Meson-antiMeson Mixing in SMEFT

Jacky Kumar
Technical University Munich

CERN 2021

Unterstützt von / Supported by
Alexander von Humboldt
Stiftung / Foundation

Technische Universität München

Based on

SMEFT Atlas of $\Delta F = 2$ transitions

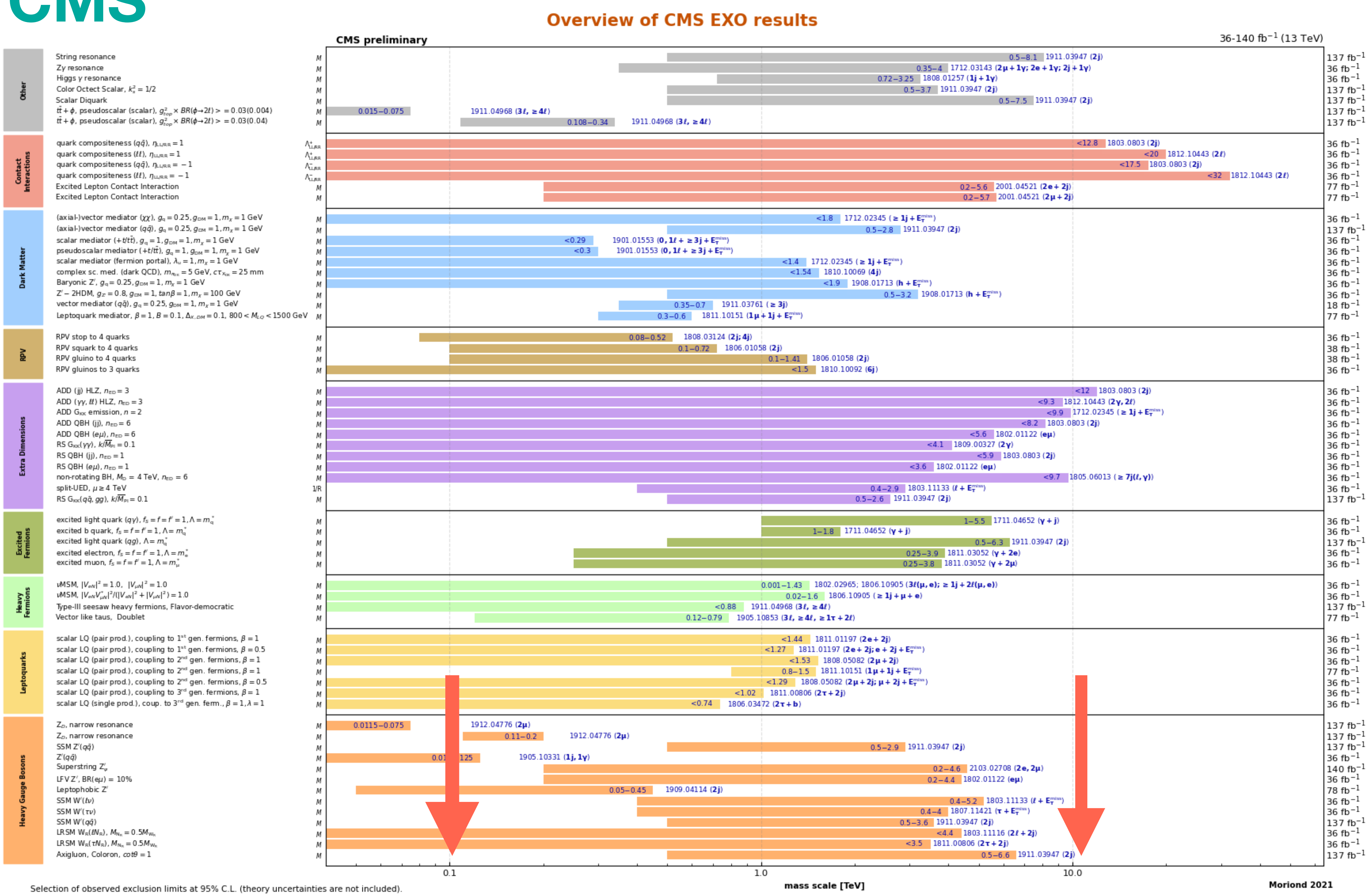
JHEP 12 (2020) 187, arXiv: 2009.07276

In collaboration with J. Aebischer, C. Bobeth and A. Buras

Direct Searches

Scale gap

CMS



EW scale

$\mathcal{O}(10\text{TeV})$

Indirect Searches

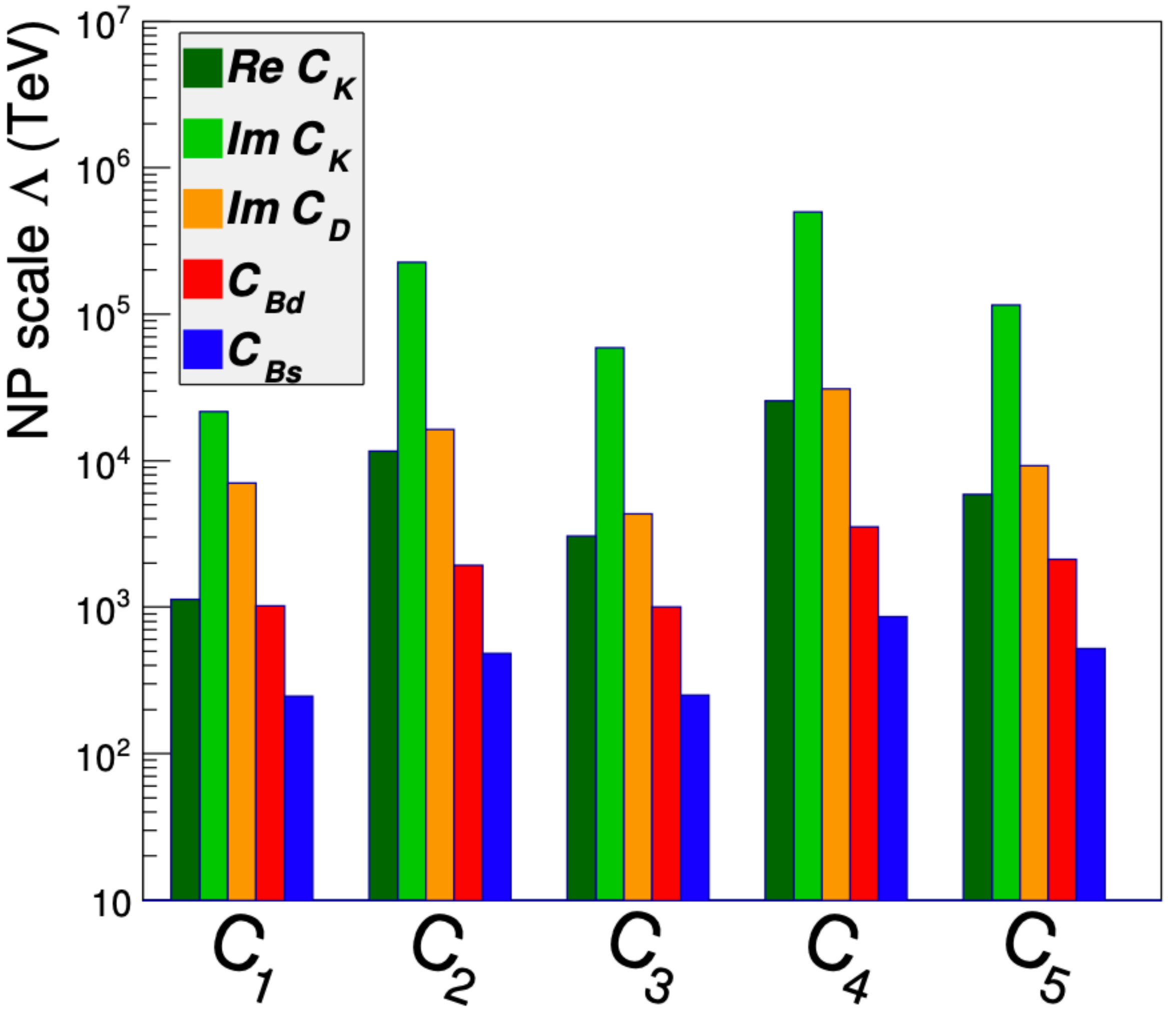
Constraints on NP scale from Meson-antiMeson mixing

$$\mathcal{H}_{\text{eff}} = C_I\, O_I$$

$$C_I = \frac{c_I}{\Lambda^2}$$

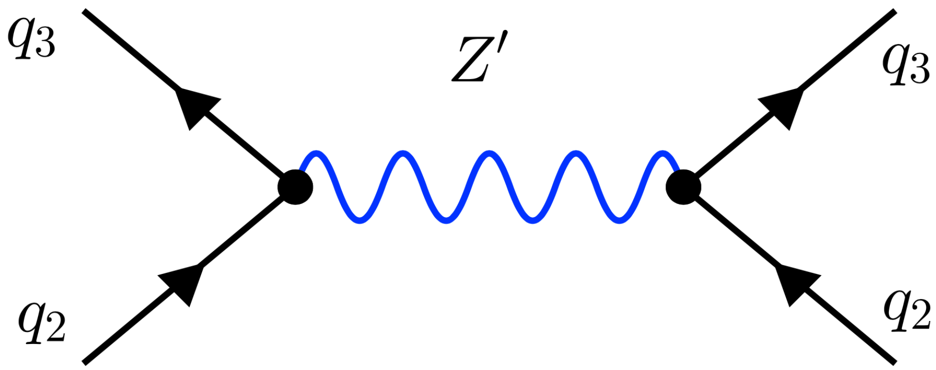
$$c_I \sim \mathcal{O}(1)$$

$$\Lambda \sim \mathcal{O}(10^2) - \mathcal{O}(10^5)\ \text{TeV}$$



M. Bona PoS (CKM2016) 096 UTfit

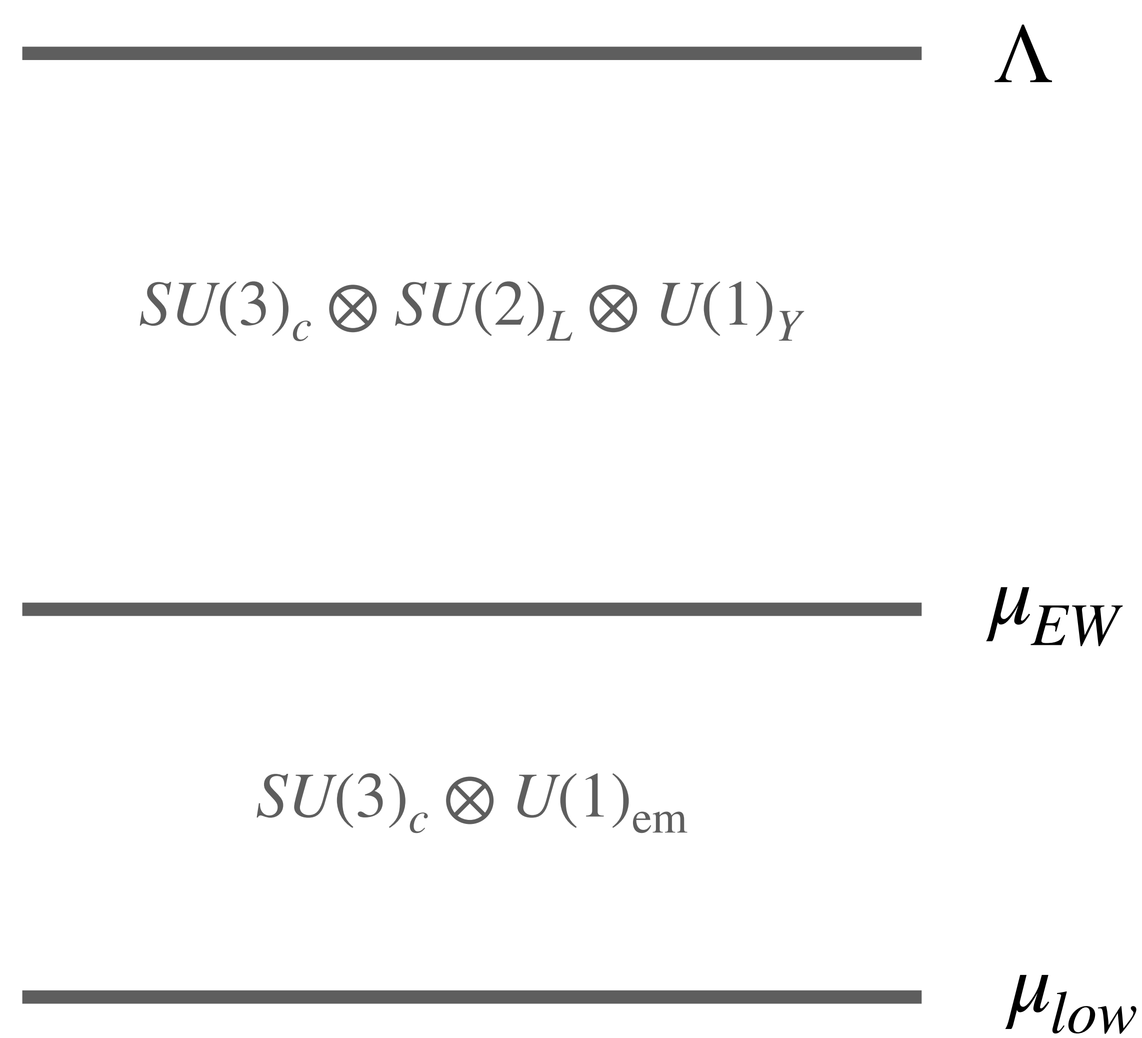
Gauge Symmetry at work



$$q_I = \begin{pmatrix} u_L^I \\ d_L^I \end{pmatrix}$$

$$\frac{c_{qq}^{(1)}(m_{Z'})}{m_{Z'}^2}(\bar{q}_3\gamma_\mu P_L q_2)(\bar{q}_3\gamma^\mu P_L q_2)$$

$$\frac{c_1(m_{Z'})}{m_{Z'}^2}(\bar{s}\gamma_\mu P_L b)(\bar{s}\gamma^\mu P_L b)$$



For $\Lambda >> \mu_{\rm EW}$ we should work with Gauge Invariant effective operators.

Standard Model Effective Field Theory

- Standard Model field content.
- Operators respect the full Gauge symmetry.
- Electroweak symmetry is broken by one Higgs-doublet.

$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \mathscr{L}_{eff}$$

Buchmuller and Wyler 1986

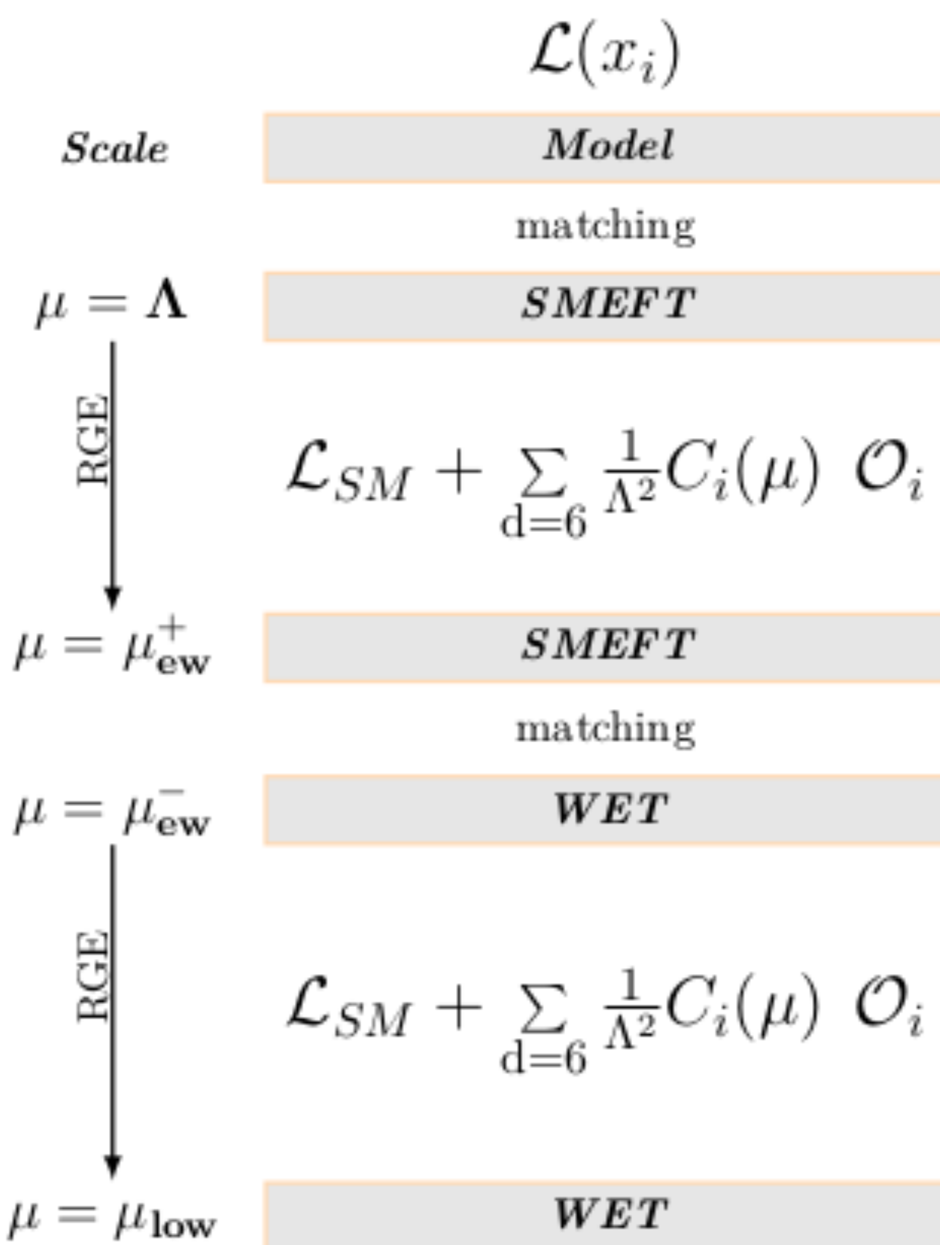
$$\mathscr{L}_{\mathrm{eff}} = \sum_{d=5,6,..} C_j O_j$$

Warsaw Basis (without Flavour and Color)

15 (Bosonic) +
19 (Single-fermion current) +
25 (Four-fermion) = 59 Operators

SMEFT Strategy

UV Completion



$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

SM Effective Field Theory (SMEFT)

EWPT, H-decays etc.

$SU(3)_c \otimes U(1)_{\rm em}$

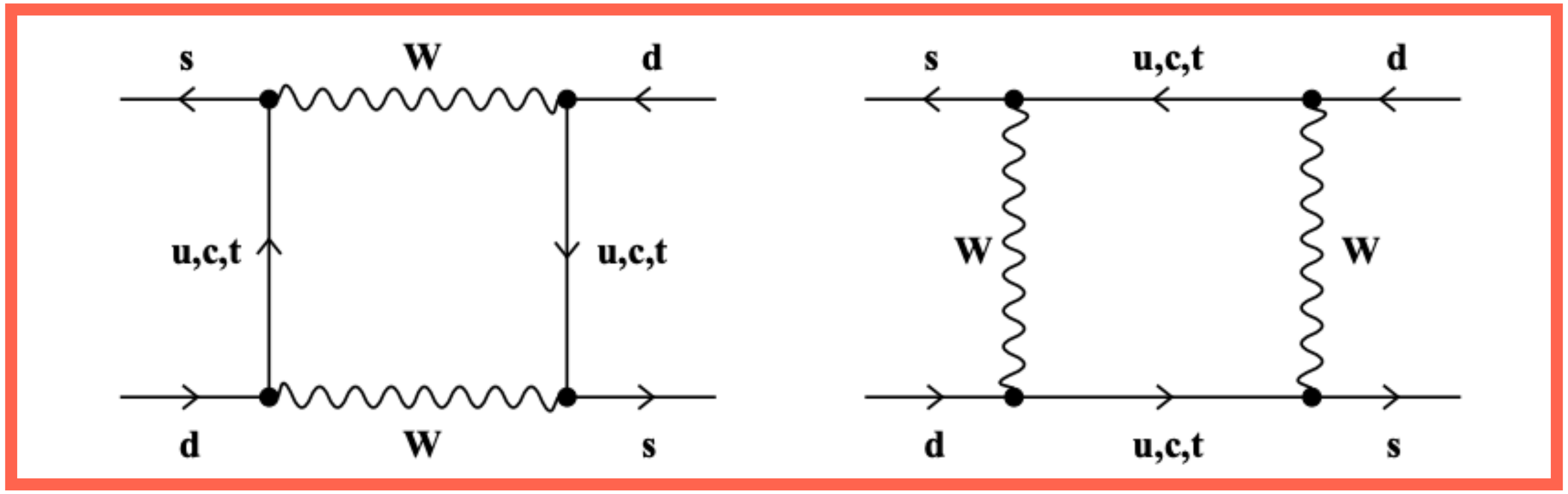
Weak Effective Theory (WET)

$\Delta F = 1, 2,\ \tau$ & μ-decays etc

Meson - antiMeson mixing in SM

$$[M_{12}^{ij}]_{\mathrm{SM}} = \langle M^0 | \mathcal{H}_{\Delta F=2}^{ij} | \overline{M}^0 \rangle$$

$$ij \ = \ ds, \ \ sb, \ \ db : \ K^0, \ \ B_s, \ \ B_d$$



$$\mathcal{H}_{eff} = \frac{G_F^2 m_W^2}{4\pi^2} \ (\lambda_t^{ij})^2 \ \ [C_{\mathrm{VLL}}^{ij}(\mu)]_{\mathrm{SM}} \ \ (\bar{d}_i \gamma^\mu P_L d_j) \ (\bar{d}_i \gamma_\mu P_L d_j) \ + \ h.c.$$

$$\lambda_t^{ij} = V_{ti}^* V_{tj}$$

Operator bases for Meson-antiMeson mixing in WET

4-Fermion operators

$$\mathscr{H}^{ij}_{\Delta F=2} = [\mathscr{H}^{ij}_{\Delta F=2}]_{\rm SM} + \sum_a C^{ij}_a Q^{ij}_a + h.c.$$

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

$$Q^{ij}_{\rm LR,1} = [\bar{d}_i \gamma_\mu P_L d_j][\bar{d}_i \gamma^\mu P_R d_j], \qquad Q^{ij}_{\rm LR,2} = [\bar{d}_i P_L d_j][\bar{d}_i P_R d_j],$$

$$Q^{ij}_{\rm SLL,1} = [\bar{d}_i P_L d_j][\bar{d}_i P_L d_j], \qquad Q^{ij}_{\rm SLL,2} = -[\bar{d}_i \sigma_{\mu\nu} P_L d_j][\bar{d}_i \sigma^{\mu\nu} P_L d_j],$$

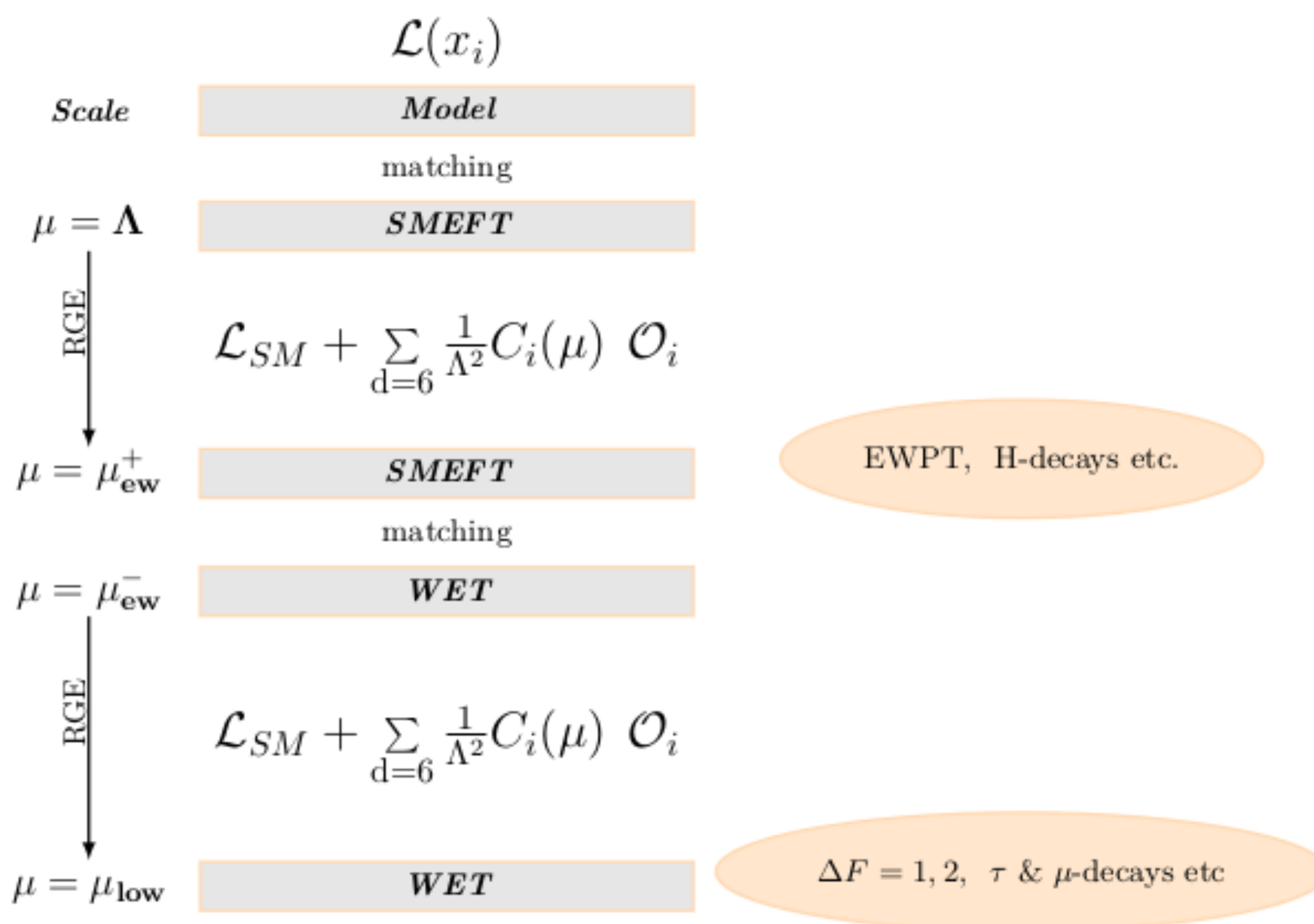
+ Chirality flipped operators

BMU Basis

Buras, Misiak, Urban 2000

Meson-antiMeson mixing in SMEFT

New operators beyond 4F structures come into play.



$$\mathscr{H}^{ij}_{\Delta F=2} = [\mathscr{H}^{ij}_{\Delta F=2}]_{\mathrm{SM}} + \sum_a C^{ij}_a(\mu) Q^{ij}_a + h.c.$$

Flavour violating Z Boson couplings in SMEFT

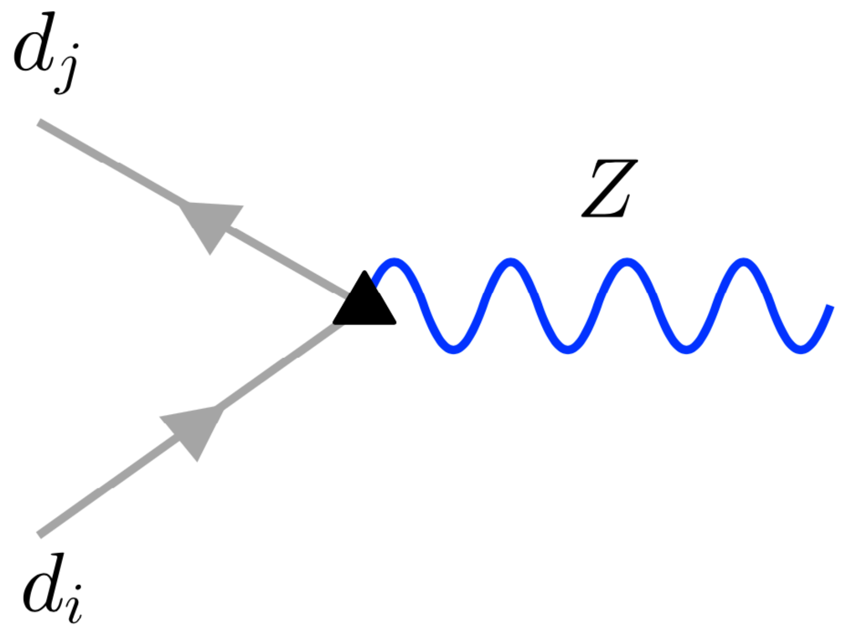
$\psi^2\phi^2 D$

$$[O_{\phi q}^{(1)}]_{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{q}_i \gamma^\mu q_j)$$

$$[O_{\phi q}^{(3)}]_{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \tau^I \phi)(\bar{q}_i \gamma^\mu \tau^I q_j)$$

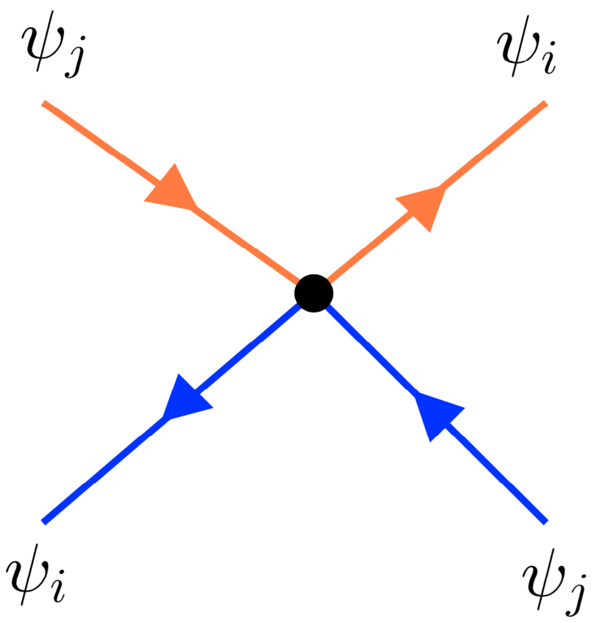
Electroweak symmetry breaking

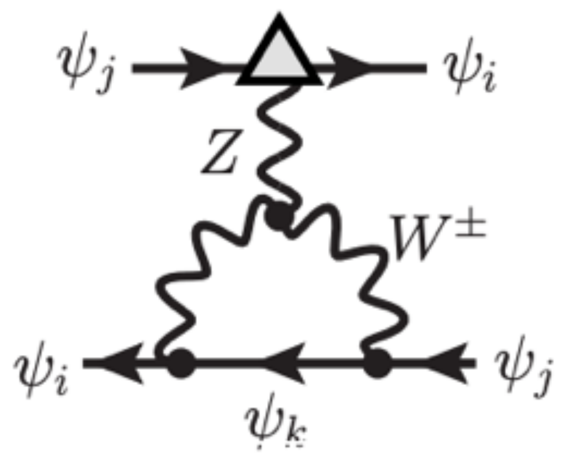
$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$



$$\propto \quad -\frac{v^2}{2}\left([C_{\phi q}^{(1)}]_{ij} + [C_{\phi q}^{(3)}]_{ij}\right)$$

New structures in SMEFT -> WET matching





ψ^4 WET

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

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

$\psi^2\phi^2 D$ SMEFT

$$[O^{(3)}_{\phi q}]_{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \tau^I \phi)(\bar{q}_i \gamma^\mu \tau^I q_j)$$

$$[O^{(1)}_{\phi q}]_{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{q}_i \gamma^\mu q_j)$$

$$[O_{\phi d}]_{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{d}_i \gamma^\mu d_j)$$

Bobeth, Buras, Celis, Jung 2017

New flavour structures in SMEFT RGE

Operator mixing due to Yukawas

$$[C^{ij}_{\rm VLL}](\mu_{\rm EW}) \;\propto\; y_t^2\,(\lambda_t^{ik}[C^{(1)}_{qq}(\Lambda)]_{kijij} - \lambda_t^{ij}[C^{(1)}_{qu}(\Lambda)]_{ij33}) + \ldots$$

y_t = **Top-Yukawa** $\qquad \lambda_t^{ij} = V^*_{ti}V_{tj}$

ψ^4 WET $\qquad\qquad \psi^4$ SMEFT

$$Q^{ij}_{\rm VLL} = [\bar d_i \gamma_\mu P_L d_j][\bar d_i \gamma^\mu P_L d_j],$$

$$[O^{(1)}_{qq}]_{ijij} = (\bar q_i \gamma_\mu q_j)(q_i \gamma^\mu q_j)$$

$$[O^{(1)}_{qu}]_{ij33} = (\bar q_i \gamma_\mu q_j)(t\gamma^\mu t)$$

Jenkins, Manohar, Trott 2013

SMEFT operators entering in ΔF=2 processes

At the NP scale

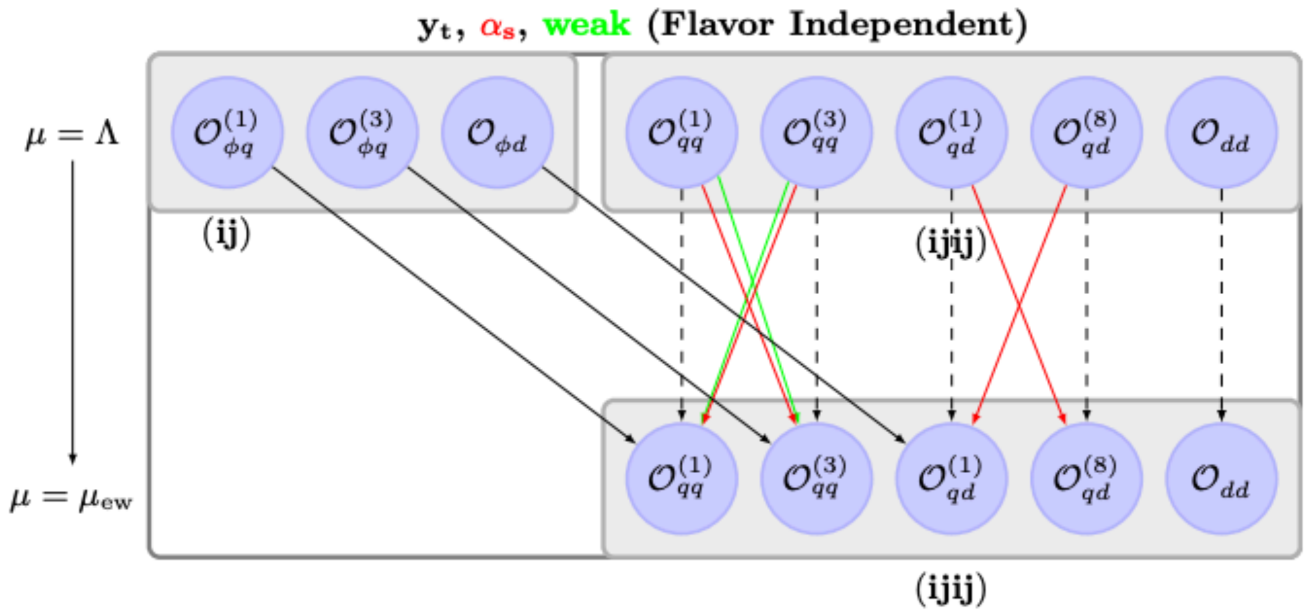
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{\ell}_p\gamma_\mu \ell_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{\ell}_p\gamma_\mu \ell_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{\ell}_p\gamma_\mu \ell_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{\ell}_p\gamma_\mu\tau^I \ell_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$\psi^2 X\phi$		$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$\mathcal{O}_{uW}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\phi}\,W_{\mu\nu}^I$	$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		$\psi^2\phi^2 D$	
$\mathcal{O}_{ledq}$	$(\bar{\ell}_p^j e_r)(\bar{d}_s q_t^j)$	$\mathcal{O}_{\phi q}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{q}_p\gamma^\mu q_r)$
$\mathcal{O}_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$	$\mathcal{O}_{\phi q}^{(3)}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu^I\phi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$	$\mathcal{O}_{\phi u}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{u}_p\gamma^\mu u_r)$
$\mathcal{O}_{lequ}^{(1)}$	$(\bar{\ell}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$	$\mathcal{O}_{\phi d}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{d}_p\gamma^\mu d_r)$
$\mathcal{O}_{lequ}^{(3)}$	$(\bar{\ell}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$	$\mathcal{O}_{\phi ud}$	$(\widetilde{\phi}^\dagger i D_\mu\phi)(\bar{u}_p\gamma^\mu d_r)$

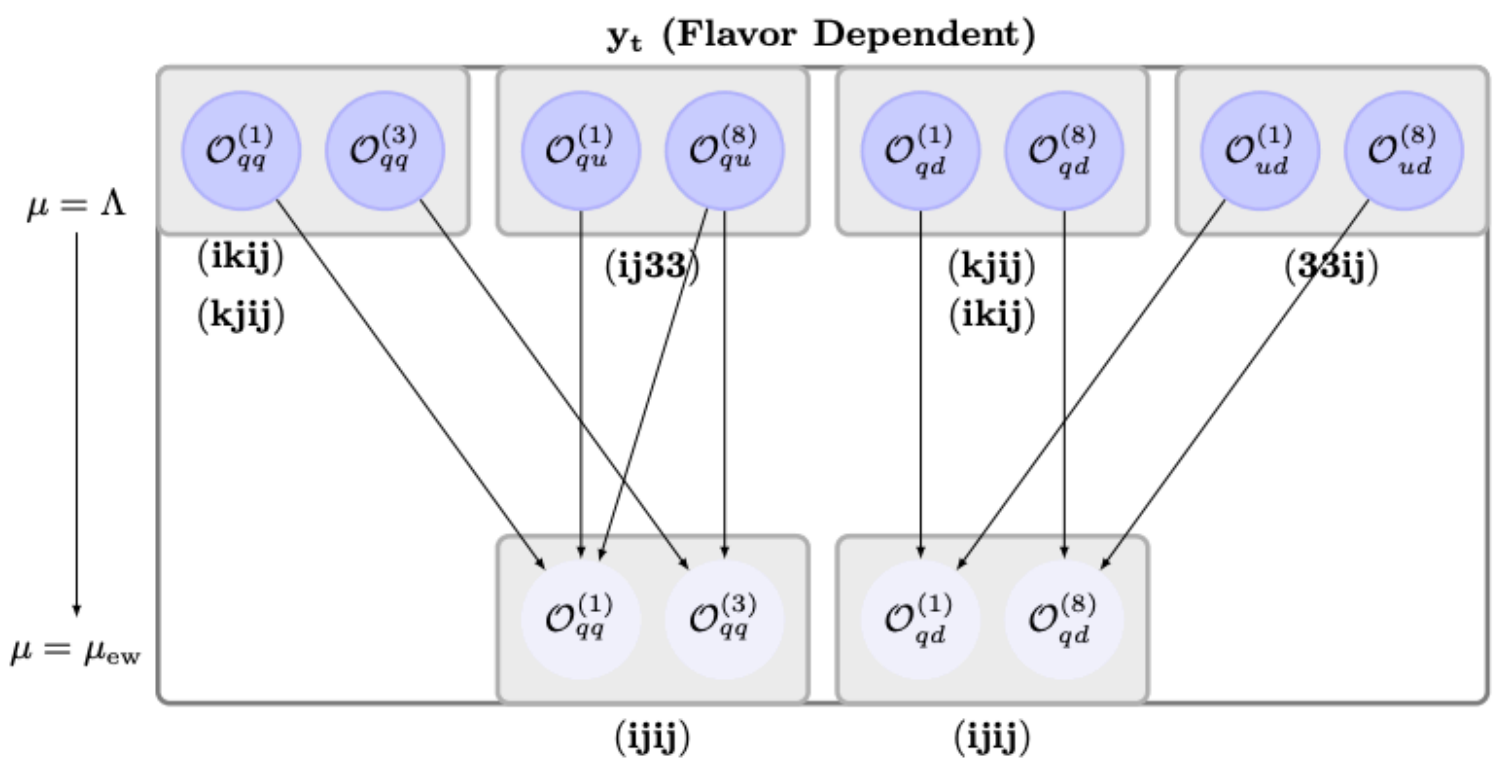
SMEFT RGEs: operator mixing

Flavour Structures

Yukawa
Strong
Weak



$ij \to ij$



$ik, kj, 33 \to ij$

$$ijij = 2323\ (B_s - \overline{B}_s)$$
$$1313\ (B_d - \overline{B}_d)$$
$$2121\ (K^0 - \overline{K}_0)$$

Master formulae

Master Formula for $\Delta F = 2$ processes in terms of all SMEFT WCs at NP scale.

Facilitate the model independent studies of $\Delta F = 2$ observables.

$$2\left[M_{12}^{ij}\right]_{\rm BSM} = (\Delta M_{ij})_{\rm exp} \sum_a P_a^{ij}(\Lambda)\ \left[\mathcal{C}_a\right]_{ij}(\Lambda) = (\Delta M_{ij})_{\rm exp} \sum_a P_a^{ij}(\Lambda) \frac{\left[c_a\right]_{ij}(\Lambda)}{\Lambda^2}$$

$C_a(\Lambda)$ **Wilson Coefficients at the NP scale.**

$P_a^{ij}(\Lambda)$ **contains all the information about:**

— **Matrix Elements.**
— **RG in WET.**
— **RG in SMEFT.**

How to read Master Formulae at $\Lambda = 5\text{TeV}$.

$$\Sigma = \frac{2[M_{12}^{ij}]_{\text{BSM}}}{(\Delta M)_{\text{exp}}}$$

Fraction of NP contribution.

$\Sigma = 0.10$ **means 10% NP contribution.**

$[O_{qq}^{(1)}]_{ijij} = (\bar{q}_i \gamma_\mu q_j)(q_i \gamma^\mu q_j)$

$$\Sigma_{qq1}^{B_s} = -3.9 \cdot 10^2 \left[c_{qq}^{(1)}\right]_{2323} - 5.4 \cdot 10^{-1} \left[c_{qq}^{(1)}\right]_{2333} + 3.1 \cdot 10^{-1} \left[c_{qq}^{(1)}\right]_{2223} - 6.8 \cdot 10^{-2} e^{i22^\circ} \left[c_{qq}^{(1)}\right]_{1232} ,$$

$B_s - \overline{B}_s$

$[O_{\phi q}^{(3)}]_{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \tau^I \phi)(\bar{q}_i \gamma^\mu \tau^I q_j)$

$$\Sigma_{\phi q3}^{B_s} = 5.4 \cdot 10^{-1} \left[c_{\phi q}^{(3)}\right]_{23} + 6.3 \cdot 10^{-3} \left[c_{\phi q}^{(3)}\right]_{33} + 5.1 \cdot 10^{-3} \left[c_{\phi q}^{(3)}\right]_{22} ,$$

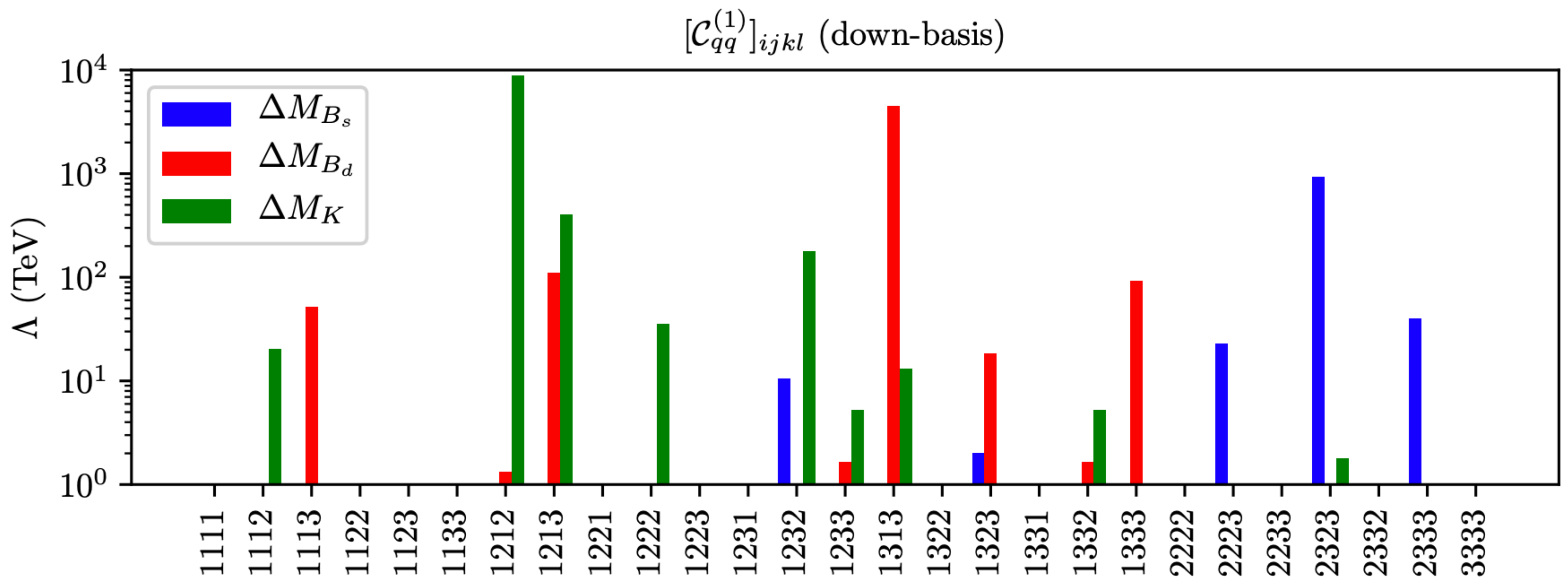
Probing High Scales using Meson mixing

$$\frac{c_{qq}^{(1)}}{\Lambda^2}(\bar{q}_i\gamma_\mu q_j)(\bar{q}_k\gamma^\mu q_l)$$

$$q^i = \begin{pmatrix} V_{ij}^\dagger u_L^i \\ d_L^i \end{pmatrix}$$

Warsaw-down basis

Values of Λ for which $\Sigma = 10\,\%$, given $c_{qq}^{(1)} = 10.$



Master Formulae for Minimal extensions of SM

G' (8,1,0)

$$\mathcal{L}_{G'} = -\Big[g_q^{ij}\,(\bar{q}^i\gamma^\mu T^A q^j) + g_u^{ij}\,(\bar{u}^i\gamma^\mu T^A u^j) + g_d^{ij}\,(\bar{d}^i\gamma^\mu T^A d^j) \Big]\, G'^A_\mu\,.$$

Tree-level matching to SMEFT at Λ

$$[\mathcal{C}_{qq}^{(1)}]_{ijkl} = \frac{g_q^{ij} g_q^{kl}}{12 M_{G'}^2} - \frac{g_q^{il} g_q^{kj}}{8 M_{G'}^2}\,, \qquad [\mathcal{C}_{qq}^{(3)}]_{ijkl} = -\frac{g_q^{il} g_q^{kj}}{8 M_{G'}^2}\,,$$

$$[\mathcal{C}_{qd}^{(8)}]_{ijkl} = -\frac{g_q^{ij} g_d^{kl}}{M_{G'}^2}\,, \qquad [\mathcal{C}_{qu}^{(8)}]_{ijkl} = -\frac{g_q^{ij} g_u^{kl}}{M_{G'}^2}$$

$$[\mathcal{C}_{dd}]_{ijkl} = \frac{g_d^{ij} g_d^{kl}}{12 M_{G'}^2} - \frac{g_d^{il} g_d^{kj}}{4 M_{G'}^2}\,, \qquad [\mathcal{C}_{uu}]_{ijkl} = \frac{g_u^{ij} g_u^{kl}}{12 M_{G'}^2} - \frac{g_u^{il} g_u^{kj}}{4 M_{G'}^2}\,, \qquad [\mathcal{C}_{ud}^{(8)}]_{ijkl} = -\frac{g_u^{ij} g_d^{kl}}{M_{G'}^2}\,.$$

Master Formulae for G' (8,1,0)

$$\frac{M_{G'}^2 \Sigma_{G'}^{B_s}}{(5\,\mathrm{TeV})^2} = -2.7\cdot 10^3 g_q^{23} g_d^{23} + 6.9\cdot 10^1 g_d^{23} g_d^{23} + 6.5\cdot 10^1 g_q^{23} g_q^{23} - 3.8 g_q^{33} g_d^{23} + 2.1 g_q^{22} g_d^{23}$$
$$+ 1.5 g_u^{33} g_d^{23} - 4.7\cdot 10^{-1} e^{i22^\circ} g_q^{12} g_d^{32} - 1.6\cdot 10^{-1} g_u^{23} g_d^{23} + 1.3\cdot 10^{-1} g_q^{23} g_d^{22}$$
$$- 1.3\cdot 10^{-1} g_q^{23} g_d^{33} - 1.1\cdot 10^{-1} g_q^{23} g_u^{33} + 8.7\cdot 10^{-2} g_q^{23} g_q^{33} - 5.2\cdot 10^{-2} g_q^{23} g_q^{22}$$
$$- 2.7\cdot 10^{-2} g_q^{23} g_d^{32} + 2.6\cdot 10^{-2} e^{-i23^\circ} g_q^{13} g_d^{23} + 1.4\cdot 10^{-2} g_q^{23} g_u^{23}$$
$$+ 1.1\cdot 10^{-2} e^{i22^\circ} g_q^{12} g_q^{32} + 5.8\cdot 10^{-3} e^{i21^\circ} g_q^{13} g_d^{32}\,,$$

$$\frac{M_{G'}^2 \Sigma_{G'}^{B_d}}{(5\,\mathrm{TeV})^2} = -6.6\cdot 10^4 g_q^{13} g_d^{13} + 1.6\cdot 10^3 g_d^{13} g_d^{13} + 1.5\cdot 10^3 g_q^{13} g_q^{13} + 5.2\cdot 10^1 g_q^{12} g_d^{13}$$
$$+ 2.1\cdot 10^1 e^{i22^\circ} g_q^{33} g_d^{13} - 1.1\cdot 10^1 e^{i22^\circ} g_q^{11} g_d^{13} - 7.9 e^{i22^\circ} g_u^{33} g_d^{13} + 3.2 g_q^{13} g_d^{12}$$
$$- 1.2 g_q^{13} g_q^{12} - 8.9\cdot 10^{-1} e^{i23^\circ} g_q^{23} g_d^{13} + 8.7\cdot 10^{-1} g_u^{23} g_d^{13} + 5.2\cdot 10^{-1} e^{i22^\circ} g_q^{13} g_u^{33}$$
$$- 4.7\cdot 10^{-1} e^{i21^\circ} g_q^{13} g_q^{33} + 2.7\cdot 10^{-1} e^{i22^\circ} g_q^{13} g_q^{11} + 1.4\cdot 10^{-1} e^{i21^\circ} g_q^{23} g_d^{31}$$
$$- 7.8\cdot 10^{-2} g_d^{13} g_d^{12} - 7.5\cdot 10^{-2} e^{i23^\circ} g_q^{13} g_d^{23} - 7.5\cdot 10^{-2} g_q^{13} g_u^{23}$$
$$- 3.6\cdot 10^{-2} e^{i21^\circ} g_q^{13} g_d^{11} + 3.5\cdot 10^{-2} e^{i21^\circ} g_q^{13} g_d^{33} - 3.1\cdot 10^{-2} e^{i44^\circ} g_q^{13} g_d^{31}$$
$$+ 1.9\cdot 10^{-2} e^{i23^\circ} g_q^{13} g_q^{23} - 1.8\cdot 10^{-2} e^{i22^\circ} g_q^{22} g_d^{13} - 7.6\cdot 10^{-3} g_u^{13} g_d^{13}$$
$$- 5.5\cdot 10^{-3} e^{i22^\circ} g_u^{11} g_d^{13} - 5.4\cdot 10^{-3} e^{i22^\circ} g_u^{22} g_d^{13}\,,$$

Summary

— Lack of observations of the new states at the LHC suggest a scale gap between the EW and NP scales.

— SMEFT provides a convenient framework to parameterise the NP effects.

— Master formulae for Meson-antiMeson mixing facilitate the model independent studies, include RG running effects above and below the EW scale.

— SMEFT RG running effects due to Yukawas can lead to complicated operator mixing pattern: Meson mixing depends on new operators and flavour structures

Thanks for your attention!!

Models to SMEFT dictionary

Spin	Rep.	$\mathcal{O}_{qq}^{(1)}$	$\mathcal{O}_{qq}^{(3)}$	$\mathcal{O}_{qd}^{(1)}$	$\mathcal{O}_{qd}^{(8)}$	$\mathcal{O}_{qu}^{(1)}$	$\mathcal{O}_{qu}^{(8)}$	$\mathcal{O}_{dd}$	$\mathcal{O}_{uu}$	$\mathcal{O}_{ud}^{(1)}$	$\mathcal{O}_{ud}^{(8)}$
	$(1,1)_0$	$\times$		$\times$		$\times$		$\times$	$\times$	$\times$	
	$(1,1)_1$									$\times$	$\times$
	$(1,3)_0$		$\times$								
	$(8,1)_0$	$\times$	$\times$		$\times$		$\times$	$\times$	$\times$		$\times$
1	$(8,1)_1$									$\times$	$\times$
	$(8,3)_0$	$\times$	$\times$								
	$(3,2)_{\frac{1}{6}}$			$\times$	$\times$						
	$(3,2)_{-\frac{5}{6}}$					$\times$	$\times$				
	$(\bar{6},2)_{\frac{1}{6}}$			$\times$	$\times$						
	$(\bar{6},2)_{-\frac{5}{6}}$					$\times$	$\times$				

Table 7: Four-quark (ψ^4) operators generated from additional vector fields.

Blas, Criado, Victoria, Santiago 2018

Operator bases for Meson-antiMeson mixing in WET

4-Fermion operators

$$\mathscr{H}^{ij}_{\Delta F=2} = [\mathscr{H}^{ij}_{\Delta F=2}]_{\rm SM} + \sum_a C^{ij}_a Q^{ij}_a + h.c.$$

$$[Q^{VLL}_{dd}]_{ijij} = Q^{ij}_{\rm VLL}\,,$$

$$[Q^{VRR}_{dd}]_{ijij} = Q^{ij}_{\rm VRR}\,,$$

$$[Q^{V1,LR}_{dd}]_{ijij} = Q^{ij}_{\rm LR,1}\,,$$

$$[Q^{V8,LR}_{dd}]_{ijij} = [\bar{d}_i \gamma_\mu P_L T^A d_j][\bar{d}_i \gamma^\mu P_R T^A d_j] = -\frac{1}{6} Q^{ij}_{\rm LR,1} - Q^{ij}_{\rm LR,2}\,,$$

$$[Q^{S1,RR}_{dd}]_{ijij} = Q^{ij}_{\rm SRR,1}\,,$$

$$[Q^{S8,RR}_{dd}]_{ijij} = [\bar{d}_i P_R T^A d_j][\bar{d}_i P_R T^A d_j] = -\frac{5}{12} Q^{ij}_{\rm SRR,1} + \frac{1}{16} Q^{ij}_{\rm SRR,2}\,,$$

+ Chirality flipped operators

JMS Basis:

Jenkins, Manohar, Stoffer 2018
Dekens, Stoffer 2019

Good for matching to SMEFT