ε'/ε beyond the Standard Model

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Outline

1. Motivation and overview
2. BSM hadronic matrix elements
3. Master formula

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

$\sim$ order of magnitude smaller!

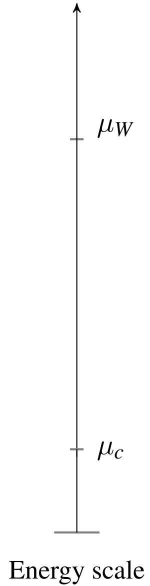
Observable

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

with

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

EFT approach



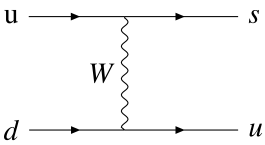
$$\mathcal{L}_{SM}$$

$$\Big\downarrow \ \text{Matching}$$

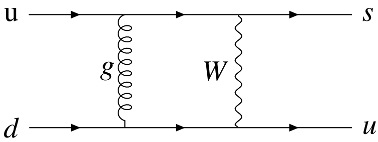
$$\mathcal{H}_{\text{eff}} = -\sum_i C_i O_i$$

$$\Rightarrow A_I = \langle (\pi\pi)_I | \mathcal{H}_{\text{eff}} | K \rangle$$

SM: Current-current operators



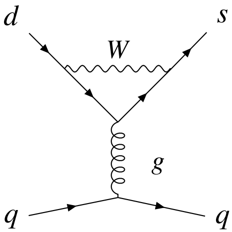
$$\longrightarrow \quad Q_2 = (\bar{s}u)_{V-A}\,(\bar{u}d)_{V-A}$$



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

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

SM: QCD- and QED-penguins



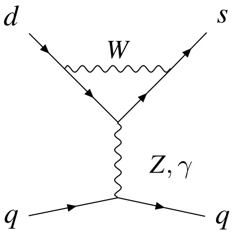
$\longrightarrow$

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

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

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

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



$\longrightarrow$

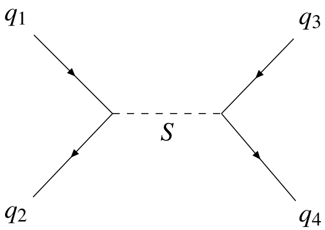
$$Q_7 = \frac{3}{2}(\bar{s}d)_{V-A} \sum_{q=u,d,s} e_q (\bar{q}q)_{V-A}$$

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

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

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

BSM: Scalar exchange



$$\longrightarrow$$

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

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

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

SM: Matrix elements

1505.07863, 1502.00263

i	$\langle Q_i \rangle_0$	$\langle Q_i \rangle_2$
3	−0.0399(652)(118)	0
4	0.267(93)(65)	0
5	−0.179(48)(46)	0
6	−0.339(97)(91)	0
7	0.155(37)(53)	0.1220(52)(71)
8	1.54(6)(41)	0.838(28)(31)
9	−0.197(54)(49)	0.0162(3)(6)

BSM MEs?

BSM hadronic matrix elements

Dual QCD

$N_C \to \infty$: QCD = Theory of free mesons

Meson representation

Quark currents in terms of lightest mesons

Meson evolution

Scale dependence of Matrix elements

DQCD results

ε'/ε Buras, Gérard 1507.0632

$B_6^{(1/2)}$ and $B_8^{(3/2)}$

Chromomagnetic operator O_8 Buras, Gérard 1803.08052

ME for $K \to \pi\pi$ and $K \to \pi$

$K^0 - \bar{K}^0$ Buras, Gérard 1804.02401

MEs for SUSY basis

DQCD basis

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	$\langle D_4 \rangle_I = 0$
	$\langle D^*_{1,2,3,4} \rangle_I = 0$

Meson evolution

Class A:

$$A(\Lambda) = \left[1 - 4\left(\frac{\Lambda}{4\pi F}\right)^2\right] A(0)$$

Class B:

$$B_{1,2}(\Lambda) = \left[1 - \frac{4}{3}\left(\frac{\Lambda}{4\pi F}\right)^2\right] B_{1,2}(0)$$

Class C:

$$C_{1,2}(\Lambda) = C_{1,2}(0) - 16\frac{M^2}{r^2}\left(\frac{\Lambda}{4\pi F}\right)^2 B_{1,2}(0)$$

$\Lambda =$ cut-off, $F =$ pion decay constant, $M^2 \sim (m_K^2 - m_\pi^2)$

Meson evolution

Class D:

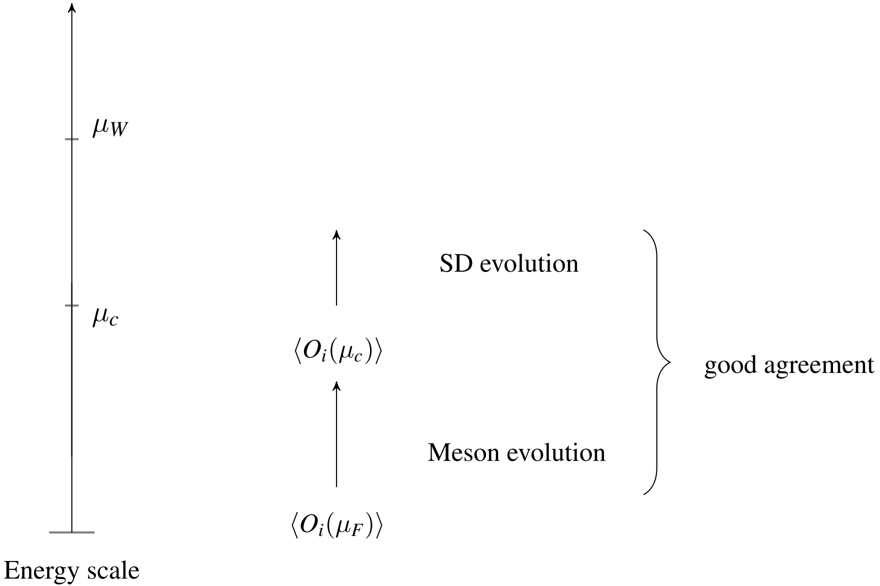
$$D_{1,2}(\Lambda) = \left[1 + \frac{4}{3}\left(\frac{\Lambda}{4\pi F}\right)^2\right] D_{1,2}(0) - 4\left(\frac{\Lambda}{4\pi F}\right)^2 D_{2,1}(0)$$

$$D_{3,4}(\Lambda) = \left[1 - \frac{8}{3}\left(\frac{\Lambda}{4\pi F}\right)^2\right] D_{3,4}(0)$$

$$D^*_{1,2}(\Lambda) = +16\left(\frac{\Lambda}{4\pi F}\right)^2 D_{2,1}(0)\,,$$

$$D^*_{3,4}(\Lambda) = +\frac{32}{3}\left(\frac{\Lambda}{4\pi F}\right)^2 D_{3,4}(0)\,,$$

Running



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

ME computation summary

BSM Matrix Elements

chirally enhanced for scalars and tensors

Vanishing ME

for (sd)(ss) operators

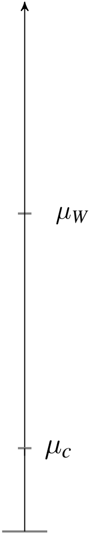
Operator mixing

tensor operators induced through running

RGE evolution

Good agreement between meson and SD evolution

→ details in JA, Buras, Gérard 18'



Energy scale

NP Model

↓ Matching

$$\mathcal{H} = -C_i(\mu_W)O_i$$

↓ RGE running

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

Master formula

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

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_i's can be found in JA, Bobeth, Buras, Gérard, Straub 18'

Numerics

`wilson`: wilson — JA et al. 1804.05033

full 1-loop WET running

`wcxf`: — JA et al. 1712.05298

change into flavio basis

`flavio`:

contribution to ε'/ε computed

Summary

BSM hadronic MEs

First computation

Large MEs

Chiral enhancement for scalars and tensors

Master formula

Constraint of ε'/ε for model building