Implication of the Subsidiary Fields Method to the Modeling of the Top Pair and Single Top Production Processes with Anomalous Wtb couplings

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three quarks generation

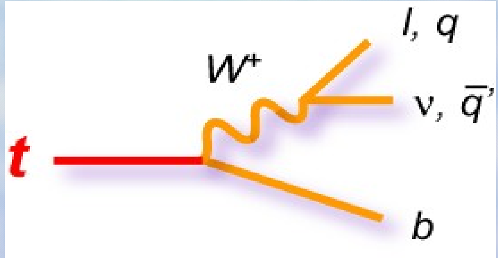
u	**c**	**t**
d	**s**	**b**

(V-A) interaction vertex

$$\Gamma_{tqW} = -\frac{g}{\sqrt{2}} V_{tq} \bar{q} \gamma_{\mu} \frac{1}{2}\left(1 - \gamma_5\right) W^{\mu} t$$

t-quark in SM

Decay mode (~100%):



$$M_{top} = 172.9\,\mathrm{GeV}$$
$$(\mathrm{PDG}, 2019)$$

...top quark is a good candidate for testing the SM...

Specificies of the single top quark production

SM

BSM

$$L_{Wtb} = -\frac{g}{\sqrt{2}} V_{tb}\,\bar{b}\,\gamma^{\mu}\,\frac{1}{2}\cdot 1\cdot(1-\gamma_5)\,t\,W_{\mu}$$

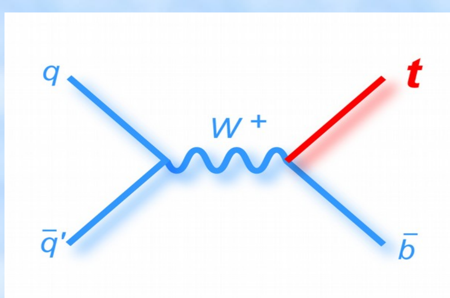
Deviations from the SM:

New particles in the single top production → W'

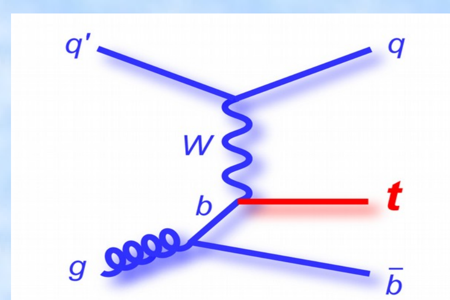
Modification of predicted by the SM values of top couplings to another particles → Anomalous Wtb couplings; FCNC

Single top quark production processes

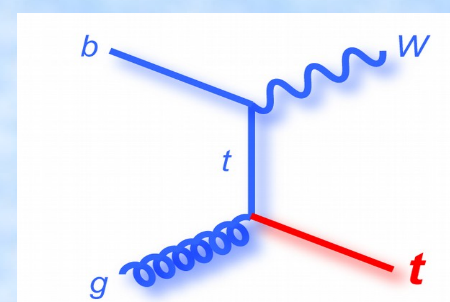
$\mathbf{p},\ \mathbf{p}(\bar{\mathbf{p}})$ →



s-channel



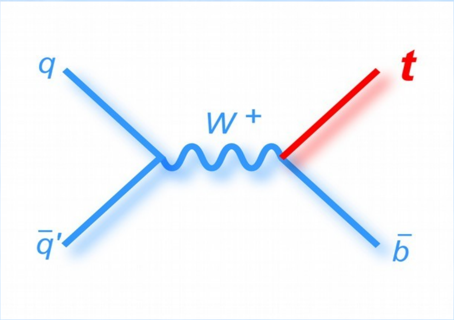
t-channel



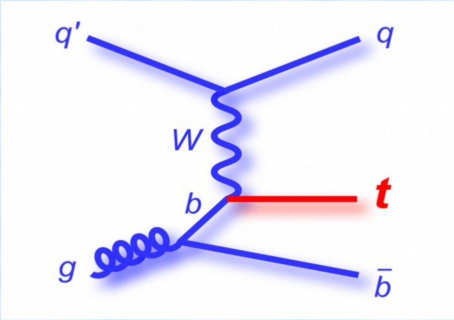
tW-channel

Single Top quark production Cross Sections

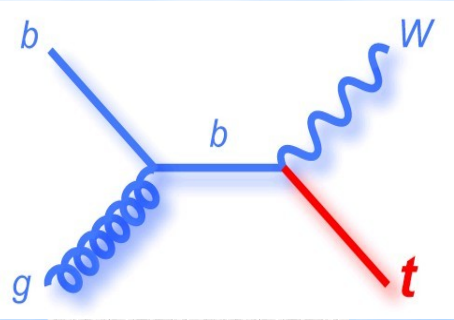
s-channel



t-channel



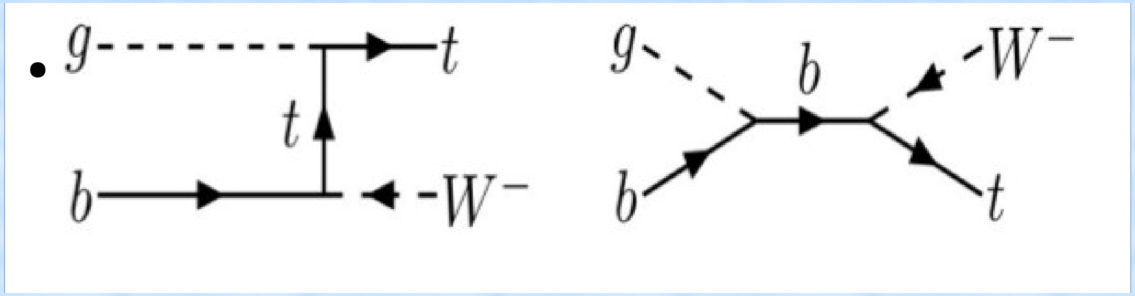
tW production



	Tevatron	*LHC 8 TeV*	*LHC 13 TeV*	*LHC 14 TeV*	*Current status*
s-channel	1.05	5.24	10.32	11.39	Tevatron s-channel observation
t-channel	2.08	84.69	217	248	TEVATRON observation ATLAS t-channel observation
tW production	0.28	22.37	71.7	84.4	CMS Observation @8TeV ATLAS and CMS combination

Double top and single top production

- Leading order (**LO**) process 2→2: **tW**-production



- Next to leading order (**NLO**), O(1/log(mt/mb)), 2→3: **tWb**-production

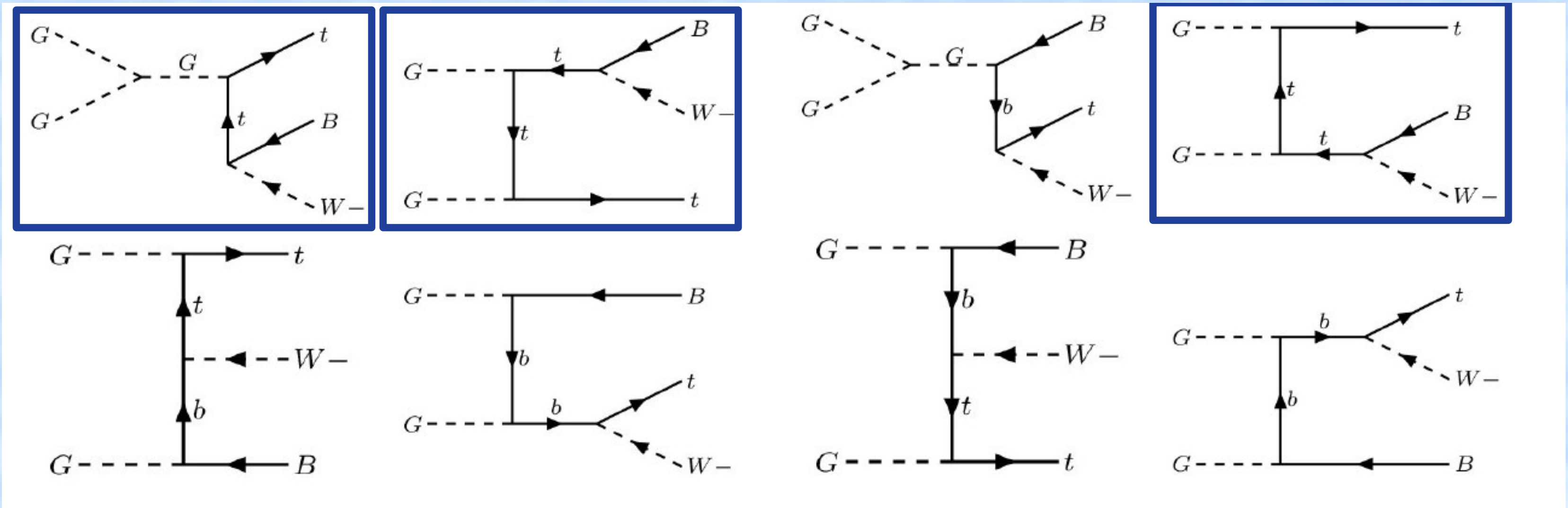
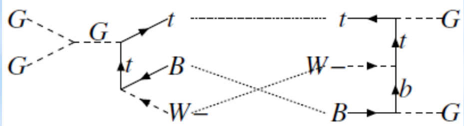
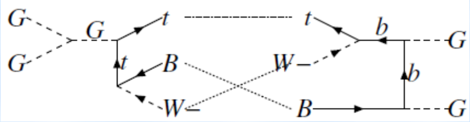


Figure 1: Diagrams for the process $gg \to t\bar{b}W^-$.

Top pair (tT) production

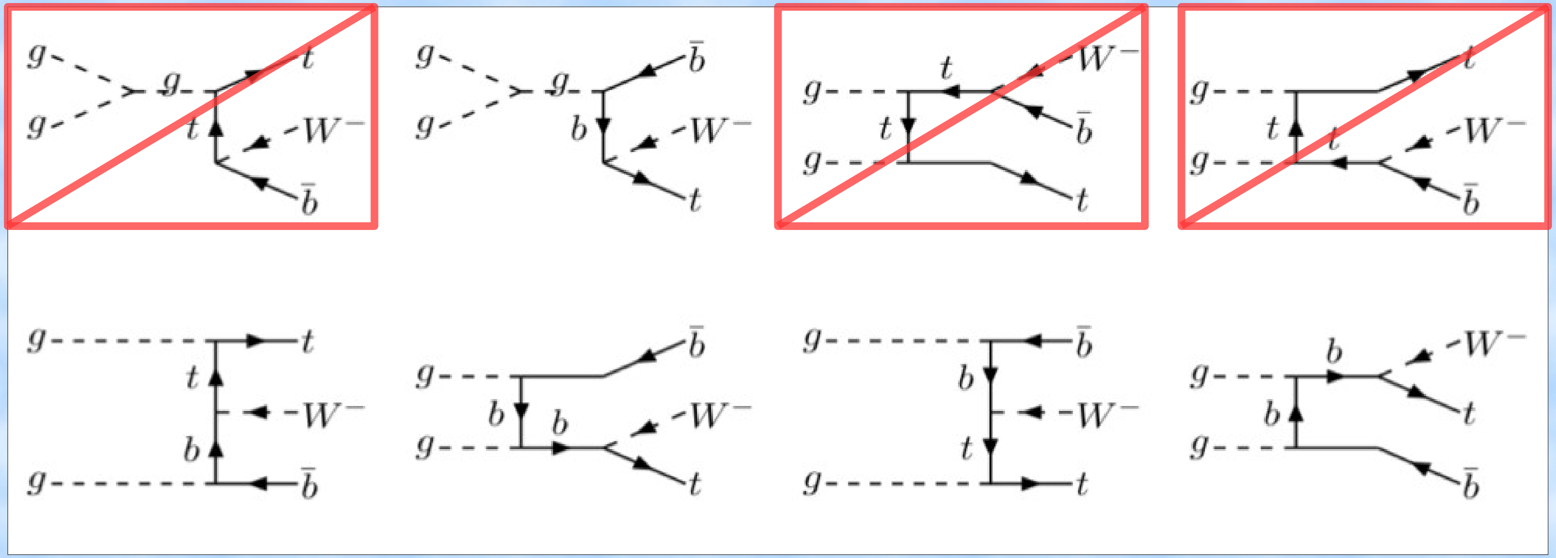
- Squared matrix element structure

|ME|^2 ~ tT^2 +  ...  + tWb^2

ATLAS CS measurements

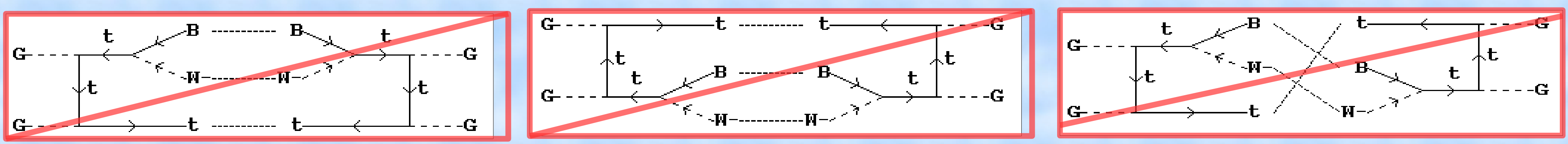
Different schemes for tWb processes highlighting

DR1 (Diagram removal scheme) S. Frixione et al., arXiv:0805.3067.



~~t t-bar production~~

DR2 (Diagram subtraction Scheme)
T. M. P. Tait, arXiv:hep-ph/9909352



DS1, DS2 schemes [arXiv:1607.05862]

- introduction of the local subtraction term:
  - *cancel the ME from double top production*
  - *gauge invariant*
  - *decrease quickly away from the resonant region*

$$|\mathcal{A}_{tWb}|^2_{\rm DS} = |\mathcal{A}_{1t} + \mathcal{A}_{2t}|^2 - \mathcal{C}_{2t}$$

EFT and Anomalous Couplings approach

- **Effective Field Theory** approach:

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

J. Aguilar-Saavedra, arXiv:1008.3225

- operators that contribute to the Wtb vertex:

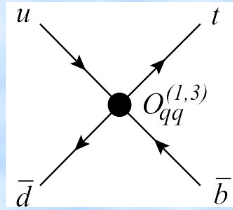
$$O_{\phi q}^{(3)} = i(\phi^+ \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$$

$$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G^A_{\mu\nu} \qquad O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W^I_{\mu\nu}$$

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

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

Zhang, Willenbrock



- **Anomalous Couplings** approach:

$$\mathcal{L} = \frac{g}{\sqrt{2}} \bar{b}\gamma^\mu V_{tb}(f_V^L P_L + f_V^R P_R) t W^-_\mu - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu V_{tb}}{M_W} (f_T^L P_L + f_T^R P_R) t W^-_\mu + h.c.$$

order: $1/\Lambda^2$	$1/\Lambda^4$
f_V^L	$(f_V^L)^2$
...	$(f_V^R)^2$
...	$(f_T^L)^2$
f_T^R	$(f_T^R)^2$

- Translation:

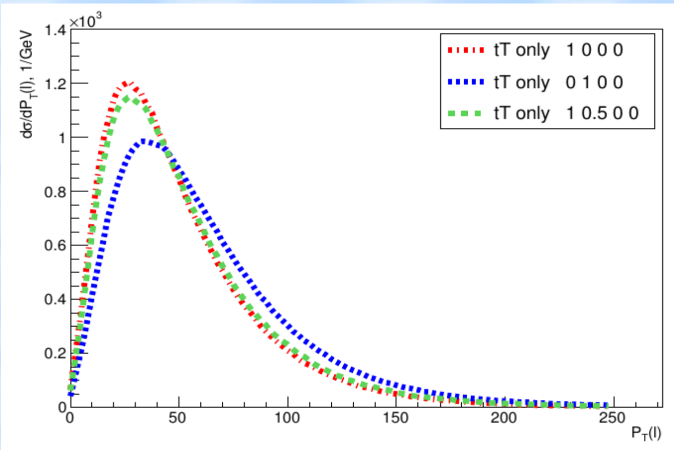
$$|f_V^L| = 1 + |C_{\phi q}| \frac{v^2}{V_{tb}\Lambda^2} \qquad |f_V^R| = \frac{1}{2}|C_{\phi\phi}| \frac{v^2}{V_{tb}\Lambda^2}$$

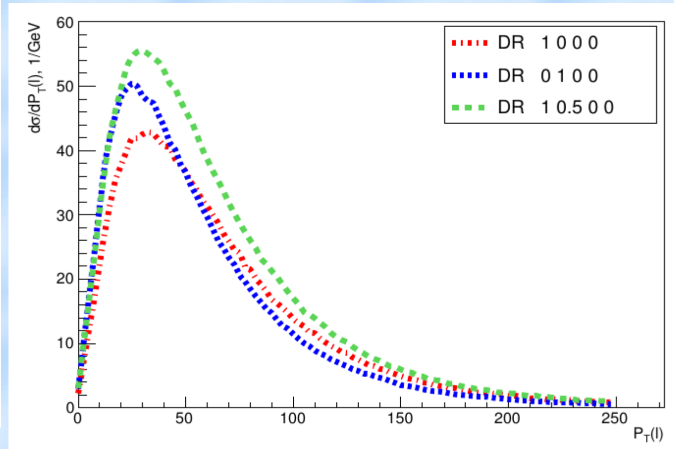
$$|f_T^L| = \sqrt{2}|C_{bW}| \frac{v^2}{V_{tb}\Lambda^2} \qquad |f_T^R| = \sqrt{2}|C_{tW}| \frac{v^2}{V_{tb}\Lambda^2}$$

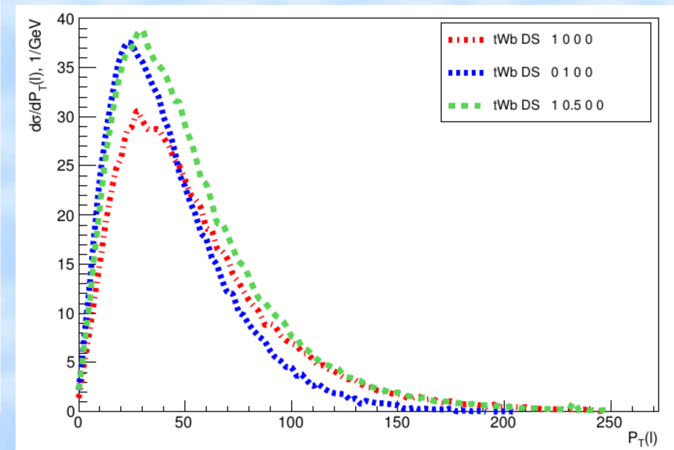
$$\sigma \propto A\cdot(f_1^L)^2 + B\cdot(f_1^R)^2 + C\cdot(f_1^L \cdot f_2^R) + D\cdot(f_1^R \cdot f_2^L) + E\cdot(f_2^L)^2 + G\cdot(f_2^R)^2$$

Schemes for tW processes highlighting (2)

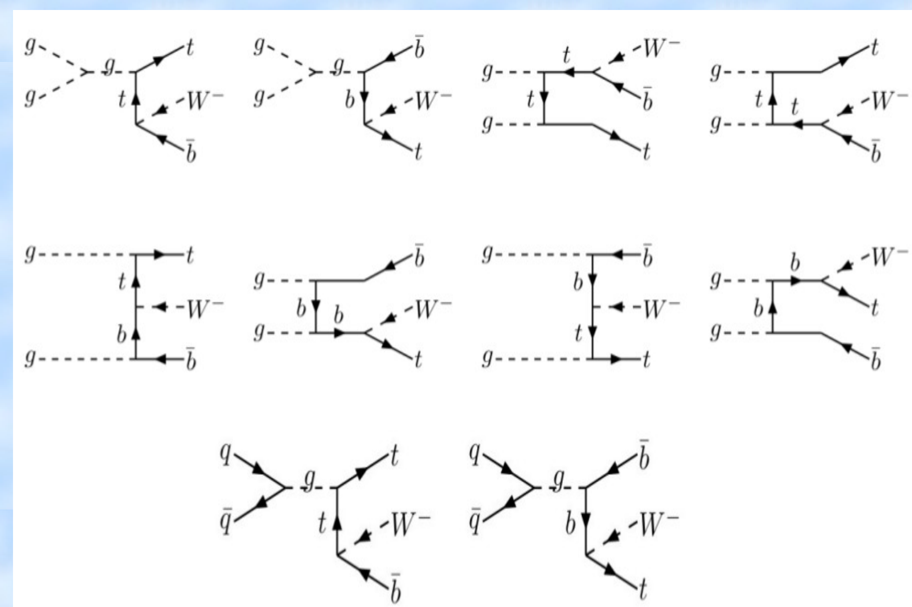
- What"s the most preferable scheme of tW highlighting for the AnomWtb couplings searches?







EPJ Web Conf., 158 (2017) 04004



- different schemes of tW highlighting have different sensitivity to the anomalous coupling
- top pair production is also sensitive to the anomalous Wtb couplings
- It's more preferable to use **full gauge-invariant set of diagrams** (without any sets deletion)

AnomWtb: CMS analysis

- «Search for new physics in top quark production in dilepton final states in proton-proton collisions at$\sqrt{s}$= 13 TeV»

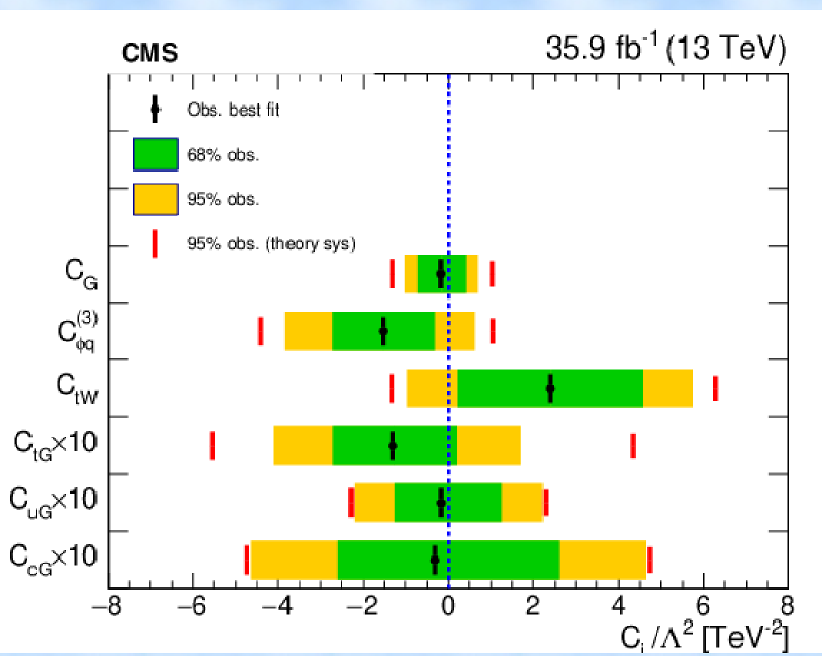
  - dilepton final state

  - EFT effects in the top quark production, not in the decay

  - the rates of tW and tT production are used to probe the $C_{\phi q}^{(3)}, C_{tW}, C_{tG}, C_G$

  - variations in both rate and kinematic distributions: C_{uG}, C_{cG}

[Eur. Phys. J. C 79 (2019) 886]()

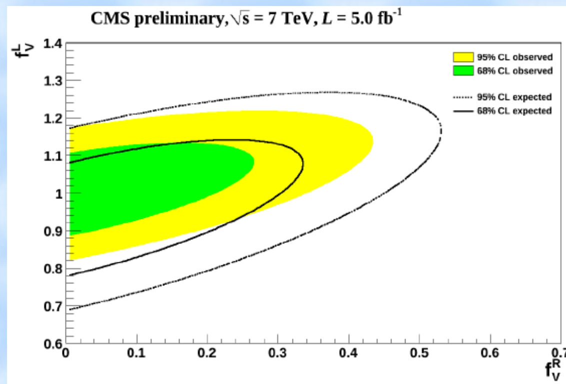


Effective coupling	Channel	Observed [TeV^{-2}] Best fit	[68% CI]	[95% CI]	Expected [TeV^{-2}] Best fit	[68% CI]	[95% CI]
C_G/Λ^2	ee	−0.14	[−0.82, 0.51]	[−1.14, 0.83]	0.00	[−0.90, 0.59]	[−1.20, 0.88]
	eμ	−0.18	[−0.73, 0.42]	[−1.01, 0.70]	0.00	[−0.82, 0.51]	[−1.08, 0.77]
	$\mu\mu$	−0.14	[−0.75, 0.44]	[−1.06, 0.75]	0.00	[−0.88, 0.57]	[−1.16, 0.85]
	Combined	−0.18	[−0.73, 0.42]	[−1.01, 0.70]	0.00	[−0.82, 0.51]	[−1.07, 0.76]
$C_{\phi q}^{(3)}/\Lambda^2$	ee	1.12	[−1.18, 2.89]	[−4.03, 4.37]	0.00	[−2.53, 1.74]	[−6.40, 3.27]
	eμ	−0.70	[−2.16, 0.59]	[−3.74, 1.61]	0.00	[−1.34, 1.12]	[−2.57, 2.15]
	$\mu\mu$	1.13	[−0.87, 2.86]	[−3.58, 4.46]	0.00	[−2.20, 1.92]	[−4.68, 3.66]
	Combined	−1.52	[−2.71, −0.33]	[−3.82, 0.63]	0.00	[−1.05, 0.88]	[−2.04, 1.63]
C_{tW}/Λ^2	ee	6.18	[−3.02, 7.81]	[−4.16, 8.95]	0.00	[−2.02, 6.81]	[−3.33, 8.12]
	eμ	1.64	[−0.80, 5.59]	[−1.89, 6.68]	0.00	[−1.40, 6.19]	[−2.39, 7.18]
	$\mu\mu$	−1.40	[−3.00, 7.79]	[−4.23, 9.01]	0.00	[−2.18, 6.97]	[−3.63, 8.42]
	Combined	2.38	[0.22, 4.57]	[−0.96, 5.74]	0.00	[−1.14, 5.93]	[−1.91, 6.70]
C_{tG}/Λ^2	ee	−0.19	[−0.40, 0.02]	[−0.65, 0.22]	0.00	[−0.22, 0.21]	[−0.44, 0.41]
	eμ	−0.03	[−0.19, 0.11]	[−0.34, 0.27]	0.00	[−0.17, 0.15]	[−0.34, 0.29]
	$\mu\mu$	−0.15	[−0.34, 0.02]	[−0.53, 0.19]	0.00	[−0.19, 0.18]	[−0.40, 0.35]
	Combined	−0.13	[−0.27, 0.02]	[−0.41, 0.17]	0.00	[−0.15, 0.14]	[−0.30, 0.28]
C_{uG}/Λ^2	ee	−0.017	[−0.22, 0.22]	[−0.37, 0.37]	0.00	[−0.29, 0.29]	[−0.42, 0.42]
	eμ	−0.017	[−0.17, 0.17]	[−0.29, 0.29]	0.00	[−0.26, 0.26]	[−0.38, 0.38]
	$\mu\mu$	−0.017	[−0.17, 0.17]	[−0.29, 0.29]	0.00	[−0.27, 0.27]	[−0.38, 0.38]
	Combined	−0.017	[−0.13, 0.13]	[−0.22, 0.22]	0.00	[−0.21, 0.21]	[−0.30, 0.30]
C_{cG}/Λ^2	ee	−0.032	[−0.47, 0.47]	[−0.78, 0.78]	0.00	[−0.63, 0.63]	[−0.92, 0.92]
	eμ	−0.032	[−0.34, 0.34]	[−0.60, 0.60]	0.00	[−0.56, 0.56]	[−0.81, 0.81]
	$\mu\mu$	−0.032	[−0.36, 0.36]	[−0.63, 0.63]	0.00	[−0.58, 0.58]	[−0.84, 0.84]
	Combined	−0.032	[−0.26, 0.26]	[−0.46, 0.46]	0.00	[−0.46, 0.46]	[−0.65, 0.65]

AnomWtb couplings search at CMS

- CMS Single Top group used this approach for the experimental searches for the Anomalous contribution to the Wtb vertex arXiv:1610.03545
- Results: 2D and 1D limits on the Anomalous Wtb couplings for 3 scenarios: (Lv,Rv), (Lv,Lt), (Lv, Rt)

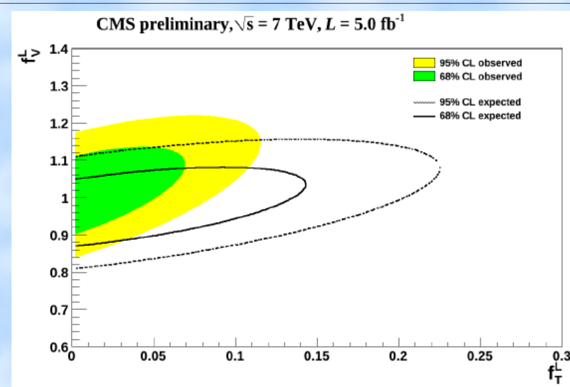
$(L_V\ R_V)$



$|L_V| > 0.97\ (0.92)$

$|R_V| < 0.28\ (0.31)$

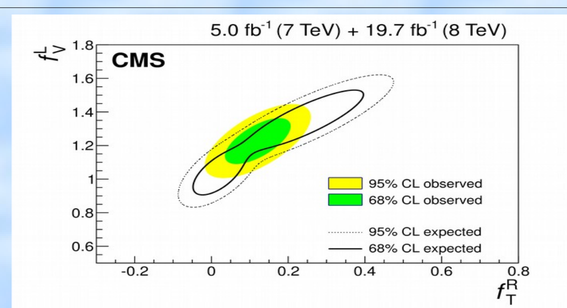
$(L_V\ L_T)$



$|L_V| > 0.92\ (0.92)$

$|L_T| < 0.10\ (0.14)$

$(L_V\ R_T)$



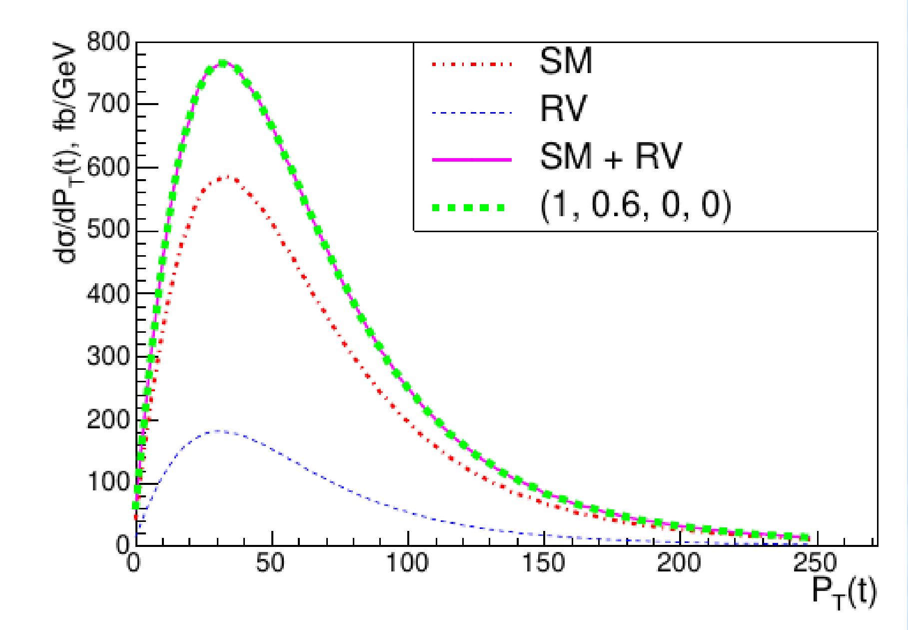
$|L_V| > 0.94\ (0.93)$

$-0.046\ (-0.050) < |R_T| < 0.046\ (0.041)$

Anomalous Wtb in single top production and decay

(Lv, Rv) scenario:

$$\mathfrak{L} = \frac{g}{\sqrt{2}} \bar{b} \gamma^{\mu} \left(f_V^L P_L + f_V^R P_R \right) t W_{\mu}^{-}$$



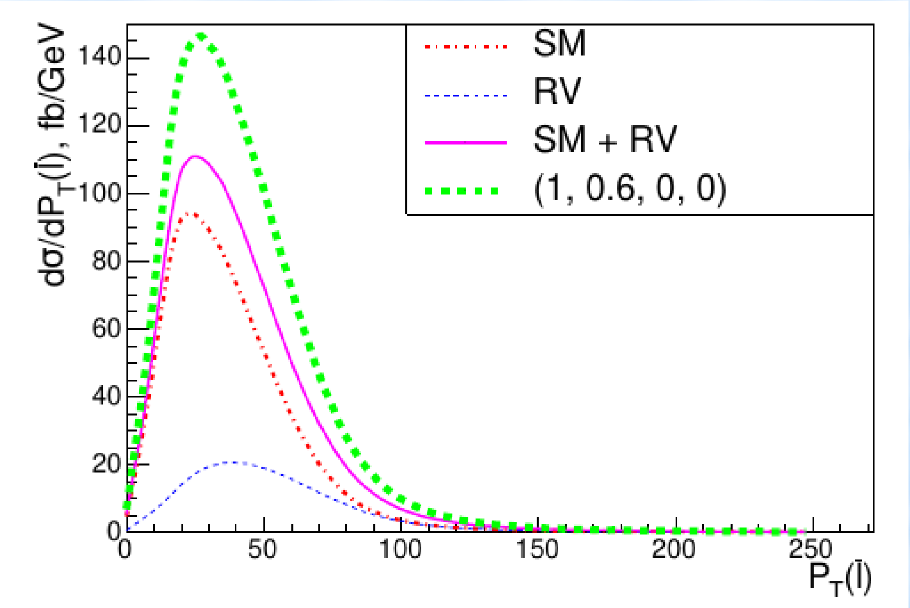
Pt (top) distributions for L_V=1, R_V=0.6

Production case:

$$\left(f_V^L, f_V^R, 0, 0\right) = \underbrace{\left(f_V^L\right)^2 \cdot (1000)}_{\text{SM}} + \underbrace{\left(f_V^R\right)^2 \cdot (0100)}_{\text{RV}}$$

Production+decay case:

$$\left(f_V^L, f_V^R, 0, 0\right) \neq \underbrace{\left(f_V^L\right)^2 \cdot (1000)}_{\text{SM}} + \underbrace{\left(f_V^R\right)^2 \cdot (0100)}_{\text{RV}}$$

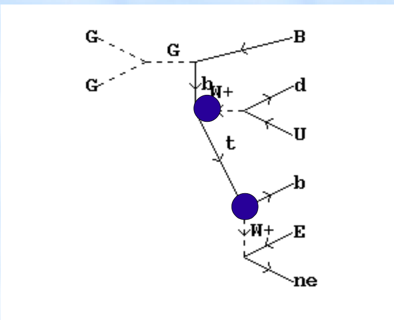


Pt (lepton from top decay) distributions for L_V=1, R_V=0.6

Anomalous Wtb, (Lv,Rv) scenario, MC modeling for tT+tW

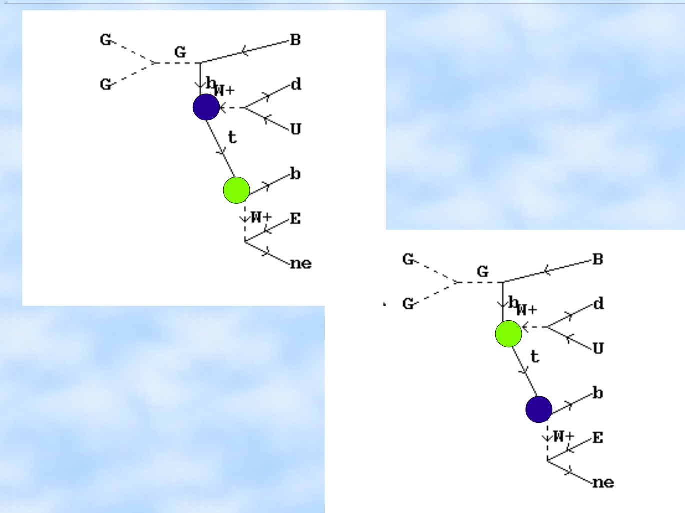
- Production+decay case, (L_V , R_V) scenario
- Modeling the general L_V and R_V dependence for tT+tW:

the sets of MC events:



L_V=1, R_V=0 in both Wtb vertices; $w_{top} = w_{1000}$

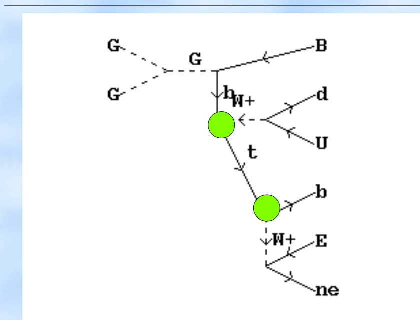
«SM»



L_V=1, R_V=0 in production Wtb vertex and

L_V=0, R_V=1 in decay Wtb vertex and vise versa

«LVRVsubs» $w_{top} = w_{subs}$



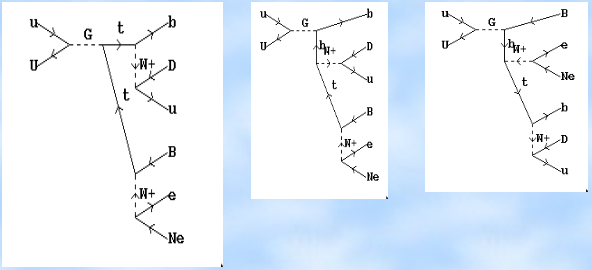
L_V=0, R_V=1 in both Wtb vertices; $w_{top} = w_{0100}$

«RV»

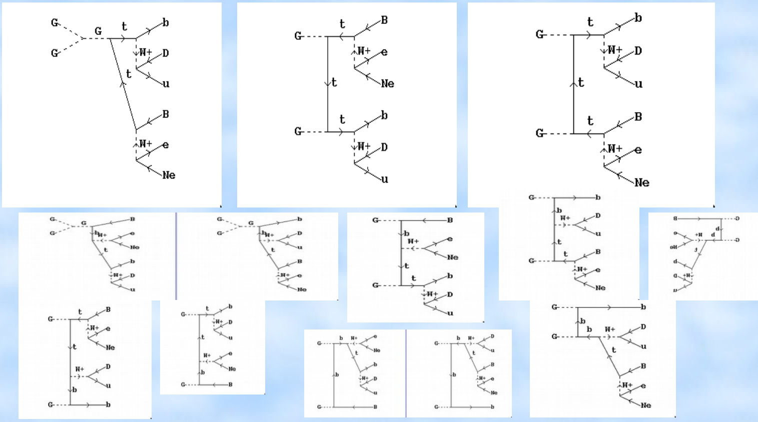
arXiv:1607.00505

Subsidiary fields method for tT+tW

- q,q -> Ne,e,u,D,b,B



- G,G -> Ne,e,u,D,b,B

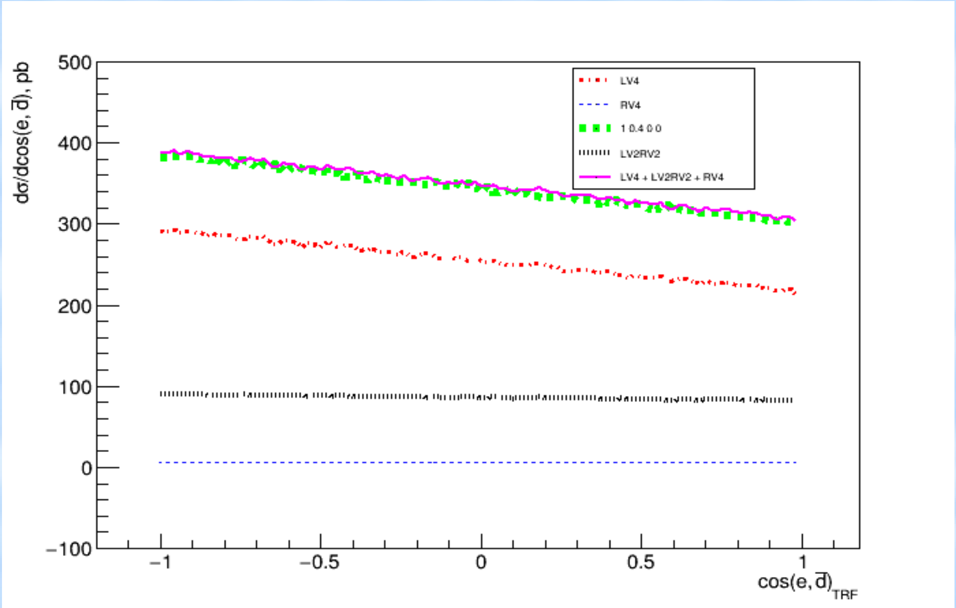


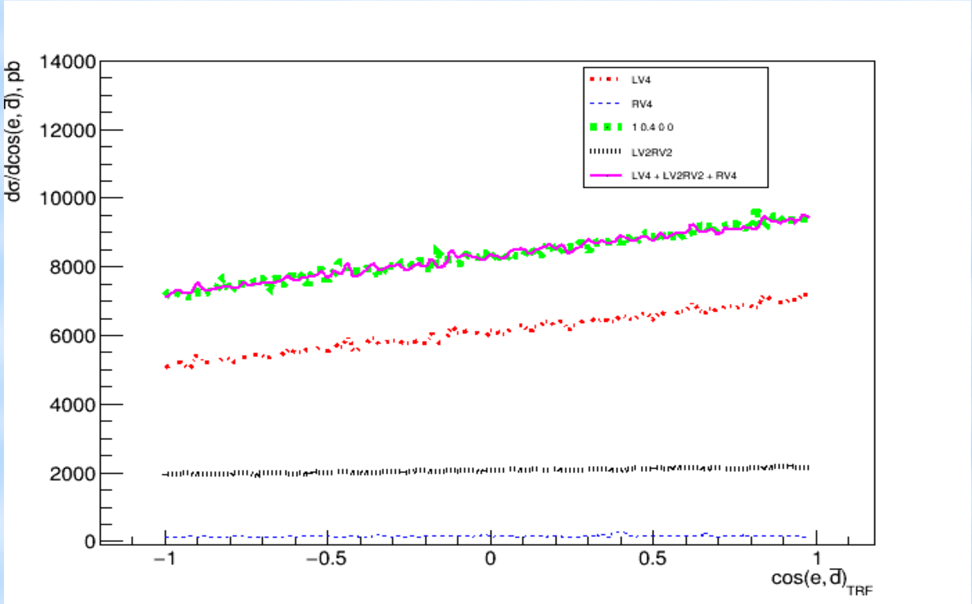
$$\sigma(L_V, R_V) = (LV\,4) + (LV\,2\,RV\,2) + (RV\,4)$$

$$LV\,4 = (L_V)^4 \left(\frac{w_{SM}}{w_{(L_V,R_V)}}\right)^2 * SM$$

$$LV\,2\,RV\,2 = (L_V)^2 \cdot (R_V)^2 \left(\frac{w_{SM}}{w_{(L_V,R_V)}}\right)^2 * LVRV_{subs}$$

$$RV\,4 = (R_V)^4 \left(\frac{w_{SM}}{w_{(L_V,R_V)}}\right)^2 * RV$$





Conclusion

- LHC has significant potential for single top production in association with W-boson processes study
- Anomalous contribution to the Wtb vertex in tW processes hasn"t been studied far and wide so far
- Different schemes of the tW processes highlighting have different sensitivity to the AnomWtb couplings and t's more preferable to use full set of the diagrams for tT+tW processes for the Anomalous Wtb couplings searches
- The modeling of the full set of the diagrams for tT+tW processes with Anomalous Wtb couplings is performed with Subsidiary Fields Method
- Necessary set of generated events for CMS analysis is ready
- First direct constraints on the Anomalous Wtb couplings in tT and tW processes will be provided by statistical analysis

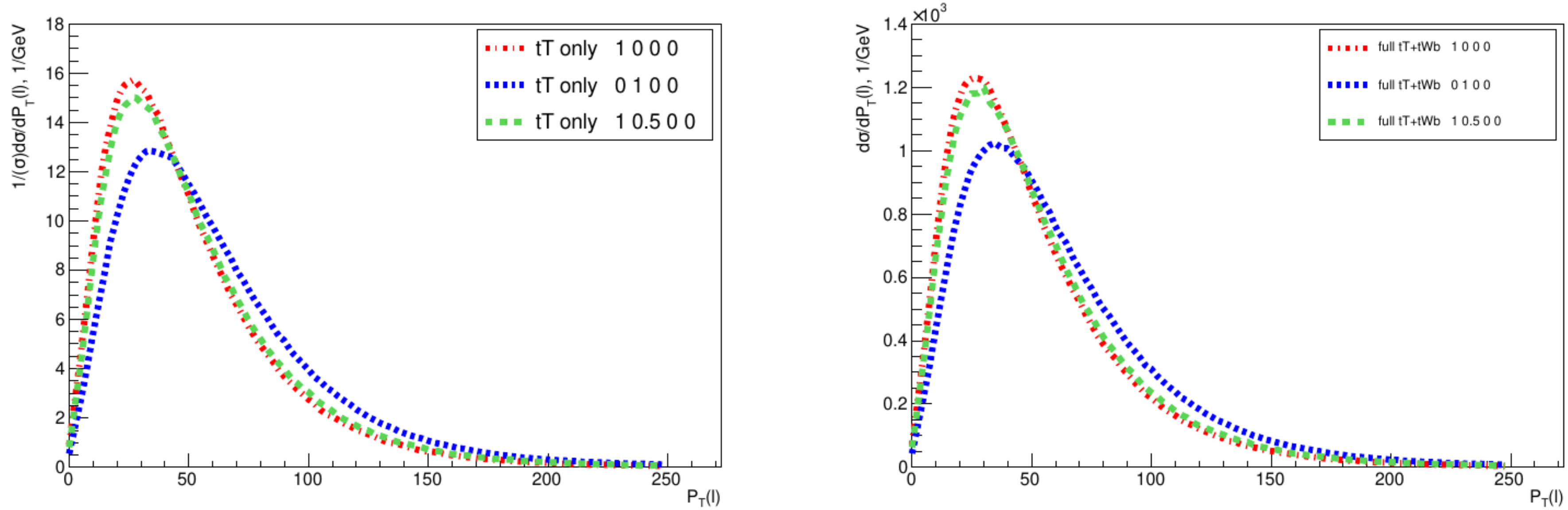


Figure 2: Transverse momentum of a lepton from $W-$boson decay for double top production (left) and for full set of diagrams from Fig.1 (right) for different values of anomalous Wtb couplings values from (1)

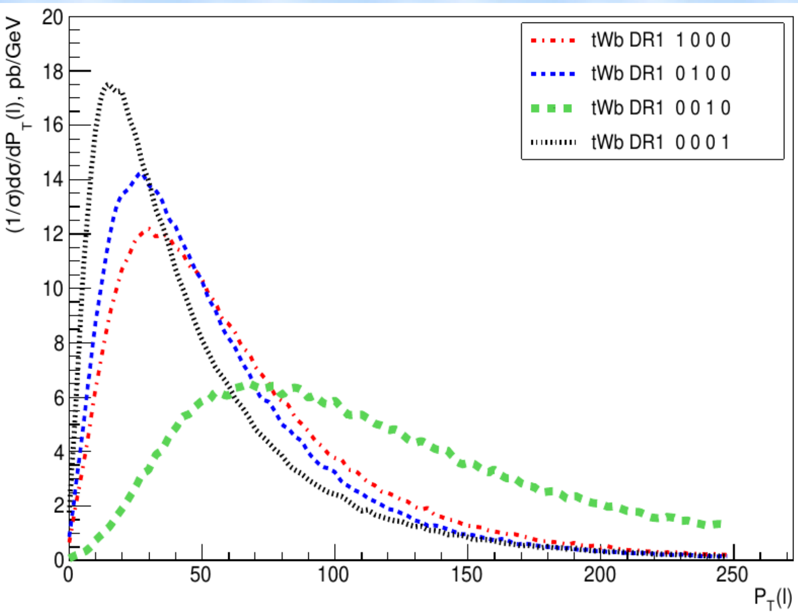


Figure 7: The distribution of the W-boson (top) and lepton from W-boson decay (bottom) momenta for the DR1 scheme and different scenarios of interaction in the Wtb vertex