Enhanced Z-mediated new physics in $\Delta S = 2$ and $\Delta B = 2$ processes

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In collaboration with Buras/Celis/Jung arXiv:1703.04753 and 1609.04783

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Motivation / Introduction

FC (flavor-changing) Z-couplings

In SM

- tree-level FC-couplings of Z to quarks (and leptons) forbidden by GIM

  [Glashow/Iliopoulos/Maiani PRD72 (1970) 1285]

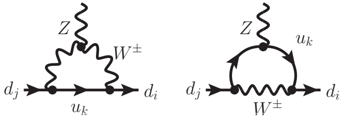
- GIM broken at one-loop by Yukawa-couplings

  → leading effect for down-type quark transitions due to top quark masses

$$Z_\mu \left[\bar{d}_i \gamma^\mu P_L d_j\right] = \frac{g_2^3 V_{ti}^* V_{tj}}{8\pi^2 c_W} C(x_t = m_t^2/m_W^2) \sim \frac{m_t^2}{m_W^2}$$

gauge-dependent Inami-Lim function

$$C(x, \xi_W = 1) = \frac{x}{8}\left(\frac{x-6}{x-1} + \frac{3x+2}{(x-1)^2}\ \ln x\right)$$



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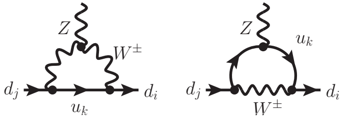

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Beyond SM naive modification of Z couplings to quarks (and analogously leptons)

$$\mathcal{L}^{\rm NP}_{\psi\bar\psi Z} = Z_\mu \sum_{\psi=u,d} \bar\psi_i \gamma^\mu \left([\Delta_L^\psi]_{ij} P_L + [\Delta_R^\psi]_{ij} P_R\right) \psi_j$$

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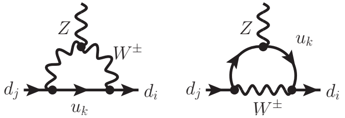

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$$\mathcal{L}^{\rm NP}_{\psi\bar{\psi}Z} = Z_\mu \sum_{\psi=u,d} \bar{\psi}_i \gamma^\mu \left([\Delta_L^\psi]_{ij} P_L + [\Delta_R^\psi]_{ij} P_R\right) \psi_j$$

!!! Adding these terms is not $\mathrm{SU(2)_L \otimes U(1)_Y}$ gauge-invariant ⇒ use SMEFT instead

SMEFT (standard model EFT)

$$\mathcal{L}_{\rm SMEFT}(\mu \ll \mu_\Lambda) = \mathcal{L}_{\rm SM}(q_L, \ell_L, u_R, d_R, e_R, H) + \sum_{\text{dim}-5,6} \mathcal{C}_i \mathcal{O}_i$$

- dim−4: just SM Lagrangian
- dim−5: “Weinberg operator” → neutrino masses
- dim−6: contains various types of operators build out of $q_L, \ell_L, u_R, d_R, e_R, H$
- all **invariant under** $\rm G_{SM} = SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

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Type of operators (a possible choice of **non-redundant** basis) [Grzadkowski/Iskrzynski/Misiak/Rosiek 1008.4884]

("Warsaw basis" used throughout)

- X^3 — X = field strength tensors $G^a_{\mu\nu}, \ldots$
- H^6
- $H^4 D$
- $\psi^2 H^3$ ← fermion masses + FC H couplings
- $X^2 H^2$
- $\psi^2 X H$ ← dipole operators
- $\psi^2 H^2 D$ ← FC Z and $W^\pm$ couplings
- ψ^4 ← 4-fermion FC operators $(\bar{L}L)(\bar{L}L),\ (\bar{R}R)(\bar{R}R),\ (\bar{L}L)(\bar{R}R),\ (\bar{L}R)(\bar{L}R),\ (\bar{L}L)(\bar{R}L)$

59 types: in total 2499 ($\mathrm{SU(2)_L} \otimes \mathrm{U(1)_Y}$ invariant) operators (3 generations / 6 flavors)

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LH (left-handed) FC Z coupl's ($W^\pm$ in $\mathcal{O}_{Hq}^{(3)}$)

$$\mathcal{O}_{Hq}^{(1)} = (H^\dagger i \overleftrightarrow{\mathcal{D}}_\mu H)[\bar{q}_L^i \gamma^\mu q_L^j]$$
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- weak eigenstates q_L^i and u_R^i, d_R^i
- mass eigenstates u_i and d_i

RH (right-handed) FC Z coupl's ($W^\pm$ in $\mathcal{O}_{Hud}$)

$$\mathcal{O}_{Hd} = (H^\dagger i \overleftrightarrow{\mathcal{D}}_\mu H)[\bar{d}_R^i \gamma^\mu d_R^j]$$
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$$\mathcal{O}_{Hud} = (\widetilde{H}^\dagger i \mathcal{D}_\mu H)[\bar{u}_R^i \gamma^\mu d_R^j]$$

- analogous op's for leptons $\mathcal{O}_{H\ell}^{(1,3)}$, $\mathcal{O}_{He}$

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EWSB (electroweak symmetry breaking) @ $\mu_{\rm ew}$

$\Rightarrow$ fermion masses receive dim-6 contr. from $\psi^2 H^3$ op's

$$m_\psi^{ij} = \frac{v}{\sqrt{2}}\left(Y_\psi^{ij} - \frac{v^2}{2}\mathcal{C}_{\psi H}^{ij}\right), \qquad (\psi = u, d)$$

$$\mathcal{O}_{uH} = (H^\dagger H)[\bar{q}_L^i u_R^j \widetilde{H}]$$

$$\mathcal{O}_{dH} = (H^\dagger H)[\bar{q}_L^i d_R^j H]$$

Transition to mass eigenstates via 3×3 unitary $\psi_L \to V_L^\psi \psi_L$ and $\psi_R \to V_R^\psi \psi_R$

$$V_L^{\psi\dagger} m_\psi V_R^\psi = m_\psi^{\rm diag}, \qquad V = (V_L^u)^\dagger V_L^d,$$

$\Rightarrow$ V is unitary and corresponds to CKM matrix of SM

FC Vq_jq_i couplings

$(V = Z, W)$

In mass basis

$(g_Z \equiv \sqrt{g_1^2 + g_2^2})$

$$\mathcal{L}^{\text{dim}-6}_{\psi\bar\psi V} = -\frac{g_Z}{2} v^2 Z_\mu \Big(\Big[V_L^{d\dagger}(\mathcal{C}^{(1)}_{Hq} + \mathcal{C}^{(3)}_{Hq}) V_L^d\Big]_{ij} [\bar d_i \gamma^\mu P_L d_j] + \Big[V_R^{d\dagger} \mathcal{C}_{Hd} V_R^d\Big]_{ij} [\bar d_i \gamma^\mu P_R d_j]$$
$$+ \Big[V_L^{u\dagger}(\mathcal{C}^{(1)}_{Hq} - \mathcal{C}^{(3)}_{Hq}) V_L^u\Big]_{ij} [\bar u_i \gamma^\mu P_L u_j] + \Big[V_R^{u\dagger} \mathcal{C}_{Hu} V_R^u\Big]_{ij} [\bar u_i \gamma^\mu P_R u_j] \Big)$$
$$+ \frac{g_2}{\sqrt{2}} v^2 \Big(\Big[V_L^{u\dagger} \mathcal{C}^{(3)}_{Hq} V_L^d\Big]_{ij} [\bar u_i \gamma^\mu P_L d_j] W^+_\mu + \Big[V_R^{u\dagger} \frac{\mathcal{C}_{Hud}}{2} V_R^d\Big]_{ij} [\bar u_i \gamma^\mu P_R d_j] W^+_\mu + \text{h.c.} \Big)$$

- v and $g_{1,2}$ differ in principle from SM values by dim-6 contr's but here dim-8 effect
- Wilson coefficients correspond to weak basis, BUT can choose special weak basis

$$V^d_{L,R} = \mathbb{1} \qquad \text{and} \qquad V^u_R = \mathbb{1} \qquad \Rightarrow \quad V^u_L = V^\dagger$$

$\Rightarrow$ d-quarks already mass states, convenient for d-type quark $\Delta F = 1, 2$ phenomenology

- additional factors of V only in coupl's of op's with LH u-quarks
- relations between down- and up-type FCNC's (in this basis)

$$\mathcal{L}^{\text{dim}-6}_{t\to cZ} \propto \sum_{k,l} V_{ck} [\mathcal{C}^{(1)}_{Hq} - \mathcal{C}^{(3)}_{Hq}]_{kl} V^*_{tl} \approx [\mathcal{C}^{(1)}_{Hq} - \mathcal{C}^{(3)}_{Hq}]_{sb} + \mathcal{O}(\lambda_C)$$

$\lambda_C \approx 0.22$ Cabibbo angle

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$$+ \Big[V_L^{u\dagger} (\mathcal{C}_{Hq}^{(1)} - \mathcal{C}_{Hq}^{(3)}) V_L^u \Big]_{ij} \big[\bar u_i \gamma^\mu P_L u_j\big] + \Big[V_R^{u\dagger} \mathcal{C}_{Hu} V_R^u \Big]_{ij} \big[\bar u_i \gamma^\mu P_R u_j\big] \Big)$$
$$+ \frac{g_2}{\sqrt{2}} v^2 \Big(\Big[V_L^{u\dagger} \mathcal{C}_{Hq}^{(3)} V_L^d \Big]_{ij} \big[\bar u_i \gamma^\mu P_L d_j\big] W_\mu^+ + \Big[V_R^{u\dagger} \frac{\mathcal{C}_{Hud}}{2} V_R^d \Big]_{ij} \big[\bar u_i \gamma^\mu P_R d_j\big] W_\mu^+ + \text{h.c.} \Big)$$

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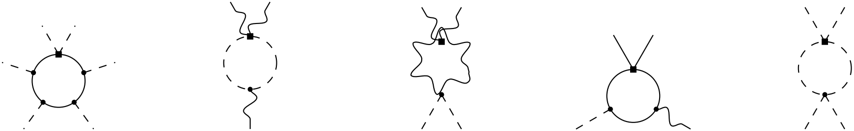
RG (renormalization group) effects in SMEFT

RG evolution relates Wilson coeff's at different scales 1stLLA = 1st leading logarithm approx.

$$\mathcal{C}_a(\mu_{\rm ew}) \approx \left(\delta_{ab} - \frac{\gamma_{ab}}{(4\pi)^2} \ln\frac{\mu_\Lambda}{\mu_{\rm ew}}\right)\mathcal{C}_b(\mu_\Lambda) + \mathcal{O}(\gamma^2, \gamma^3, \ldots), \qquad \gamma_{ab} \propto \lambda,\ Y^2,\ g_1^2,\ g_2^2,\ g_3^2$$

$\Rightarrow$ γ_{ab} = ADM (anomalous dimension matrix) completely known at 1-loop



[(Alonso)/Jenkins/Manohar/Trott 1308.2627, 1310.4838, (1312.2014)]

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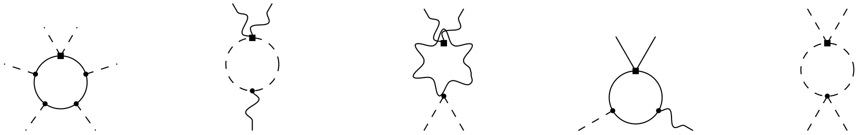

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In SMEFT corrletions among flavor sectors possible due to **flavor-changing**

Higgs (Yukawa) couplings	$\mathrm{SU}(2)_\mathrm{L}$ gauge couplings	dim-6 operators
$(\bar{q}_{iL} Y_{u,ij} u_{jR})\widetilde{H} + (\bar{q}_{iL} Y_{d,ij} d_{jR})H$	$u_L \leftrightarrow d_L$	various flavor structures

- numerically largest RG effects $4\pi\alpha_s \sim 1.4$ $\Rightarrow$ BUT $\mathrm{SU}(3)_c$ flavor-diagonal
- top-Yukawa $y_t^2 \sim 1$ $\Rightarrow$ flavor-mixing $\Leftarrow$ phenomenologically most interesting

Top-Yukawa RG effects of $\psi^2 H^2 D$ op's for $\Delta F = 2$

- $\psi^2 H^2 D$ operators mix into ψ^4 4-quark op's via top-Yukawa $\qquad \Delta F = 2$: $kl = ij$

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\begin{array}{lll}
(\bar{\mathbf{L}}\mathbf{L})(\bar{\mathbf{L}}\mathbf{L}) & [\mathcal{O}_{qq}^{(1)}]_{ijkl} = [\bar{q}_L^i \gamma_\mu q_L^j][\bar{q}_L^k \gamma^\mu q_L^l] & [\mathcal{O}_{qq}^{(3)}]_{ijkl} = [\bar{q}_L^i \gamma_\mu \sigma^a q_L^j][\bar{q}_L^k \gamma^\mu \sigma^a q_L^l] \\
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- only 3 contribute to down-type $\Delta F = 2$ $\qquad \dot{\mathcal{C}}_a \equiv (4\pi)^2 \mu \frac{\mathrm{d}\mathcal{C}_a}{\mathrm{d}\mu}$ $\qquad$ [Jenkins/Manohar/Trott 1310.4838]

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- in mass eigen basis (neglecting dim-6 effects in RG evolution of dim-6 Wilson coefficients)

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Y_u \overset{\text{dim}-4}{\approx} \frac{\sqrt{2}}{v} V_L^u m_U^{\text{diag}} V_R^{u\dagger} = \frac{\sqrt{2}}{v} V_{\text{CKM}}^\dagger m_U^{\text{diag}},
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the ADMs are given in terms of top-quark mass and CKM elements $\lambda_t^{ij} \equiv V_{ti}^* V_{tj}$

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$$(\bar{\mathbf{R}}\mathbf{R})(\bar{\mathbf{R}}\mathbf{R}) \quad [\mathcal{O}_{ud}^{(1)}]_{ijkl} = [\bar{u}_R^i \gamma_\mu u_R^j][\bar{d}_R^k \gamma^\mu d_R^l] \qquad [\mathcal{O}_{uu}]_{ijkl} = [\bar{u}_R^i \gamma_\mu u_R^j][\bar{u}_R^k \gamma^\mu u_R^l]$$

- only 3 contribute to down-type $\Delta F = 2$ $\qquad \dot{\mathcal{C}}_a \equiv (4\pi)^2 \mu \frac{\mathrm{d}\mathcal{C}_a}{\mathrm{d}\mu}$ $\qquad$ [Jenkins/Manohar/Trott 1310.4838]

$$(\bar{\mathbf{L}}\mathbf{L})(\bar{\mathbf{L}}\mathbf{L}) \quad [\dot{\mathcal{C}}_{qq}^{(1)}]_{ijij} = +[Y_u Y_u^\dagger]_{ij}[\mathcal{C}_{Hq}^{(1)}]_{ij} + \ldots \qquad [\dot{\mathcal{C}}_{qq}^{(3)}]_{ijij} = -[Y_u Y_u^\dagger]_{ij}[\mathcal{C}_{Hq}^{(3)}]_{ij} + \ldots$$

$$(\bar{\mathbf{L}}\mathbf{L})(\bar{\mathbf{R}}\mathbf{R}) \quad [\dot{\mathcal{C}}_{qd}^{(1)}]_{ijij} = +[Y_u Y_u^\dagger]_{ij}[\mathcal{C}_{Hd}]_{ij} + \ldots$$

- in mass eigen basis (neglecting dim-6 effects in RG evolution of dim-6 Wilson coefficients)

$$Y_u \overset{\text{dim}-4}{\approx} \frac{\sqrt{2}}{v} V_L^u m_U^{\text{diag}} V_R^{u\dagger} = \frac{\sqrt{2}}{v} V_{\text{CKM}}^\dagger m_U^{\text{diag}},$$

the ADMs are given in terms of top-quark mass and CKM elements $\lambda_t^{ij} \equiv V_{ti}^* V_{tj}$

$$[Y_u Y_u^\dagger]_{ij} = \frac{2}{v^2} \sum_{k=u,c,t} m_k^2 V_{ki}^* V_{kj} \approx \frac{2}{v^2} m_t^2 \lambda_t^{ij},$$

$\psi^2 H^2 D$ quark operators
in $\Delta S, B = 1, 2$ phenomenology

Matching to $\Delta F = 2$ EFT: Tree-Level

EFT below $\mu_{\rm ew}$ $\mathcal{H}^{ij}_{\Delta F=2} = \mathcal{N}_{ij} \sum_a C^{ij}_a P^{ij}_a + \text{h.c.}$

$$P^{ij}_{\rm VLL} = [\bar{d}_i \gamma_\mu P_L d_j][\bar{b}_i \gamma^\mu P_L d_j]$$

$$P^{ij}_{\rm LR,1} = [\bar{d}_i \gamma_\mu P_L d_j][\bar{b}_i \gamma^\mu P_R d_j]$$

$$P^{ij}_{\rm LR,2} = [\bar{d}_i P_L d_j][\bar{b}_i P_R d_j]$$

$$P^{ij}_{\rm SLL,1} = [\bar{d}_i P_L d_j][\bar{b}_i P_L d_j]$$

$$P^{ij}_{\rm SLL,2} = -[\bar{d}_i \sigma_{\mu\nu} P_L d_j][\bar{b}_i \sigma^{\mu\nu} P_L d_j]$$

$+\ \rm VLL \to VRR$ and $\rm SLL \to SRR$

[Buras/Misiak/Urban hep-ph/0005183]

in SM only non-zero

$$C_1^{\rm VLL}(\mu_{\rm ew})\Big|_{\rm SM} = S_0(x_t), \qquad \mathcal{N}_{ij} = \frac{G_F^2}{4\pi^2} m_W^2 (\lambda_t^{ij})^2$$

$S_0(x_t) \Rightarrow$ gauge- and log $\mu_{\rm ew}$-independent

Matching to $\Delta F = 2$ EFT: Tree-Level

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$$P^{ij}_{\rm VLL} = [\bar{d}_i \gamma_\mu P_L d_j][\bar{b}_i \gamma^\mu P_L d_j]$$

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$$P^{ij}_{\rm LR,2} = [\bar{d}_i P_L d_j][\bar{b}_i P_R d_j]$$

$$P^{ij}_{\rm SLL,1} = [\bar{d}_i P_L d_j][\bar{b}_i P_L d_j]$$

$$P^{ij}_{\rm SLL,2} = -[\bar{d}_i \sigma_{\mu\nu} P_L d_j][\bar{b}_i \sigma^{\mu\nu} P_L d_j]$$

$+\,\rm VLL \to VRR$ and $\rm SLL \to SRR$

[Buras/Misiak/Urban hep-ph/0005183]

Matching SMEFT on $\Delta F = 2$ EFT @ $\mu_{\rm ew}$

$$\Delta C^{ij}_{\rm VLL} = -\mathcal{N}_{ij}^{-1}\left([\mathcal{C}^{(1)}_{qq}]_{ijij} + [\mathcal{C}^{(3)}_{qq}]_{ijij}\right) \qquad \Delta C^{ij}_{\rm VRR} = -\mathcal{N}_{ij}^{-1}[\mathcal{C}_{dd}]_{ijij}$$

$$\Delta C^{ij}_{\rm LR,1} = -\mathcal{N}_{ij}^{-1}\left([\mathcal{C}^{(1)}_{qd}]_{ijij} - [\mathcal{C}^{(8)}_{qd}]_{ijij}/(2N_c)\right) \qquad \Delta C^{ij}_{\rm LR,2} = \mathcal{N}_{ij}^{-1}[\mathcal{C}^{(8)}_{qd}]_{ijij}$$

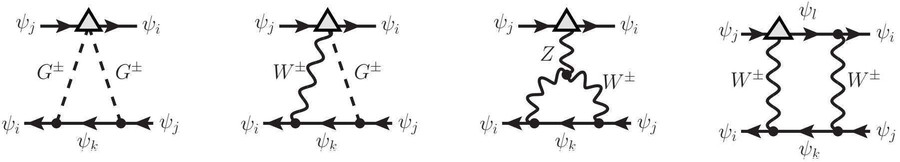
at tree-level, using 1stLLA for RG evolution of $[\mathcal{C}^{(1,3)}_{Hq,Hd}]_{ijij}$

$$\Delta C^{ij}_{\rm LR,1}(\mu_{\rm ew}) = v^2 \frac{[\mathcal{C}_{Hd}]_{ij}(\mu_\Lambda)}{\lambda_t^{ij}} x_t \ln\frac{\mu_\Lambda}{\mu_{\rm ew}}$$

$$\Delta C^{ij}_{\rm VLL}(\mu_{\rm ew}) = v^2 \frac{[\mathcal{C}^{(1)}_{Hq}]_{ij}(\mu_\Lambda) - [\mathcal{C}^{(3)}_{Hq}]_{ij}(\mu_\Lambda)}{\lambda_t^{ij}} x_t \ln\frac{\mu_\Lambda}{\mu_{\rm ew}}$$

$$x_t \equiv \frac{m_t^2}{m_W^2}$$

Matching to $\Delta F = 2$ EFT: One-Loop



- 1-loop yields gauge-independent $H_{1,2}(x_t, \mu_{\rm ew})$
- $H_{1,2}(x_t, \mu_{\rm ew}) \sim \ln \mu_{\rm ew}/m_W$ cancel $\mu_{\rm ew}$ dep. of 1stLLA contribution
- box-diagram only for $\mathcal{O}_{Hq}^{(3)}$, is gauge dependent $\Rightarrow$ needed to obtain gauge-independent H_2
- box-diagram introduces dependence on all $[\mathcal{C}_{Hq}^{(3)}]_{mj}$ and $[\mathcal{C}_{Hq}^{(3)}]_{im}$

$$\Delta C_{\rm LR,1}^{ij}(\mu_{\rm ew}) = v^2 \frac{[\mathcal{C}_{Hd}]_{ij}}{\lambda_t^{ij}} x_t \left\{ \ln \frac{\mu_\Lambda}{\mu_{\rm ew}} + H_1(x_t, \mu_{\rm ew}) \right\}$$

NLO corr.

$$\Delta C_{\rm VLL}^{ij}(\mu_{\rm ew}) = \frac{v^2}{\lambda_t^{ij}} x_t \left\{ [\mathcal{C}_{Hq}^{(1)} - \mathcal{C}_{Hq}^{(3)}]_{ij} \ln \frac{\mu_\Lambda}{\mu_{\rm ew}} + [\mathcal{C}_{Hq}^{(1)}]_{ij} H_1(x_t, \mu_{\rm ew}) - [\mathcal{C}_{Hq}^{(3)}]_{ij} H_2(x_t, \mu_{\rm ew}) + \frac{2 S_0(x_t)}{x_t} \sum_m \left(\lambda_t^{im} [\mathcal{C}_{Hq}^{(3)}]_{mj} + [\mathcal{C}_{Hq}^{(3)}]_{im} \lambda_t^{mj} \right) \right\}$$

Numerical impact

$x_t \approx 4$

- $\mathcal{O}_{Hd}$, $\mathcal{O}^{(1)}_{Hq}$: NLO correction about 28 – 15% depending on μ_Λ

$$\Delta C^{ij}_{\mathrm{LR},1}(\mu_{\mathrm{ew}}) = v^2 \frac{[\mathcal{C}_{Hd}]_{ij}(\mu_\Lambda)}{\lambda^{ij}_t} x_t \left[\left\{ \begin{array}{ll} 2.5 & \text{for } \mu_\Lambda = 1\,\text{TeV} \\ 4.8 & \text{for } \mu_\Lambda = 10\,\text{TeV} \end{array} \right\} - 0.7 \right]$$

- $\mathcal{O}^{(3)}_{Hq}$: NLO correction due to

A) $H_2 \sim 100\%$ and constructive to 1stLLA term

$$\ln \frac{\mu_\Lambda}{M_W} + H_2(x_t, M_W) = \left\{ \begin{array}{ll} 2.5 & \text{for } \mu_\Lambda = 1\,\text{TeV} \\ 4.8 & \text{for } \mu_\Lambda = 10\,\text{TeV} \end{array} \right\} + 3.0\,,$$

B) the part due to boxes proportional to

$$\frac{2S_0(x_t)}{x_t} \quad \to \quad 1.1$$

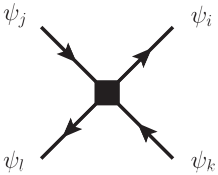
$\Rightarrow$ to $B_{d,s}$-meson mixing $ij = bs, bd$ without suppression: $\lambda^{bb}_t [\mathcal{C}^{(3)}_{Hq}]_{bj} \sim \mathcal{O}1 \times [\mathcal{C}^{(3)}_{Hq}]_{bj}$

$\Rightarrow$ to K^0 mixing $ij = sd$ with $\lambda^{sb}_t [\mathcal{C}^{(3)}_{Hq}]_{bd} \sim \lambda^2_C \times [\mathcal{C}^{(3)}_{Hq}]_{bd}$ (quadratic Cabibbo suppression)

!!! if hierarchy $[\mathcal{C}^{(3)}_{Hq}]_{sd} \approx \lambda^2_C \times [\mathcal{C}^{(3)}_{Hq}]_{bd}$, then can not be neglected

$\psi^2 H^2 D$ contributions to $\Delta F = 2, 1$ @ $\mu_{\rm ew}$

$\Delta F = 2$



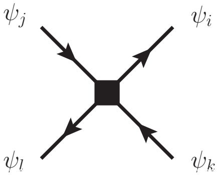
dim-6

1stLLA contribution from
$\psi^2 H^2 D \to \psi^4$ mixing
is 1-loop suppressed

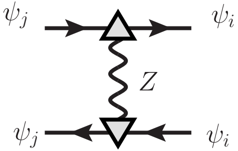
$$\sim v^2/{\mu_\Lambda}^2 \times (4\pi)^{-2}$$

$\psi^2 H^2 D$ contributions to $\Delta F = 2, 1$ @ μ_{ew}

$\Delta F = 2$



dim-6



dim-8

1stLLA contribution from
$\psi^2 H^2 D \to \psi^4$ mixing
is 1-loop suppressed

(for example)
double-insertion of $\psi^2 H^2 D$

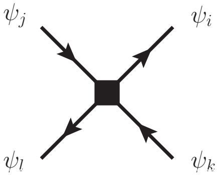
$\sim v^2/\mu_\Lambda{}^2 \times (4\pi)^{-2}$

$\sim v^4/\mu_\Lambda{}^4$

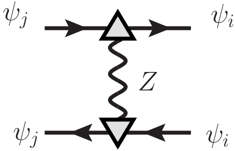
$\Rightarrow$ transition region $\mu_\Lambda \sim 4\pi v \approx 3$ TeV,
where both numerically similar

$\psi^2 H^2 D$ contributions to $\Delta F = 2, 1$ @ $\mu_{\rm ew}$

$\Delta F = 2$

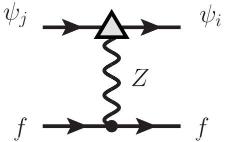


dim-6



dim-8

$\Delta F = 1$



dim-6

1stLLA contribution from $\psi^2 H^2 D \to \psi^4$ mixing is 1-loop suppressed

(for example) double-insertion of $\psi^2 H^2 D$

single insertion of $\psi^2 H^2 D$

$\sim v^2/{\mu_\Lambda}^2 \times (4\pi)^{-2}$

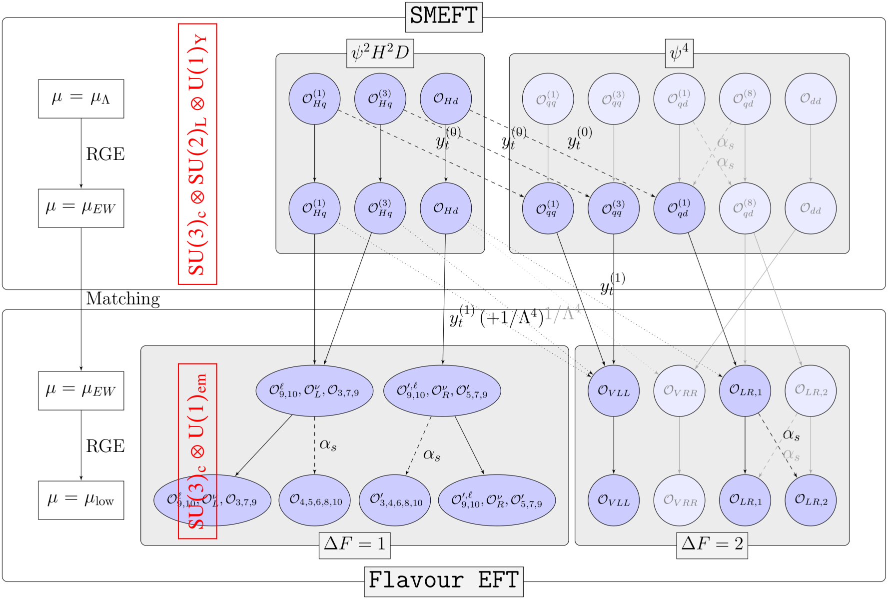
$\sim v^4/{\mu_\Lambda}^4$

$\sim v^2/{\mu_\Lambda}^2$

$\Rightarrow$ transition region $\mu_\Lambda \sim 4\pi v \approx 3$ TeV, where both numerically similar

$f = \nu\bar\nu,\ \ell\bar\ell,\ q\bar q$ all flavor-diagonal

RGE for SMEFT and low-energy EFT



$\Delta F = 2$ Meson mixing

- RG evolution below $\mu_{\rm ew}$ $\Rightarrow$ QCD ADM of $C_{\rm LR,1}$ gives enhancement
- hadronic matrix element of $P_{\rm LR,1}$ chirality enhanced, especially in K^0-mixing

[Endo/Kitahara/Mishima/Yamamoto 1612.08839]

Mass difference

$$\frac{M_{12}^{sd\,*}}{\mathcal{F}_{sd}} = \left[168.7 + \mathrm{i}\,194.1 + 0.8\,\Delta C_{\rm VLL}^{sd}\right] B_1^{sd} - \Delta C_{\rm LR,1}^{sd}\left(25.9\,B_4^{sd} + 14.1\,B_5^{sd}\right)$$

$$\frac{M_{12}^{bj\,*}}{\widetilde{\mathcal{F}}_{bj}} = \left[1.95 + 0.84\,\Delta C_{\rm VLL}^{bj}\right] F_{B_j}^2 B_1^{bj} - \Delta C_{\rm LR,1}^{bj}\, F_{B_j}^2\left(1.18\,B_4^{bj} + 1.42\,B_5^{bj}\right)$$

here NLO QCD RG evolution from $\mu_{\rm ew}$ to $\mu_{\rm low}$ and with C_a^{ij} at $\mu_{\rm ew}$

ij	$\mu_{\rm low}$ [GeV]	N_f	r_χ	B_1^{ij}	B_4^{ij}	B_5^{ij}
sd	3.0	3	30.8	0.525(16)	0.920(20)	0.707(45)
				$F_{B_j}^2 B_1^{ij}$	$F_{B_j}^2 B_4^{ij}$	$F_{B_j}^2 B_5^{ij}$
bd	4.18	5	1.6	0.0342(30)	0.0390(29)	0.0361(36)
bs	4.18	5	1.6	0.0498(32)	0.0534(32)	0.0493(37)

Lattice results: [RBC/UKQCD 1609.03334, Fermilab/FNAL 1602.03560]

$\Delta F = 1$ Constraints from $d_j \to d_i + (\ell\bar{\ell},\, \nu\bar{\nu})$

$$\mathcal{H} = -\frac{4G_F}{\sqrt{2}} \lambda_t^{ij} \frac{\alpha_e}{4\pi} \sum_a C_a^{ij} O_a^{ij}$$

$$O_{9(9')}^{ij} = [\bar{d}_i \gamma_\mu P_{L(R)} d_j][\bar{\ell}\gamma^\mu \ell]$$

$$O_{10(10')}^{ij} = [\bar{d}_i \gamma_\mu P_{L(R)} d_j][\bar{\ell}\gamma^\mu \gamma_5 \ell]$$

$$O_{L(R)}^{ij} = [\bar{d}_i \gamma_\mu P_{L(R)} d_j][\bar{\nu}\gamma^\mu (1-\gamma_5)\nu]$$

- tree-level matching at $\mu_{\rm ew}$ of SMEFT on $\Delta F = 1$ EFT
- LH depends on $\mathcal{C}_{Hq}^{(+)} \equiv \mathcal{C}_{Hq}^{(1)} + \mathcal{C}_{Hq}^{(3)}$

$$\Delta C_9^{ij} - \frac{\pi}{\alpha_e} \frac{v^2}{\lambda_t^{ij}} (1 - 4s_W^2) \left[\mathcal{C}_{Hq}^{(1)} + \mathcal{C}_{Hq}^{(3)}\right]_{ij} + \ldots \qquad \Delta C_{10,\,L}^{ij} = \frac{\pi}{\alpha_e} \frac{v^2}{\lambda_t^{ij}} \left[\mathcal{C}_{Hq}^{(1)} + \mathcal{C}_{Hq}^{(3)}\right]_{ij} + \ldots$$

$$\Delta C_{9'}^{ij} = -(1 - 4s_W^2) \frac{\pi}{\alpha_e} \frac{v^2}{\lambda_t^{ij}} [\mathcal{C}_{Hd}]_{ij} + \ldots \qquad \Delta C_{10',\,R}^{ij} = \frac{\pi}{\alpha_e} \frac{v^2}{\lambda_t^{ij}} [\mathcal{C}_{Hd}]_{ij} + \ldots$$

- expect different interference of RH contributions in semileptonic vs. leptonic decays
- X and Y are SM contribution

$$Br[M_j \to P_i(\ell\bar{\ell},\, \nu\bar{\nu})] \propto \left| -\frac{X(x_t)}{s_W^2} + \frac{\pi}{\alpha_e} \frac{v^2}{\lambda_t^{ij}} \left[\mathcal{C}_{Hq}^{(1)} + \mathcal{C}_{Hq}^{(3)} + \mathcal{C}_{Hd}\right]_{ij} \right|^2$$

$$Br[M_{ij} \to \ell\bar{\ell}] \propto \left| -\frac{Y(x_t)}{s_W^2} + \frac{\pi}{\alpha_e} \frac{v^2}{\lambda_t^{ij}} \left[\mathcal{C}_{Hq}^{(1)} + \mathcal{C}_{Hq}^{(3)} - \mathcal{C}_{Hd}\right]_{ij} \right|^2$$

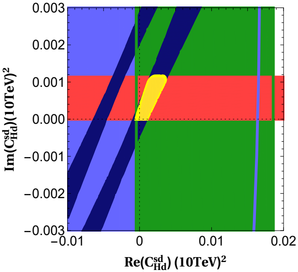
RH Scenario $\mathcal{O}_{Hd}$

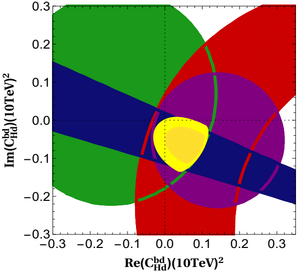
[CB/Buras/Celis/Jung 1703.04753]

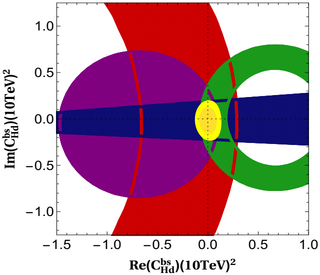
- assume only $[\mathcal{C}_{Hd}]_{ij}$ $\Rightarrow$ neglect ψ^4 op's in
  $\Delta F = 2$: $\mathcal{C}_{qq}^{(1,3)}$, $\mathcal{C}_{qd}^{(1,8)}$, $\mathcal{C}_{dd}$ and $\Delta F = 1$: $\mathcal{C}_{\ell q}^{(1,3)}$, $\mathcal{C}_{ed,\ell d,qe,\ell edq,\ell edq'}$
- $M \to \ell\bar{\ell} \propto C_L - C_R$ and $M \to P\ell\bar{\ell} \propto C_L + C_R$ $\Rightarrow$ complementarity from small intersection
- very strong bounds $\sim \mathcal{O}(1) \times (10\ \mathrm{TeV})^{-2}$

$\mu_\Lambda = 10$ TeV

$|\mathcal{C}_{Hd}^{sd}| \lesssim \dfrac{0.004}{(10\,\mathrm{TeV})^2}$ $|\mathcal{C}_{Hd}^{bd}| \lesssim \dfrac{0.15}{(10\,\mathrm{TeV})^2}$ $|\mathcal{C}_{Hd}^{bs}| \lesssim \dfrac{0.25}{(10\,\mathrm{TeV})^2}$







- ε_K
- $Br(K^+ \to \pi^+ \nu\bar{\nu})$
- $Br(K_L \to \mu\bar{\mu})_{\mathrm{SD}}$
- $(\varepsilon'/\varepsilon)_{\mathrm{NP}} \in [0, 2] \times 10^{-3}$

- ΔM_d
- $\sin(2\beta_d)$
- $Br(B^+ \to \pi^+ \mu\bar{\mu})_{[15,22]}$
- $Br(B_d \to \mu\bar{\mu})$

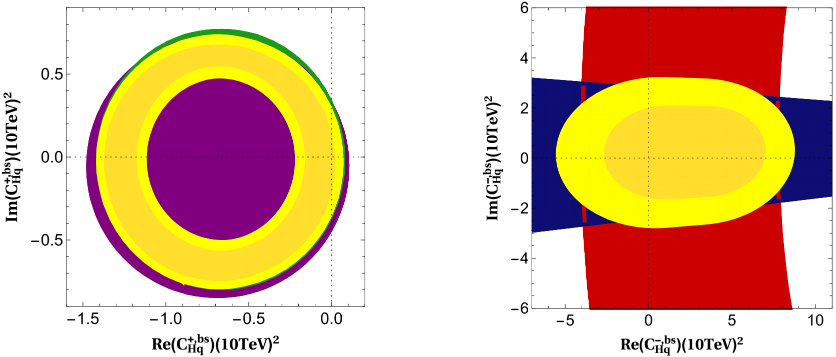
- ΔM_s
- $\sin(2\beta_s)$
- $Br(B^+ \to K^+ \mu\bar{\mu})_{[15,22]}$
- $Br(B_s \to \mu\bar{\mu})$

LH Scenario $\mathcal{O}_{Hq}^{(1,3)}$

[CB/Buras/Celis/Jung 1703.04753]

- two coefficients $\mathcal{C}_{Hq}^{(1)}$ and $\mathcal{C}_{Hq}^{(3)}$
- $\Delta F = 1$ depends on $\mathcal{C}_{Hq}^{(+)} \equiv \mathcal{C}_{Hq}^{(1)} + \mathcal{C}_{Hq}^{(3)}$
- $\Delta F = 2$ on $\mathcal{C}_{Hq}^{(-)} \equiv \mathcal{C}_{Hq}^{(1)} - \mathcal{C}_{Hq}^{(3)}$ and at NLO also on $\mathcal{C}_{Hq}^{(+)}$

Example $b \to s$



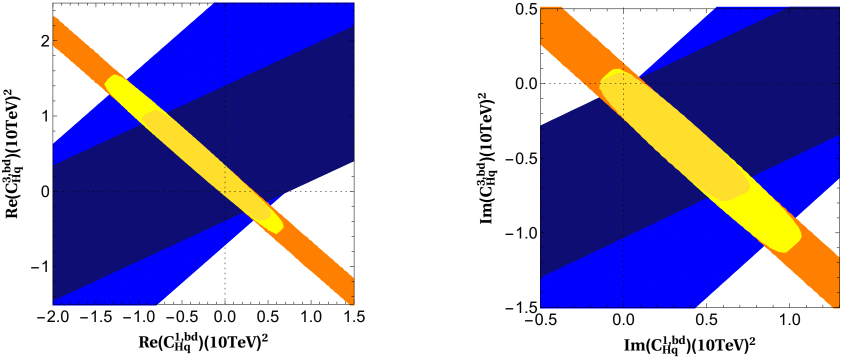
$\Delta F = 1$: $\quad |[\mathcal{C}_{Hq}^{(+)}]_{bs}| \lesssim \dfrac{1.5}{(10\,\mathrm{TeV})^2}$

$\Delta F = 2$ (LO only): $\quad |[\mathcal{C}_{Hq}^{(-)}]_{bs}| \lesssim \dfrac{9}{(10\,\mathrm{TeV})^2}$

NLO corrections

[CB/Buras/Celis/Jung 1703.04753]

- fit with 1stLLA (brighter colors) versus 1stLLA + NLO (darker colors) for $b \to d$ complex-valued $[\mathcal{C}_{Hq}^{(1,3)}]_{bd}$
- NLO corrections to $\Delta F = 2$ bring in additional dependence on $[\mathcal{C}_{Hq}^{(+)}]_{bd}$
  $\Rightarrow$ rotation of $\Delta F = 2$ constraint



combined $\Delta F = 2$ combined $\Delta F = 1$ combination of $\Delta F = 1, 2$

Toy-UV completion: Vector-like Quarks

Simplest extension of SM with VLQ's

Classification of renormalizable extensions with VLQs [del Aguila/Perez-Victoria/Santiago hep-ph/0007316]

- for VLQ's (triplets under $SU(3)_c$) $\Rightarrow$ 8 possibilities, but only 5 relevant for down-type FCNC's

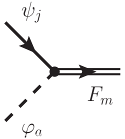
$(SU(2)_L, U(1)_Y)$			
	singlets :	$D(1,-1/3)$	
	doublets :	$Q_V(2,+1/6)$	$Q_d(2,-5/6)$
	triplets :	$T_d(3,-1/3)$	$T_u(3,+2/3)$

- Kinetic + gauge interactions

$$\mathcal{L}_{\rm kin} = \overline{D}(i\not{D} - M_D)D + \sum_{a=V,d} \overline{Q}_a(i\not{D} - M_{Q_a})\, Q_a + \sum_{a=d,u} {\rm Tr}\left[\overline{T}_a(i\not{D} - M_{T_a})\, T_a\right],$$

- SM has one scalar doublet H ($\widetilde{H} \equiv i\sigma_2 H^*$) $\Rightarrow$ **new Yukawa couplings $\lambda_i^{\rm VLQ}$**

$$-\mathcal{L}_{\rm Yuk}(H) = \left(\lambda_i^D\, H^\dagger \overline{D}_R + \lambda_i^{T_d}\, H^\dagger \overline{T}_{dR} + \lambda_i^{T_u}\, \widetilde{H}^\dagger \overline{T}_{uR}\right) q_L^i$$
$$+ \lambda_i^{V_u}\, \bar{u}_R^i \widetilde{H}^\dagger Q_{VL} + \bar{d}_R^i \left(\lambda_i^{V_d}\, H^\dagger Q_{VL} + \lambda_i^{Q_d}\, \widetilde{H}^\dagger Q_{dL}\right) + \text{h.c.}$$



- **new parameters:** $M_{\rm VLQ}$ heavy masses, direct searches $\gtrsim \mathcal{O}(1\text{ TeV})$

  $\lambda_i^{\rm VLQ}$ are complex-valued $\Rightarrow$ new sources of CP violation

Decoupling of heavy VLQ's @ μ_Λ

[del Aguila/Perez-Victoria/Santiago hep-ph/0007316]

Decoupling =

$$M_{Z,W,H} \sim v \quad \ll \quad M_{\rm VLQ}$$

$\mathcal{O}$(100 GeV) $\ll$ $\mathcal{O}$(1 TeV)

(throughout as assumption)

- above scale $\mu_\Lambda \approx M_{\rm VLQ}$ full theory with VLQ's
- below μ_Λ SMEFT without VLQ's

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm dim-4} + \sum_a \mathcal{C}_a \mathcal{O}_a,$$

Decoupling of heavy VLQ's @ μ_Λ

[del Aguila/Perez-Victoria/Santiago hep-ph/0007316]

Decoupling =

$M_{Z,W,H} \sim v \ll M_{\rm VLQ}$

$\mathcal{O}(100\ \text{GeV}) \ll \mathcal{O}(1\ \text{TeV})$

(throughout as assumption)

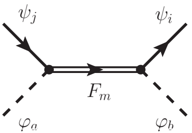
- above scale $\mu_\Lambda \approx M_{\rm VLQ}$ full theory with VLQ's
- below μ_Λ SMEFT without VLQ's

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm dim-4} + \sum_a \mathcal{C}_a \mathcal{O}_a,$$

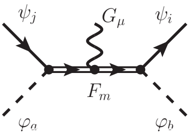
At tree-level only few diagrams for decoupling VLQ = F_m:

all light fields treated as massless

light SM quarks: $\psi = (q_L, u_R, d_R)$
light scalars: $\varphi = H$
light gauge boson: $G_\mu = Z, W^\pm$, photon, gluon, depending on $\mathrm{SU}(2)_\mathrm{L}$ representation of F_m



(a)



(b)

$$\propto \frac{(\lambda_i^m)^* \lambda_j^m}{M_{\rm VLQ}^2}$$

- (a) + (b) decoupling of a VLQ = F_m $\Rightarrow$ give rise to $\psi^2 H^2 D$ op's
  $\Rightarrow$ via EOM also $\psi^2 H^3$ op's

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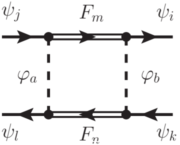
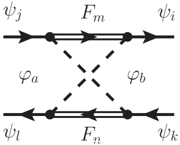
At 1-loop-level $\Rightarrow$ example 4-quark process

"direct" box contribution to ψ^4 @ μ_Λ

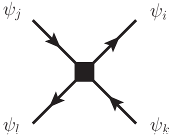




crossed graph only for certain $F_m \neq F_n$

$$\propto \frac{\left[(\lambda_i^m)^* \lambda_j^m\right]^2}{M_m^2}, \quad (m = n)$$

mixing-induced $\psi^2 H^2 D \to \psi^4$ @ $\mu_{\rm ew}$



$$\propto \frac{\left[(\lambda_i^m)^* \lambda_j^m \times \lambda_t^{ij}\right]}{M_m^2}$$

$\Rightarrow$ different VLQ-Yukawa dependence of direct and mixing-induced contributions

Coupling structure in SMEFT

VLQ	Z-type	$\psi^2 H^2 D$	$\psi^2 H^3$
D	LH	$\mathcal{C}_{Hq}^{(1)} = \mathcal{C}_{Hq}^{(3)}$	$\mathcal{C}_{dH}$
Q_d	RH	$\mathcal{C}_{Hd}$	$\mathcal{C}_{dH}$
Q_V	RH	$\mathcal{C}_{Hd}, \mathcal{C}_{Hu}, \mathcal{C}_{Hud}$	$\mathcal{C}_{dH}, \mathcal{C}_{uH}$
T_u	LH	$\mathcal{C}_{Hq}^{(1)} = +3\,\mathcal{C}_{Hq}^{(3)}$	$\mathcal{C}_{dH}, \mathcal{C}_{uH}$
T_d	LH	$\mathcal{C}_{Hq}^{(1)} = -3\,\mathcal{C}_{Hq}^{(3)}$	$\mathcal{C}_{dH}, \mathcal{C}_{uH}$

- all $\mathcal{C}_{\psi^2 H^2 D}, \mathcal{C}_{\psi^2 H^3} \propto \Lambda_{ij}^m$
- only products of VLQ-Yukawa's $\lambda_i^{\rm VLQ}$ appear

$$\Lambda_{ij}^m = (\lambda_i^m)^* \lambda_j^m \quad \text{for} \quad F_m = D, T_d, T_u$$

$$\Lambda_{ij}^m = \lambda_i^m (\lambda_j^m)^* \quad \text{for} \quad F_m = Q_d, Q_V$$

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- 3 complex-valued VLQ-Yukawa's per representation F_m $\quad \lambda_i^m \equiv |\lambda_i^m|\, e^{i\phi_i^m}$
- 1 phase non-observable, fixing $\phi_d^m = 0 \Rightarrow$ 5 real parameters

$$|\lambda_d^m|,\ |\lambda_s^m|,\ |\lambda_b^m|,\ \phi_s^m,\ \phi_b^m$$

- each sector $j \to i$ constrains complex-valued

$$\Lambda_{ij}^m = \left|\Lambda_{ij}^m\right| e^{i\varphi_{ij}^m}, \qquad \varphi_{bs}^m = \varphi_{bd}^m - \varphi_{sd}^m$$

  with one relation on the phases

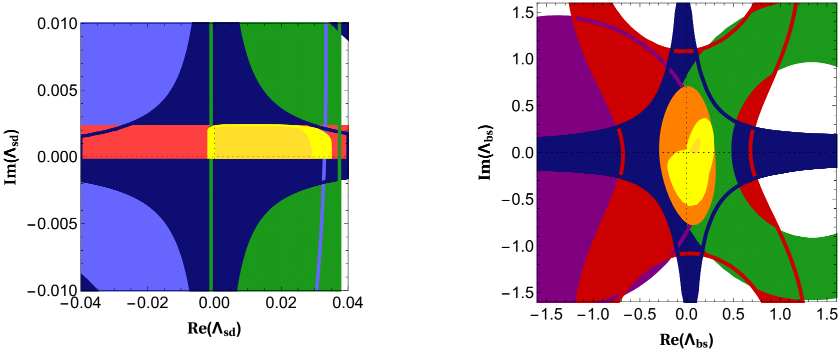
- below a **"global fit"** = simultaneous fit of 5 pmr's with all 3 sectors

Numerical effects $\Delta F = 1, 2$

example RH VLQ = Q_V for $\mu_\Lambda = 10$ TeV

[CB/Buras/Celis/Jung 1609.04783v1]

without mixing-induced



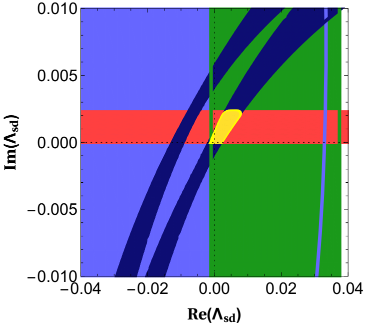
$s \to d$ $\qquad$ $b \to s$

- mixing-induced contribution only relevant for RH VLQ scenarios Q_V and Q_d
  $\Rightarrow$ chirality enhancement of $P_{\mathrm{LR},1}$
- in LH VLQ scenarios direct box-contr. $\propto (\lambda_i^* \lambda_j)^2$
  larger than mixing-induced $\propto (\lambda_i^* \lambda_j) \times V_{ti}^* V_{tj}$
  $\Rightarrow$ non-trivial numerical interplay of $\Delta F = 1, 2$ constraints and CKM

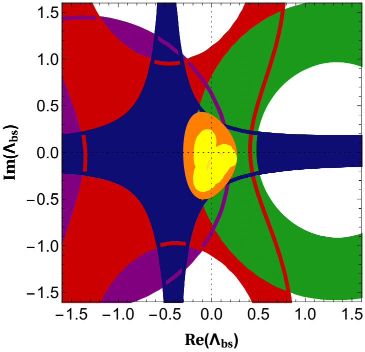
Numerical effects $\Delta F = 1, 2$

example RH VLQ = Q_V for $\mu_\Lambda = 10$ TeV [CB/Buras/Celis/Jung 1609.04783v3]

with mixing-induced



$s \to d$



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Summary

- constraints on new physics flavor-changing Z couplings from $\Delta S, B = 2$ in SMEFT
- arise from top-Yukawa mixing of $\psi^2 H^2 D \to \psi^4$ operators
- NLO threshold corrections at $\mu_{\rm ew}$ can be sizable
- for $\mathcal{O}_{Hq}^{(3)}$ box-type diagrams involve sum over all flavors

  $\Rightarrow$ whole set of $\psi^2 H^2 D$ Wilson coefficients
- most relevant for right-handed $\mathcal{O}_{Hd}$, because below $\mu_{\rm ew}$ enhanced by 1) large QCD-running and 2) chirality-enhanced $\Delta F = 2$ matrix elements

  $\Rightarrow$ especially ε_K
- neutral meson mixing and $\Delta F = 1$ processes can provide strong constraints on $\psi^2 H^2 D$ Wilson coefficients

  $\Rightarrow$ could be included in SMEFT fits of LEP data and EWPO,
  of course in global fit other ψ^4 operators enter
- in toy-UV completion vector-like quarks: mixing-induced Z-effects must compete with direct ψ^4 one-loop contributions

  $\Rightarrow$ numerically only relevant in RH VLQ scenarios, not for LH VLQ scenarios