

# SMEFT interpretation of $\Delta F = 2$ transitions

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# Outline

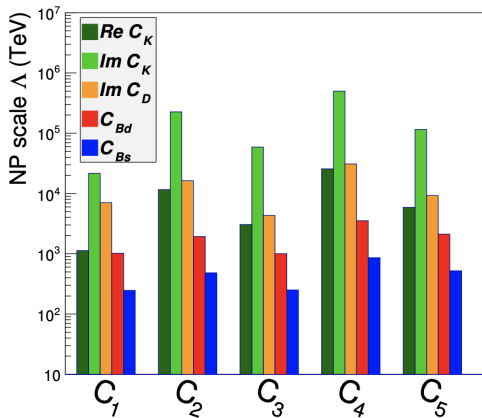
- 1 Motivation
- 2 Meson mixing
- 3 Master formula in WET
- 4 Master formula in SMEFT
- 5 Summary

based on: [2009.07276](#) in collaboration with C. Bobeth, A. Buras and J. Kumar

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# NP from $\Delta F = 2$ processes



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# Meson mixing

## Schrödinger equation

$$i\frac{d}{dt}|\psi\rangle = \hat{H}|\psi\rangle$$

## States

$$|\psi(t)\rangle = \begin{pmatrix} |M^0(t)\rangle \\ |\bar{M}^0(t)\rangle \end{pmatrix}$$

## Hamiltonian

$$\hat{H} = \hat{M} - \frac{i}{2}\hat{\Gamma} = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}$$

$M_{12}$  = virtual transition

$\Gamma_{12}$  = physical transition

# $M_{12}$

## Neutral mesons

$$D^0 - \bar{D}^0, K^0 - \bar{K}^0, B_{s,d}^0 - \bar{B}_{s,d}^0$$

## Observables

$$D^0 : x_{12} = \frac{2|M_{12}^{cu}|}{\Gamma}$$

$$K^0 : \Delta M_K = 2 \operatorname{Re}(M_{12}^{ds})$$

$$B_s^0 : \Delta M_{B_s} = 2|M_{12}^{sb}|$$

$$B_d^0 : \Delta M_{B_d} = 2|M_{12}^{db}|$$

## Decomposition

$$M_{12} = M_{12}^{\text{SM}} + M_{12}^{\text{BSM}}$$

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# Ingredients

## Weak effective theory (WET)

$$\mathcal{H}_{\text{eff}} = - \sum_i C_i O_i, \quad \Rightarrow \quad M_{12}^{\text{BSM}} = \frac{1}{2M} \sum_i C_i \langle O_i \rangle$$

## Running

Two-loop QCD running for all Wilson coefficients

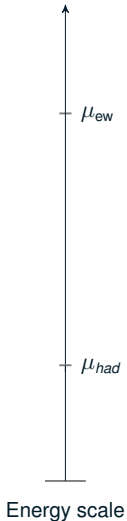
Buras/Misiak/Urban: hep-ph/0005183

## Matrix elements (MEs)

From lattice

FLAG: 1902.08191

# Master formula in WET



$$\mathcal{H}_{\text{eff}} = - \sum_i C_i O_i$$

two-loop running

MEs



Master formula

# WET

## Symmetry

$SU(3)_C \times U(1)_{em}$ , Poincaré

## Fields

$u, d, c, s, b, \ell, \nu_\ell, g, \gamma$

## Dimensionality

$\dim \geq 4$

## $\Delta F = 2$ Hamiltonian

$$\mathcal{H}_{\Delta F=2}^{ij} = \sum_a C_a^{ij}(\mu) Q_a^{ij} + \text{h.c.},$$

for  $D^0 - \bar{D}^0$ :

$$Q_{VLL}^{cu} = [\bar{c}\gamma_\mu P_L u][\bar{c}\gamma^\mu P_L u],$$

$$Q_{LR,1}^{cu} = [\bar{c}\gamma_\mu P_L u][\bar{c}\gamma^\mu P_R u], \quad Q_{LR,2}^{cu} = [\bar{c}P_L u][\bar{c}P_R u],$$

$$Q_{SLL,1}^{cu} = [\bar{c}P_L u][\bar{c}P_L u], \quad Q_{SLL,2}^{cu} = -[\bar{c}\sigma_{\mu\nu} P_L u][\bar{c}\sigma^{\mu\nu} P_L u].$$

similar for  $ij = sd, db, sb$

## Matrix elements

$ij$	$\mu_{\text{had}}$ [GeV]	$N_f$	$\langle Q_1^{ij} \rangle$ [GeV <sup>4</sup> ]	$\langle Q_2^{ij} \rangle$ [GeV <sup>4</sup> ]	$\langle Q_3^{ij} \rangle$ [GeV <sup>4</sup> ]	$\langle Q_4^{ij} \rangle$ [GeV <sup>4</sup> ]	$\langle Q_5^{ij} \rangle$ [GeV <sup>4</sup> ]
$sd$	3.0	3	0.002156(34)	-0.0420(16)	0.0128(6)	0.0930(30)	0.0241(14)
$cu$	3.0	4	0.0806(56)	-0.1442(72)	0.0452(31)	0.2745(140)	0.1035(74)
$db$	4.16	5	0.56(2)	-0.53(3)	0.106(8)	0.96(5)	0.51(2)
$sb$	4.16	5	0.86(3)	-0.85(5)	0.174(11)	1.40(6)	0.74(3)

# WET master formula

## At EW scale

$$2M_{12}^{\text{BSM}} = \sum_a P_a(\mu_{\text{ew}}) C_a(\mu_{\text{ew}})$$

## $P_a$ factors

Contain running and MEs

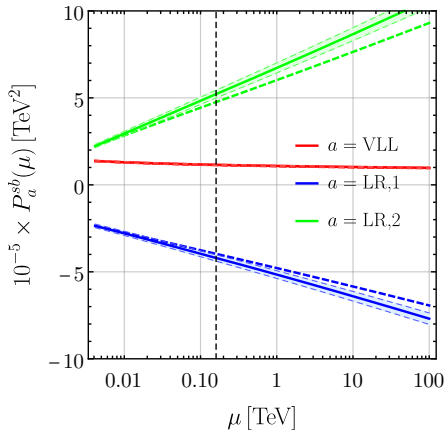
## NP Model

Determine  $C_a$  at  $\mu_{\text{ew}}$

## WET $P_a$ factors

	$P_{VLL}$	$P_{SLL,1}$	$P_{SLL,2}$	$P_{LR,1}$	$P_{LR,2}$
$K^0$	0.102(2)	-4.32(16)	-7.93(37)	-8.55(28)	14.14(82)
$D^0$	0.56(4)	-2.20(11)	-4.04(28)	-4.23(22)	6.18(44)
$B_d$	2.67(10)	-4.99(28)	-9.05(68)	-10.29(54)	12.75(50)
$B_s$	1.15(4)	-2.24(13)	-4.08(26)	-4.20(18)	5.22(21)

# QCD evolution



Dashed: LO

Solid: NLO



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# Ingredients

## Running

One-loop in SMEFT

Alonso/Jenkins/Manohar/Trott: 1312.2014, 1308.2627, 1310.4838

## Matching

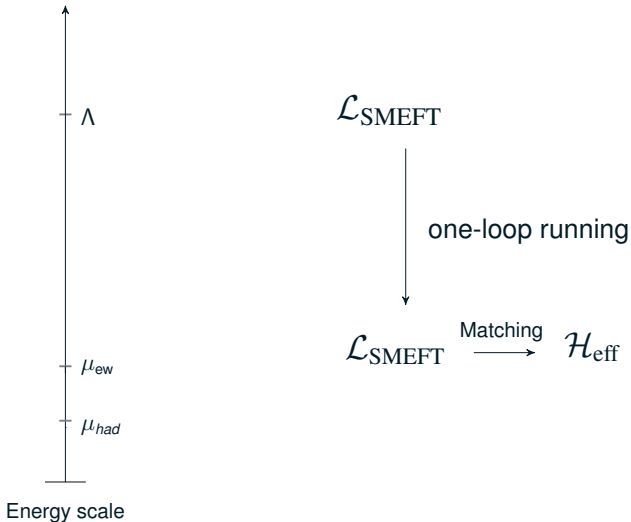
One-loop onto WET

Dekens/Stoffer:1908.05295

## WET Master formula

derived before

# Master formula in SMEFT



# SM Effective Theory (SMEFT)

## Symmetry

$SU(3)_C \times SU(2)_L \times U(1)_Y$ , Poincaré

## Fields

$q, \ell, u, d, e$  + gauge fields + H

## Dimensionality

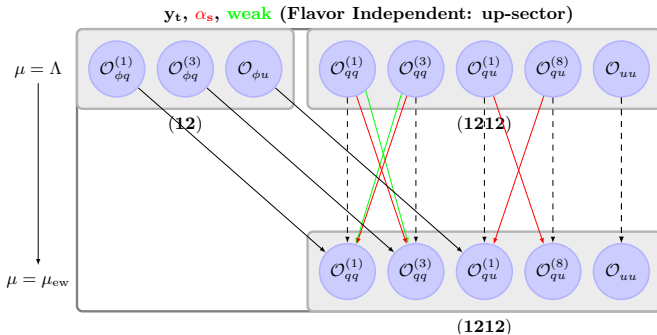
$\dim \geq 4$

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}^{(4)} + \sum_{d \geq 5} \frac{1}{\Lambda^{d-4}} C_i \mathcal{O}_i^d$$

# SMEFT operators

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{\ell}_p \gamma_\mu \ell_r)(\bar{u}_s \gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{\ell}_p \gamma_\mu \ell_r)(\bar{d}_s \gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{\ell}_p \gamma_\mu \ell_r)(\bar{q}_s \gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{\ell}_p \gamma_\mu \tau^I \ell_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$\psi^2 X \phi$		$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$\mathcal{O}_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\phi} W'_{\mu\nu}$	$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		$\psi^2 \phi^2 D$			
$\mathcal{O}_{ledq}$	$(\bar{\ell}_p e_r)(\bar{d}_s d_t^j)$	$\mathcal{O}_{\phi q}^{(1)}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{q}_p \gamma^\mu q_r)$		
$\mathcal{O}_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \epsilon_{jk} (\bar{q}_s^k d_t)$	$\mathcal{O}_{\phi q}^{(3)}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu^I \phi)(\bar{q}_p \tau^I \gamma^\mu q_r)$		
$\mathcal{O}_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \epsilon_{jk} (\bar{q}_s^k T^A d_t)$	$\mathcal{O}_{\phi u}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{u}_p \gamma^\mu u_r)$		
$\mathcal{O}_{lequ}^{(1)}$	$(\bar{\ell}_p^j e_r) \epsilon_{jk} (\bar{q}_s^k u_t)$	$\mathcal{O}_{\phi d}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{d}_p \gamma^\mu d_r)$		

# SMEFT running



A Python package, which includes

### **SMEFT running**

Complete 1-loop RGEs

Alonso/Jenkins/Manohar/Trott: 1312.2014, 1308.2627, 1310.4838

### **Matching**

Complete tree-level matching

JA/Crivellin/Fael/Greub:1512.02830  
Jenkins/Manohar/Stoffer:1709.04486

Complete one-loop matching

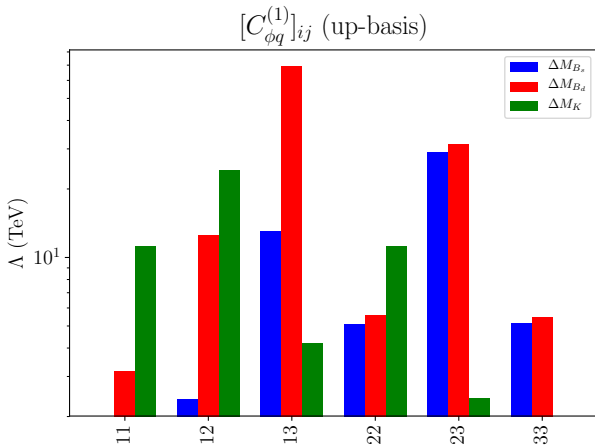
Dekens/Stoffer:1908.05295

### **WET running**

Complete 1-loop running

JA/Fael/Greub/Virto:1704.06639  
Jenkins/Manohar/Stoffer:1711.05270

# SMEFT bounds



$$\mathcal{O}_{\phi q}^{(1)} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{q}_p \gamma^\mu q_r)$$



# Flavour basis

## Above EW scale

$M_u$  diagonal  $\rightarrow$  up-basis

or

$M_d$  diagonal  $\rightarrow$  down-basis

## Broken through RGEs

Off-diagonal entries in  $M_{u,d}$  generated

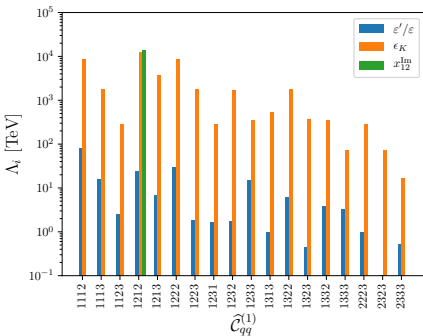
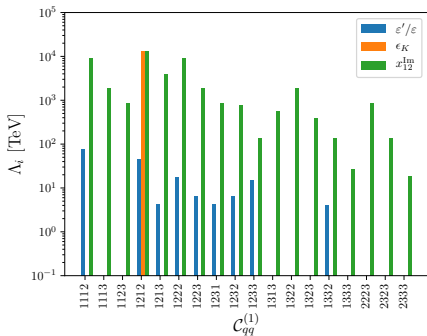
## Back-rotation

Flavour violation through WCs

JA/Kumar: 2005.12283

# $D^0 - \bar{D}^0$ vs $K^0 - \bar{K}^0$

JA/Bobeth/Buras/Straub: 1808.00466



$$\mathcal{O}_{qq}^{(1)} = (\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$$

$$[\hat{C}_{qq}^{(1)}]_{1212} = V_{ui} V_{cj}^* V_{uk} V_{cl}^* [C_{qq}^{(1)}]_{ijkl}$$

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# Summary

## Master formula in WET

2loop QCD running, MEs

## Master formula in SMEFT

1loop SMEFT running, 1loop SMEFT-WET matching

## Flavour basis

Up- vs down-basis