f_{LT}) \right] \end{aligned}$$

$$\beta^2 = 1 - \frac{m_t^2}{\hat{s}}, \quad a_1 = 1 + \frac{\beta^2 \hat{s}}{m_W^2},$$

$$c_p = \frac{\hat{s}}{(\hat{s} - m_t^2 + m_W^2)},$$

$$c_0 = \frac{\hat{s}}{m_W^2}, \quad c_1 = \frac{2m_W^2}{\hat{s}} + \beta^2;$$

# Simulation of the anomalous Wtb contribution

- ~ Couplings are in the production and in the decay of top, (**LV, RV**)

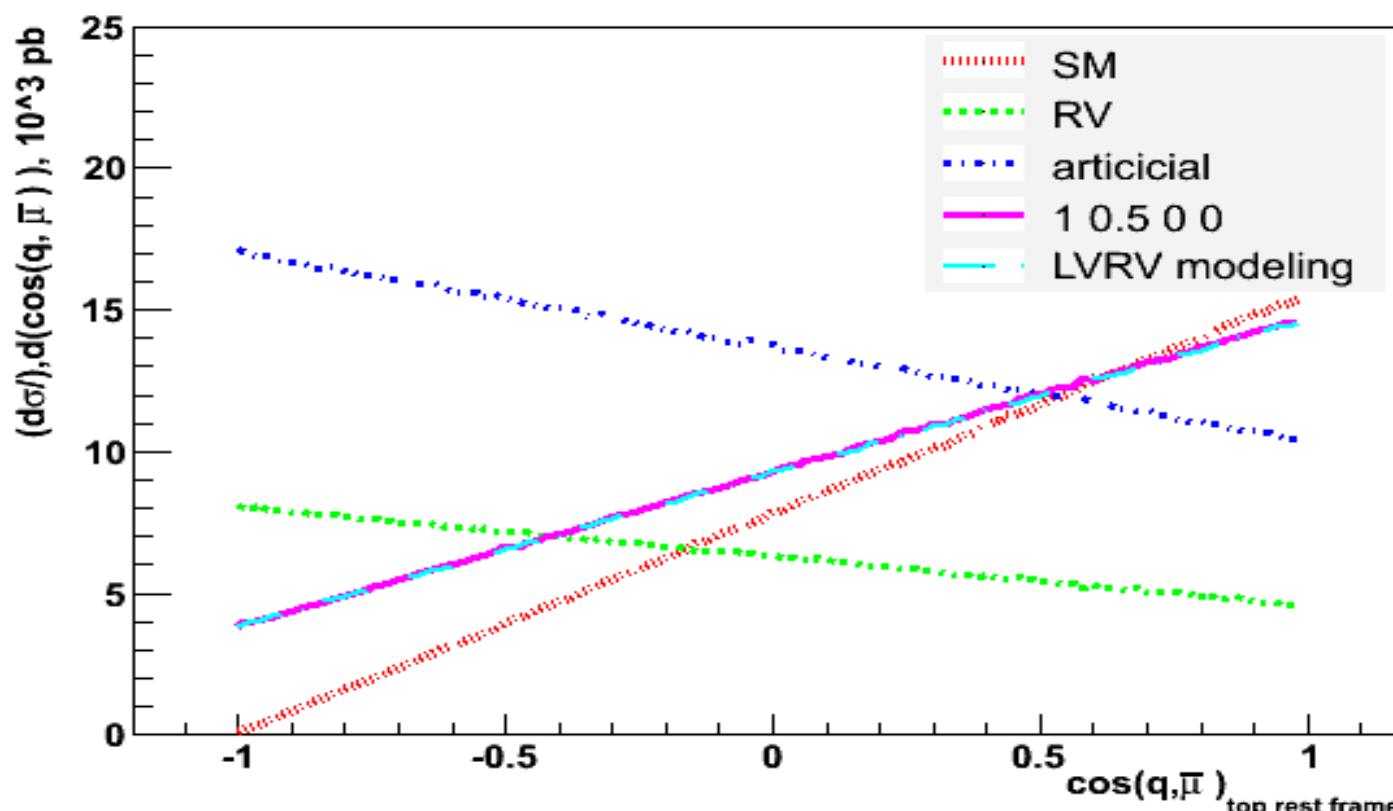
сценарий

$$\sigma_{\%prod+decay}(f_V^L \ f_V^R) = m \cdot (\text{SM}) + n \cdot (\text{artificial}) + k \cdot (0100)$$

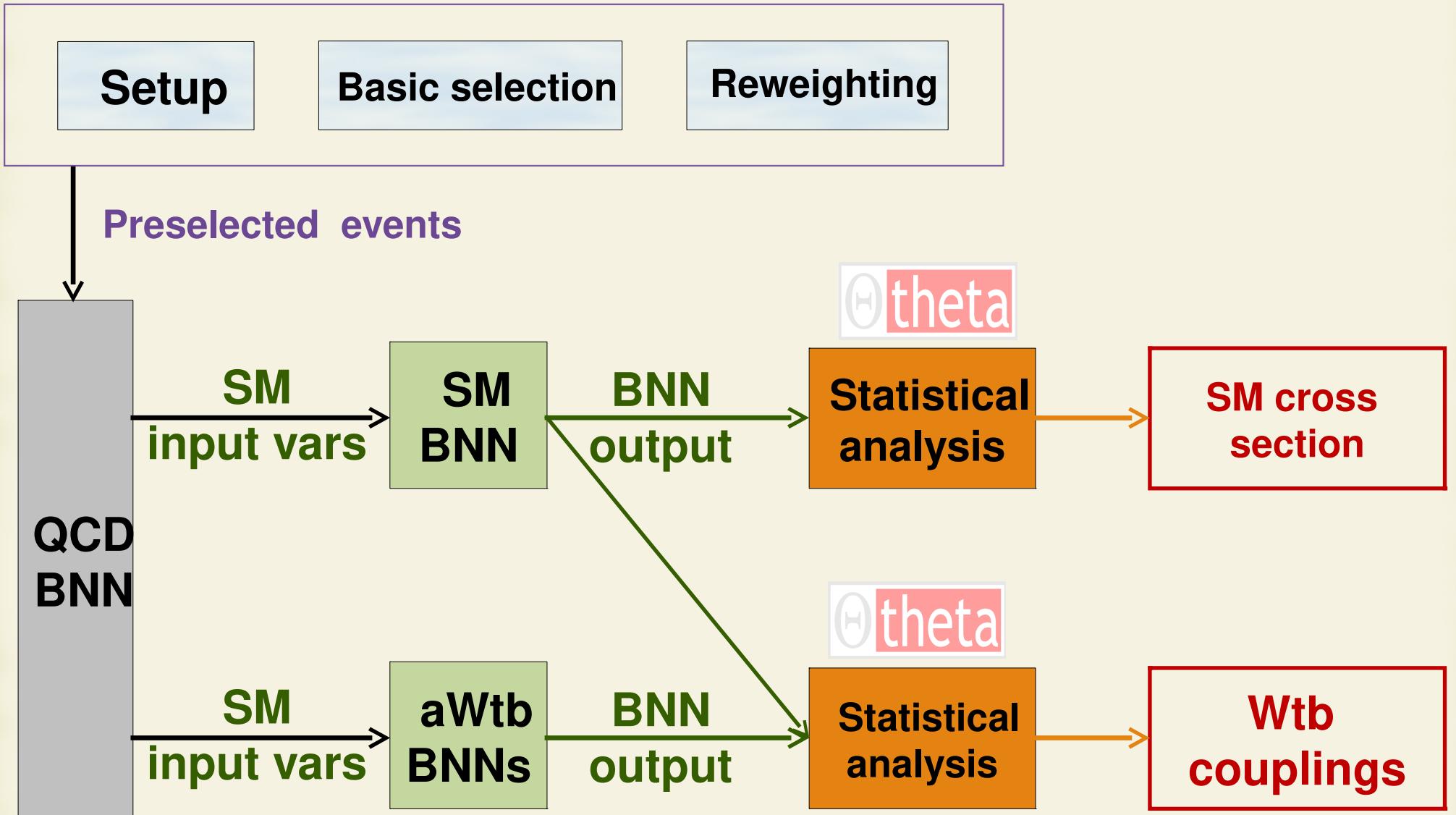
- ~ Correct simulation of kinematic properties for all possible values of the couplings, simulated with CompHEP

[Int.J.Mod.Phys. A32 \(2016\) 1750008](#)

$$\left. \begin{array}{l} m = (f_V^L)^4 \frac{w_{SM}}{w_{(f_V^L, f_V^R)}} \\ n = (f_V^L)^2 \cdot (f_V^R)^2 \frac{w_{art}}{w_{(f_V^L, f_V^R)}} \\ k = (f_V^R)^4 \frac{w_{0100}}{w_{(f_V^L, f_V^R)}} \end{array} \right\}$$



# Direct search for the anomalous Wtb couplings



# Anomalous couplings in W helicity fractions 10

The anomalous couplings could be obtained from partial width for the top decay into a W boson with -1 (left), 0 or +1 (right) helicity:

Eur.Phys.J.C50:519-533,2007

$$\Gamma_0 = W_0 \Gamma = \frac{g^2 |\vec{q}|}{32\pi} A_0 \quad \Gamma_{\pm} = W_{\pm} \Gamma = \frac{g^2 |\vec{q}|}{32\pi} (B_0 \pm 2 \frac{|\vec{q}|}{m_t} B_1)$$

Where

$$A_0 = \frac{m_t^2}{M_W^2} [|V_L|^2 + |V_R|^2] (1 - x_W^2) + [|g_L|^2 + |g_R|^2] (1 - x_W^2) \\ - 4x_b \operatorname{Re} [V_L V_R^* + g_L g_R^*] - 2 \frac{m_t}{M_W} \operatorname{Re} [V_L g_R^* + V_R g_L^*] (1 - x_W^2) \\ + 2 \frac{m_t}{M_W} x_b \operatorname{Re} [V_L g_L^* + V_R g_R^*] (1 + x_W^2) ,$$

$$B_0 = [|V_L|^2 + |V_R|^2] (1 - x_W^2) + \frac{m_t^2}{M_W^2} [|g_L|^2 + |g_R|^2] (1 - x_W^2) \\ - 4x_b \operatorname{Re} [V_L V_R^* + g_L g_R^*] - 2 \frac{m_t}{M_W} \operatorname{Re} [V_L g_R^* + V_R g_L^*] (1 - x_W^2) \\ + 2 \frac{m_t}{M_W} x_b \operatorname{Re} [V_L g_L^* + V_R g_R^*] (1 + x_W^2) ,$$

$$B_1 = - [|V_L|^2 - |V_R|^2] + \frac{m_t^2}{M_W^2} [|g_L|^2 - |g_R|^2] + 2 \frac{m_t}{M_W} \operatorname{Re} [V_L g_R^* - V_R g_L^*] \\ + 2 \frac{m_t}{M_W} x_b \operatorname{Re} [V_L g_L^* - V_R g_R^*] ,$$

$$f_V^{L,R} = \operatorname{Re}(V_{L,R})$$

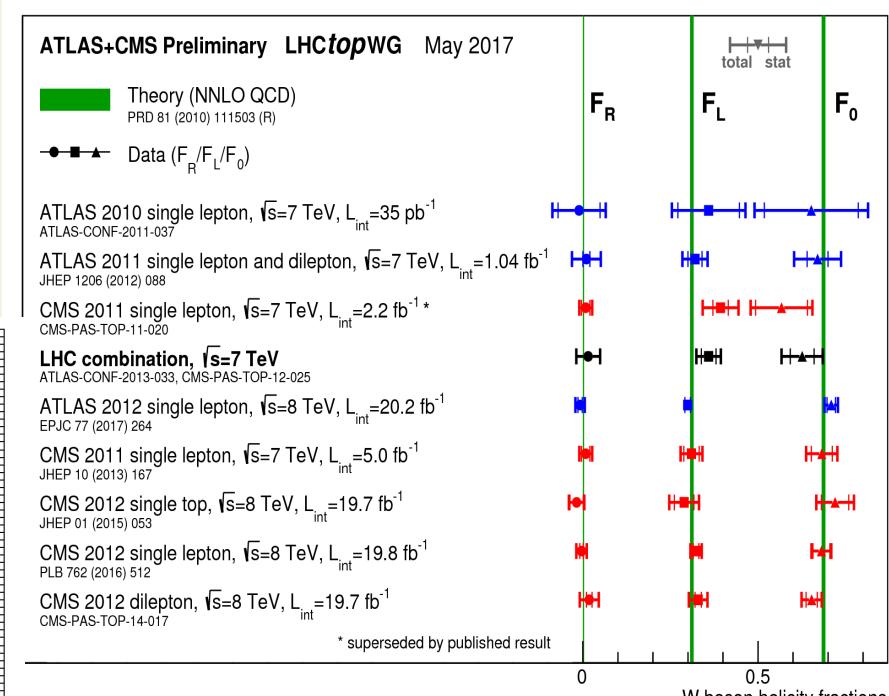
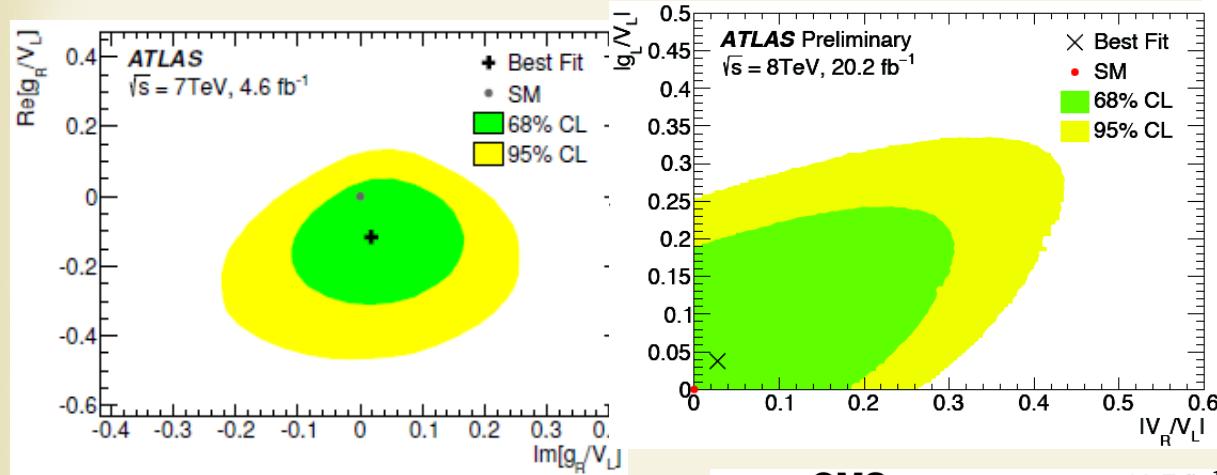
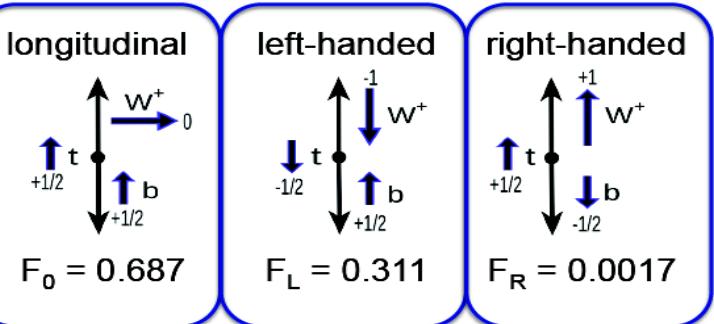
$$f_T^{L,R} = \operatorname{Re}(g_{L,R})$$

If CP is conserved, the  
couplings could be taken as real

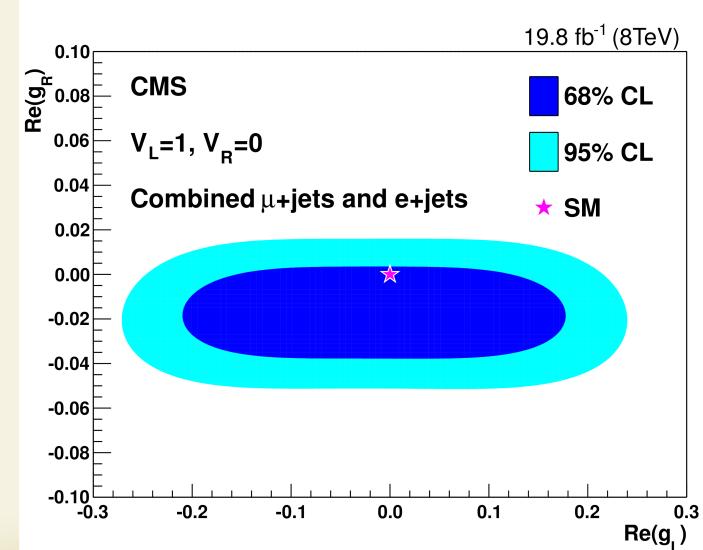
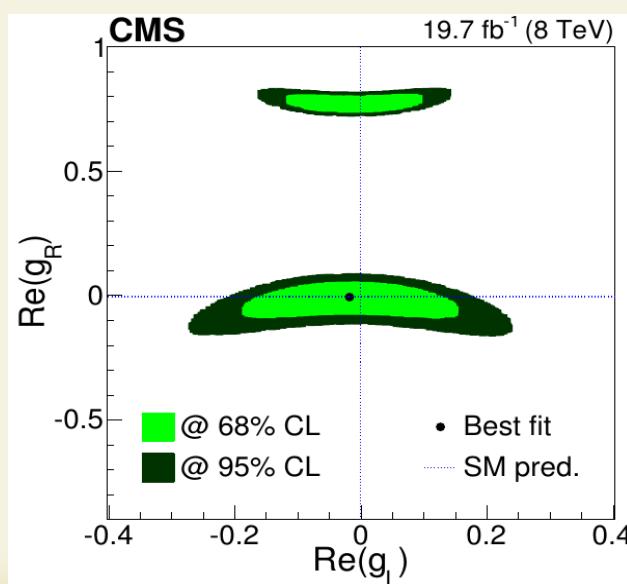
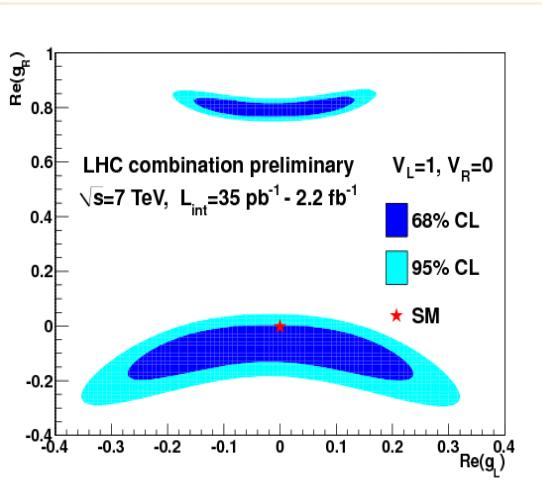
$$x_W = M_W/m_t$$

$$x_b = m_b/m_t$$

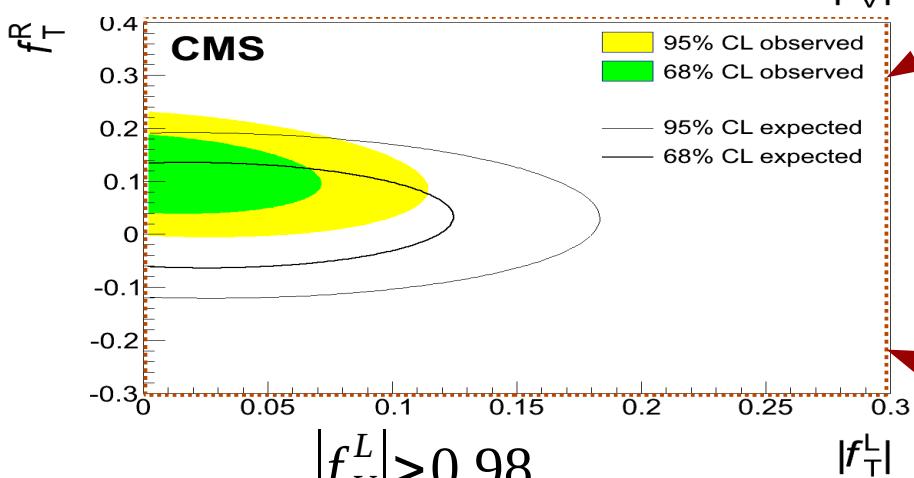
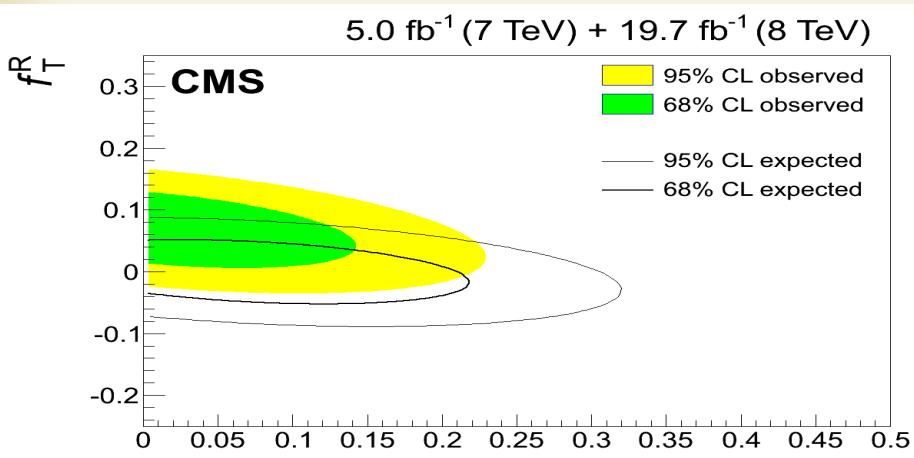
# W helicity, top polarisation and Wtb



$\text{Im } g_R \in [-0.18, 0.06]$



# Comparison of the direct search and W helicity in single top



$$\begin{aligned} |f_V^L| &> 0.98, \\ |f_V^R| &< 0.16, \\ |f_T^L| &< 0.057, \\ -0.049 &< f_T^R < 0.048 \end{aligned}$$

[JHEP 02 \(2017\) 028](#)

