Institut
"Jožef Stefan"
Ljubljana, Slovenija

CKM2014

Probing anomalous *ttZ* interactions with rare meson decays

Admir Greljo

In collaboration with: Joachim Brod, Emmanuel Stamou, Patipan Uttayarat

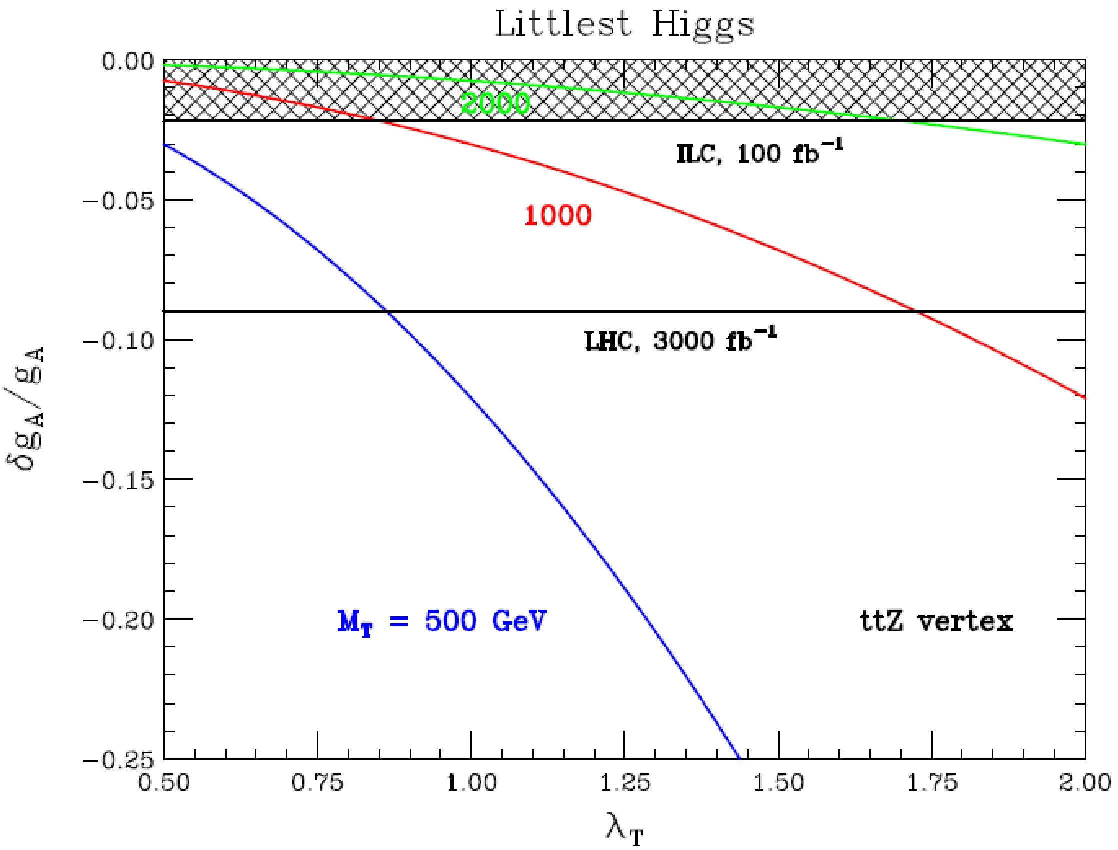
Vienna, 09/09/2014

Outline

- Motivation
- Anomalous *ttZ* in the Effective Field Theory
- Indirect searches
  - Electroweak precision observables
  - Rare meson decays
- Direct searches
  - *ttZ* production at the LHC
- Conclusions

Why deviations in *ttZ* coupling?

- Top quark – special role in EWSB
- Example of natural theories: Little Higgs Models



[Berger, Perelstein, Petriello]

Effective field theory

- SM + dimension six operators

$$\mathcal{L}^{\text{eff}} = \mathcal{L}^{\text{SM}} + \sum_k \frac{1}{\Lambda^2} C_k Q_k$$

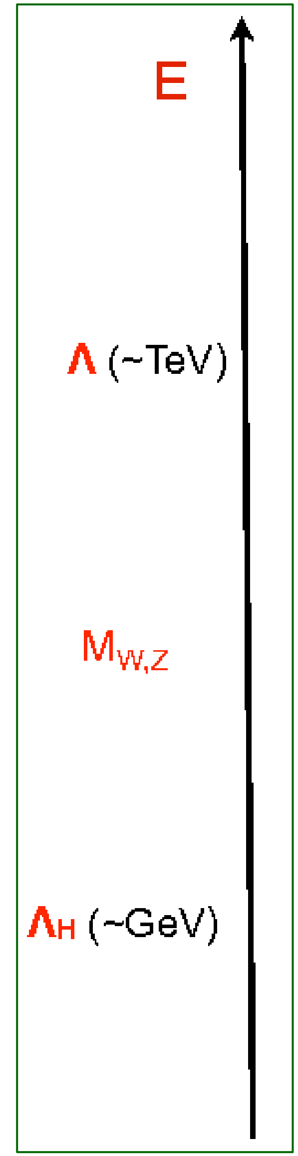
- The operators

$$Q^{(3)}_{\phi q,33} \equiv (\phi^\dagger i \overleftrightarrow{D}^a_\mu \phi)(\bar{Q}_{L,3}\gamma^\mu \sigma^a Q_{L,3}) \,,$$
$$Q^{(1)}_{\phi q,33} \equiv (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{Q}_{L,3}\gamma^\mu Q_{L,3}) \,,$$
$$Q_{\phi u,33} \equiv (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{t}_R \gamma^\mu t_R) \,.$$

$$Q_{L,3} \equiv \begin{bmatrix} t_L \\ \sum_j V_{3j} d_{L,j} \end{bmatrix}$$

- Anomalous *ttZ* at tree level

$$\delta g^t_L = \frac{v^2}{2\Lambda^2}\left(C^{(3)}_{\phi q,33} - C^{(1)}_{\phi q,33}\right) \,, \qquad \delta g^t_R = -\frac{v^2}{2\Lambda^2} C_{\phi u,33} \,,$$
$$\delta g^b_L = -\frac{v^2}{2\Lambda^2} \sum_{i=1,2,3} V^*_{i3} V_{i3}\left(C^{(3)}_{\phi q,ii} + C^{(1)}_{\phi q,ii}\right) \,.$$



Effective field theory - Mixings

- Electroweak and top Yukawa corrections induce mixing into

$$
\begin{aligned}
Q^{(3)}_{\phi q,ii} &\equiv (\phi^\dagger i \overleftrightarrow{D}^a_\mu \phi)(\bar{Q}_{L,i}\gamma^\mu \sigma^a Q_{L,i}) \,, \\
Q^{(1)}_{\phi q,ii} &\equiv (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{Q}_{L,i}\gamma^\mu Q_{L,i}) \,, \\
Q^{(3)}_{lq,33jj} &\equiv (\bar{Q}_{L,3}\gamma_\mu \sigma^a Q_{L,3})(\bar{L}_{L,j}\gamma^\mu \sigma^a L_{L,j}) \,, \\
Q^{(1)}_{lq,33jj} &\equiv (\bar{Q}_{L,3}\gamma_\mu Q_{L,3})(\bar{L}_{L,j}\gamma^\mu L_{L,j}) \,, \\
Q_{\phi WB} &\equiv (\phi^\dagger \sigma^a \phi) W^a_{\mu\nu} B^{\mu\nu} \,, \\
Q_{\phi D} &\equiv \left|\phi^\dagger D_\mu \phi\right|^2 \,,
\end{aligned}
$$

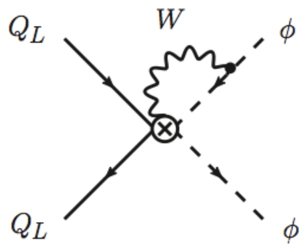
- Assumptions for the initial conditions at the scale Λ:
  - Non-zero Wilson coefficients: $C^{(3)}_{\phi q,33}, C^{(1)}_{\phi q,33}, C_{\phi u,33}$
  - $C^{(3)}_{\phi q,33} + C^{(1)}_{\phi q,33} = 0$ - for example, models with VLQs

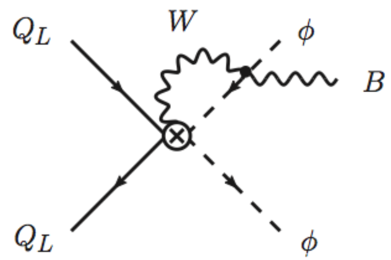
    [Aguila, Perez-Victoria, Santiago]

Electroweak precision observables: Z → bb

- The relevant part of the RGE-s:

$$\mu\frac{d}{d\mu}C^{(3)}_{\phi q,33} = \frac{y_t^2}{16\pi^2}\left(8C^{(3)}_{\phi q,33} - 3C^{(1)}_{\phi q,33}\right) - \frac{g_2^2}{16\pi^2}\frac{11}{3}C^{(3)}_{\phi q,33}\,,$$
$$\mu\frac{d}{d\mu}C^{(1)}_{\phi q,33} = \frac{y_t^2}{16\pi^2}\left(-9C^{(3)}_{\phi q,33} + 10C^{(1)}_{\phi q,33} - C_{\phi u}\right) + \frac{g_1^2}{16\pi^2}\frac{1}{9}\left(5C^{(1)}_{\phi q,33} + 4C_{\phi u}\right),$$
$$\mu\frac{d}{d\mu}C^{(3)}_{\phi q,11} = \mu\frac{d}{d\mu}C^{(3)}_{\phi q,22} = \frac{g_2^2}{16\pi^2}2C^{(3)}_{\phi q,33}\,,$$
$$\mu\frac{d}{d\mu}C^{(1)}_{\phi q,11} = \mu\frac{d}{d\mu}C^{(1)}_{\phi q,22} = \frac{g_1^2}{16\pi^2}\frac{2}{9}\left(C^{(1)}_{\phi q,33} + 2C_{\phi u}\right),$$





- In the leading–log approximation at the electroweak scale

$$\delta g_L^b = -\frac{e}{2s_w c_w}\frac{v^2}{\Lambda^2}\frac{\alpha}{4\pi}\left\{V_{33}^* V_{33}\left[\frac{x_t}{2s_w^2}\left(8C^{(1)}_{\phi q,33}(\Lambda) - C_{\phi u}(\Lambda)\right) + \frac{17c_w^2 + s_w^2}{3s_w^2 c_w^2}C^{(1)}_{\phi q,33}(\Lambda)\right]\right.$$
$$\left. + \left[\frac{2s_w^2 - 18c_w^2}{9s_w^2 c_w^2}C^{(1)}_{\phi q,33}(\Lambda) + \frac{4}{9c_w^2}C_{\phi u}(\Lambda)\right]\right\}\log\frac{\mu_W}{\Lambda}\,.$$

Electroweak precision observables: T-parameter

- The relevant part of the RGE-s:

$$16\pi^2\mu\frac{d}{d\mu}C_{\phi WB} = 0\,,$$

$$16\pi^2\mu\frac{d}{d\mu}C_{\phi D} = \frac{8}{3}g_1^2\left(C^{(1)}_{\phi q,33} + 2C_{\phi u,33}\right) + 24y_t^2\left(C^{(1)}_{\phi q,33} - C_{\phi u,33}\right)$$

- In the leading–log approximation at the electroweak scale

$$S = 0\,,$$

$$T = -\frac{v^2}{2\alpha\Lambda^2}C_{\phi D}$$

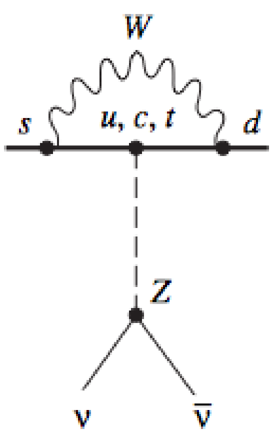
$$= -\frac{v^2}{\Lambda^2}\left[\frac{1}{3\pi c_w^2}\left(C^{(1)}_{\phi q,33} + 2C_{\phi u,33}\right) + \frac{3x_t}{2\pi s_w^2}\left(C^{(1)}_{\phi q,33} - C_{\phi u,33}\right)\right]\log\frac{\mu_W}{\Lambda}$$

Rare meson decays

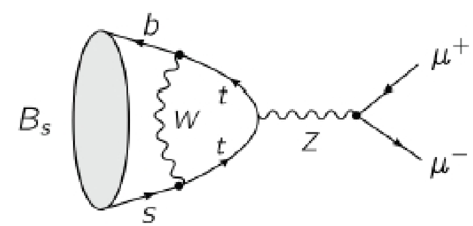
- The relevant part of the RGE-s:

$$\mu\frac{d}{d\mu}C_{lq}^{(3)} = -\frac{g_2^2}{16\pi^2}\frac{1}{3}C_{\phi q,33}^{(3)}\,, \qquad \mu\frac{d}{d\mu}C_{lq}^{(1)} = \frac{g_1^2}{16\pi^2}\frac{1}{3}C_{\phi q,33}^{(1)}$$

- The observables:



$$\mathrm{Br}(B_q \to \mu^+\mu^-) = \frac{|N|^2 M_{B_q}^3 f_{B_q}^2}{8\pi\Gamma_H^q}\beta_{q\mu} r_{q\mu}^2 \left|-2Y_t\right|^2$$



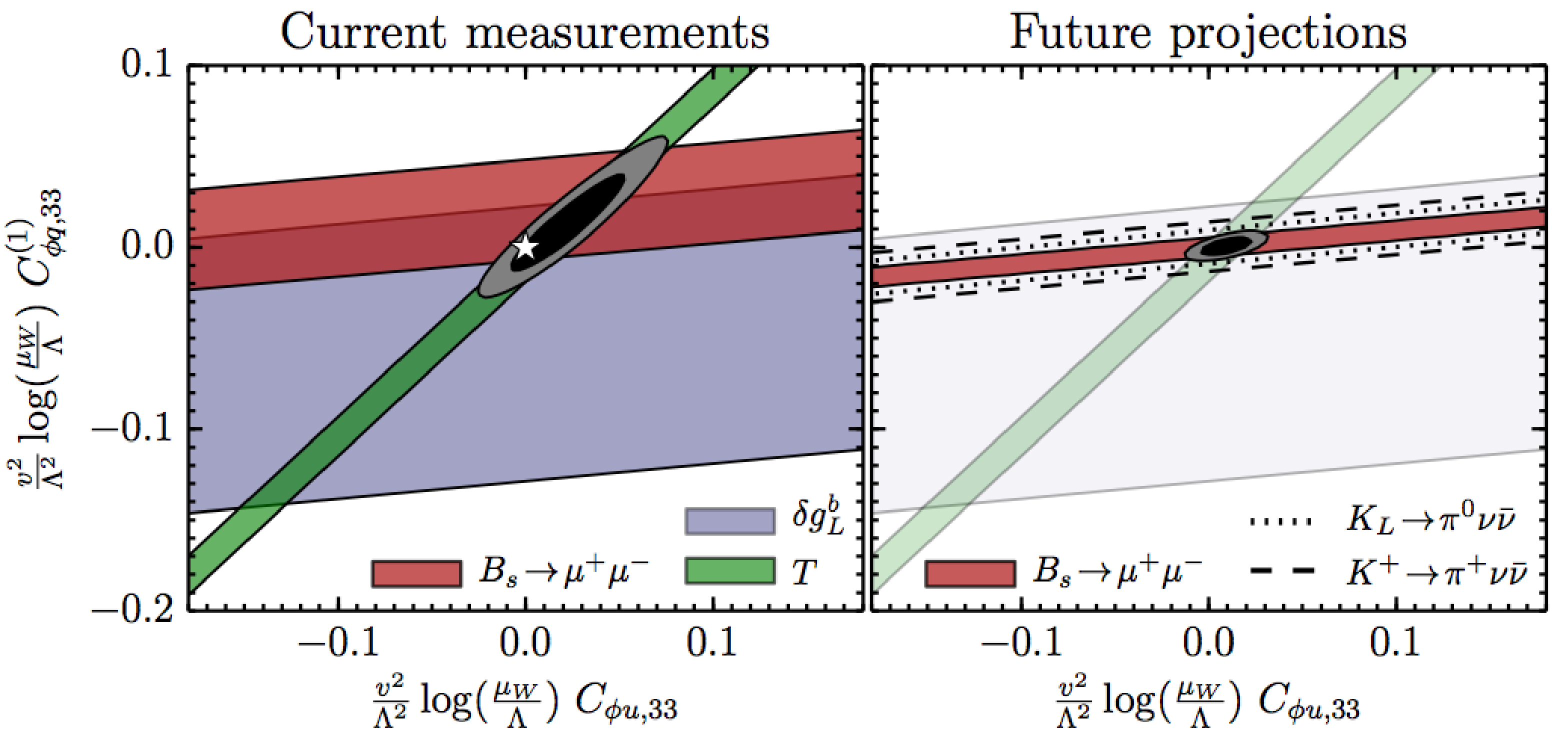
$$\mathrm{Br}\left(K^+ \to \pi^+\nu\bar{\nu}(\gamma)\right) = \kappa_+(1+\Delta_{\mathrm{EM}})\left[\left(\frac{\mathrm{Im}\lambda_t}{\lambda^5}X_t\right)^2 + \left(\frac{\mathrm{Re}\lambda_c}{\lambda}\left(P_c + \delta P_{c,u}\right) + \frac{\mathrm{Re}\lambda_t}{\lambda^5}X_t\right)^2\right]$$

$$\mathrm{Br}\left(K_L \to \pi^0\nu\bar{\nu}\right) = \kappa_L\left(\frac{\mathrm{Im}\lambda_t}{\lambda^5}X_t\right)^2$$

- The modification due to the anomalous *ttZ*

$$\delta Y^{\mathrm{NP}} = \delta X^{\mathrm{NP}} = \frac{x_t}{8}\left(C_{\phi u}(\Lambda) - \frac{12+8x_t}{x_t}C_{\phi q,33}^{(1)}\right)\frac{v^2}{\Lambda^2}\log\frac{\mu_W}{\Lambda}$$

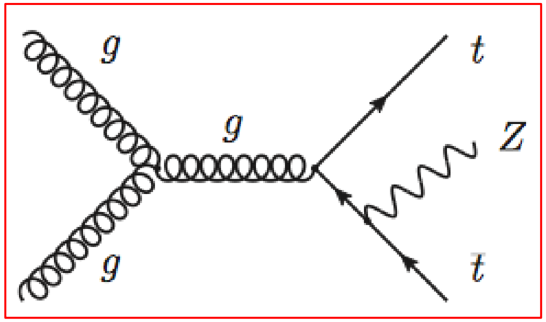
Indirect constraints: Results

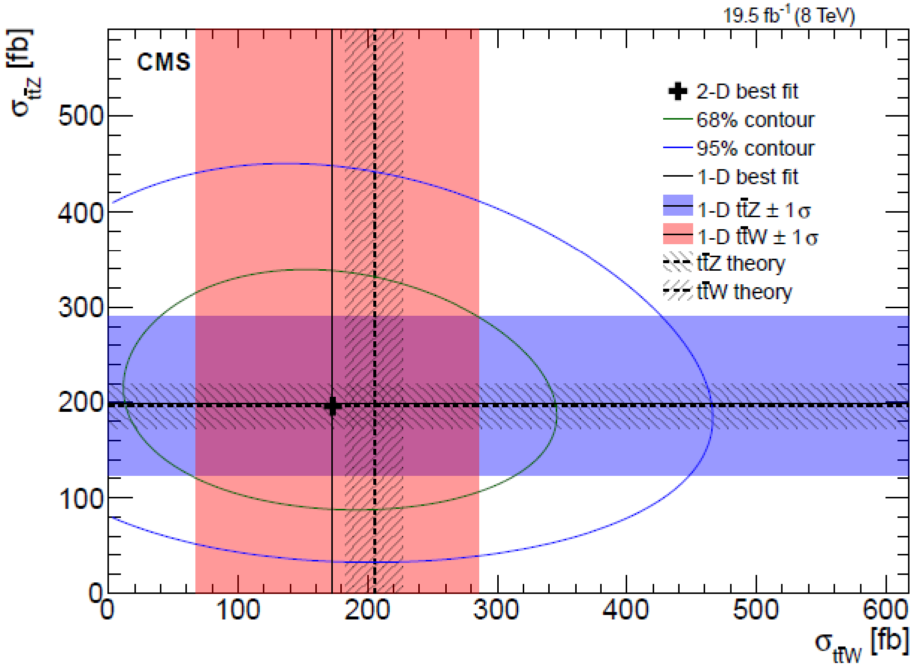


Observable	Value	Ref.
T	0.08 ± 0.07	[14]
δg_L^b	0.0016 ± 0.0015	[14]
$\mathrm{Br}(B_s \to \mu^+\mu^-)$ [CMS]	$(3.0^{+1.0}_{-0.9}) \times 10^{-9}$	[29]
$\mathrm{Br}(B_s \to \mu^+\mu^-)$ [LHCb]	$(2.9^{+1.1}_{-1.0}) \times 10^{-9}$	[30]
$\mathrm{Br}(K^+ \to \pi^+\nu\bar{\nu})$	$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$	[51]

Direct searches

- CMS-TOP-12-036: $pp \to t\bar{t}+Z \to t(\to \ell\nu b)\,\bar{t}(\to jj\bar{b})\,Z(\to \ell\ell)$





- Current and future-projected LHC limits [Rontsh,Schulze]

$$-0.50 \leq \frac{v^2}{\Lambda^2}\,\mathrm{Re}\left[C_{\phi q}^{(3,33)}\right] \leq 0.68,$$
$$-0.82 \leq \frac{v^2}{\Lambda^2}\,\mathrm{Re}\left[C_{\phi u}^{33}\right] \leq 1.59.$$

$$\left.\begin{array}{l}-0.25\\-0.22\\-0.19\end{array}\right\} \leq \frac{v^2}{\Lambda^2}\,\mathrm{Re}\left[C_{\phi q}^{(3,33)}\right] \leq \left\{\begin{array}{ll}0.26 & \text{with } 30\,\mathrm{fb}^{-1}\\0.10 & \text{with } 300\,\mathrm{fb}^{-1}\\0.04 & \text{with } 3000\,\mathrm{fb}^{-1}\end{array}\right.,$$

$$\left.\begin{array}{l}-0.27\\-0.19\\-0.13\end{array}\right\} \leq \frac{v^2}{\Lambda^2}\,\mathrm{Re}\left[C_{\phi u}^{33}\right] \leq \left\{\begin{array}{ll}0.67 & \text{with } 30\,\mathrm{fb}^{-1}\\0.47 & \text{with } 300\,\mathrm{fb}^{-1}\\0.32 & \text{with } 3000\,\mathrm{fb}^{-1}\end{array}\right..$$

Conclusions

- ✓ Indirect probes are powerful - Direct searches not competitive
- ✓ Future rare meson decay measurements - route to discovery
- ✓ Disclaimer: Indirect searches depend on the assumptions about UV completion