Constraints on Nonstandard Top Quark Couplings from Precision Electroweak Data

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arXiv:1104.3122, Nicolas Greiner, Scott Willenbrock, Cen Zhang

Constraints on Nonstandard Top Quark Couplings

Nonstandard top quark couplings can be constrained:

- Directly from colliders (cross sections, branching ratios, etc):

  Degrande, Gerard, Grojean, Maltoni, Servant, 11

  Aguilar-Saavedra, Carvalho, Castro, Onofre, Veloso, 07

  Cao, Wudka, Yuan, 07

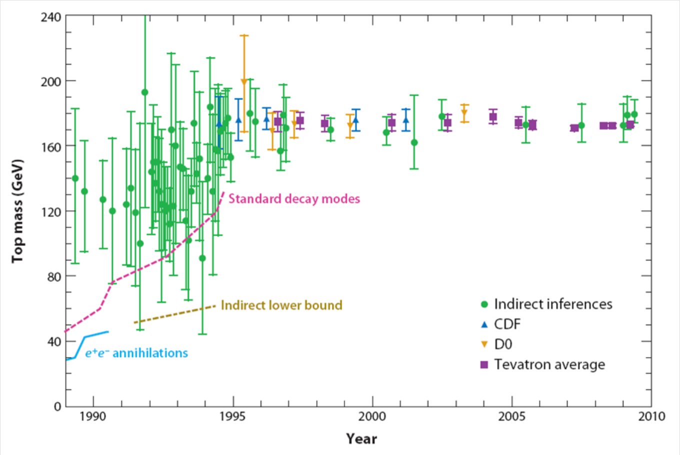
- From B physics (B meson decay, $B\bar{B}$ mixing):

  Grzadkowski,Misiak, 08

  Drobnak, Fajfer, Kamenik, 11

- $\boxed{\text{Indirectly from Precision Electroweak Data (}Z\text{-pole, }W\text{-mass, DIS, LEP2, etc.)}}$

History of Top Quark Mass



Quigg

Effective Theory Approach

- Effective Field Theory

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \left(\frac{1}{\Lambda^2} C_i O_i + \text{h.c.} \right)$$

- The Operators:

$$\begin{aligned}
O^{(3)}_{\phi q} &= i(\phi^\dagger \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q), \qquad O^{(1)}_{\phi q} = i(\phi^\dagger D_\mu \phi)(\bar{q}\gamma^\mu q),\\
O_{\phi t} &= i(\phi^\dagger D_\mu \phi)(\bar{t}\gamma^\mu t), \qquad O_{\phi b} = i(\phi^\dagger D_\mu \phi)(\bar{b}\gamma^\mu b),\\
O_{\phi\phi} &= i(\tilde{\phi}^\dagger D_\mu \phi)(\bar{t}\gamma^\mu b), \qquad O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W^I_{\mu\nu},\\
O_{bW} &= (\bar{q}\sigma^{\mu\nu}\tau^I b)\phi W^I_{\mu\nu}, \qquad O_{tB} = (\bar{q}\sigma^{\mu\nu} t)\tilde{\phi} B_{\mu\nu},\\
O_{bB} &= (\bar{q}\sigma^{\mu\nu} b)\phi B_{\mu\nu}.
\end{aligned}$$

- Couplings can be computed from C_i:

$$V_L = C^{(3)}_{\phi q}\frac{v^2}{\Lambda^2}, \quad V_R = C_{\phi\phi}\frac{v^2}{2\Lambda^2}, \cdots, \qquad \text{(Aguilar-Saavedra, 08)}$$

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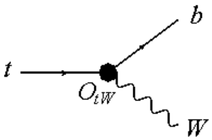
Constraint from Direct Measurement

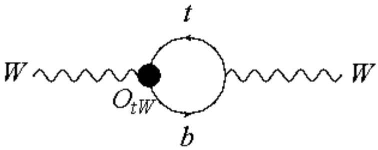
- Constraint on O_{tW}, from the decay of the top quark to W boson of a given helicity:

$$\frac{C_{tW}}{\Lambda^2} = 1.1 \pm 2.1 \ \mathrm{TeV}^{-2} \quad \text{(CDF)},$$
$$\frac{C_{tW}}{\Lambda^2} = -0.8 \pm 1.2 \ \mathrm{TeV}^{-2} \quad \text{(D0)}.$$

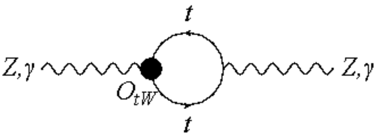


Loop Corrections to W, Z, γ

- $\Pi_{WW}(q^2)$



- $\Pi_{ZZ,\gamma\gamma,\gamma Z}(q^2)$



The S Parameter

- In d dimension,

$$\alpha S = N_c \frac{C_{tW}}{2\pi^2} \frac{\sqrt{2} m_W m_t}{\Lambda^2} \frac{5}{3} s_W^2 \left(\frac{1}{\epsilon} - \gamma + \ln 4\pi - \ln \frac{m_t^2}{\mu^2} - 2 \frac{\sqrt{4m_t^2 - m_Z^2}}{m_Z} \arctan \frac{m_Z}{\sqrt{4m_t^2 - m_Z^2}} + 2 \right) .$$

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- At tree level, need to include $O_{WB} = (\phi^\dagger \tau^I \phi) W^I_{\mu\nu} B^{\mu\nu}$,

- In the $\overline{\mathrm{MS}}$ scheme,

$$\alpha S = 4 \frac{C_{WB}(\mu) v^2}{\Lambda^2} s_W c_W + N_c \frac{C_{tW}}{2\pi^2} \frac{\sqrt{2} m_W m_t}{\Lambda^2} \frac{5}{3} s_W^2 \left(- \ln \frac{m_t^2}{\mu^2} - 2 \frac{\sqrt{4m_t^2 - m_Z^2}}{m_Z} \arctan \frac{m_Z}{\sqrt{4m_t^2 - m_Z^2}} + 2 \right)$$

The T Parameter

- $T = 0$
- At tree level, need $O_{\phi}^{(3)} = (\phi^\dagger D^\mu \phi)[(D_\mu \phi)^\dagger \phi]$.

$$T = -C_{\phi}^{(3)} \frac{v^2}{\Lambda^2}$$

The U Parameter

- U is finite, because there is no available counterterm at dimension-six.

$$U = N_c \frac{C_{tW}}{\pi^2} \frac{\sqrt{2} m_W m_t}{\Lambda^2} s_W^2 \left[\frac{m_t^2}{m_W^2} + \left(\frac{m_t^2}{m_W^2} - 1 \right)^2 \ln \left(1 - \frac{m_W^2}{m_t^2} \right) - 2 \frac{\sqrt{4m_t^2 - m_Z^2}}{m_Z} \arctan \frac{m_Z}{\sqrt{4m_t^2 - m_Z^2}} \right] .$$

- From PDG, $U = 0.06 \pm 0.10$, for $m_t = 173~\mathrm{GeV}$ and $m_h = 117~\mathrm{GeV}$, so

$$\frac{C_{tW}}{\Lambda^2} = -0.7 \pm 1.1~\mathrm{TeV}^{-2}.$$

$$\left(\frac{C_{tW}}{\Lambda^2} = \begin{cases} 1.10 \pm 2.06~\mathrm{TeV}^{-2} & \text{(from CDF),} \\ -0.79 \pm 1.19~\mathrm{TeV}^{-2} & \text{(from D0).} \end{cases} \right)$$

- Note that we have neglected other dim-6 operators that contribute at tree level, except for O_{WB} and $O_{\phi}^{(3)}$.

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More operators and data...

- Operators

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- Data

	Notation	Measurement
Z-pole	Γ_Z	Total Z width
	σ_{had}	Hadronic cross section
	$R_f (f = e, \mu, \tau, b, c)$	Ratios of decay rates
	$A^{0,f}_{FB} (f = e, \mu, \tau, b, c, s)$	Forward-backward asymmetries
	$\bar{s}^2_l$	Hadronic charge asymmetry
	$A_f (f = e, \mu, \tau, b, c, s)$	Polarized asymmetries
Fermion pair production at LEP2	$\sigma_f (f = q, \mu, \tau)$	Total cross sections for $e^+e^- \to f\bar{f}$
	$A^f_{FB} (f = \mu, \tau)$	Forward-backward asymmetries for $e^+e^- \to f\bar{f}$
DIS and atomic parity violation	$Q_W(Cs)$	Weak charge in Cs
	$Q_W(Tl)$	Weak charge in Tl
	$Q_W(e)$	Weak charge of the electron
	g^2_L, g^2_R	ν_μ-nucleon scattering from NuTeV
	$g^{\nu e}_V, g^{\nu e}_A$	ν-e scattering from CHARM II
W mass	m_W	W mass from LEP and Tevatron

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	Notation	Measurement
Z-pole	Γ_Z σ_{had} $R_f(f = e, \mu, \tau, b, c)$ $A^{0,f}_{FB}(f = e, \mu, \tau, b, c, s)$ $\bar{s}^2_l$ $A_f(f = e, \mu, \tau, b, c, s)$	Total Z width Hadronic cross section Ratios of decay rates Forward-backward asymmetries Hadronic charge asymmetry Polarized asymmetries
Fermion pair production at LEP2	$\sigma_f(f = q, \mu, \tau)$ $A^f_{FB}(f = \mu, \tau)$	Total cross sections for $e^+e^- \to f\bar{f}$ Forward-backward asymmetries for $e^+e^- \to f\bar{f}$
DIS and atomic parity violation	$Q_W(Cs)$ $Q_W(Tl)$ $Q_W(e)$ g_L^2, g_R^2 $g_V^{\nu e}, g_A^{\nu e}$	Weak charge in Cs Weak charge in Tl Weak charge of the electron ν_μ-nucleon scattering from NuTeV ν-e scattering from CHARM II
W mass	m_W	W mass from LEP and Tevatron

Global Fit

One sigma bounds on 8 operators:

$$\begin{pmatrix}
-0.702 & -0.701 & -0.000 & +0.128 & -0.004 & +0.000 & -0.000 & -0.000 \\
-0.093 & -0.087 & -0.002 & -0.992 & -0.018 & +0.001 & -0.000 & -0.000 \\
-0.250 & +0.258 & -0.238 & +0.017 & -0.895 & +0.071 & -0.082 & -0.041 \\
-0.402 & +0.400 & -0.672 & -0.004 & +0.422 & -0.051 & -0.216 & +0.005 \\
-0.129 & +0.129 & -0.123 & +0.001 & -0.007 & -0.210 & +0.905 & +0.297 \\
+0.046 & -0.045 & +0.046 & +0.001 & -0.097 & -0.916 & -0.280 & +0.259 \\
-0.006 & +0.006 & +0.056 & +0.000 & -0.007 & +0.329 & -0.219 & +0.917 \\
+0.506 & -0.506 & -0.686 & -0.000 & -0.108 & +0.028 & +0.042 & +0.048
\end{pmatrix}$$

$$\times \frac{(\mathrm{TeV})^2}{\Lambda^2} \begin{pmatrix} C_{\phi q}^{(3)} \\ C_{\phi q}^{(1)} \\ C_{\phi t} \\ C_{\phi b} \\ C_{tW} \\ C_{bW} \\ C_{tB} \\ C_{bB} \end{pmatrix} = \left(\begin{array}{rl}
-0.0131 & \pm 0.0142 \\
+0.595 & \pm 0.268 \\
+0.359 & \pm 1.21 \\
-3.13 & \pm 2.12 \\
-8.48 & \pm 10.8 \\
-58.1 & \pm 27.8 \\
-32.5 & \pm 118 \\
-3200 & \pm 1290
\end{array}\right)
\begin{array}{l}
\left.\vphantom{\begin{array}{c}a\\a\end{array}}\right\} \text{from tree level } Zb\bar{b} \text{ couplings} \\
\left.\vphantom{\begin{array}{c}a\\a\\a\\a\\a\\a\end{array}}\right\} \text{from loop level effects}
\end{array}$$

Summary

- We obtain bound on O_{tW} from a loop level calculation of U parameter.
- We perform a global analysis using all major precision electroweak measurements, and put constraints on 8 operators that involve nonstandard top quark interaction.

Thank you..

Dim-6 Operators We Have Neglected

$$
\begin{aligned}
O_{ll}^{s} &= \frac{1}{2}(\bar{l}\gamma^{\mu} l)(\bar{l}\gamma_{\mu} l), \quad O_{ll}^{t} = \frac{1}{2}(\bar{l}\gamma^{\mu}\sigma^{a} l)(\bar{l}\gamma_{\mu}\sigma^{a} l), \\
O_{lq}^{s} &= (\bar{l}\gamma^{\mu} l)(\bar{q}\gamma_{\mu} q), \quad O_{lq}^{t} = (\bar{l}\gamma^{\mu}\sigma^{a} l)(\bar{q}\gamma_{\mu}\sigma^{a} q), \\
O_{le} &= (\bar{l}\gamma^{\mu} l)(\bar{e}\gamma_{\mu} e), \quad O_{qe} = (\bar{q}\gamma^{\mu} q)(\bar{e}\gamma_{\mu} e), \\
O_{lu} &= (\bar{l}\gamma^{\mu} l)(\bar{u}\gamma_{\mu} u), \quad O_{ld} = (\bar{l}\gamma^{\mu} l)(\bar{d}\gamma_{\mu} d), \\
O_{ee} &= \frac{1}{2}(\bar{e}\gamma^{\mu} e)(\bar{e}\gamma_{\mu} e), \quad O_{eu} = (\bar{e}\gamma^{\mu} e)(\bar{u}\gamma_{\mu} u), \\
O_{ed} &= (\bar{e}\gamma^{\mu} e)(\bar{d}\gamma_{\mu} d), \\
O_{hl}^{s} &= i(h^{+} D^{\mu} h)(\bar{l}\gamma_{\mu} l) + h.c., \quad O_{hl}^{t} = i(h^{+}\sigma^{a} D^{\mu} h)(\bar{l}\gamma_{\mu}\sigma^{a} l) + h.c., \\
O_{hq}^{s} &= i(h^{+} D^{\mu} h)(\bar{q}\gamma_{\mu} q) + h.c., \quad O_{hq}^{t} = i(h^{+}\sigma^{a} D^{\mu} h)(\bar{q}\gamma_{\mu}\sigma^{a} q) + h.c., \\
O_{hu} &= i(h^{+} D^{\mu} h)(\bar{u}\gamma_{\mu} u) + h.c., \quad O_{hd} = i(h^{+}\sigma^{a} D^{\mu} h)(\bar{d}\gamma_{\mu}\sigma^{a} d) + h.c., \\
O_{he} &= i(h^{+} D^{\mu} h)(\bar{e}\gamma_{\mu} e) + h.c., \quad O_{W} = \epsilon^{abc} W_{\mu}^{a\nu} W_{\nu}^{b\lambda} W_{\lambda}^{c\mu}
\end{aligned}
$$

Z. Han and W. Skiba, Phys. Rev. D **71**, 075009 (2005)

A Weaker Assumption..

- Assume an oblique new physics in general. Include:

$$O_{WB} = (\phi^\dagger \tau^I \phi) W^I_{\mu\nu} B^{\mu\nu} \ , \qquad O^{(3)}_\phi = (\phi^\dagger D^\mu \phi)[(D_\mu \phi)^\dagger \phi] \ ,$$

$$O_{DB} = \tfrac{1}{2}(\partial_\rho B_{\mu\nu})(\partial^\rho B^{\mu\nu}) \ , \qquad O_{DW} = \frac{1}{2}(D_\rho W^I_{\mu\nu})(D^\rho W^{I\mu\nu}) \ .$$

- Tree level:

$$\hat{S} = C_{WB} \frac{c_W}{s_W} \frac{v^2}{\Lambda^2}, \ \hat{T} = -C^{(3)}_\phi \frac{v^2}{2\Lambda^2},$$

$$W = -2C_{DW} \frac{m_W^2}{\Lambda^2}, \ Y = -2C_{DB} \frac{m_W^2}{\Lambda^2}.$$

- Loop level:

$$\hat{U} = N_c \frac{gC_{tW}}{4\pi^2} \frac{\sqrt{2} v m_t}{4\Lambda^2}, \qquad V = -N_c \frac{gC_{tW}}{4\pi^2} \frac{\sqrt{2} v m_t}{\Lambda^2} \frac{m_W^2}{12 m_t^2},$$

$$X = N_c \frac{gC_{tW}}{4\pi^2} \frac{\sqrt{2} v m_t}{\Lambda^2} \frac{5 m_Z^2}{72 m_t^2} s_W c_W.$$

$$\Rightarrow \frac{C_{tW}}{\Lambda^2} = -3.6 \pm 1.6 \ \mathrm{TeV}^{-2}.$$

Parametrization

- Vertex function

$$
\begin{aligned}
\mathcal{L}_{Wtb} &= -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}[(1+V_L)P_L + V_R P_R]tW_{\mu}^{-} \\
&\quad -\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_L P_L + g_R P_R)tW_{\mu}^{-} + \mathrm{h.c.} \\
\mathcal{L}_{Ztt} &= -\frac{g}{2c_W}\bar{t}\gamma^{\mu}[(1+X_L)P_L + X_R P_R - \frac{4}{3}s_W^2]tZ_{\mu} \\
&\quad -\frac{g}{2c_W}\bar{t}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_Z}(d_V^Z + i d_A^Z\gamma^5)tZ_{\mu}^{-} \\
\mathcal{L}_{\gamma tt} &= -\frac{2}{3}e\bar{t}\gamma^{\mu}tA_{\mu} - e\bar{t}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_t}(d_V^{\gamma} + i d_A^{\gamma}\gamma^5)tA_{\mu}
\end{aligned}
$$

Comparison with Constraints from Direct Measurement and B Physics

Bounds on individual operator (only one operator is turned on at a time), assuming $\Lambda = 1$ TeV.

Operators	EW	direct	$b \to s\gamma$	$B\bar{B}$ mixing
$O_{\phi q}^{(3)} + O_{\phi q}^{(1)}$	$+0.009 \pm 0.010$			
$O_{\phi q}^{(3)} - O_{\phi q}^{(1)}$	$+1.5 \pm 1.7$	-2.0 ± 1.2	-0.8 ± 1.3	-0.0 ± 1.3
$O_{\phi t}$	$+3.1 \pm 2.7$			
$O_{\phi b}$	-0.17 ± 0.10			
$O_{\phi\phi}$			$+0.03 \pm 0.05$	
O_{tW}	-0.7 ± 1.1	-0.1 ± 1.2	$+2.4 \pm 4.2$	-0.1 ± 1.6
O_{bW}	$+22 \pm 13$		-0.006 ± 0.011	
O_{tB}	$+4.1 \pm 6.7$			
O_{bB}	-23 ± 22			