Rare Kaon (and *B*) Decays in Generic-*Z* and VLQ Models

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

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Motivation / Introduction

Rare Kaon physics

CP violation in $K \to \pi\pi$: ε'/ε another flavor-"anomaly"

Measurement → rather precisely known

$$1 - 6\,\mathrm{Re}\frac{\varepsilon'}{\varepsilon} \simeq \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2$$

defines ε'/ε experimentally
⇒ double-ratio of decay width's is measured

$$\eta_{ab} = \frac{A(K_L \to \pi^a \pi^b)}{A(K_S \to \pi^a \pi^b)} \qquad (a, b = 0, \pm)$$

average of NA48 (CERN) & KTeV

$$(\varepsilon'/\varepsilon)_{\mathrm{exp}} = (16.6 \pm 2.3) \times 10^{-4}$$

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Prediction

QCD isospin amplitudes ($I = 0, 2$)

$$\frac{\varepsilon'}{\varepsilon} = -\frac{\omega_+}{\sqrt{2}|\varepsilon_K|}\left[\frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}(1 - \hat{\Omega}_{\mathrm{eff}}) - \frac{1}{a}\frac{\mathrm{Im}A_2}{\mathrm{Re}A_2}\right]$$

$$A_I = \sum_i f_{\mathrm{CKM}} \times C_i(\mu) \times \langle(\pi\pi)_I|\,Q_i\,|K\rangle(\mu)$$

$\mathrm{Im}A_2$ only EW penguin op's Q_{7-10}

- $C_i(\mu)$ known NLO (NNLO work in progress 1611.08276) [Buras et al. hep-ph/9303284, Ciuchini et al. 9304257]
- $\langle(\pi\pi)_I\,|\,Q_i\,|\,K\rangle(\mu)$ 1st lattice calculations [RBC-UKQCD 1502.00263, 1505.07863]
- $\omega_+ = a\,\mathrm{Re}A_2/\mathrm{Re}A_0 = (4.53 \pm 0.02) \times 10^{-2}$ from experiment,
  $\hat{\Omega}_{\mathrm{eff}}$ leading isospin breaking [Cirigliano/Ecker/Neufeld/Pich hep-ph/0310351, 0307030]
- $|\varepsilon_K|$ from experiment

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$\mathrm{Re}(\varepsilon'/\varepsilon)_{\mathrm{SM}} = 1.38(5.15)_{\mathrm{stat}}(4.59)_{\mathrm{sys}} \times 10^{-4}$	$(2.1\,\sigma)$	[RBC-UKQCD 1505.07863]
$\mathrm{Re}(\varepsilon'/\varepsilon)_{\mathrm{SM}} = (1.9 \pm 4.5) \times 10^{-4}$	$(2.9\,\sigma)$	[Buras/Grobahn/Jamin/Jäger 1507.06346]
$\mathrm{Re}(\varepsilon'/\varepsilon)_{\mathrm{SM}} = (1.06 \pm 5.07) \times 10^{-4}$	$(2.8\,\sigma)$	[Kitahara/Nierste/Tremper 1607.06727]

BGJJ and KNT assume that $\mathrm{Re}\,A_{0,2}$ fully described by SM dynamics ⇒ experimental values used to determine hadr. matrix elements of $(V-A)\otimes(V-A)$ op's and lattice only for $(V-A)\otimes(V+A)$ op's

Other "rare" Kaon observables

$\boxed{\Delta F = 1}$

$K \to \pi\nu\bar{\nu}$

- theory uncert's below 3%
- large parametric uncert's from CKM

$$Br(K^+ \to \pi^+\nu\bar{\nu})_{\rm exp} = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

$$Br(K_L \to \pi^0\nu\bar{\nu})_{\rm exp} < 2.6 \times 10^{-8} \; (90\%{\rm CL})$$

- $K^+ \to \pi^+\nu\bar{\nu}$ with 10% uncert. from NA62 by 2018/19
- $K_L \to \pi^0\nu\bar{\nu}$ at KOTO (2020+)

$K_L \to \mu\bar{\mu}$

- dominated by LD contributions
- theory issue: sign of interf. of LD and SD
- conservative bound: allowing both signs
  $|\chi_{\rm SD}| \leq 3.1$ [Isidori/Unterdorfer hep-ph/0311084]
- choice of particular sign
  $-3.1 \leq \chi_{\rm SD} \leq 1.7$ [D'Ambrosio/Portoles 9610244, Gomez Dumm/Pich 9801298]
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$\Delta F = 2$

$\varepsilon_K \propto \mathrm{Im}(M_{12}^{sd})$

- small LD contribution
- large pert. uncert's for $N_f = 3$ NNLO [Brod/Gorbahn 1108.2036]
  $\to$ calculate $B_{K,\ldots}$ on lattice for $N_f = 4$
- strong dependence on V_{cb}

$$\varepsilon_K|_{\rm exp} = (2.228 \pm 0.011) \times 10^{-3}$$

$$\varepsilon_K|_{\rm SM} = (2.21^{+0.39}_{-0.32}) \times 10^{-3}$$

$\Delta M_K \propto \mathrm{Re}(M_{12}^{sd})$

$$\Delta M_K|_{\rm exp} = 3.483(6) \times 10^{-12}\ \mathrm{MeV}$$

- LD dominated $\to$ requires lattice

$$\Delta M_K|_{\rm SM} = 3.19(41)_{\rm stat}(96)_{\rm sys} \times 10^{-12}\ \mathrm{MeV}$$

[RBC-UKQCD 1406.0916]

Flavor-changing Z couplings
(in SMEFT)

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]

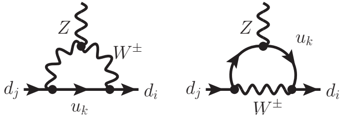
- GIM broken at one-loop by (top-) Yukawa-couplings

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

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

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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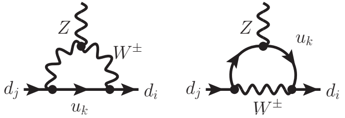

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Beyond SM naive modification of Z couplings to quarks (and analogously leptons)

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

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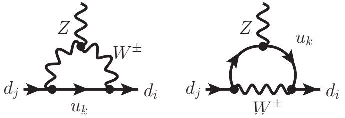

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!!! Adding these terms is not $\mathrm{SU(2)_L \otimes U(1)_Y}$ gauge-invariant $\Rightarrow$ may use SMEFT instead

SMEFT (standard model EFT)

[Buchmüller/Wyler NPB268(1986)621]

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

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

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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 ↔ Yukawa + FC H couplings
- $X^2 H^2$
- $\psi^2 XH$ ← 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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$\psi^2 H^2 D$–Op's = FC couplings of $Vq_j q_i$ ($V = Z, W$)

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

$$\mathcal{O}_{Hq}^{(1)} = (H^\dagger i\overleftrightarrow{\mathcal{D}}_\mu H)[\bar{q}_L^i \gamma^\mu q_L^j]$$

$$\mathcal{O}_{Hq}^{(3)} = (H^\dagger i\overleftrightarrow{\mathcal{D}}_\mu^a H)[\bar{q}_L^i \sigma^a \gamma^\mu q_L^j]$$

- 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 $\mathcal{O}_{Hud}$)

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

$$\mathcal{O}_{Hu} = (H^\dagger i\overleftrightarrow{\mathcal{D}}_\mu H)[\bar{u}_R^i \gamma^\mu u_R^j]$$

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

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

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$$\mathcal{O}^{(3)}_{Hq} = (H^\dagger i \overleftrightarrow{\mathcal{D}}^a_\mu H)[\bar{q}^i_L \sigma^a \gamma^\mu q^j_L]$$

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EWSB (electroweak symmetry breaking) **@ $\mu_{\rm ew}$** (fermion masses receive dim-6 contr. from $\psi^2 H^3$ **op's**)

$$\mathcal{L}^{\rm dim-6}_{\psi\bar\psi V} = -\frac{g_Z}{2} v^2 Z_\mu \Big(\left[V^{d\dagger}_L (\mathcal{C}^{(1)}_{Hq} + \mathcal{C}^{(3)}_{Hq}) V^d_L\right]_{ij} [\bar{d}_i \gamma^\mu P_L d_j] + \left[V^{d\dagger}_R \mathcal{C}_{Hd} V^d_R\right]_{ij} [\bar{d}_i \gamma^\mu P_R d_j]$$
$$+ \left[V^{u\dagger}_L (\mathcal{C}^{(1)}_{Hq} - \mathcal{C}^{(3)}_{Hq}) V^u_L\right]_{ij} [\bar{u}_i \gamma^\mu P_L u_j] + \left[V^{u\dagger}_R \mathcal{C}_{Hu} V^u_R\right]_{ij} [\bar{u}_i \gamma^\mu P_R u_j] \Big)$$
$$+ \frac{g_2}{\sqrt{2}} v^2 \Big(\left[V^{u\dagger}_L \mathcal{C}^{(3)}_{Hq} V^d_L\right]_{ij} [\bar{u}_i \gamma^\mu P_L d_j] W^+_\mu + \left[V^{u\dagger}_R \frac{\mathcal{C}_{Hud}}{2} V^d_R\right]_{ij} [\bar{u}_i \gamma^\mu P_R d_j] W^+_\mu + \text{h.c.} \Big)$$

$\Rightarrow$ left-handed down- and up-type FCNC's related (in the basis $V^d_{L,R} = \mathbb{1}$ and $V^u_R = \mathbb{1}$ $\Rightarrow$ $V^u_L = V^\dagger_{\rm CKM}$)

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

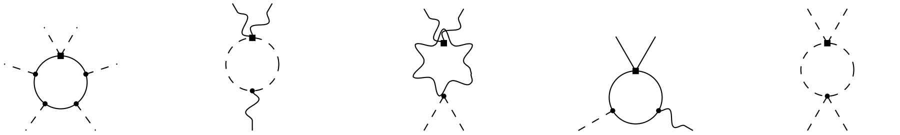
$\lambda_C \approx 0.22$ Cabibbo angle

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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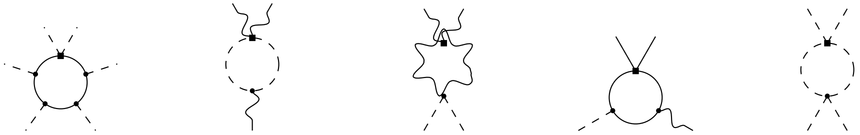

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$\Rightarrow$ In SMEFT corrletions among flavor sectors possible due to **flavor-changing**

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 $\mathrm{SU}(3)_\mathrm{c}$ flavor-diagonal
- top-Yukawa $y_t^2 \sim 1$ $\Rightarrow$ flavor-mixing $\Leftarrow$ phenomenologically most interesting

Flavor-changing Z couplings and $\Delta F = 2$ processes in SMEFT

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 $\qquad \Delta F = 2$: $kl = ij$

$$(\bar{L}L)(\bar{L}L) \quad [\mathcal{O}_{qq}^{(1)}]_{ijkl} = [\bar{q}_L^i \gamma_\mu q_L^j][\bar{q}_L^k \gamma^\mu q_L^l] \qquad [\mathcal{O}_{qq}^{(3)}]_{ijkl} = [\bar{q}_L^i \gamma_\mu \sigma^a q_L^j][\bar{q}_L^k \gamma^\mu \sigma^a q_L^l]$$

$$(\bar{L}L)(\bar{R}R) \quad [\mathcal{O}_{qd}^{(1)}]_{ijkl} = [\bar{q}_L^i \gamma_\mu q_L^j][\bar{d}_R^k \gamma^\mu d_R^l] \qquad [\mathcal{O}_{qu}^{(1)}]_{ijkl} = [\bar{q}_L^i \gamma_\mu q_L^j][\bar{u}_R^k \gamma^\mu u_R^l]$$

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

- 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]

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

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

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

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

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

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

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 $\qquad \Delta F = 2$: $kl = ij$

$(\bar{\mathbf{L}}\mathbf{L})(\bar{\mathbf{L}}\mathbf{L})$ $\quad [\mathcal{O}^{(1)}_{qq}]_{ijkl} = [\bar{q}^i_L \gamma_\mu q^j_L][\bar{q}^k_L \gamma^\mu q^l_L] \qquad [\mathcal{O}^{(3)}_{qq}]_{ijkl} = [\bar{q}^i_L \gamma_\mu \sigma^a q^j_L][\bar{q}^k_L \gamma^\mu \sigma^a q^l_L]$

$(\bar{\mathbf{L}}\mathbf{L})(\bar{\mathbf{R}}\mathbf{R})$ $\quad [\mathcal{O}^{(1)}_{qd}]_{ijkl} = [\bar{q}^i_L \gamma_\mu q^j_L][\bar{d}^k_R \gamma^\mu d^l_R] \qquad [\mathcal{O}^{(1)}_{qu}]_{ijkl} = [\bar{q}^i_L \gamma_\mu q^j_L][\bar{u}^k_R \gamma^\mu u^l_R]$

$(\bar{\mathbf{R}}\mathbf{R})(\bar{\mathbf{R}}\mathbf{R})$ $\quad [\mathcal{O}^{(1)}_{ud}]_{ijkl} = [\bar{u}^i_R \gamma_\mu u^j_R][\bar{d}^k_R \gamma^\mu d^l_R] \qquad [\mathcal{O}_{uu}]_{ijkl} = [\bar{u}^i_R \gamma_\mu u^j_R][\bar{u}^k_R \gamma^\mu u^l_R]$

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

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

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

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

$$Y_u \overset{\text{dim}-4}{\approx} \frac{\sqrt{2}}{v} V^u_L m^{\text{diag}}_U V^{u\dagger}_R = \frac{\sqrt{2}}{v} V^\dagger_{\text{CKM}} m^{\text{diag}}_U,$$

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

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

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

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$$(\bar{\mathbf{L}}\mathbf{L})(\bar{\mathbf{L}}\mathbf{L}) \quad [\mathcal{O}_{qq}^{(1)}]_{ijkl} = [\bar{q}_L^i \gamma_\mu q_L^j][\bar{q}_L^k \gamma^\mu q_L^l] \qquad [\mathcal{O}_{qq}^{(3)}]_{ijkl} = [\bar{q}_L^i \gamma_\mu \sigma^a q_L^j][\bar{q}_L^k \gamma^\mu \sigma^a q_L^l]$$

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

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

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

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

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

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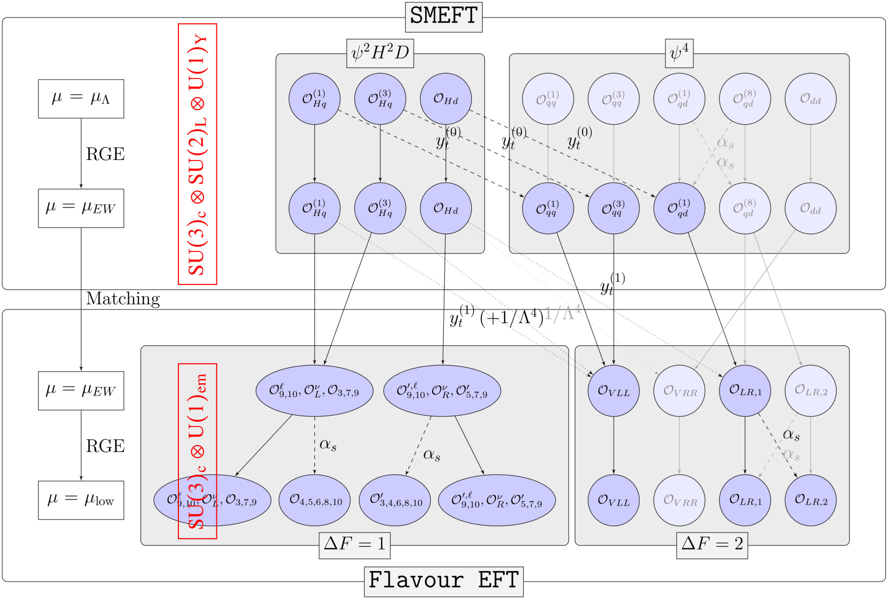
RGE for SMEFT and low-energy EFT



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

$$\mathcal{H}^{ij}_{\Delta F=2} = \frac{G_F^2}{4\pi^2} m_W^2 (\lambda_t^{ij})^2 \sum_a C_a^{ij} P_a^{ij} \; + \; \text{h.c.}$$

in SM only non-zero

$$C_1^{\mathrm{VLL}}(\mu_{\mathrm{ew}})\Big|_{\mathrm{SM}} = S_0(x_t),$$

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

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

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

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

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

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

$$\mathcal{H}^{ij}_{\Delta F=2} = \frac{G_F^2}{4\pi^2} m_W^2 (\lambda_t^{ij})^2 \sum_a C_a^{ij} P_a^{ij} + \text{h.c.}$$

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

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

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

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

in SM only non-zero

$$C_1^{\rm VLL}(\mu_{\rm ew})\Big|_{\rm SM} = S_0(x_t),$$

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

Matching SMEFT on $\Delta F = 2$ EFT @ $\mu_{\rm ew}$ using 1stLLA for RG evolution of $[\mathcal{C}^{(1,3)}_{Hq,Hd}]_{ij}$

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

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

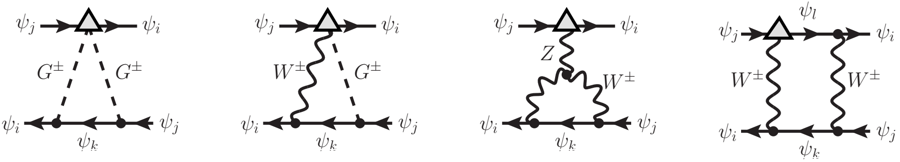
$$x_t \equiv \frac{m_t^2}{m_W^2}$$

$\Rightarrow$ here neglected "self-mixing": $\mathcal{C}_{\psi^2 H^2 D}(\mu_{\rm ew}) \approx \mathcal{C}_{\psi^2 H^2 D}(\mu_\Lambda)$

!!! the same linear combination enters $Z_\mu[\bar{u}_i \gamma^\mu P_L u_j]$

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

[CB/Buras/Celis/Jung 1703.04753]



- 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 $[\mathcal{C}_{Hq}^{(3)}]_{im}$

$$\Delta C^{ij}_{\rm LR,1}(\mu_{\rm ew}) = v^2 \frac{[\mathcal{C}_{Hd}]_{ij}}{\lambda_t^{ij}} x_t \left\{ \ln \frac{\mu_\Lambda}{\mu_{\rm ew}} + H_1(x_t, \mu_{\rm ew}) \right\} \qquad \text{NLO corr's} \approx -(15-30)\%$$

$$\Delta C^{ij}_{\rm VLL}(\mu_{\rm ew}) = \frac{v^2}{\lambda_t^{ij}} x_t \left\{ [\mathcal{C}_{Hq}^{(1)} - \mathcal{C}_{Hq}^{(3)}]_{ij} \ln \frac{\mu_\Lambda}{\mu_{\rm ew}} + [\mathcal{C}_{Hq}^{(1)}]_{ij} H_1(x_t, \mu_{\rm ew}) - [\mathcal{C}_{Hq}^{(3)}]_{ij} H_2(x_t, \mu_{\rm ew}) \right.$$
$$\left. + \frac{2 S_0(x_t)}{x_t} \sum_m \left(\lambda_t^{im} [\mathcal{C}_{Hq}^{(3)}]_{mj} + [\mathcal{C}_{Hq}^{(3)}]_{im} \lambda_t^{mj} \right) \right\} \qquad \approx +\mathcal{O}(100\%)$$

$\Delta F = 2$ 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 $\mu_{\rm ew}$

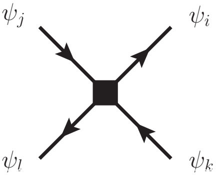
ij	$\mu_{\rm low}$ [GeV]	N_f	r_χ	B_1^{ij}	B_4^{ij}	B_5^{ij}
sd	3.0	3	30.8	0.525(16)	0.920(20)	0.707(45)
				$F_{B_j}^2 B_1^{ij}$	$F_{B_j}^2 B_4^{ij}$	$F_{B_j}^2 B_5^{ij}$
bd	4.18	5	1.6	0.0342(30)	0.0390(29)	0.0361(36)
bs	4.18	5	1.6	0.0498(32)	0.0534(32)	0.0493(37)

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

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

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

$\boxed{\Delta F = 2}$



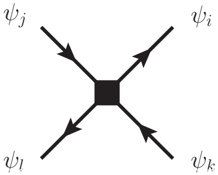
dim-6

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

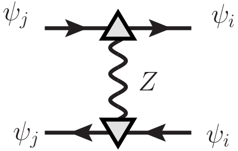
$$\sim v^2/\mu_\Lambda{}^2 \times (4\pi)^{-2}$$

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

$\boxed{\Delta F = 2}$



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 $\psi^2 H^2 D$

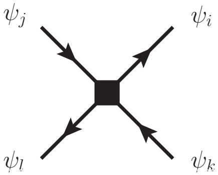
$\sim v^2/\mu_\Lambda{}^2 \times (4\pi)^{-2}$

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

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

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

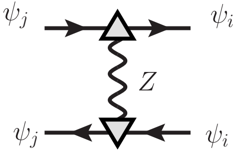
$\boxed{\Delta F = 2}$



dim-6

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

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



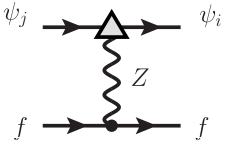
dim-8

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

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

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

$\boxed{\Delta F = 1}$



dim-6

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

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

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

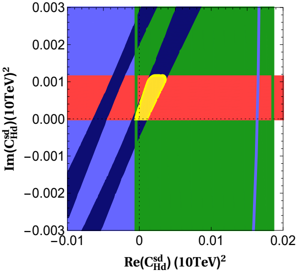
RH Scenario $\mathcal{O}_{Hd}$

[CB/Buras/Celis/Jung 1703.04753]

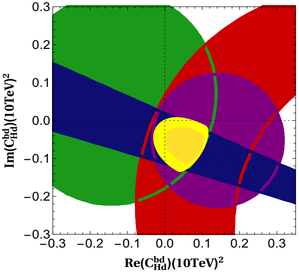
- assume only $[\mathcal{C}_{Hd}]_{ij}$ $\Rightarrow$ neglect ψ^4 op's in
  $\Delta F = 2$: $\mathcal{C}_{qq}^{(1,3)}$, $\mathcal{C}_{qd}^{(1,8)}$, $\mathcal{C}_{dd}$ and $\Delta F = 1$: $\mathcal{C}_{\ell q}^{(1,3)}$, $\mathcal{C}_{ed,\ell d,qe,\ell edq,\ell edq'}$
- $M \to \ell\bar{\ell} \propto C_L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

$\boxed{\mu_\Lambda = 10\text{ TeV}}$

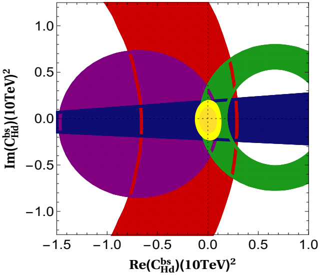
$$|\mathcal{C}_{Hd}^{sd}| \lesssim \frac{0.004}{(10\,\mathrm{TeV})^2} \qquad |\mathcal{C}_{Hd}^{bd}| \lesssim \frac{0.15}{(10\,\mathrm{TeV})^2} \qquad |\mathcal{C}_{Hd}^{bs}| \lesssim \frac{0.25}{(10\,\mathrm{TeV})^2}$$



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



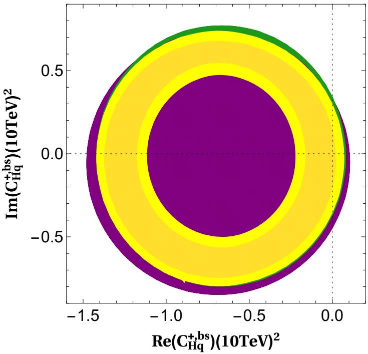
- ΔM_s
- $\sin(2\beta_s)$
- $Br(B^+ \to K^+ \mu\bar{\mu})_{[15,22]}$
- $Br(B_s \to \mu\bar{\mu})$

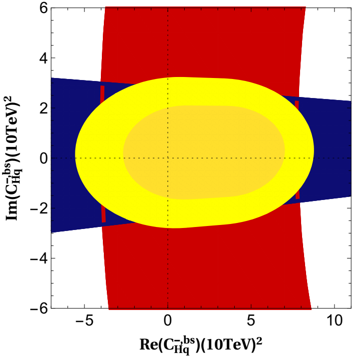
LH Scenario $\mathcal{O}_{Hq}^{(1,3)}$

[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 $b \to s$





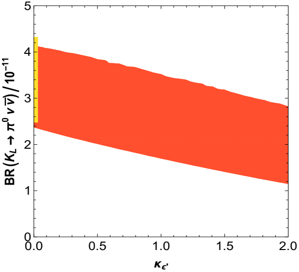
$\Delta F = 1$: $|[\mathcal{C}_{Hq}^{(+)}]_{bs}| \lesssim \dfrac{1.5}{(10\,\mathrm{TeV})^2}$

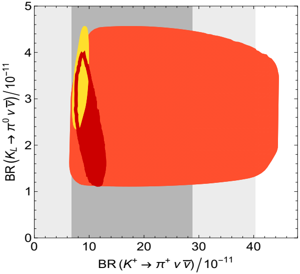
$\Delta F = 2$ (LO only): $|[\mathcal{C}_{Hq}^{(-)}]_{bs}| \lesssim \dfrac{9}{(10\,\mathrm{TeV})^2}$

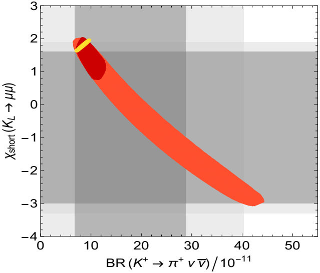
Correlations ε'/ε, $K \to \pi\nu\bar{\nu}$, $K_L \to \mu\bar{\mu}$, ε_K

[CB/Buras/Celis/Jung 1703.04753]

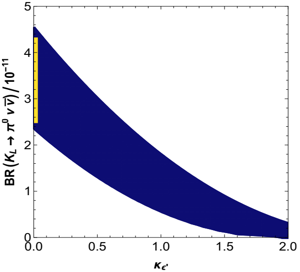
RH scenario: strong constraint from $\Delta S = 2$ in RH scenario $\Rightarrow$ with and without ε_K

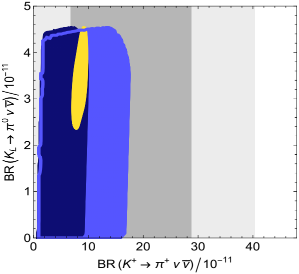






LH scenario:





ε'/ε anomaly can be resolved
$(\varepsilon'/\varepsilon)_{\mathrm{NP}} = \kappa_{\varepsilon'} \times 10^{-3}$

SM

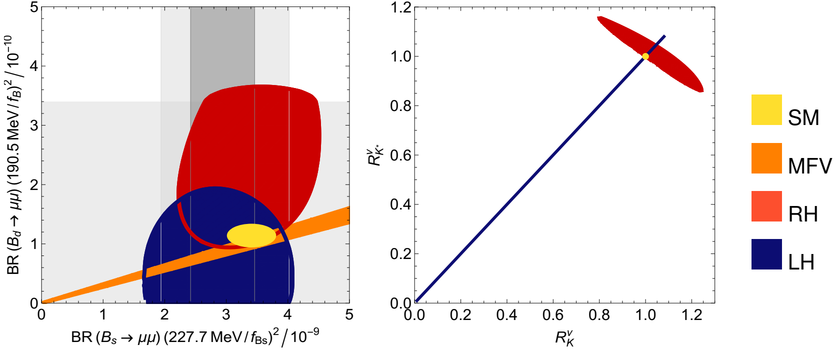
without ε_K — with ε_K

strong $K_L \to \mu\bar{\mu}$

weak $K_L \to \mu\bar{\mu}$

LH versus RH in B decays $B_{s,d} \to \mu\bar{\mu}$ and $B \to K^{(*)}\nu\bar{\nu}$

[CB/Buras/Celis/Jung 1703.04753]



$$R_{K^{(*)}} \equiv \frac{Br(B \to K^{(*)}\nu\bar{\nu})}{Br(B \to K^{(*)}\nu\bar{\nu})_{\rm SM}}$$

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 $\mathrm{SU}(3)_c$) $\Rightarrow$ 8 possibilities, but only 5 relevant for down-type FCNC's

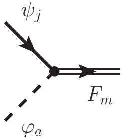
$$
\big(\mathrm{SU}(2)_L, \mathrm{U}(1)_Y\big) \qquad
\begin{array}{rll}
\text{singlets}: & D(1, -1/3) & \\
\text{doublets}: & Q_V(2, +1/6) & Q_d(2, -5/6) \\
\text{triplets}: & T_d(3, -1/3) & T_u(3, +2/3)
\end{array}
$$

- Kinetic + gauge interactions

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

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

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



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

  $\boldsymbol{\lambda_i^{\rm VLQ}}$ 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 =

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

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

(throughout as assumption)

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

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

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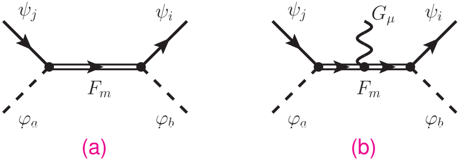
$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm dim-4} + \sum_a \mathcal{C}_a \mathcal{O}_a,$$

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 $\mathrm{SU(2)_L}$ representation of F_m



$$\boxed{\propto \frac{(\lambda_i^m)^* \lambda_j^m}{M_m^2}}$$

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

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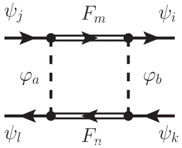
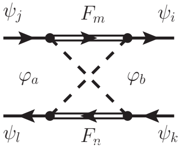
$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm dim-4} + \sum_a \mathcal{C}_a \mathcal{O}_a,$$

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

"direct" box contribution to ψ^4 @ μ_Λ

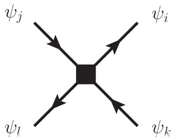




crossed graph only for certain $F_m \neq F_n$

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

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



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

$\Rightarrow$ 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 λ_i^{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 $\qquad \lambda_i^m \equiv |\lambda_i^m|\, e^{i\phi_i^m}$

- 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

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

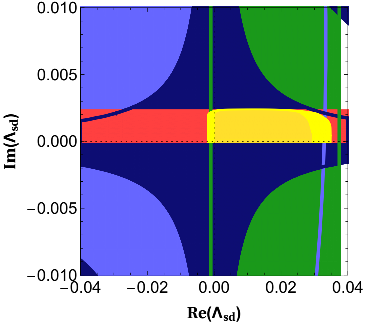
  with one relation on the phases

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

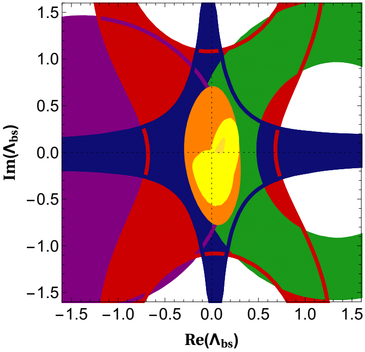
Numerical effects $\Delta F = 1, 2$

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

without mixing-induced



$s \to d$



$b \to s$

- 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

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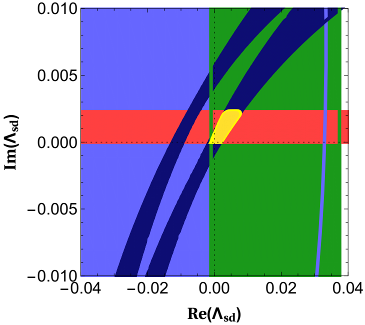
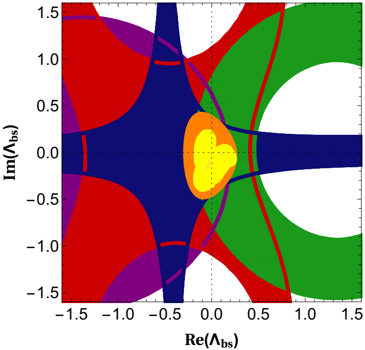


$s \to d$



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Summary

- FC Z-couplings are viable explanation of tension in ε'/ε
  $\Rightarrow$ ε'/ε itself puts strong constraints on imaginary parts of couplings

- 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 $\mathcal{O}_{Hq}^{(3)}$

- for $\mathcal{O}_{Hq}^{(3)}$ box-type diagrams involve sum over several flavors

  $\Rightarrow$ whole set of $\psi^2 H^2 D$ Wilson coefficients

- $\Delta F = 2$ 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

- in toy-UV completion with VLQs: top-Yukawa mixing-induced Z-effects in $\Delta F = 2$ must compete with direct ψ^4 one-loop contributions

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

Backup Slides

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

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

$$\begin{aligned}
O_{9(9')}^{ij} &= [\bar{d}_i \gamma_\mu P_{L(R)} d_j][\bar{\ell}\gamma^\mu \ell] \\
O_{10(10')}^{ij} &= [\bar{d}_i \gamma_\mu P_{L(R)} d_j][\bar{\ell}\gamma^\mu \gamma_5 \ell] \\
O_{L(R)}^{ij} &= [\bar{d}_i \gamma_\mu P_{L(R)} d_j][\bar{\nu}\gamma^\mu (1-\gamma_5)\nu]
\end{aligned}$$

- 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

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

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

Numerical impact of NLO crr's

[CB/Buras/Celis/Jung 1703.04753]

$x_t \approx 4$

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

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

- $\mathcal{O}_{Hq}^{(3)}$: 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

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

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

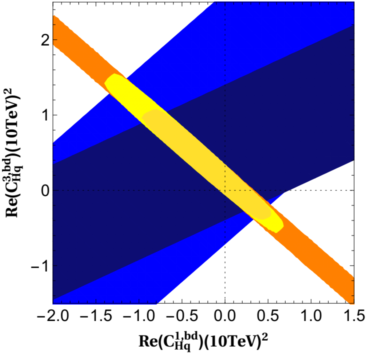
$\Rightarrow$ to K^0 mixing $ij = sd$ with $\lambda_t^{sb} [\mathcal{C}_{Hq}^{(3)}]_{bd} \sim \lambda_C^2 \times [\mathcal{C}_{Hq}^{(3)}]_{bd}$ (quadratic Cabibbo suppression)

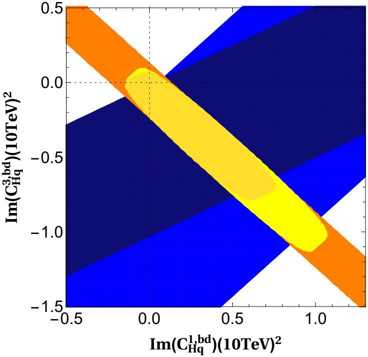
!!! if hierarchy $[\mathcal{C}_{Hq}^{(3)}]_{sd} \approx \lambda_C^2 \times [\mathcal{C}_{Hq}^{(3)}]_{bd}$, then can not be neglected

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 $\Delta F = 1, 2$