Electroweak top-quark couplings

Indirect constraints

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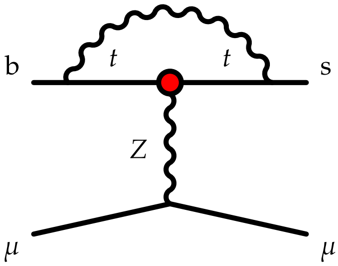
Rare decay constrain *ttZ* coupling

Anomalous *ttZ* couplings enter rare decays via EW loops



But what is really meant by this diagram?

Indirect constraints on top-quark couplings

Message

- Rare B and K decays and EWPO strongly constrain anomalous top-quark couplings

Disclaimer

- Measurements of different observables are never correlated
  e.g. $\sigma(pp \to t\bar{t}Z)$ has a priori nothing to do with $\mathrm{Br}(B_s \to \mu^+\mu^-)$.
- Observables can only be correlated within a model

Supplement to message

- if the SM is a good EFT below $\Lambda > \mu_{\mathrm{EW}}$

The setup I

Status

- ATLAS and CMS found a d.o.f. , the Higgs
- Direct searches have yet to find d.o.f. beyond the SM
- New physics effects are small

Interpretation

- EWSB is mostly linearly realised
- New particles are heavy $M = \Lambda > v$ or interact very weakly with SM

[see talk by Kamenik]

Phenomenological picture

- keep $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariance explicit
- parametrise NP effects in a v/Λ expansion

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\text{dim-6}} + \cdots$$

- operators in $\mathcal{L}_{\text{dim-6}}$ constructed from SM fields

  [e.g. Buchmüller et al, 86; Grzadkowski et al, 10]

The setup II

Correlating high-p_T observables ($\mathcal{O}^{p_T}$) with low-energy observables ($\mathcal{O}^{\text{low}}$)

Strategy

- at Λ **only** operators contributing to $\mathcal{O}^{p_T}$ are generated by NP
- they contribute to $\mathcal{O}^{p_T}$ at the tree-level
- they also contribute to low-energy observables by EW **mixing** (here T, δe_b, $B_s \to \mu^+\mu^-$, $K \to \pi\nu\bar{\nu}$)

Examples:

- anomalous *ttZ* couplings [Brod, Greljo, ES, Uttayarat 14]
- anomalous *WWZ* couplings [Bobeth, Haisch 15].

Assumption I: only operators for *ttZ*

The three operator inducing anomalous *ttZ* couplings at the tree level

$$Q_{Hq}^{(3)} \equiv (H^\dagger i \overleftrightarrow{D}_\mu^a H)(\bar{Q}_{L,3}\gamma^\mu \sigma^a Q_{L,3})$$
$$Q_{Hq}^{(1)} \equiv (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{Q}_{L,3}\gamma^\mu Q_{L,3})$$
$$Q_{Hu} \equiv (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{t}_R\gamma^\mu t_R)$$

- Here, $Q_{L,3}^T = (t_L, V_{ti} d_{L,i})$
- Allow only their Wilson coefficient to be $C(\Lambda) \neq 0$ (Assumption I)
- $\sigma(pp \to t\bar{t}Z)$ constrain $C_{Hq}^{(3)}(\mu_{\rm EW})$, $C_{Hq}^{(1)}(\mu_{\rm EW})$, $C_{Hu}(\mu_{\rm EW})$
  [Rötsch, Schulze 14; talk by Schulze]
- What else are they inducing?

Assumption II: LEP

After EWSB these operators induce

$$\mathcal{L}' = g'_R\, \bar{t}_R \not{Z} t_R + g'_L\, \bar{t}_L \not{Z} t_L + g''_L\, V^*_{3i} V_{3j} \bar{d}_{L,i} \not{Z} d_{L,j} + (k_L\, V_{3i}\, \bar{t}_L \not{W}^+ d_{L,i} + \text{h.c.})$$

with

$$g'_R \propto C_{Hu} \qquad g'_L \propto C^3_{Hq} - C^1_{Hq} \qquad \boldsymbol{g''_L \propto C^3_{Hq} + C^1_{Hq}} \qquad k_L \propto C^3_{Hq}$$

- LEP data for $Z \to b\bar{b}$ imply $g''_L < 10^{-3}$
- LEP ➜ $\boldsymbol{C^3_{Hq}(\Lambda) + C^1_{Hq}(\Lambda) = 0}$ (Assumption II)
- also kills tree-level FCNC's
- realisable in models with vector-like fermions

[del Aguila, et al 00]

Assumption III: only top Yukawa running

- only top-quark Yukawa non-zero
- neglect other Yukawas in RGE
- this is totally consistent in the setup of $\mathcal{L}^{\text{SM}}_{\text{dim-6}}$
  - bottom-quark Yukawa fixed by bottom mass
  - models with extended Higgs sector have enlarged bottom Yukawa

Electroweak mixing

Gauge-boson and higgs exchanges induce mixing into the operators:

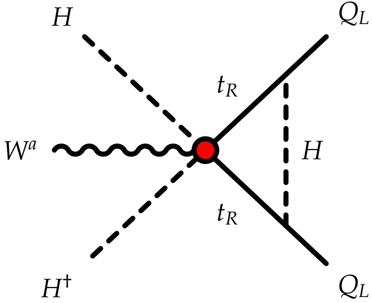
[Jenkins et al. 13; see also Brod, Greljo, ES, Uttahyarat et al. 14]

- $Q^{(3)}_{Hq,ii} \equiv (H^\dagger i \overleftrightarrow{D}^a_\mu H)(\bar{Q}_{L,i}\gamma^\mu \sigma^a Q_{L,i})$ → ***$b\bar{b}Z$***
- $Q^{(1)}_{Hq,ii} \equiv (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{Q}_{L,i}\gamma^\mu Q_{L,i})$ → ***$b\bar{b}Z$***
- $Q^{(3)}_{lq,33jj} \equiv (\bar{Q}_{L,3}\gamma_\mu \sigma^a Q_{L,3})(\bar{L}_{L,j}\gamma^\mu \sigma^a L_{L,j})$ → **rare K / B**
- $Q^{(1)}_{lq,33jj} \equiv (\bar{Q}_{L,3}\gamma_\mu Q_{L,3})(\bar{L}_{L,j}\gamma^\mu L_{L,j})$ → **rare K / B**
- $Q_{HD} \equiv \left|H^\dagger D_\mu H\right|^2$ → **T parameter**

No mixing into S parameter operator $Q_{HWB} = (H^\dagger \sigma^a H) W^a_{\mu\nu} B^{\mu\nu}$.

Electroweak mixing: examples

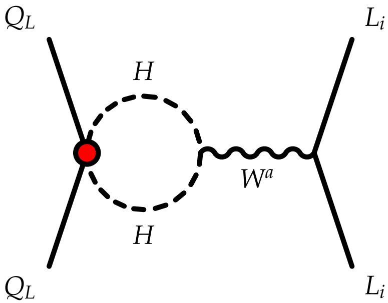
Mixing of Q_{Hu} into $Q_{Hq}^{(1)}$



Go to the broken phase ➜ induces $Z \to b\bar{b}$

Electroweak mixing: examples

Mixing of $Q_{Hq}^{(3)}$ into $Q_{lq,33ii}^{(3)}$ [1]



Go to the broken phase ➜ induces e.g. $B_s \to \mu^+\mu^-$

[1] here over eom operator

Analytic results

$Z \to b\bar{b}$

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

$$\left. + \left[\frac{2s_w^2 - 18c_w^2}{9s_w^2 c_w^2} C_{\phi q,33}^{(1)} + \frac{4}{9c_w^2} C_{\phi u}\right]\right\} \frac{v^2}{\Lambda^2} \log\frac{\mu_{\rm EW}}{\Lambda}$$

T parameter

$$\delta T = -\left[\frac{1}{3\pi c_w^2}\left(C_{\phi q,33}^{(1)} + 2C_{\phi u,33}\right) + \frac{3x_t}{2\pi s_w^2}\left(C_{\phi q,33}^{(1)} - C_{\phi u,33}\right)\right] \frac{v^2}{\Lambda^2} \log\frac{\mu_{\rm EW}}{\Lambda}$$

rare B/K decays

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

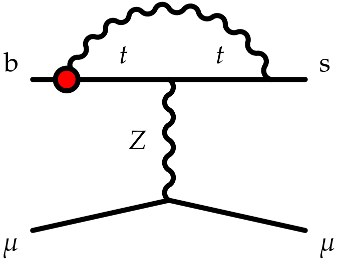
Comment on past approaches

- indirect bounds on anomalous *qtZ* and *tbW* have been derived using a similar approach

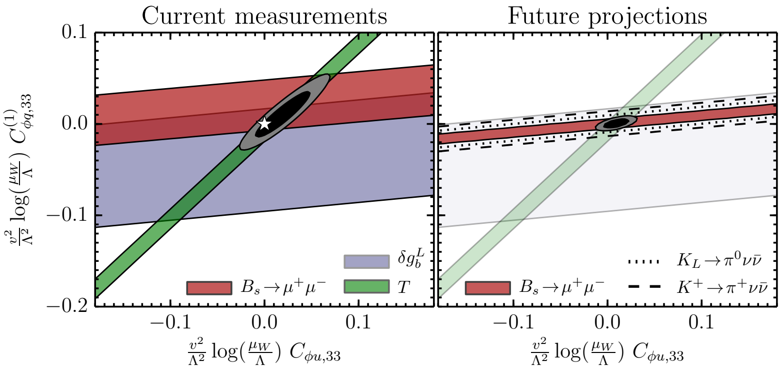
  [arxiv:1112.2674, arxiv:1301.7535, arxiv:1109.2357]
- the attempt is to use $C(\mu_{\rm EW})$ as input not $C(\Lambda)$
- calculation gives:

$$\mathcal{A} = \frac{g^2}{16\pi^2} C \left(A + \log \frac{\mu}{M_W} \right)$$

- they vary $\mu \sim \mu_{\rm EW}$. Miss the leading log.
- + finite part A is renormalisation scheme dependent



Results



Order of magnitute stronger bounds than direct reach with 3000/fb!

T	0.08 ± 0.07	[Ciuchini et al., arxiv:1306.4644]
δg_L^b	0.0016 ± 0.0015	[Ciuchini et al., arxiv:1306.4644]
$\mathrm{Br}(B_s \to \mu^+\mu^-)$ [CMS]	$(3.0^{+1.0}_{-0.9}) \times 10^{-9}$	[CMS, arxiv:1307.5025]
$\mathrm{Br}(B_s \to \mu^+\mu^-)$ [LHCb]	$(2.9^{+1.1}_{-1.0}) \times 10^{-9}$	[LHCb, arxiv:1307.5024]
$\mathrm{Br}(K^+ \to \pi^+\nu\bar{\nu})$	$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$	[E949, arxiv:0808.2459]

How general are our results?

These contributions are there, but constraints are **indirect**.

➜ **cancellations** from additional operators **possible**
➜ definitely worth looking for $pp \to t\bar{t}Z$

- Generic NP can generate FCNC transitions in up-sector
- Consider model with large bottom Yukawa (2HDM)
- + MFV counting, e.g. $\bar{Q}_L(Y_u Y_u^\dagger + Y_d Y_d^\dagger)Q_L$

➜ large y_b induces off-diagonal operators in up sector
➜ suppressed by powers of $\lambda \equiv |V_{us}| \sim 0.22$
➜ $D - \bar{D}^0$ suppressed by $\lambda^{10} \sim 10^{-7}$
➜ FCNC top decays

$$\mathrm{Br}(t \to cZ) \simeq \frac{\lambda^4 v^4}{\Lambda^4}\left[\left(C^{(3)}_{\phi q,33} - C^{(1)}_{\phi q,33}\right)^2 + C^2_{\phi u,33}\right].$$

$\mathrm{Br}(t \to cZ) < 0.05\%$[CMS, arxiv:1312.4194] ➜ not competitive

Summary and conclusions

Message

- flavour-violating observables constrain flavour-diagonal couplings
- indirect constraints often stronger than from high-p_T observables

Framework

- expansion in v/Λ
- correlations mostly model-independent within the setup of SM-EFT
- transparent assumptions ➜ guidance for model building

- Exp. and theo. efforts in measuring and predicting precision observables pay off

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Thank you.