Technical aspects of the search for anomalous Wtb couplings.

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Outline

- What we call anomalous Wtb couplings
    - Operators and vertex approaches
- Anomalous couplings in production cross section
- Anomalous couplings in the decay of top quark

Effective operators in the field theory:

In the units where $\hbar = c = 1$, the fields of the SM have mass dimensions:

scalar: $\dim\ \phi = 1$

vector: $\dim\ A_\mu = 1$

fermion: $\dim\ \psi = 3/2$

Every term in L_{SM} is of dimension-4,

while the new four-fermion interaction is of dimension-6:

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

where Λ is the scale of the new physics ~ 1TeV

Full list of effective operators that have effects on single top quark processes at order $1/\Lambda^2$:

Operators that contribute to the Wtb vertex:

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

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

J. A. Aguilar-Saavedra, arXiv:1008.3225v1 [hep-ph]

Operators which lead to contact four-fermion interactions:

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

Cen Zhang, Scott Willenbrock, arXiv:1008.3869 [hep-ph]

1. Vertex function approach

Using gauge invariant operators:

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

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

one can derive vertices:

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

Where corrections to SM coupling:

$$V_L = V_{tb} + C_{\phi q}^{(3,3+3)}\,\frac{v^2}{\Lambda^2}, \qquad g_L = \sqrt{2}C_{dW}^{33}\,\frac{v^2}{\Lambda^2},$$

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

2. Effective operators approach

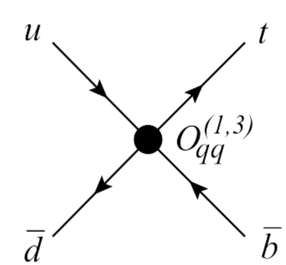
We take into account only the dimension-6 operators (order $1/\Lambda^2$), that contribute to the single top processes. The following operators contribute (for $m_b = 0$) :

$$
\begin{aligned}
O_{\phi q}^{(3)} &= i(\phi^{+}\tau^{I} D_{\mu}\phi)(\bar{q}\gamma^{\mu}\tau^{I} q) \\
O_{tW} &= (\bar{q}\sigma^{\mu\nu}\tau^{I} t)\tilde{\phi} W_{\mu\nu}^{I} \\
O_{qq}^{(1,3)} &= (\bar{q}^{i}\gamma_{\mu}\tau^{I} q^{j})(\bar{q}\gamma^{\mu}\tau^{I} q)
\end{aligned}
$$

The first two operators $O_{\varphi q}$ and O_{tW} will affect the Wtb coupling.

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

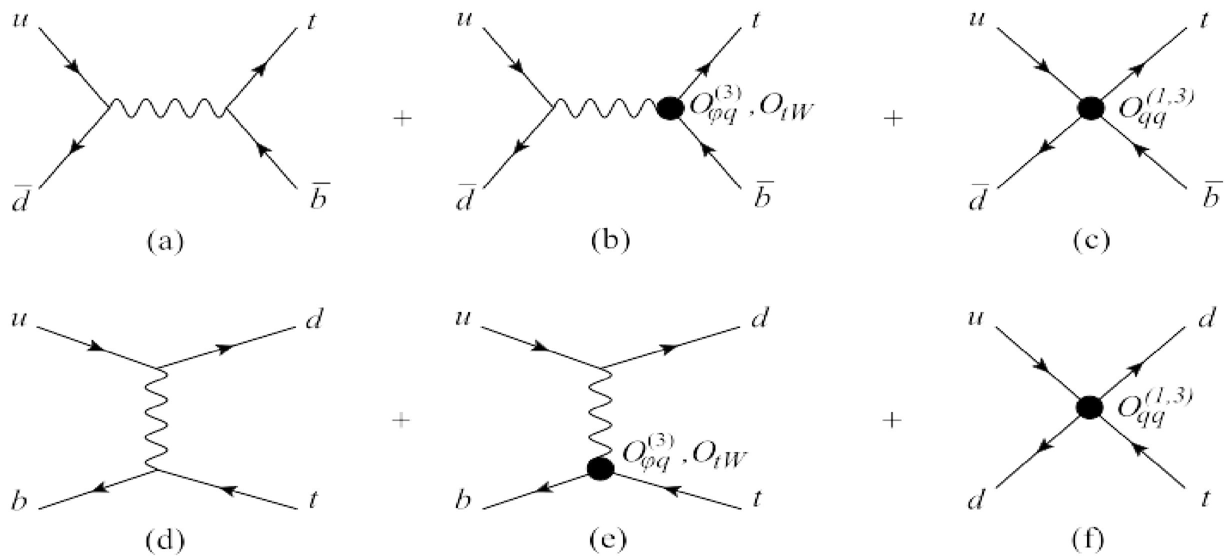
The operator O_{qq} is four-fermion interaction that couples light quarks to third generation quarks.



This additional vertex is not a part of Wtb.

2. Effective operators approach

Single top production processes:



To follow this approach we have to remove all terms of order $1/\Lambda^4$.
The corrections to the SM squared amplitudes include only terms of order $1/\Lambda^2$:
Anomalous operators contribute only to interference with SM.

s-channel:

$$\frac{1}{4}\Sigma|M_{u\bar{d}\to t\bar{b}}|^2 = \left(V_{tb}^2 + \frac{2C_{\phi q}^{(3)}V_{tb}v^2}{\Lambda^2}\right)\frac{g^4 u(u-m_t^2)}{4(s-m_W^2)^2} - \frac{2\sqrt{2}\mathrm{Re}C_{tW}V_{tb}m_t m_W}{\Lambda^2}\frac{g^2 su}{(s-m_W^2)^2} + \frac{2C_{qq}^{(1,3)}V_{tb}}{\Lambda^2}\frac{g^2 u(u-m_t^2)}{s-m_W^2} \quad (26)$$

t-channel:

$$\frac{1}{4}\Sigma|M_{ub\to dt}|^2 = \left(V_{tb}^2 + \frac{2C_{\phi q}^{(3)}V_{tb}v^2}{\Lambda^2}\right)\frac{g^4 s(s-m_t^2)}{4(t-m_W^2)^2} - \frac{2\sqrt{2}\mathrm{Re}C_{tW}V_{tb}m_t m_W}{\Lambda^2}\frac{g^2 st}{(t-m_W^2)^2} + \frac{2C_{qq}^{(1,3)}V_{tb}}{\Lambda^2}\frac{g^2 s(s-m_t^2)}{t-m_W^2} \quad (27)$$

$$\frac{1}{4}\Sigma|M_{\bar{d}b\to\bar{u}t}|^2 = \left(V_{tb}^2 + \frac{2C_{\phi q}^{(3)}V_{tb}v^2}{\Lambda^2}\right)\frac{g^4 u(u-m_t^2)}{4(t-m_W^2)^2} - \frac{2\sqrt{2}\mathrm{Re}C_{tW}V_{tb}m_t m_W}{\Lambda^2}\frac{g^2 ut}{(t-m_W^2)^2} + \frac{2C_{qq}^{(1,3)}V_{tb}}{\Lambda^2}\frac{g^2 u(u-m_t^2)}{t-m_W^2} \quad (28)$$

Cen Zhang, Scott Willenbrock, arXiv:1008.3869 [hep-ph]

Vertex functions

The interference terms between SM amplitudes and dimension-6 operators are proportional to $1/\Lambda^2$, and the pure dimension-6 operators corrections to $1/\Lambda^4$.

Contribution to matrix element from Wtb anomalous couplings (for $m_b = 0$):

order: $1/\Lambda^2$	$1/\Lambda^4$
V_L	$(V_L)^2$
-	$(V_R)^2$
-	$(g_L)^2$
g_R	$(g_R)^2$

The practical difference between the two approaches

Vertex function at order $1/\Lambda^2$

Effective operators at order $1/\Lambda^2$

Takes into account all matrix element terms with coupings V_L, V_R, g_L, g_R.
dim. $1/\Lambda^2$,$1/\Lambda^4$

Takes into account only interference terms with SM, that include couplings V_L, g_R, and contact interaction dim. $1/\Lambda^2$ only.

One can use both strategies in experiment:
In addition to complete Wtb search set additional limits to effective operators which are linear to $1/\Lambda^2$.

Production Cross Section

s-channel:

$$\sigma(\hat{s}) = \frac{V_{ud}^2 V_{tb}^2 e^4}{16\pi \sin^4\theta_{\mathrm{W}}} \Bigg[\left((f_1^L)^2 + (f_1^R)^2\right) \times \frac{\beta^2}{24} \frac{2\hat{s} + M_t^2}{(\hat{s} - M_W^2)^2} + \left((f_2^L)^2 + (f_2^R)^2\right) \times \frac{\hat{s}\beta^4}{24 M_W^2} \frac{\hat{s} + 2M_t^2}{(\hat{s} - M_W^2)^2} \Bigg]$$

t-channel:

$$\sigma(\hat{s}) = \frac{V_{ud}^2 V_{tb}^2 e^4}{16\pi \sin^4\theta_{\mathrm{W}}} \tag{7}$$

$$\times \frac{1}{4} \Bigg[\Bigg[(f_1^L)^2 \frac{\beta^4}{M_W^2 \left(1 - \frac{M_t^2}{\hat{s}} + \frac{M_W^2}{\hat{s}}\right)}$$

$$+ (f_1^R)^2 \left(\beta^2 \left(\frac{1}{M_W^2} + \frac{2}{\hat{s}} \right) - \frac{1}{\hat{s}} \left(1 + \beta^2 + \frac{2M_W^2}{\hat{s}} \right) \right.$$

$$\left. \times \ln \left(1 + \frac{\hat{s}\beta^2}{M_W^2} \right) \right) \Bigg] + \frac{1}{M_W^2} \Bigg[(f_2^L)^2$$

$$\times \left(\left(1 + \frac{2M_W^2}{\hat{s}} \right) \ln \left(1 + \frac{\hat{s}\beta^2}{M_W^2} \right) \right.$$

$$\left. - \beta^2 \left(\frac{\hat{s} + M_W^2}{\hat{s}\beta^2 + M_W^2} + 1 \right) \right) + (f_2^R)^2 \beta^2$$

$$\times \left(\left(\beta^2 + \frac{2M_W^2}{\hat{s}} \right) \ln \left(1 + \frac{\hat{s}\beta^2}{M_W^2} \right) - 2\beta^2 \right) \Bigg] \Bigg]$$

From the formulas we can see that Left (f_L^1) and right (f_R^1) vector terms are completely (kinematically) different in t-channel and we have to model both of the couplings correctly in our MC model.

Phys.Atom.Nucl.73:971-984,2010

http://top.sinp.msu.ru/tmp/PhysAtom_73-6-2010.pdf

How we can prepare MC model of production in model independent way

(vertex approach)

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(F_L^1 P_L + F_R^1 P_R)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}(F_L^2 P_L + F_R^2 P_R) + \text{h.c.}$$

$$W_{\mu\nu}^{\pm} = D_\mu W_\nu^{\pm} - D_\nu W_\mu^{\pm}$$ $$P_{L,R} = 1/2\cdot(1 \mp \gamma_5)$$

$$D_\mu = \delta_\mu - ieA_\mu; \quad \sigma^{\mu\nu} = (i/2)[\gamma_\mu, \gamma_\nu];$$

$$F_{L,R}^1 = V_{tb} f_{L,R}^1 \qquad F_{L,R}^2 = V_{tb} f_{L,R}^2$$

$$\sigma_{pp\to t\bar{b}}^{\text{tot}} \sim A(f_L^1)^2 + B(f_R^1)^2 + C(f_L^2)^2 + D(f_R^2)^2 + E(f_L^1 f_L^2) + G(f_R^1 f_R^2),$$

With these 6 samples we can describe
All possible values (models) of the
Couplings in production of single top
Including the interference terms
(approximation with massless b quark)

Notation	f_L^1	f_R^1	f_L^2	f_R^2
1000	1	0	0	0
0100	0	1	0	0
0010	0	0	1	0
0001	0	0	0	1
1010	1	0	1	0
0101	0	1	0	1

Anomalous Wtb couplings in the production and in decay of top

$$\sigma(2 \to 5) \sim (f_{L1}^2 * AP(p) + f_{R1}^2 * BP(p))(f_{L1}^2 * AD(p) + f_{R1}^2 * BD(p))/(f_{L1}^2 + f_{R1}^2) = (f_{L1}^4 * A(p) + f_{R1}^4 * B(p) + f_{L1}^2 * f_{R1}^2 * C(p))/(f_{L1}^2 + f_{R1}^2)$$

$$A(p) \sim 1000; B(p) \sim 0100; C(p) \sim (1100 - 1000 - 0100)$$

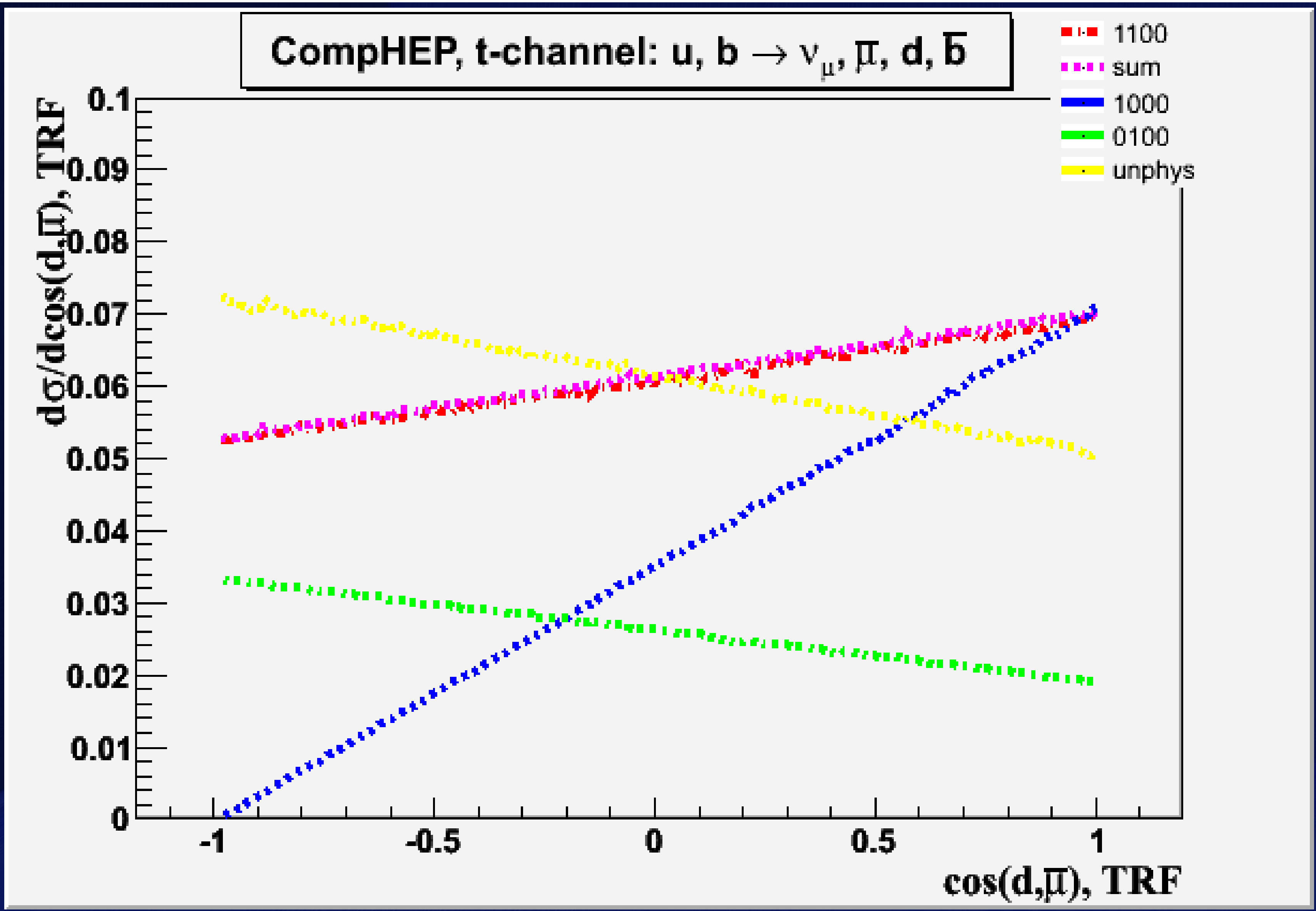
$$\sigma_{2\to5}(f_{L1}, f_{R1}) = a * 1000 + b * 0100 + c * (1100 - 1000 - 0100)$$

where $a = f_{L1}^4/(f_{L1}^2 + f_{R1}^2); b = f_{R1}^4/(f_{L1}^2 + f_{R1}^2); c = f_{L1}^2 f_{R1}^2/(f_{L1}^2 + f_{R1}^2);$

Therefore, we can correctly model all possible values of vector couplings with three samples: 1000, 0100 and (1100-1000-0100)
The last one is unphysical gauge invariant sample with left coupling in Production and right couplings in decay of top and vice versa.

Distributions at the parton level

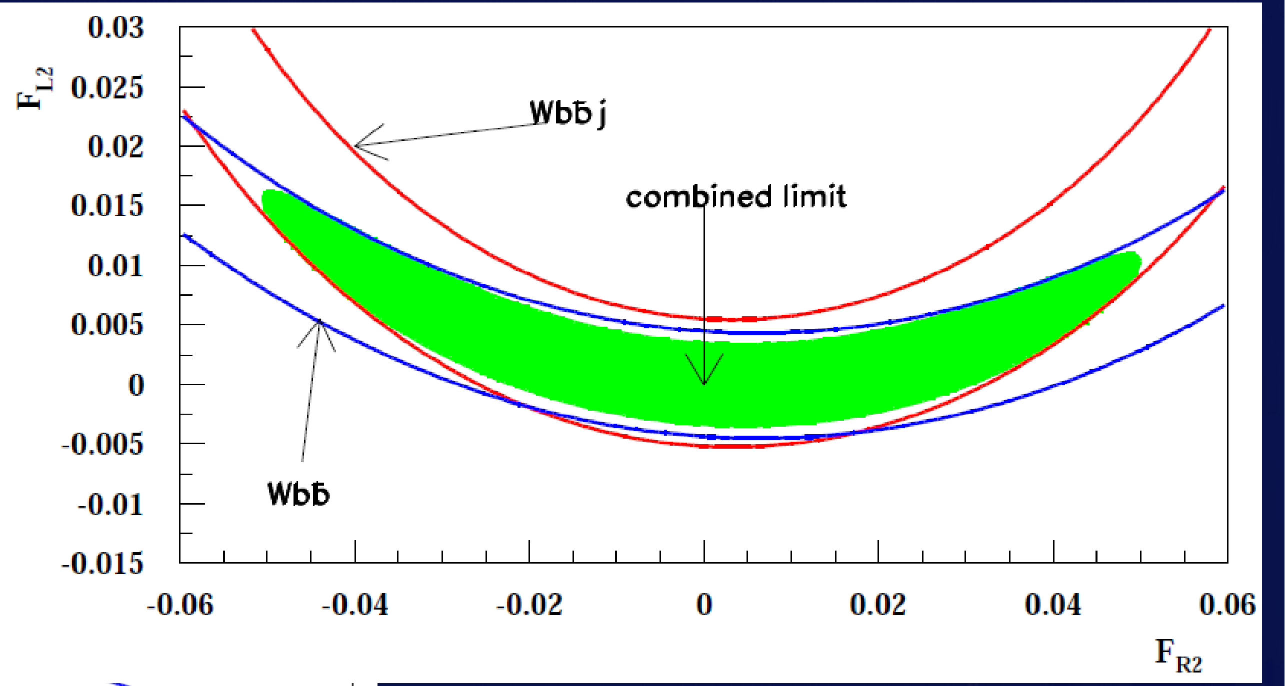
$$d\sigma_{(1100)}/dcos = \frac{1}{2}d\sigma_{(1000)}/dcos + \frac{1}{2}d\sigma_{(0100)}/dcos + \frac{1}{2}d\sigma_{(unphysical)}/dcos$$

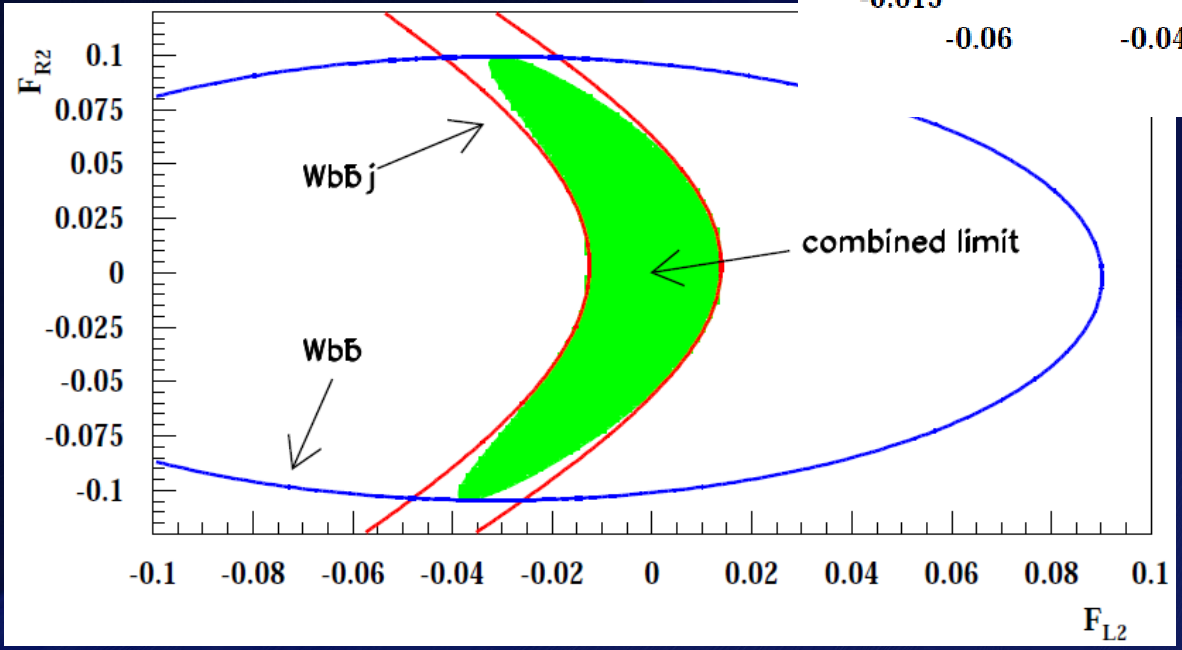


Importance of s-channel signal to limit the anomalous Wtb couplings

Eur.Phys.J. C11 (1999) 473-484

Combination of s- and t-channel partial limits provides much more tight limits on anomalous couplings.





Practical realization of both approaches in MC generator SingleTop (based on CompHEP)

- For the vertex approach create a model with four couplings
- For the operators approach create a model of vertex function approach with anomalous couplings V_L, g_R only.
- For the contact term:
  - - Introduce an auxiliary massive vector particle P (M_P >> sqrt(s)) and vertices of SM-like interaction P with fermions.
  - - Set Pqq couplings parameters ~M_P.
  - - Calculate total matrix element and keep only SM terms and terms of interference SM with processes including anomalous V_L, g_R and (P,quark,quark) interactions
  - (i.e. remove all V^2_L, g^2_R and Pqq^2 terms).

Conclusion

- There are two approaches for the anomalous Wtb couplings, one can set the limits in both of them (In addition to complete Wtb couplings search we can set additional limits to effective operators which are linear to $1/\Lambda^{2}$).
- We know how to describe correctly all possible values of couplings with few MC samples and provide model independent limits
- The generator SingleTop has implemented already in D0 analysis and for CMS analysis. The samples created for LHC community are available in LHEF format in MCDB http://mcdb.cern.ch

Backup Slides

Advantages of using vertex function approach:

- The possibility to explore all new physics effects whose contribution is proportional quadratic corrections from anomalous couplings V_R , g_L
  (One well-known example is given by top FCNC processes, extremely suppressed in the SM, which are of order $1/\Lambda^4$).
- The possibility of direct measurement of V_{tb} coupling parameters.

Problems of vertex function approach:

- We use operators with different mass dimensions.
  (This is not very accurate from the point of view of quantum field theory.)

Advantages of using effective operators approach:

- All correction terms in the matrix element of the same order of mass scale parameter.

- Takes into account the contribution from the contact four-fermion interactions.

Limitations of effective operators approach:

- Not taken into account the contribution from anomalous couplings V_R , g_L
- It is difficult to measure directly the V_{tb} coupling parameters (due to additional four-fermion vertex).