

Electroweak Loops as a Probe of Dimension-six Operators of the SMEFT in $t\bar{t}$ Production

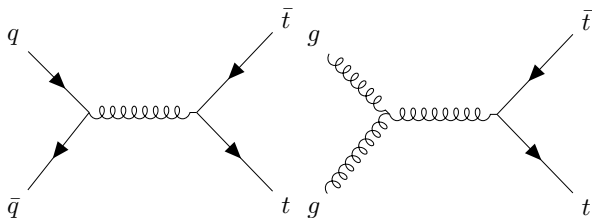
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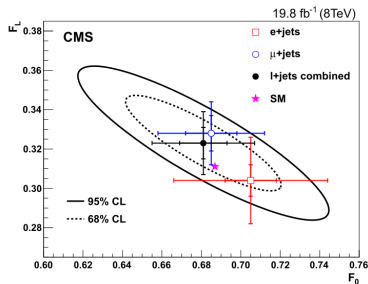
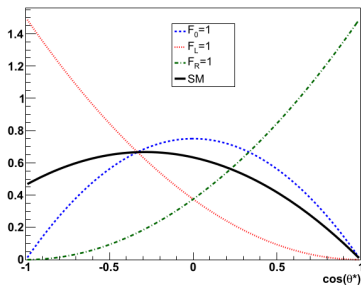
Top Quark Pairs Production



Top Quark Pairs: Phys.Lett.B 762(2016)512-534

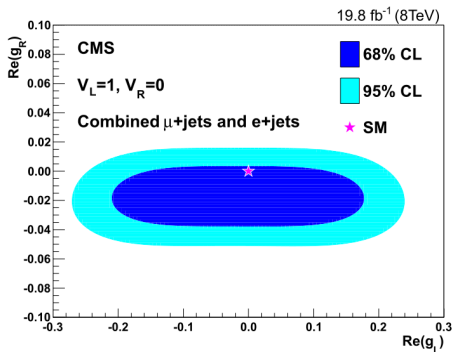
W boson helicity fractions:

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8} (1 - \cos\theta^*)^2 F_L + \frac{3}{4} (\sin\theta^*)^2 F_0 + \frac{3}{8} (1 + \cos\theta^*)^2 F_R$$



Top Quark Pairs: Phys.Lett.B 762(2016)512-534

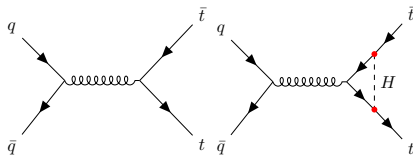
$$\begin{aligned}\mathcal{L}_{Wtb} = & -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W_\mu^- \\ & -\frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (g_L P_L + g_R P_R) t W_\mu^- + \text{h.c.}\end{aligned}$$



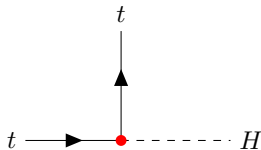
SMEFT in Warsaw basis: arXiv:1008.4884

| X^3 | | φ^6 and $\varphi^4 D^2$ | | $\psi^2 \varphi^3$ | |
|--------------------------|---|---------------------------------|---|-----------------------|--|
| Q_G | $f^{ABC} G_{\mu}^{A\nu} G_{\nu}^{B\rho} G_{\rho}^{C\mu}$ | Q_{φ} | $(\varphi^\dagger \varphi)^3$ | $Q_{e\varphi}$ | $(\varphi^\dagger \varphi)(\bar{l}'_p e'_r \varphi)$ |
| $Q_{\tilde{G}}$ | $f^{ABC} \tilde{G}_{\mu}^{A\nu} G_{\nu}^{B\rho} G_{\rho}^{C\mu}$ | $Q_{\varphi\Box}$ | $(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$ | $Q_{u\varphi}$ | $(\varphi^\dagger \varphi)(\bar{q}'_p u'_r \tilde{\varphi})$ |
| Q_W | $\epsilon^{IJK} W_{\mu}^{I\nu} W_{\nu}^{J\rho} W_{\rho}^{K\mu}$ | $Q_{\varphi D}$ | $(\varphi^\dagger D_{\mu} \varphi)^* (\varphi^\dagger D_{\mu} \varphi)$ | $Q_{d\varphi}$ | $(\varphi^\dagger \varphi)(\bar{q}'_p d'_r \varphi)$ |
| $Q_{\tilde{W}}$ | $\epsilon^{IJK} \tilde{W}_{\mu}^{I\nu} W_{\nu}^{J\rho} W_{\rho}^{K\mu}$ | | | | |
| $X^2 \varphi^2$ | | $\psi^2 X \varphi$ | | $\psi^2 \varphi^2 D$ | |
| $Q_{\varphi G}$ | $\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$ | Q_{eW} | $(\bar{l}'_p \sigma^{\mu\nu} e'_r) \tau^I \varphi W_{\mu\nu}^I$ | $Q_{\varphi l}^{(1)}$ | $(\varphi^\dagger D_{\mu} \varphi)(\bar{l}'_p \gamma^{\mu} l'_r)$ |
| $Q_{\varphi \tilde{G}}$ | $\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$ | Q_{eB} | $(\bar{l}'_p \sigma^{\mu\nu} e'_r) \varphi B_{\mu\nu}$ | $Q_{\varphi l}^{(3)}$ | $(\varphi^\dagger D_{\mu}^I \varphi)(\bar{l}'_p \tau^I \gamma^{\mu} l'_r)$ |
| $Q_{\varphi W}$ | $\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$ | Q_{uG} | $(\bar{q}'_p \sigma^{\mu\nu} T^A u'_r) \tilde{\varphi} G_{\mu\nu}^A$ | $Q_{\varphi e}$ | $(\varphi^\dagger D_{\mu} \varphi)(\bar{e}'_p \gamma^{\mu} e'_r)$ |
| $Q_{\varphi \tilde{W}}$ | $\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$ | Q_{uW} | $(\bar{q}'_p \sigma^{\mu\nu} u'_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$ | $Q_{\varphi q}^{(1)}$ | $(\varphi^\dagger D_{\mu} \varphi)(\bar{q}'_p \gamma^{\mu} q'_r)$ |
| $Q_{\varphi B}$ | $\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$ | Q_{uB} | $(\bar{q}'_p \sigma^{\mu\nu} u'_r) \tilde{\varphi} B_{\mu\nu}$ | $Q_{\varphi q}^{(3)}$ | $(\varphi^\dagger D_{\mu}^I \varphi)(\bar{q}'_p \tau^I \gamma^{\mu} q'_r)$ |
| $Q_{\varphi \tilde{B}}$ | $\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$ | Q_{dG} | $(\bar{q}'_p \sigma^{\mu\nu} T^A d'_r) \varphi G_{\mu\nu}^A$ | $Q_{\varphi u}$ | $(\varphi^\dagger D_{\mu} \varphi)(\bar{u}'_p \gamma^{\mu} u'_r)$ |
| $Q_{\varphi WB}$ | $\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$ | Q_{dW} | $(\bar{q}'_p \sigma^{\mu\nu} d'_r) \tau^I \varphi W_{\mu\nu}^I$ | $Q_{\varphi d}$ | $(\varphi^\dagger D_{\mu} \varphi)(\bar{d}'_p \gamma^{\mu} d'_r)$ |
| $Q_{\varphi \tilde{WB}}$ | $\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$ | Q_{dB} | $(\bar{q}'_p \sigma^{\mu\nu} d'_r) \varphi B_{\mu\nu}$ | $Q_{\varphi ud}$ | $i(\tilde{\varphi}^\dagger D_{\mu} \varphi)(\bar{u}'_p \gamma^{\mu} d'_r)$ |

Top Quark Pairs including EW NLO



Three excess vertices arise: Htt , Ztt , Wtb

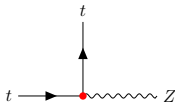


$$-\frac{i}{v}m_t - ivC^{\varphi\Box}m_t + \frac{iv}{4}C^{\varphi D}m_t + \frac{iv^2}{\sqrt{2}}(P_L C_{33}^{u\varphi*} + P_R C_{33}^{u\varphi})$$

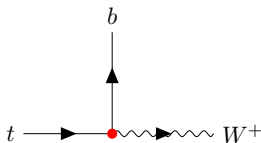
$$\rho = \frac{|J_{C.C}|^2}{|J_{N.C.}|^2} = \frac{\bar{g}^2 M_Z^2}{\bar{g}_Z^2 M_W^2} = 1 + \frac{1}{2}C^{\varphi D}v^2$$

$$M_h^2 = \lambda v^2 - \left(3C^{\varphi} - 2\lambda C^{\varphi\Box} + \frac{\lambda}{2}C^{\varphi D}\right)v^4$$

Ztt Coupling in SMEFT: arXiv:1704.03888



$$\begin{aligned}
 & + \frac{i}{6\sqrt{\bar{g}^2 + \bar{g}'^2}} \left((\bar{g}'^2 - 3\bar{g}^2) \gamma^\mu P_L + 4\bar{g}'^2 \gamma^\mu P_R \right) \\
 & - \frac{i\bar{g}\bar{g}'v^2}{6(\bar{g}^2 + \bar{g}'^2)^{3/2}} C^{\varphi WB} \left((3\bar{g}'^2 - \bar{g}^2) \gamma^\mu P_L - 4\bar{g}^2 \gamma^\mu P_R \right) \\
 & - \frac{\sqrt{2}\bar{g}v}{\sqrt{\bar{g}^2 + \bar{g}'^2}} p^\nu \left(C_{33}^{uW*} \sigma^{\mu\nu} P_L + C_{33}^{uW} \sigma^{\mu\nu} P_R \right) \\
 & + \frac{\sqrt{2}\bar{g}'v}{\sqrt{\bar{g}^2 + \bar{g}'^2}} p^\nu \left(C_{33}^{uB*} \sigma^{\mu\nu} P_L + C_{33}^{uB} \sigma^{\mu\nu} P_R \right) \\
 & + \frac{1}{2} i v^2 \sqrt{\bar{g}^2 + \bar{g}'^2} K_{33} K_{33}^* \textcolor{red}{C}_{33}^{\varphi q1} \gamma^\mu P_L \\
 & - \frac{1}{2} i v^2 \sqrt{\bar{g}^2 + \bar{g}'^2} K_{33} K_{33}^* \textcolor{red}{C}_{33}^{\varphi q3} \gamma^\mu P_L \\
 & + \frac{1}{2} i v^2 \sqrt{\bar{g}^2 + \bar{g}'^2} \textcolor{red}{C}_{33}^{\varphi u} \gamma^\mu P_R
 \end{aligned}$$



$$\begin{aligned}
 & -\frac{i\bar{g}}{\sqrt{2}} K_{33} \gamma^\mu P_L - 2vp^\nu K_{33} C_{33}^{dW} \sigma^{\mu\nu} P_R - \frac{i\bar{g}v^2}{\sqrt{2}} K_{33} C_{33}^{\varphi q3} \gamma^\mu P_L \\
 & -\frac{i\bar{g}v^2}{2\sqrt{2}} C_{33}^{\varphi ud} \gamma^\mu P_R - 2vp^\nu K_{33} \sigma^{\mu\nu} P_L C_{33}^{uW*}
 \end{aligned}$$

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

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

- V_L : $C_{33}^{\varphi q3}$
- V_R : $C_{33}^{\varphi ud}$
- g_L : C_{33}^{uW*}
- g_R : C_{33}^{dW}

EW NLO effects are important for probing modified EW interaction