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Flavorful Electroweak Precision Constraints on Dimension 6 Operators

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based on work in progress with

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INTRODUCTION

- Currently, no signs of new physics (NP) at the LHC.
- The Standard Model (SM) is a good approximation at the weak scale.
- Heavy new physics effects can be captured by higher dimensional operators.
- Precision measurements of the Z- and W-pole observables can probe high energy (LEP and other…).

INTRODUCTION

Working assumptions:

- Poincare invariance (Lorentz+translations)
- Linearly realized *SU(3)×SU(2)×U(1)* local gauge symmetry broken by Higgs doublet
- New physics at heavy scale, use dimension 6 operators
- Do NOT assume any flavour structure

$$\mathcal{L}_{\rm eff} = \mathcal{L}^{\rm SM} + \frac{1}{v^2}\mathcal{L}^{D=6}, \qquad \mathcal{L}^{D=6} = \sum_i c_i O_i$$

$$c_i/v^2 \approx g_{\rm NP}^2/\Lambda_{\rm NP}^2 \quad \Rightarrow \quad \Lambda_{\rm NP} \approx 7.8\, g_{\rm NP} \left(\frac{10^{-3}}{c_i}\right)^{1/2} \ {\rm TeV}$$

The Framework

consider only Z and W pole observables → simple effective Lagrangian (basis independent)

correction to m_W

$$\mathcal{L}_{\rm eff}^{VV} = \frac{(g_L^2+g_Y^2)v^2}{8} Z_\mu Z_\mu + \frac{g_L^2 v^2}{4}\,(1+2\delta m)\,W_\mu^+ W_\mu^-$$

$$\begin{aligned}\mathcal{L}_{\rm eff}^{Vff} =& eA_\mu \sum_{f\in u,d,e} Q_f(\bar f\bar\sigma_\mu f + f^c\sigma_\mu \bar f^c) + g_s G_\mu^a \sum_{f\in u,d} (\bar f\bar\sigma_\mu T^a f + f^c\sigma_\mu T^a \bar f^c)\\ &+ \frac{g_L}{\sqrt{2}}\left(W_\mu^+ \bar u\bar\sigma_\mu(\mathbb{I}+\delta g_L^{Wq})V_{\rm CKM} d + W_\mu^+ \bar u\bar\sigma_\mu \delta g_R^{Wq} d_R + W_\mu^+\bar\nu\bar\sigma_\mu(\mathbb{I}+\delta g_L^{W\ell})e + h.c.\right)\\ &+ \sqrt{g_L^2+g_Y^2}\,Z_\mu\left[\sum_{f\in u,d,e,\nu}\bar f\bar\sigma_\mu(\mathbb{I}T_f^3 - \mathbb{I}s_\theta^2 Q_f + \delta g_L^{Zf})f + \sum_{f^c\in u^c,d^c,e^c} f^c\sigma_\mu(-\mathbb{I}s_\theta^2 Q_f + \delta g_R^{Zf})\bar f^c\right]\end{aligned}$$

corrections to the W couplings

corrections to the Z couplings

any dimension 6 set of operators can be mapped to this Lagrangian

the framework and fit results

THE FRAMEWORK

SU(2)×U(1) invariance of the NP implies:

$$\delta g_L^{Z\nu} = \delta g_L^{Ze} + \delta g_L^{W\ell} \qquad \delta g_L^{Wq} = \delta g_L^{Zu} - \delta g_L^{Zd}$$

the EFT dimension 6 operators effects on the *W* and *Z* pole observables can be parameterized by

$$\delta m\,,\ \delta g_L^{Ze}\,,\ \delta g_R^{Ze}\,,\ \delta g_L^{W\ell}\,,\ \delta g_L^{Zu}\,,\ \delta g_R^{Zu}\,,\ \delta g_L^{Zd}\,,\ \delta g_R^{Zd}\,,\ \delta g_R^{Wq}$$

3×3 generic matrices

different flavour models predict relations inside and among them

fit for δg's (model/basis independent) → map to dimension 6 specific basis → consider different flavor models (alignment, MFV, FN)

The Pole Observables

Fit inputs: $G_F\,,\ m_Z\,,\ \alpha(o)$

receive corrections at order δg

The pole observables

Fit inputs: $G_F\,,\ m_Z\,,\ \alpha(o)$

Z-pole: $\Gamma_Z = \sum_f \Gamma(Z\to f\bar f)$

$$\sigma_{\rm had} = \frac{12\pi}{m_Z^2}\frac{\Gamma(Z\to e^+e^-)\Gamma(Z\to q\bar q)}{\Gamma_Z^2}$$

$$R_\ell = \frac{\sum_q \Gamma(Z\to q\bar q)}{\Gamma(Z\to \ell^+\ell^-)}\,,\ \ell = e,\mu,\tau$$

$$R_q = \frac{\Gamma(Z\to q\bar q)}{\sum_q \Gamma(Z\to q\bar q)}\,,\ q = b,c$$

$$R_{uc} = \frac{\Gamma(Z\to u\bar u)+\Gamma(Z\to c\bar c)}{2\sum_q \Gamma(Z\to q\bar q)}$$

$$\mu_{ttZ} = \frac{(g_L^{Zt})^2+(g_R^{Zt})^2}{g_{L,\rm SM}^{Zt})^2+(g_{R,\rm SM}^{Zt})^2}$$

$$A_f = \frac{\Gamma(Z\to f_L\bar f_L)-\Gamma(Z\to f_R\bar f_R)}{\Gamma(Z\to f\bar f)}\,,\ f = e,\mu,\tau,b,c,s$$

$$A_f^{\rm FB} = \frac{3}{4}A_eA_f\,,\ f = e,\mu,\tau,b,c$$

receive corrections at order δg

The Pole Observables

Fit inputs: $G_F\,,\ m_Z\,,\ \alpha(o)$

Z-pole:

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$$A_f = \frac{\Gamma(Z \to f_L\bar{f}_L) - \Gamma(Z \to f_R\bar{f}_R)}{\Gamma(Z \to f\bar{f})}\,,\ f = e,\mu,\tau,b,c,s$$

$$A_f^{\rm FB} = \frac{3}{4}A_eA_f\,,\ f = e,\mu,\tau,b,c$$

W-pole:

$$m_W\,,\Gamma_W$$

$$\text{BR}(W \to \ell\nu)\,,\ \ell = e,\mu,\tau$$

$$R_{Wc} = \frac{\Gamma(W \to cs)}{\Gamma(W \to cs) + \Gamma(W \to us)}$$

$$R_\sigma = g_L^{Wq_3}/g_{L,\rm SM}^{Wq_3}$$

receive corrections at order δg

The Pole Observables

- The pole observables are not sensitive to:
  - CPV, flavor off-diagonal
  - δg_R^{Wq}- does not interfere with the SM enters only at higher order
  - One linear combination of the first generation quarks - flat direct

$$[\delta\hat{g}_L^{Zu}]_{11} = [\delta g_L^{Zu}]_{11} - \frac{2g_Y^2}{3g_L^2 + g_Y^2}[\delta g_R^{Zd}]_{11},$$

$$[\delta\hat{g}_L^{Zd}]_{11} = [\delta g_L^{Zd}]_{11} - \frac{2g_Y^2}{3g_L^2 + g_Y^2}[\delta g_R^{Zd}]_{11},$$

$$[\delta\hat{g}_R^{Zu}]_{11} = [\delta g_R^{Zu}]_{11} - \frac{3g_L^2 - g_Y^2}{2(3g_L^2 + g_Y^2)}[\delta g_R^{Zd}]_{11},$$

$$[\delta\hat{g}_L^{Zu}]_{11} = [\delta\hat{g}_L^{Zd}]_{11} = [\delta\hat{g}_R^{Zu}]_{11} = 0$$

- 27 different observables
- 3×7+1=22 parameters - 1 flat direction = 21 parameters to fit

The Fit Result

$$\delta m = (2.6 \pm 1.9) \times 10^{-4}$$ W mass

$$[\delta g_L^{Ze}]_{ii} = \begin{pmatrix} -0.34 \pm 0.30 \\ 0.25 \pm 0.70 \\ 0.07 \pm 0.55 \end{pmatrix} \times 10^{-3}$$

$$[\delta g_R^{Ze}]_{ii} = \begin{pmatrix} -0.53 \pm 0.28 \\ 0.17 \pm 0.87 \\ 0.24 \pm 0.61 \end{pmatrix} \times 10^{-3}$$

$$[\delta g_L^{We}]_{ii} = \begin{pmatrix} -1.01 \pm 0.64 \\ -1.37 \pm 0.59 \\ 1.98 \pm 0.79 \end{pmatrix} \times 10^{-2}$$ Z to *νν* same order

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$$\begin{pmatrix} [\delta \hat{g}_L^{Zu}]_{11} \\ [\delta g_L^{Zu}]_{22} \\ [\delta g_L^{Zu}]_{33} \end{pmatrix} = \begin{pmatrix} -1.9 \pm 2.4 \\ -0.17 \pm 0.28 \\ -0.4 \pm 3.8 \end{pmatrix} \times 10^{-2}$$

$$\begin{pmatrix} [\delta \hat{g}_R^{Zu}]_{11} \\ [\delta g_R^{Zu}]_{22} \\ [\delta g_R^{Zu}]_{33} \end{pmatrix} = \begin{pmatrix} -1.0 \pm 4.1 \\ -0.44 \pm 0.38 \\ 9 \pm 16 \end{pmatrix} \times 10^{-2}$$

$$\begin{pmatrix} [\delta \hat{g}_L^{Zd}]_{11} \\ [\delta g_L^{Zd}]_{22} \\ [\delta g_L^{Zd}]_{33} \end{pmatrix} = \begin{pmatrix} -2.3 \pm 4.7 \\ 1.4 \pm 4.1 \\ 0.21 \pm 0.11 \end{pmatrix} \times 10^{-2}$$

$$\begin{pmatrix} [\delta g_R^{Zd}]_{22} \\ [\delta g_R^{Zd}]_{33} \end{pmatrix} = \begin{pmatrix} 2.5 \pm 6.3 \\ 1.81 \pm 0.57 \end{pmatrix} \times 10^{-2}$$

couplings to ***t*** and ***s*** are constrained only at the 10% level

mapping to flavor models

The non universal EFT

$$\mathcal{L}_{\rm eff} = \mathcal{L}^{\rm SM} + \frac{1}{v^2}\mathcal{L}^{D=6}, \qquad \mathcal{L}^{D=6} = \sum_i c_i O_i$$

	Operator	flavor structure
$O_{H\ell}$	$i\bar{\ell}\bar{\sigma}_\mu \ell H^\dagger \overleftrightarrow{D}_\mu H$	$\bar{L}\times L$
$O'_{H\ell}$	$i\bar{\ell}\sigma^i\bar{\sigma}_\mu \ell H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$	$\bar{L}\times L$
O_{He}	$ie^c\sigma_\mu \bar{e}^c H^\dagger \overleftrightarrow{D}_\mu H$	$\bar{E}\times E$
O_{Hq}	$i\bar{q}\bar{\sigma}_\mu q H^\dagger \overleftrightarrow{D}_\mu H$	$\bar{Q}\times Q$
O'_{Hq}	$i\bar{q}\sigma^i\bar{\sigma}_\mu q H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$	$\bar{Q}\times Q$
O_{Hu}	$iu^c\sigma_\mu \bar{u}^c H^\dagger \overleftrightarrow{D}_\mu H$	$\bar{U}\times U$
O_{Hd}	$id^c\sigma_\mu \bar{d}^c H^\dagger \overleftrightarrow{D}_\mu H$	$\bar{D}\times D$
O_T	$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	universal
O_{WB}	$g_L g_Y H^\dagger \sigma^i H\, W^i_{\mu\nu} B_{\mu\nu}$	universal
$O'_{\ell\ell}$	$-4(\bar{\nu}_\mu\bar{\sigma}_\rho\mu)(\bar{e}\bar{\sigma}_\rho\nu_e)$	specific

(in Warsaw basis)

The non universal EFT

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(in Warsaw basis)

resulting bounds:

$c_i \lesssim 10^{-2}, 10^{-3}$

$\Lambda_{\rm NP}/g_{\rm NP} \gtrsim 2, 8\,\text{TeV}$

BUT

from flavor precision NP at the TEV scale cannot have anarchy flavor structure (meson mixing, rare decays)

→ some alignment with the SM (or universality)

ALIGNMENT

the higher dimension operators are aligned with the masses:

- right handed current: can be aligned simultaneously to the up and down sectors ⇒ no right handed FCNC
- left handed current: can be aligned to the up sector or to the down sector ⇒ left handed FCNC suppressed by CKM
- no special relations between the diagonal elements

$c_{Hu}\ ,\ \ c_{Hd}$ - diagonal

V - CKM

$Q_{d,u}$-diagonal

$c_{Hq}^{(\prime)}$	**up basis**	**down basis**	
up-alignment	Q_u	$V^\dagger Q_u V$	Kaon mixing, B mixing
down-alignment	$V Q_d V^\dagger$	Q_d	charm mixing, top FCNC

ALIGNMENT

constraint on the left handed operators: $(c^{(\prime)}_{Hq})_{ii} \lesssim 4\times 10^{-2}$
(@1sigma)

assume that this bound is saturated, look on FCNCs

up-alignment: problematic with Kaon mixing, ok with *B*-mixing

down-alignment: charm-mixing can have only coupling to third generation, ok with top FCNC

MINIMAL FLAVOR VIOLATION

- the SM has approximate flavor symmetry of (at the limit of vanishing Yukawa):

$$SU(3)_Q \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E$$

- assume that at the terms are formally invariant under this approximate symmetry
- all flavor violation are a result of the SM Yukawa

$$c_{Hq}^{(\prime)} = c_{q1}^{(\prime)} + c_{q2}^{(\prime)} Y_u Y_u^\dagger + c_{q3}^{(\prime)} Y_d Y_d^\dagger$$

$$c_{Hu} = c_{u1} + c_{q2} Y_u^\dagger Y_u$$

$$c_{Hd} = c_{d1} + c_{d2} Y_d^\dagger Y_d$$

$$c_{H\ell}^{(\prime)} = c_{\ell 1}^{(\prime)} + c_{\ell 2}^{(\prime)} Y_\ell Y_\ell^\dagger$$

FCNC are suppressed, deviations from universality are hierarchical (mainly 3rd generation) relevant references:

- **ex**: LEP hep-ex/0509008; SLD hep-ex/006019; CMS 1406.7830; ATLAS-CONF-2014-38; CDF/D0 1204.0042
- **th**: M. Baak *et al.* 1407.3792; Cacciapaglia *et al*. hep-ph/0604111; Grzadowski *et al.* 1008.4884; Falkowski/Riva 1411.0669; Pomarol/Riva 1308.2803; Elias-Miro *et al.* 1308.1879; Willenbrock/Zhang 1401.0470; Ciuchini *et al.* 1410.6940; Eillis *et al.* 1410.7703; Han/Skiba hep-ph/0412166; del Aguila/de Blas 1105.6103

Summary

- We derive the model independent bounds form the Z and W pole observables on dimension 6 operators without assuming flavor universality.
- There is one flat direction, related to the first generation quarks (not measure asymmetry).
- The deviation of the Z couplings to top and strange quarks can be up to 10% of the SM value, much weaker bound than the other coupling.

Backup slides

The Pole Observables

Z-pole

Observable	Definition
Γ_Z [GeV]	$\sum_f \Gamma(Z \to f\bar{f})$
σ_{had} [nb]	$\frac{12\pi}{m_Z^2} \frac{\Gamma(Z\to e^+e^-)\Gamma(Z\to q\bar{q})}{\Gamma_Z^2}$
R_e	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to e^+e^-)}$
R_μ	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \mu^+\mu^-)}$
R_τ	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \tau^+\tau^-)}$
$A_{\text{FB}}^{0,e}$	$\frac{3}{4}A_e^2$
$A_{\text{FB}}^{0,\mu}$	$\frac{3}{4}A_e A_\mu$
$A_{\text{FB}}^{0,\tau}$	$\frac{3}{4}A_e A_\tau$
R_b	$\frac{\Gamma(Z\to b\bar{b})}{\sum_q \Gamma(Z\to q\bar{q})}$
R_c	$\frac{\Gamma(Z\to c\bar{c})}{\sum_q \Gamma(Z\to q\bar{q})}$
A_b^{FB}	$\frac{3}{4}A_e A_b$
A_c^{FB}	$\frac{3}{4}A_e A_c$

Observable	Definition
A_e	$\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to e^+e^-)}$
A_μ	$\frac{\Gamma(Z\to \mu_L^+\mu_L^-)-\Gamma(Z\to e_\mu^+\mu_R^-)}{\Gamma(Z\to \mu^+\mu^-)}$
A_τ	$\frac{\Gamma(Z\to \tau_L^+\tau_L^-)-\Gamma(Z\to \tau_R^+\tau_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$
A_b	$\frac{\Gamma(Z\to b_L\bar{b}_L)-\Gamma(Z\to b_R\bar{b}_R)}{\Gamma(Z\to b\bar{b})}$
A_c	$\frac{\Gamma(Z\to c_L\bar{c}_L)-\Gamma(Z\to c_R\bar{c}_R)}{\Gamma(Z\to c\bar{c})}$
A_s	$\frac{\Gamma(Z\to s_L\bar{s}_L)-\Gamma(Z\to s_R\bar{s}_R)}{\Gamma(Z\to s\bar{s})}$
R_{uc}	$\frac{\Gamma(Z\to u\bar{u})+\Gamma(Z\to c\bar{c})}{2\sum_q \Gamma(Z\to q\bar{q})}$
μ_{ttZ}	$\frac{(g_L^{Zt})^2+(g_R^{Zt})^2}{(g_{L,\text{SM}}^{Zu})^2+(g_{R,\text{SM}}^{Zu})^2}$

W-pole

Observable	Definition
m_W [GeV]	$\frac{g_L v}{2}(1+\delta m)$
Γ_W [GeV]	$\sum_f \Gamma(W \to f f')$
$\text{Br}(W\to e\nu)$	$\frac{\Gamma(W\to e\nu)}{\sum_f \Gamma(W\to f f')}$
$\text{Br}(W\to \mu\nu)$	$\frac{\Gamma(W\to \mu\nu)}{\sum_f \Gamma(W\to f f')}$
$\text{Br}(W\to \tau\nu)$	$\frac{\Gamma(W\to \tau\nu)}{\sum_f \Gamma(W\to f f')}$
R_{Wc}	$\frac{\Gamma(W\to cs)}{\Gamma(W\to ud)+\Gamma(W\to cs)}$
R_σ	$g_L^{Wq_3}/g_{L,\text{SM}}^{Wq_3}$

fit inputs: $G_F\,,\ m_Z\,,\ \alpha(o)$

only observables which are linear in δg

(δg^2 formally higher order in EFT)