ε'/ε in and beyond the Standard Model

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arXiv:1807.01709, 1807.02520, 1808.00466

CKM 2018

19.09.2018

Outline

1. Motivation and overview
2. Short-distance and long-distance effects
3. Master formula for BSM effects
4. ε'/ε and SMEFT

Motivation

$K \to \pi\pi$

ε' : direct CP violation in $K_L \to \pi\pi$

ε : indirect CP violation in $K_L \to \pi\pi$

Measurement — hep-ex/0208009, hep-ex/0208007

NA48 and KTeV: $(\varepsilon'/\varepsilon)_{\text{exp}} = (16.6 \pm 2.3) \times 10^{-4}$

SM prediction

Lattice: $(1.4 \pm 6.9) \times 10^{-4}$	RBC-UKQCD: 1502.00263, 1505.07863
$(1.9 \pm 4.5) \times 10^{-4}$	Buras/Gorbahn/Jamin/Jäger:1507.06345
$(1.1 \pm 5.1) \times 10^{-4}$	Kitahara/Nierste/Tremper: 1607.06727
DQCD: $\leq (6 \pm 2.4) \times 10^{-4}$	Buras/Gérard 1507.06326
χPT: $(15 \pm 7) \times 10^{-4}$	Gisbert/Pich 1712.06147

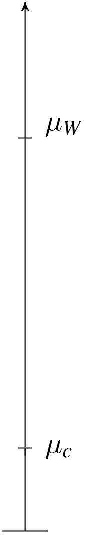
Observable

$$\frac{\varepsilon'}{\varepsilon} = -\frac{\omega}{\sqrt{2}|\varepsilon_K|}\left[\frac{\mathrm{ImA}_0}{\mathrm{ReA}_0} - \frac{\mathrm{ImA}_2}{\mathrm{ReA}_2}\right]$$

with

$$\omega = \frac{\mathrm{ReA}_2}{\mathrm{ReA}_0},\ \varepsilon_K = \text{Kaon mix par},\ A_i = \text{Isospin amplitudes}$$

EFT approach



Energy scale

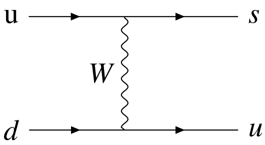
$$\mathcal{L}_{SM} + \mathcal{L}_{BSM}$$

$\downarrow$ Matching

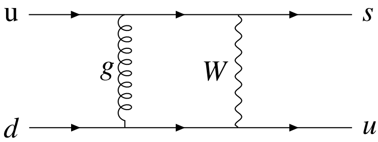
$$\mathcal{H}_{\text{eff}} = -\sum_i C_i O_i$$

$$\Rightarrow A_I = -\sum_i C_i \langle (\pi\pi)_I | O_i | K \rangle$$

SD SM: Current-current operators



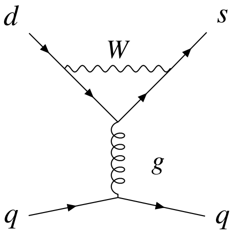
$$\longrightarrow \qquad Q_2 = (\bar{s}u)_{V-A}\,(\bar{u}d)_{V-A}$$



$$\longrightarrow \qquad Q_1 = (\bar{s}_\alpha u_\beta)_{V-A}\,(\bar{u}_\beta d_\alpha)_{V-A}$$

$$V \pm A = \gamma^\mu(1 \pm \gamma_5)$$

SD SM: QCD- and EW-penguins



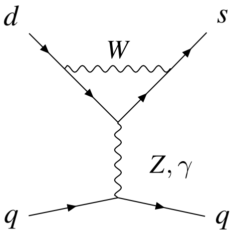
$\longrightarrow$

$$Q_3 = (\bar{s}d)_{V-A} \sum_{q=u,d,s} (\bar{q}q)_{V-A}$$

$$Q_4 = (\bar{s}_\alpha d_\beta)_{V-A} \sum_{q=u,d,s} (\bar{q}_\beta q_\alpha)_{V-A}$$

$$Q_5 = (\bar{s}d)_{V-A} \sum_{q=u,d,s} (\bar{q}q)_{V+A}$$

$$Q_6 = (\bar{s}_\alpha d_\beta)_{V-A} \sum_{q=u,d,s} (\bar{q}_\beta q_\alpha)_{V+A}$$



$\longrightarrow$

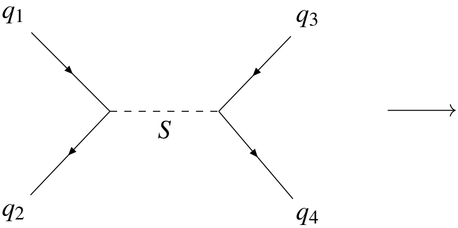
$$Q_7 = \frac{3}{2}(\bar{s}d)_{V-A} \sum_{q=u,d,s} e_q(\bar{q}q)_{V-A}$$

$$Q_8 = \frac{3}{2}(\bar{s}_\alpha d_\beta)_{V-A} \sum_{q=u,d,s} e_q(\bar{q}_\beta q_\alpha)_{V-A}$$

$$Q_9 = \frac{3}{2}(\bar{s}d)_{V-A} \sum_{q=u,d,s} e_q(\bar{q}q)_{V+A}$$

$$Q_{10} = \frac{3}{2}(\bar{s}_\alpha d_\beta)_{V-A} \sum_{q=u,d,s} e_q(\bar{q}_\beta q_\alpha)_{V+A}$$

SD BSM: Scalar exchange



$$O^{SLL}_{sdqq} = (\bar{s} P_L d)\,(\bar{q} P_L q)$$
$$O^{SLR}_{sdqq} = (\bar{s} P_L d)\,(\bar{q} P_R q)$$
$$O^{TLL}_{sdqq} = (\bar{s} \sigma_{\mu\nu} P_L d)\,(\bar{q} \sigma^{\mu\nu} P_L q)$$
$$\widetilde{O}^{SLL}_{sdqq} = (\bar{s}_\alpha P_L d_\beta)\,(\bar{q}_\beta P_L q_\alpha)$$
$$\widetilde{O}^{SLR}_{sdqq} = (\bar{s}_\alpha P_L d_\beta)\,(\bar{q}_\beta P_R q_\alpha)$$
$$\widetilde{O}^{TLL}_{sdqq} = (\bar{s}_\alpha \sigma_{\mu\nu} P_L d_\beta)\,(\bar{q}_\beta \sigma^{\mu\nu} P_L q_\alpha)$$

Number of operators

SM

$Q_1 - Q_{10}$ and Fierz rel. $\longrightarrow$ 7

BSM

$P_A \otimes P_B, \ \sigma_{\mu\nu} P_A \otimes \sigma^{\mu\nu} P_A$ $\longrightarrow$ 13

$$\mathcal{H}_{\text{eff}} = -\sum_{i=1}^{7} C_i Q_i - \sum_{j=1}^{13} C_j O_j^{\text{BSM}}$$

LD: Dual QCD

Large N_c limit

Witten, t'Hooft: QCD = Theory of free mesons

Dual QCD Approach

Bardeen Buras Gérard: Applied to weak decays from 1986-now

Bardeen/Buras/Gerard: 1401.1385

Meson representation

Quark currents in terms of lightest mesons

Meson evolution

Non-factorizable $1/N_c$ LD contributions

LD: SM

Hierarchy

Largest MEs: $\langle Q_6 \rangle_0 \sim B_6^{(1/2)}, \quad \langle Q_8 \rangle_2 \sim B_8^{(3/2)}$

Hierarchy: $B_6^{(1/2)} < B_8^{(3/2)} < 1$ Buras/Gérard: 1507.06326

Upper bounds

$B_6^{(1/2)}(m_c) \leq 0.6$

$B_8^{(3/2)}(m_c) = 0.8 \pm 0.1$ Buras/Gérard: 1507.06326

FSI

Negligible for ε'/ε Bardeen/Buras/Gérard: 1401.1385

LD: BSM

JA/Buras/Gérard: 1807.01709

First computation

In DQCD approach, no lattice results available

Basis

Results given in DQCD and SD basis

RGEs

Complete derivation of meson evolution

LD: BSM

Class A:

$$A = (\bar{s}\gamma^\mu P_L d)[\bar{d}\gamma_\mu P_L d] - (\bar{s}\gamma^\mu P_L d)[\bar{s}\gamma_\mu P_L s]\,,$$

Class B:

$$B_1 = (\bar{s}P_R d)[\bar{u}P_L u]\,, \qquad B_2 = (\bar{s}P_R d)[\bar{d}P_L d] - (\bar{s}P_R s)[\bar{s}P_L d]\,,$$

Class C:

$$C_1 = (\bar{s}\gamma^\mu P_L u)[\bar{u}\gamma_\mu P_R d]\,, \quad C_2 = (\bar{s}\gamma^\mu P_L d)[\bar{d}\gamma_\mu P_R d] - (\bar{s}\gamma^\mu P_L d)[\bar{s}\gamma_\mu P_R s]\,,$$

Class D:

$$D_1 = (\bar{s}P_L u)[\bar{u}P_L d]\,, \qquad D_2 = (\bar{s}P_L d)[\bar{u}P_L u]\,,$$

$$D_3 = (\bar{s}P_L d)[\bar{d}P_L d]\,, \qquad D_4 = (\bar{s}P_L d)[\bar{s}P_L s]\,,$$

$$D_1^* = -(\bar{s}\sigma^{\mu\nu}P_L u)[\bar{u}\sigma_{\mu\nu}P_L d]\,, \qquad D_2^* = -(\bar{s}\sigma^{\mu\nu}P_L d)[\bar{u}\sigma_{\mu\nu}P_L u]\,,$$

$$D_3^* = -(\bar{s}\sigma^{\mu\nu}P_L d)[\bar{d}\sigma_{\mu\nu}P_L d]\,, \qquad D_4^* = -(\bar{s}\sigma^{\mu\nu}P_L d)[\bar{s}\sigma_{\mu\nu}P_L s]\,.$$

DQCD ME results

Class A

rather small $\langle A \rangle_I \sim (m_K^2 - m_\pi^2)$

Class B

enhanced $\langle B_{1,2} \rangle_I \sim r^2 = 2m_K^2/(m_s + m_d)$

Class C

rather small $\langle C_{1,2} \rangle_I \sim (m_K^2 - m_\pi^2)$

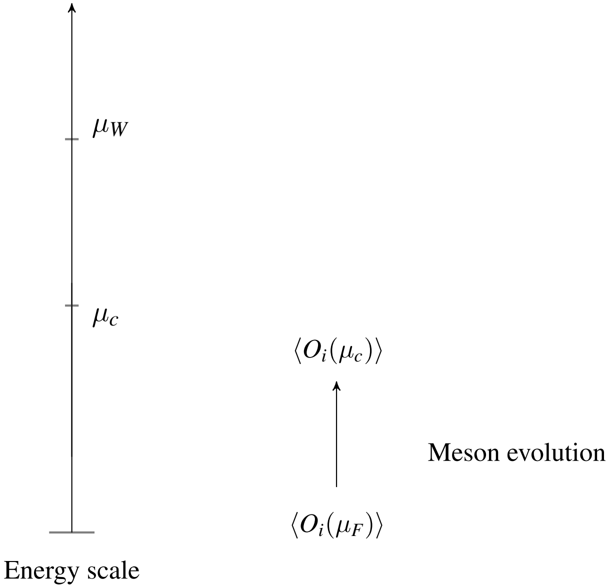
Class D

enhanced $\langle D_{1,2,3} \rangle_I \sim r^2$

zero $\langle D_4 \rangle_I = 0$

$\langle D^*_{1,2,3,4} \rangle_I = 0$

Running



μ_W
μ_c
$\langle O_i(\mu_c)\rangle$
Meson evolution
$\langle O_i(\mu_F)\rangle$
Energy scale

BSM MEs at μ_c

In SMEFT:

$I=0$	A	B_2	C_2	D_1	D_2	D_1^*	D_2^*
	0.001	0.070	-0.015	-0.044	-0.044	-0.213	-0.214

$I=2$	A	B_2	C_2	D_1	D_2	D_1^*	D_2^*
	-0.001	0.050	-0.006	-0.031	-0.031	-0.151	-0.151

Without SMEFT:

$I=0$	B_1	C_1	D_3	D_4	D_3^*	D_4^*
	0.141	-0.030	-0.088	0	-0.298	0

$I=2$	B_1	C_1	D_3	D_4	D_3^*	D_4^*
	-0.050	0.006	0.031	0	0.105	0

BSM ME computation summary

BSM Matrix Elements

Chiral enhancement for scalars and tensors

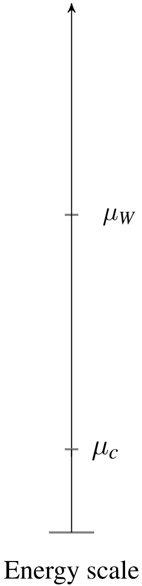
Operator mixing

Tensor operators induced through LD meson evolution from scalar operators

RGE evolution

Good agreement between meson and SD evolution

ε'/ε beyond the SM



NP Model

↓ Matching

$$\mathcal{H}^{N_f=5} = -C_j(\mu_W)O_j$$

↑ RGE running

$$\mathcal{H}^{N_f=3} = -C_i(\mu_c)O_i$$

Master formula

JA/Bobeth/Buras/Gérard/Straub:1807.02520

$$\left(\frac{\varepsilon'}{\varepsilon}\right)_{\text{NP}} = \sum_i P_i(\mu_W)\,\text{Im}[C_i(\mu_W) - C_i'(\mu_W)]$$

with

$$P_i(\mu_W) = \sum_j \sum_{I=0,2} p_{ij}^{(I)}(\mu_W, \mu_c)\,\left[\frac{\langle O_j(\mu_c)\rangle_I}{\text{GeV}^3}\right]$$

$$p_{ij}^{(I)}(\mu_W, \mu_c) = \text{Evolution from } \mu_c \text{ to } \mu_W$$

$$\langle O_j(\mu_c)\rangle_I = \text{Hadronic MEs}$$

$P_i(\mu_W)$: SM operators

class	O_i	P_i	$\frac{\Lambda}{\text{TeV}}$	SMEFT
I	$O^u_{VLR} = (\bar{s}^i\gamma_\mu P_L d^i)(\bar{u}^j\gamma^\mu P_R u^j)$	-125.8	354	✓
	$\widetilde{O}^u_{VLR} = (\bar{s}^i\gamma_\mu P_L d^j)(\bar{u}^j\gamma^\mu P_R u^i)$	-435.5	659	✓
	$O^d_{VLR} = (\bar{s}^i\gamma_\mu P_L d^i)(\bar{d}^j\gamma^\mu P_R d^j)$	122.9	350	✓
	$O^d_{SLR} = (\bar{s}^i P_L d^i)(\bar{d}^j P_R d^j)$	-214.4	462	✓
	$O^s_{SLR} = (\bar{s}^i P_L d^i)(\bar{s}^j P_R s^j)$	-0.04	6	✓
	$O^c_{VLL} = (\bar{s}^i\gamma_\mu P_L d^i)(\bar{c}^j\gamma^\mu P_L c^j)$	0.7	25	✓
	$\widetilde{O}^b_{VLR} = (\bar{s}^i\gamma_\mu P_L d^j)(\bar{b}^j\gamma^\mu P_R b^i)$	-0.1	8	✓

$P_i(\mu_W)$: BSM operators

class	O_i	P_i	$\frac{\Lambda}{\text{TeV}}$	SMEFT
II	$O^u_{SLL} = (\bar{s}^i P_L d^i)(\bar{u}^j P_L u^j)$	-74.1	272	✓
	$O^u_{TLL} = (\bar{s}^i \sigma_{\mu\nu} P_L d^i)(\bar{u}^j \sigma^{\mu\nu} P_L u^j)$	161.8	402	✓
	$\widetilde{O}^u_{SLL} = (\bar{s}^i P_L d^j)(\bar{u}^j P_L u^i)$	15.6	124	✓
	$\widetilde{O}^u_{TLL} = (\bar{s}^i \sigma_{\mu\nu} P_L d^j)(\bar{u}^j \sigma^{\mu\nu} P_L u^i)$	508.6	713	✓
III	$O^d_{SLL} = (\bar{s}^i P_L d^i)(\bar{d}^j P_L d^j)$	87.4	295	
	$O^d_{TLL} = (\bar{s}^i \sigma_{\mu\nu} P_L d^i)(\bar{d}^j \sigma^{\mu\nu} P_L d^j)$	-190.9	436	
IV	$O^u_{SLR} = (\bar{s}^i P_L d^i)(\bar{u}^j P_R u^j)$	266.2	515	
	$\widetilde{O}^u_{SLR} = (\bar{s}^i P_L d^j)(\bar{u}^j P_R u^i)$	59.7	244	✓

$P_i(\mu_W)$: Summary

Class I

Large values for $O_V^{u,d}$ due to $\langle O_{7,8}^{\mathrm{SM}} \rangle_2$

Small impact of $O_i^{s,c,b}$ through mixing

Class II and III

Large values for $O_{S,T}^{u,d}$ due to $\langle O_{S,T}^{\mathrm{BSM}} \rangle$

Class IV

Large values for O_{SLR}^{u} due to $\langle O_{7,8}^{\mathrm{SM}} \rangle_2$

SMEFT RGE effects

y_t and gauge mixing

Matching

Tree level at μ_W

Correlations

$\Delta S = 2$, $\Delta C = 1, 2$, Neutron EDM, K$\to \pi\nu\bar{\nu}$

Vector mediator

Z'

$$\mathcal{L} = \left[\lambda_q^{ij}(\bar{q}_i\gamma_\mu q_j) + \lambda_u^{ij}(\bar{u}_i\gamma_\mu u_j) + \lambda_d^{ij}(\bar{d}_i\gamma_\mu d_j)\right] Z'^\mu$$

ε'/ε and ε_K

$\lambda_u^{11} \sim (10\ \text{TeV})^{-1}$

Collider constraints

$pp \to jj$ could exclude such a scenario

Scalar mediator

Φ

$\mathcal{L}$ = -$X_d^{ij}\,\bar{q}_i\,T^A d_j\,\Phi^A - X_u^{ij}\,\bar{q}_i\,T^A u_j\,\tilde{\Phi}^A$ + h.c.

ε_K

$$C_{qd}^{(1),2121} = -\frac{2}{9}\,\frac{X_d^{12*}X_d^{21}}{M_\Phi^2}$$

Neutron EDM

Possible constraints on $C_{quqd}^{(8),ijkl} = \frac{X_u^{ij}X_d^{kl}}{M_\Phi^2}$

Summary

BSM hadronic MEs

First computation

Chiral enhancement for scalars and tensors

Master formula

Simple description of NP effects

Constraint of ε'/ε for model building

ε'/ε and SMEFT

Correlations with other observables

Interesting cases like Z' and scalar

Greetings from A. Buras: $\left(\frac{\varepsilon'}{\varepsilon}\right)^{\text{Buras}}_{\text{SM}} = (5 \pm 2) \times 10^{-4}$