Dual QCD @ Work

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QCD@Work
Matera, June 2018

Overture

AJB:

Strong Belief in Great Future of Kaon Flavour Physics

The Renaissance of Kaon Flavour Physics

1606.06735

The Revival of Kaon Flavour Physics

1609.05711

Kaon Flavour Physics strikes back

1611.06206

The Return of Kaon Flavour Physics

1805.11096

Present Superstars of K Physics

$$\frac{\varepsilon'}{\varepsilon} = (16.6 \pm 2.3) \cdot 10^{-4}$$

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

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

$$\varepsilon = e^{i\varphi_\varepsilon} (2.23 \pm 0.01) \cdot 10^{-3}$$

$K^0 - \bar{K}^0$ **Mixing**

$(\Delta I = 1/2 \text{ Rule})$

$$\frac{\text{Re}\, A_0}{\text{Re}\, A_2} = 22.35$$

$A_0 = A(K \to (\pi\pi)_{I=0})$

$A_2 = A(K \to (\pi\pi)_{I=2})$

$$K^+ \to \pi^+ \nu\bar{\nu}, \; K_L \to \pi^0 \nu\bar{\nu}$$

ΔM_K

$K_L - K_S$ Mass difference

Effective Hamiltonian and OPE

$$H_{eff} = \sum_i C_i O_i^{SM} + \sum_j C_j^{NP} O_j^{NP}$$

$$C_i = C_i^{SM} + \Delta_i^{NP}$$

Absent in SM

$$A(K \to \pi\pi) = \sum_i \underbrace{C_i(\mu)}_{SD} \underbrace{\langle \pi\pi | O_i^{SM}(\mu) | K \rangle}_{LD} + \sum_j \underbrace{C_j^{NP}(\mu)}_{SD} \underbrace{\langle \pi\pi | O_j^{NP}(\mu) | K \rangle}_{LD}$$

<u>Example:</u>

$$O^{SM} = \left(\bar{s}\gamma_\mu (1-\gamma_5) d\right)\left(\bar{d}\gamma^\mu (1-\gamma_5) d\right)$$

$$O^{NP} = \left(\bar{s}(1-\gamma_5) d\right)\left(\bar{d}(1-\gamma_5) d\right)$$

$\mu \approx 1-3$ GeV

Renormalization scale

Impact of QCD at SD and LD Scales

(K-physics)

SD

Fully under control: NLO + NNLO
AJB: „Climbing NLO and NNLO Summits of Weak Decays“
(1102.5650; last update 2014)
Including BSM

(Munich, Rome + Gorbahn, Brod, Haisch, Jäger, Nierste, Cerda-Sevilla)
(early 1990s)

LD

Lattice QCD (ETM, SWME, RBC-UKQCD, …)

(Numerical sophisticated and demanding calculations lasting many years) (from first principles)

BSM operators only for $K^0-\bar{K}^0$ mixing

Analytic

Dual QCD (Bardeen, AJB, Gérard, 1985 →)
(Much faster than LQCD, very suitable for non-leptonic transitions)
($K^0-\bar{K}^0$ mixing, $K\to\pi\pi$)

SM+ BSM (2018)

Chiral Pertubation Theory (Gasser, Leutwyler, 1980 →)
(Much faster than LQCD, very suitable for leptonic, semi-leptonic decays)
($K_L\to\pi ll$, $K\to ll$, $K\to\pi\nu\bar{\nu}$)

Plan for next 23 min

1. Dual QCD News

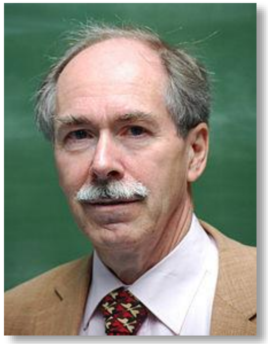
2. ε'/ε strikes back

3. Beyond SM

4. Summary

1. Dual QCD

Large N QCD



Gerard ´t Hooft (1974)

Edward Witten (1979, 1980)

At Large N QCD becomes a theory of weakly interacting mesons

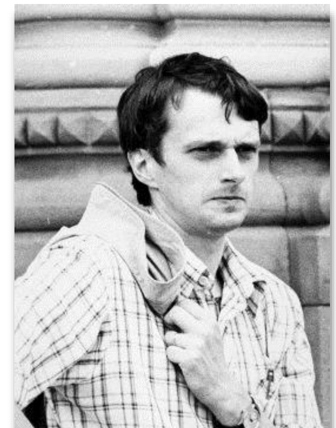
with coupling $\frac{1}{f_\pi^2} \sim \frac{1}{N}$

In the strict Large N limit QCD becomes a free theory of mesons.

Dual QCD Approach for Weak Decays

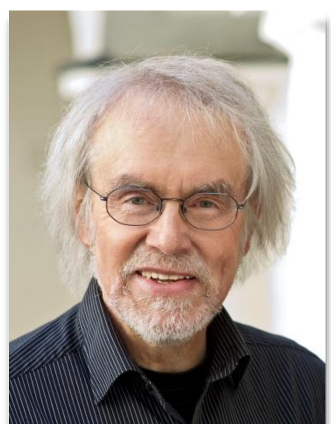
Successful low energy approximation of QCD

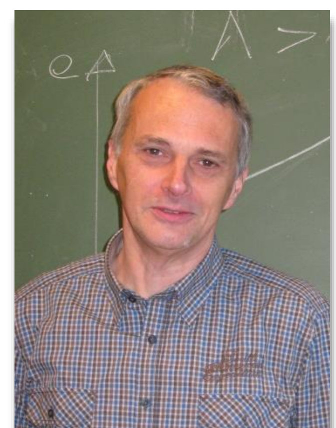
1985



W. Bardeen | AJB | J.-M. Gérard

2014





Basics of Dual QCD

Chivukula, Flynn, Georgi
Bardeen, AJB, Gérard
(1986)

$$L_{tr} = \frac{F^2}{8}\left[\mathrm{Tr}\left(D_\mu U D^\mu U^+\right) + r\,\mathrm{Tr}\left(m U^+ + h.c\right) + 0\left(1/\Lambda_\chi^2\right)\right]$$

$$U = \exp\left[i\sqrt{2}\,\frac{\Pi}{F}\right]$$

$$r(\mu) = \frac{2m_K^2}{m_s(\mu) + m_d(\mu)}$$

$\Pi =$ octet of pseudoscalar mesons

$$F \approx F_\pi \sim 0\left(\frac{1}{\sqrt{N}}\right)$$

Meson representation of

$$\bar{q}_L^b \gamma_\mu q_L^a = i\frac{F^2}{8}\left[\left(\partial_\mu U\right)U^+ + 0\left(\frac{1}{\Lambda_\chi^2}\right)\right]^{ab}$$

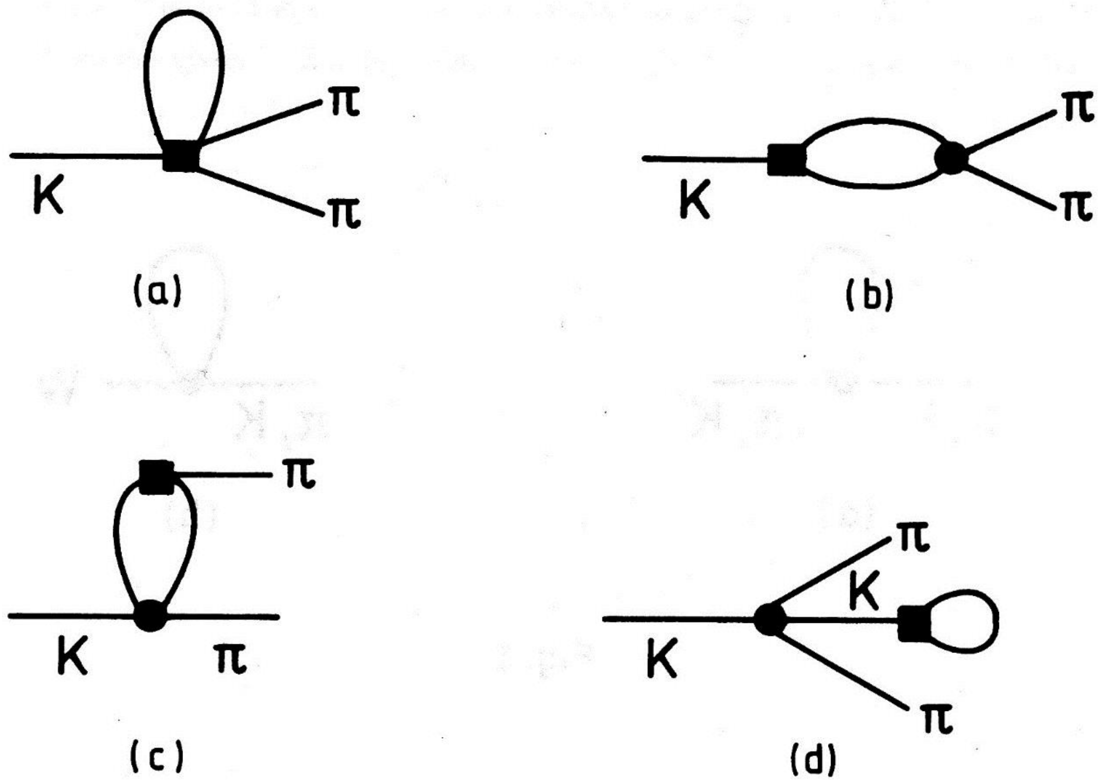
quark-currents

$$\bar{q}_R^b q_L^a = -\frac{F^2}{8} r(\mu)\left[U - \frac{1}{\Lambda_\chi^2}\partial^2 U\right]^{ab}$$

quark-densities

Meson Evolution

Loops with a physical cutt-off Λ : 1/N non-factorizable contributions



■ weak

● strong

Very different philosophy from Chiral PTh

No dimensional regularisation !!!

Basic Structure of DQCD for $K \to \pi\pi$, $K^0 - \bar{K}^0$ mixing

(ε'/ε, ε, $\Delta I = 1/2$ Rule, ΔM_K)

SM and BSM Operators

Reviews: 1401.1385, 1408.4820

Λ_{NP}

SMEFT with SM and BSM Operators

RG Evolution

α_s, α_2, α_1

top Yukawa

EW

QCD + QED with SM and BSM Operators (Quark-Gluon Evolution)

α_s, α_{QED}

1 GeV

Non-Factorizable contributions

Λ_{DQCD} ≈ 0.8 GeV

DQCD: Meson Evolution (1/N)

$0(m_\pi, m_K) \to \Lambda_{DQCD} \approx 0.8$ GeV

SM and BSM operators

m_π, m_K

Factorization Scale

for hadronic matrix elements

($N \to \infty$)

Crucial strong dynamics

Responsible for $\Delta I = 1/2$ Rule, ε'/ε, ε, ΔM_K, $K \to \pi\pi$ in general.

The Main Role of DQCD

1. Efficient approximate method for obtaining results for non-leptonic decays: years, even decades before Lattice QCD.

(1986-2012)

BSM:2018

2. Giving insight in numerical results obtained by Lattice QCD at 2-3 GeV.

Progress in LQCD
↓
(2012 →)

3. The only existing QCD method allowing to study analytically the dominant dynamics between m_K and 1 GeV.

MESON EVOLUTION :

The pattern of operator mixing found to agree with SD mixing. both for SM and BSM operators.

$\Delta I = 1/2$ Rule

$$R = \frac{\text{Re}\, A_0}{\text{Re}\, A_2} \approx 22.4$$

Since 1955

Gell-Mann Pais
$R = \sqrt{2}$ in Fermi-Theory
(No QCD)

1974

Octet Enhancement
(Current-Current Operators)

Altarelli + Maiani
Gaillard + Lee

$R \approx 3$

(Asymptotic Freedom)
SD evolution

1976

QCD Penguins (Shifman et al)
(Fit hadronic matrix elements
at $\mu = 0.3$ GeV $\rightarrow \varepsilon'/\varepsilon \sim 0(10^{-2})$)
(Gilman + Wise)

1986

Dual QCD (BBG)

(Main Dynamics Behind $\Delta I = 1/2$ Rule)

Octet Enhancement including LD part (Meson Evolution)
QCD Penguins at 10%

2014: $R = 16.0 \pm 1.5$

FSI ? (Pich)
New Physics ?
(1404.3824, G')
AJB, De Fazio, Girrbach

2015
(2012)

RBC-UKQCD $R = 31 \pm 11$

Confirmation of Octet Enhancement

$\hat{B}_K$ Parameter for $K^0 - \bar{K}^0$ Mixing, ε_K

1986 Donoghue et al
Pich + Rafael $\hat{B}_K \approx 0.33$ $\hat{B}_K \approx 0.4$ Lattice QCD $\hat{B}_K \approx 1$

1987 BBG $\hat{B}_K = 0.67 \pm 0.07$ $\hat{B}_K = 0.75$ (Large N limit)

2018 BBG $\hat{B}_K = 0.73 \pm 0.02$ Lattice QCD: $\hat{B}_K = 0.766 \pm 0.010$

Gérard: $\hat{B}_K < 0.75$

QCD and Electroweak Penguin Matrix Elements

1986 BBG strict Large N limit $B_6^{1/2} = B_8^{3/2} = 1$ $\left(\mu \approx 0(m_\pi)\right)$

2015 AJB + Gérard
1507.06326

Including 1/N
(meson evolution
for B_6, B_8)

$B_6^{1/2} < B_8^{3/2} < 1$ at $\mu \geq 1\text{GeV}$

More about it later.

2018 Results in DQCD

: BSM hadronic Matrix elements

★ **1.**

Matrix elements of chromomagnetic penguins
AJB + Gérard 1803.08052 (First on-shell $K \to \pi\pi$ calculation to date)

Confirmation of $K \to \pi$ matrix element by ETM collaboration 1712.09824

$B_{CMO} \approx 1/3$

Much smaller than early estimates in chiral quark model

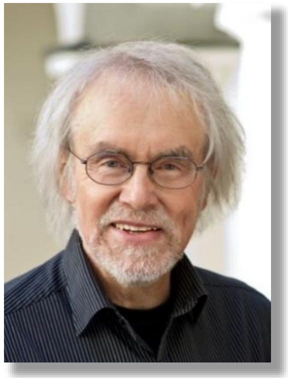
★ **2.**

Explanation of BSM B_i parameters ($K^0 - \bar{K}^0$ Mixing) obtained by Lattice QCD 1804.02401 (AJB + Gérard)

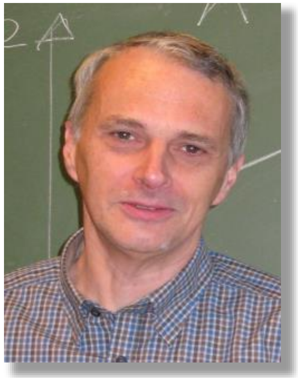
★ **3.**

$K \to \pi\pi$ matrix elements of all BSM 4-quark operators

Jason Aebischer



AJB



J.-M. Gérard

(1807.xxxxx)

Section 2
ε′/ε strikes back

2015 Anatomy of ε′/ε : 1507.06345

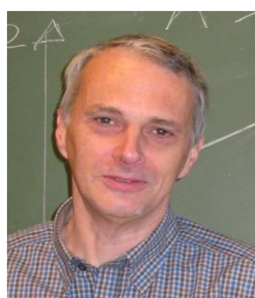
AJB

Martin Gorbahn

Sebastian Jäger

Matthias
Jamin

AJB



Jean-Marc Gérard

Large N news
1507.06326

FSI
1603.05686

Present Status of ε´/ε in the SM

June 2018

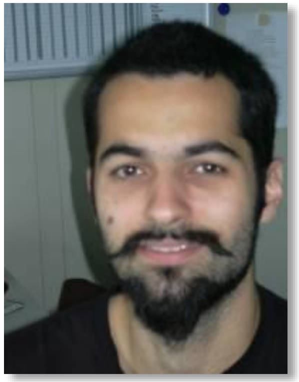
RBC-UKQCD (1505.07863)	$(\varepsilon'/\varepsilon)_{SM} = (1.4 \pm 6.9)\cdot 10^{-4}$	No isospin breaking correction (IB)
AJB, Gorbahn, Jäger Jamin (1507.06345)	$(\varepsilon'/\varepsilon)_{SM} = (1.9 \pm 4.5)\cdot 10^{-4}$	Lattice results + IB
AJB + Gérard (1507.06326)	$(\varepsilon'/\varepsilon)_{SM} < (6.0 \pm 2.4)\cdot 10^{-4}$	Dual QCD bound
Kitahara, Nierste, Tremper (1607.06727)	$(\varepsilon'/\varepsilon)_{SM} = (1.1 \pm 5.1)\cdot 10^{-4}$	Lattice results + IB
Gisbert, Pich (1712.06147)	$(\varepsilon'/\varepsilon)_{SM} = (15 \pm 7)\cdot 10^{-4}$	Chiral Pert. Th.
Experiment (NA48, KTeV)	$(\varepsilon'/\varepsilon)^{exp} = (16.6 \pm 2.3)\cdot 10^{-4}$	

2016 Standard Model Results

Teppei Kitahara

Ulrich Nierste

Paul Tremper



NLO $$\left(\varepsilon'/\varepsilon\right)_{SM} = \left(1 \pm 5\right)\cdot 10^{-4}$$ **1607.06727**

2018

First NNLO Result for $(\varepsilon'/\varepsilon)_{SM}$

New IAS Postdoc

Maria Cerda-Sevilla

Martin Gorbahn

Sebastian Jäger

Ahmet Kokulu

New TUM Postdoc

Four dominant contributions to ε′/ε in the SM

AJB, Jamin, Lautenbacher (1993); AJB, Gorbahn, Jäger, Jamin (2015)

From ReA_0 → −3.6 + 21.4 · $B_6^{(1/2)}$; From ReA_2 → +1.2 − 10.4 · $B_8^{(3/2)}$

$$\mathrm{Re}(\varepsilon'/\varepsilon) = \left[\frac{\mathrm{Im}(V_{td}V_{ts}^{*})}{1.4\cdot 10^{-4}}\right] 10^{-4}\left[-3.6 + 21.4\cdot B_6^{(1/2)} + 1.2 - 10.4\cdot B_8^{(3/2)}\right]$$

(NLO)	(Q_4)	−3.6: (V-A) ⊗ (V-A) QCD Penguins	21.4 · $B_6^{(1/2)}$: (V-A) ⊗ (V+A) QCD Penguins	1.2: (V-A) ⊗ (V-A) EW Penguins	10.4 · $B_8^{(3/2)}$: (V-A) ⊗ (V+A) EW Penguins

Assumes that ReA_0 and ReA_2 (ΔI=1/2 Rule) fully described by SM (includes isospin breaking corrections)

$B_6^{(1/2)} = B_8^{(3/2)} = 1$ in the large N limit

Extracted from ⇩

RBC-UKQCD : $B_6^{(1/2)} = 0.57 \pm 0.19$ $B_8^{(3/2)} = 0.76 \pm 0.05$

Main Actors in ε′/ε in SM

Q_6 – QCD Penguin operator

Q_8 – Electroweak Penguin operator

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

$$Q_8 = (\bar{s}_\alpha d_\beta)_{V-A} \sum_q e_q (\bar{q}_\beta q_\alpha)_{V+A}$$

Why $B_6^{(1/2)} < B_8^{(3/2)} < 1$?

and not $B_6^{(1/2)} > 1$, $B_8^{(3/2)} < 1$ (Pallante, Pich… 2000) FSI

Answer in Large N (Dual QCD) Approach

AJB + Gérard (1507.06326)

Before 2015 it was wrongly assumed that

$$B_6^{(1/2)} = B_8^{(3/2)} = 1 \quad \text{at} \quad \mu \approx 0(1\,\text{GeV})$$

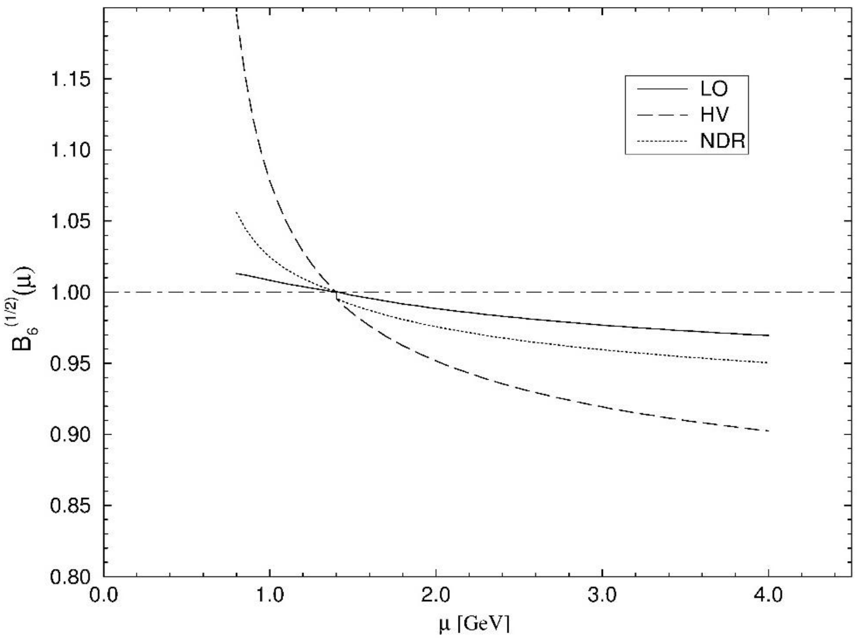
But $B_6^{(1/2)} = B_8^{(3/2)} = 1$ is large N prediction

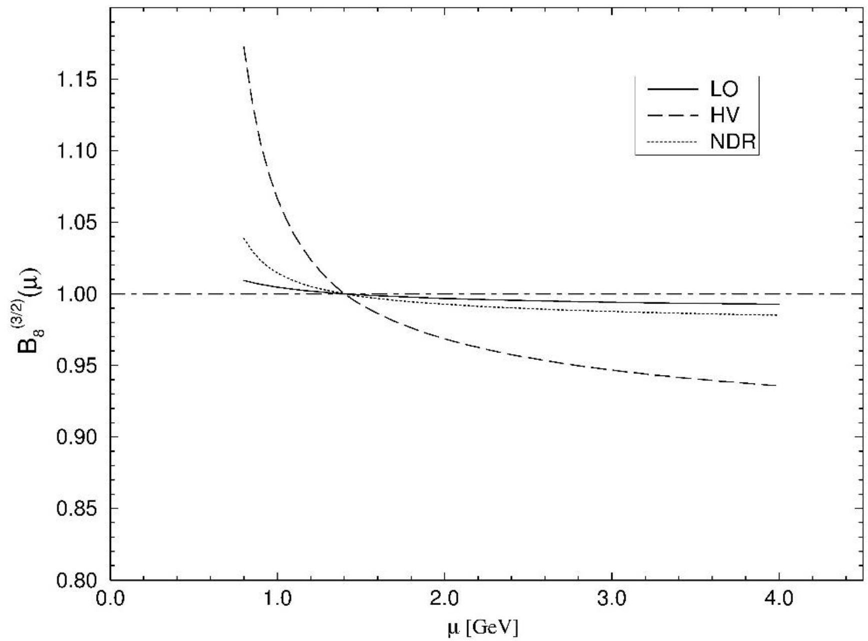
for $\mu = m_\pi$ **not** $\mu = 0(1\,\text{GeV})$

Meson evolution $m_\pi \to \mu = 0(1\,\text{GeV})$ suppresses $B_6^{(1/2)}$ and $B_8^{(3/2)}$ below 1 and $B_6^{(1/2)}$ stronger than $B_8^{(3/2)}$ in accordance with quark evolution for $\mu > 1\,\text{GeV}$

B_6 and B_8 in the Perturbative Regime (1993!)

AJB, Jamin, Lautenbacher, (9303284)



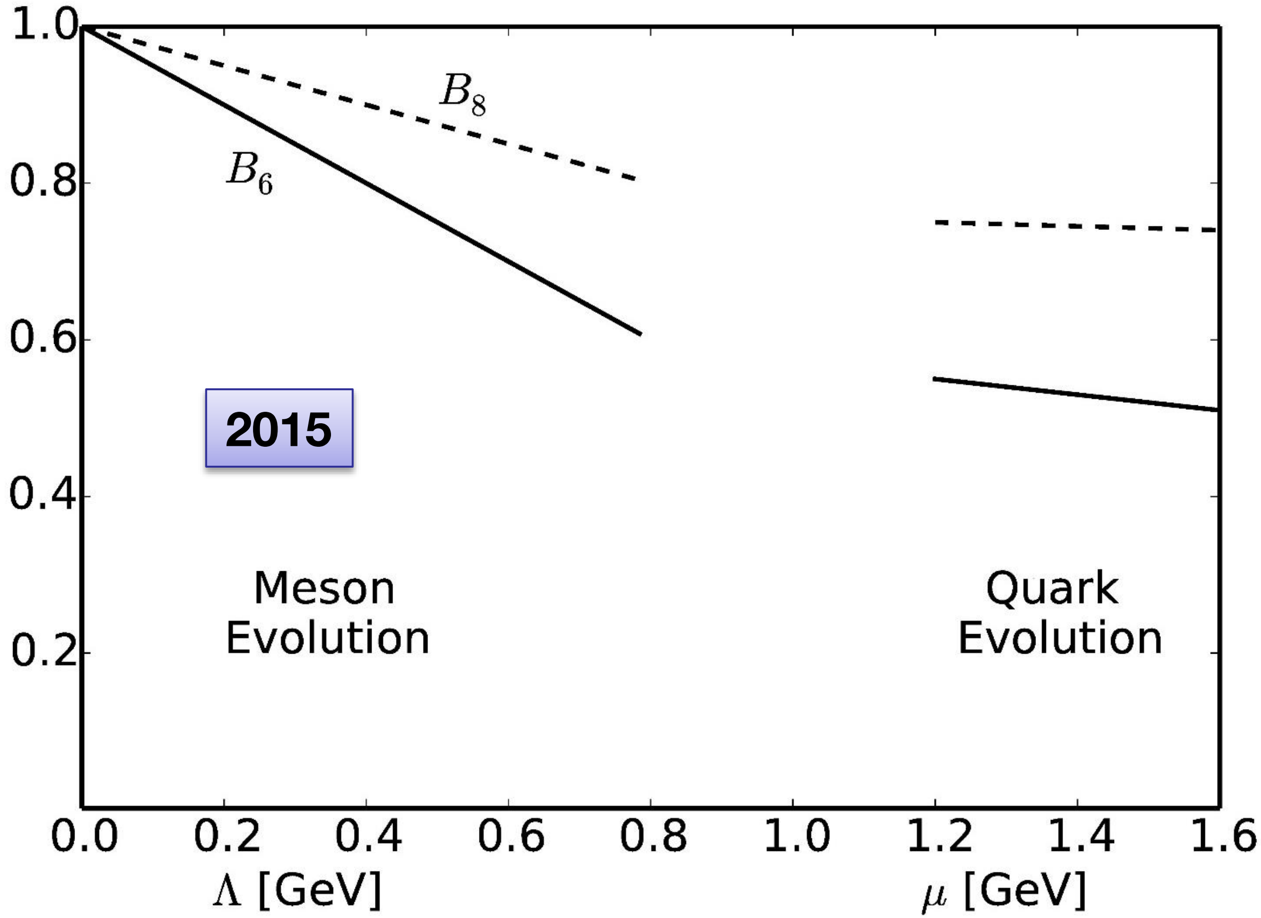


B_6 and B_8 decrease with increasing μ!

Note $B_6 = B_8 = 1$ at $\mu = m_c$ wrong!!

Scale Dependence of B_6 and B_8

AjB+ Gerard (1507.06326)



FSI in $K \to \pi\pi$

AJB, Gérard 1603.05686

Relevant for $\Delta I=1/2$ Rule
(in agreement with Pallante, Pich,…)

Less important for ε'/ε
(in variance with Pallante, Pich,…)

As the existence of Meson Evolution has been questioned over last 30 years by some Chiral Experts by some Lattice Experts

Let me demonstrate its existence by considering BSM operators in **($K^0 - \bar{K}^0$ Mixing)**

Very good test !

Important : The controversal issue of Final State interactions is absent here !!!

and four parameters to our disposal B_2, B_3, B_4, B_5

$\Delta S = 2$ Operators in SUSY Basis

SM $$0_1 = \left(\bar{s}^{\alpha}\gamma_{\mu}P_L d^{\alpha}\right)\left(\bar{s}^{\beta}\gamma_{\mu}P_L d^{\beta}\right) \to B_1$$

BSM
$$\begin{cases} 0_2 = \left(\bar{s}^{\alpha}P_L d^{\alpha}\right)\left(\bar{s}^{\beta}P_L d^{\beta}\right) \to B_2 \\ 0_3 = \left(\bar{s}^{\alpha}P_L d^{\beta}\right)\left(\bar{s}^{\beta}P_L d^{\alpha}\right) \to B_3 \\ 0_4 = \left(\bar{s}^{\alpha}P_L d^{\alpha}\right)\left(\bar{s}^{\beta}P_R d^{\beta}\right) \to B_4 \\ 0_5 = \left(\bar{s}^{\alpha}P_L d^{\beta}\right)\left(\bar{s}^{\beta}P_R d^{\alpha}\right) \to B_5 \end{cases}$$

$$\langle 0_i(\mu)\rangle \approx \frac{B_i(\mu)}{m_s^2(\mu)}$$

$$B_1(0) = 0.75 \Rightarrow B_1(0.7\ \text{GeV}) = 0.62 \quad | \quad | \quad 0.61 = B_1(1\ \text{GeV}) \Leftarrow 0.53 = B_1(3\ \text{GeV})$$

$N \to \infty$

Meson Evolution

Gap filled vector mesons (2014)

Quark-Gluon Evolution

LQCD

DQCD : Explaining Values for B_2, B_3, B_4, B_5 from Lattice QCD

(AJB + Gérard, 1804.02401) (ETM15, SWME, RBC-QCD)

μ	B_2	B_3	B_4	B_5	$K^0 - \bar{K}^0$ mixing
3 GeV	0.49	0.77	0.90	0.65	AJB Lattice Average (± 5%)
Quark Gluon Evolution ⇩ 1 GeV					$B_2=B_3=B_4=B_5=1$ Vacuum insertion
gap : Vector mesons					
(0.70) GeV Meson Evolution ⇧					Meson Evolution in the chiral limit
Factorization Scale ≈ 0					← $N \to \infty$

DQCD : Explaining Values for B_2, B_3, B_4, B_5 from Lattice QCD

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(gap)					gap : Vector mesons
(0.70) GeV Meson Evolution ⇧					Meson Evolution in the chiral limit
Factorization Scale ≈ 0	1.2	3.0	1.0	0.23	⟵ $N \to \infty$

DQCD : Explaining Values for B_2, B_3, B_4, B_5 from Lattice QCD

(AJB + Gérard, 1804.02401) (ETM15, SWME, RBC-QCD)

μ	B_2	B_3	B_4	B_5	$K^0 - \bar{K}^0$ mixing
3 GeV	0.49	0.77	0.90	0.65	AJB Lattice Average (± 5%)
Quark Gluon Evolution ↓					
1 GeV	0.62	1.10	0.90	0.45	$B_2=B_3=B_4=B_5=1$ Vacuum insertion
					} gap : Vector mesons
(0.70) GeV					
Meson Evolution ↑					Meson Evolution in the chiral limit
Factorization Scale ≈ 0	1.2	3.0	1.0	0.23	← $N \to \infty$

DQCD : Explaining Values for B_2, B_3, B_4, B_5 from Lattice QCD

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3 GeV	0.49	0.77	0.90	0.65	AJB Lattice Average (± 5%)
Quark Gluon Evolution ⇩					B_2=B_3=B_4=B_5=1 Vacuum insertion
1 GeV	0.62	1.10	0.90	0.45	
					} gap : Vector mesons
(0.70) GeV	0.79	0.96	0.83	0.30	
Meson Evolution ⇧					Meson Evolution in the chiral limit
Factorization Scale ≈ 0	1.2	3.0	1.0	0.23	← $N \to \infty$

BSM

$K^0 - \bar{K}^0$ Mixing

Meson Evolution $B_i(\Lambda)$ in the Chiral Limit

$\Lambda \approx 0.65 \pm 0.05$ GeV

(Pattern consistent with quark-gluon evolution)

$$B_2(\Lambda) = 1.2\left[1 - \frac{8}{3}\frac{\Lambda^2}{(4\pi F_K)^2}\right]$$ (strong suppression)

$$B_3(\Lambda) = 3.0\left[1 - \frac{16}{3}\frac{\Lambda^2}{(4\pi F_K)^2}\right]$$ (even stronger suppression)

$$B_4(\Lambda) = 1.0\left[1 - \frac{4}{3}\frac{\Lambda^2}{(4\pi F_K)^2}\right]$$ (moderate suppression)

$$B_5(\Lambda) = 0.23\left[1 + 4\frac{\Lambda^2}{(4\pi F_K)^2}\right]$$ (strong enhancement)

$\Lambda =$ Cut-off, physical — separates the non-factorizable meson evolution from the quark-gluon evolution.

Important !

$$\langle 0_i(\mu)\rangle \approx \frac{B_i(\mu)}{m_s^2(\mu)}$$

Similar to B_6 and B_8

No FSI

Meson evolution exhibited much clearer than in $K \to \pi\pi$

This insight in B_i values from Lattice QCD has been obtained from DQCD without ANY input beyond $\Lambda \approx m_\rho$ (Only pseudoscalar masses, F_K and α_{QCD} involved)

No low-energy constants L_i etc. familiar from Chiral Pert. Th.

Question : Can this insight be obtained from Chiral Pert. Th. ?

⇨ Support for ε'/ε anomaly from DQCD

Summary on ε´/ε in the SM

ε´/ε anomaly could turn out to be the largest anomaly in flavour physics !

$$(\varepsilon'/\varepsilon) = (\varepsilon'/\varepsilon)_{SM} + (\varepsilon'/\varepsilon)_{NP}$$

$$(\varepsilon'/\varepsilon)_{NP} = \kappa_{\varepsilon'} \cdot 10^{-3}$$

$$0.5 < \kappa_{\varepsilon'} < 1.5$$

$$(\varepsilon'/\varepsilon)_{SM} < (6.0 \pm 2.4) \cdot 10^{-4}$$

Dual QCD

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

Will new RBC-QCD results support this claim?

Section 3

Beyond SM

Effective Hamiltonian and OPE

$$H_{eff} = \sum_i C_i O_i^{SM} + \sum_j C_j^{NP} O_j^{NP}$$

$$C_i = C_i^{SM} + \Delta_i^{NP}$$

Absent in SM

$$A(K \to \pi\pi) = \sum_i \underbrace{C_i(\mu)}_{SD} \underbrace{\langle \pi\pi | O_i^{SM}(\mu) | K \rangle}_{LD} + \sum_j \underbrace{C_j^{NP}(\mu)}_{SD} \underbrace{\langle \pi\pi | O_j^{NP}(\mu) | K \rangle}_{LD}$$

Example:

$$O^{SM} = \left(\bar{s}\gamma_\mu(1-\gamma_5)d\right)\left(\bar{d}\gamma^\mu(1-\gamma_5)d\right)$$

$$O^{NP} = \left(\bar{s}(1-\gamma_5)d\right)\left(\bar{d}(1-\gamma_5)d\right)$$

$$\mu \approx 1-3\ \text{GeV}$$

Renormalization scale

All Dimension 6 Operators beyond SM

(lineary independent)

SM : 7

BSM : 7´ obtained from SM through L ↔ R (primed operators)

QCD ∗ QED invariant

13 operators unrelated to SM operators

13´ primed operators L ↔ R

33 new operators with 33 new Wilson coefficients calculable in a given NP model

SMEFT

Invariance under SM gauge group

(13 + 13´) → (7 + 7´) operators unrelated to SM

→ 21 new Wilson coefficients

How many new hadronic matrix elements have to be calculated (contributing to A_0 and A_2)?

QCD ∗ QED invariant

In principle : 2 x 33 = **66** matrix elements

But in reality : 2 x 13 = **26**

(40 matrix elements obtained from L ↔ R by just reversing the sign)

SMEFT : 2 x 7 = **14**

Message : More work for Lattice QCD (26 or 14)

No more work for DQCD :

Aebischer, AJB, Gérard (1807.xxxxx)

all 26 matrix elements recently calculated including meson evolution in the chiral limit

Magnificant Seven

Allowed by SMEFT

$$Q_1^{\mathrm{VLL},d-s} = (\bar{s}^\alpha \gamma_\mu P_L d^\alpha)\left[(\bar{d}^\beta \gamma^\mu P_L d^\beta) - (\bar{s}^\beta \gamma^\mu P_L s^\beta)\right],$$

★ $$Q_1^{\mathrm{VLR},d-s} = (\bar{s}^\alpha \gamma_\mu P_L d^\beta)\left[(\bar{d}^\beta \gamma^\mu P_R d^\alpha) - (\bar{s}^\beta \gamma^\mu P_R s^\alpha)\right],$$

$$Q_2^{\mathrm{VLR},d-s} = (\bar{s}^\alpha \gamma_\mu P_L d^\alpha)\left[(\bar{d}^\beta \gamma^\mu P_R d^\beta) - (\bar{s}^\beta \gamma^\mu P_R s^\beta)\right].$$

$$Q_1^{\mathrm{SLL},u} = (\bar{s}^\alpha P_L d^\beta)(\bar{u}^\beta P_L u^\alpha),$$

$$Q_2^{\mathrm{SLL},u} = (\bar{s}^\alpha P_L d^\alpha)(\bar{u}^\beta P_L u^\beta),$$

★ $$Q_3^{\mathrm{SLL},u} = -(\bar{s}^\alpha \sigma_{\mu\nu} P_L d^\beta)(\bar{u}^\beta \sigma^{\mu\nu} P_L u^\alpha),$$

★ $$Q_4^{\mathrm{SLL},u} = -(\bar{s}^\alpha \sigma_{\mu\nu} P_L d^\alpha)(\bar{u}^\beta \sigma^{\mu\nu} P_L u^\beta),$$

Forbidden by SMEFT but allowed by QCD∗QED

$$Q_1^{\mathrm{SLR},u} = (\bar{s}^\alpha P_L d^\beta)\,(\bar{u}^\beta P_R\, u^\alpha),$$
$$Q_2^{\mathrm{SLR},u} = (\bar{s}^\alpha P_L d^\alpha)\,(\bar{u}^\beta P_R\, u^\beta)$$

$$Q_1^{\mathrm{SLL},d} = (\bar{s}^\alpha P_L d^\beta)\,(\bar{d}^\beta P_L\, d^\alpha),$$
$$Q_2^{\mathrm{SLL},d} = (\bar{s}^\alpha P_L d^\alpha)\,(\bar{d}^\beta P_L\, d^\beta).$$

$$Q_1^{\mathrm{SLL},s} = (\bar{s}^\alpha P_L d^\beta)\,(\bar{s}^\beta P_L\, s^\alpha),$$
$$Q_2^{\mathrm{SLL},s} = (\bar{s}^\alpha P_L d^\alpha)\,(\bar{s}^\beta P_L\, s^\beta).$$

Anatomy of ε′/ε beyond the SM in progress:
Aebischer, Bobeth, AJB, Straub, 1807.xxxxx

NP Models and ε'/ε Anomaly

Bobeth + AJB (1712.01295)

Littlest Higgs (T parity)	Blanke, AJB, Recksiegel (1507.06316)
Z-FCNC	AJB (1601.00005), Bobeth, AJB, Celis, Jung (1703.04753) Endo, Kitahara, Mishima, Yamamoto (1612.08839)
Z´-Models	AJB (1601.00005), AJB, Buttazzo, Knegjens (1507.08672)
331- Models	AJB, De Fazio (1512.02869, 1604.02344)
Vector-Like Quarks	Bobeth, AJB, Celis, Jung (1609.04783)
SUSY	Tanimoto, Yamamoto (1603.07960) Kitahara, Nierste, Tremper (1604.07400) Endo, Mishima, Ueda, Yamamoto (1608.01444) Crivellin, D'Ambrosio, Kitahara, Nierste (1703.05786) Endo, Goto, Kitahara, Mishima, Ueda, Yamamoto (1712.04959)
Right-handed Currents	Cirigliano, Dekens, De Vries, Meraghetti (1703.04751)
$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$	Haba, Umeeda, Yamada (1802.09903)
Leptoquark Models	Bobeth, AJB (1712.01295)

Main Messages on LQs in ε'/ε and rare K Decays

If improved lattice calculations will confirm the ε'/ε anomaly at the level $(\varepsilon'/\varepsilon)_{NP} \geq 5 \cdot 10^{-4}$ LQs are likely not responsible for it.

But if ε'/ε anomaly disappears large NP effects from LQs in rare K decays still possible.

(Need non-zero couplings to first generation!!)
(Need imaginary couplings!)
(Need both left-handed and right-handed couplings!)

In contrast to most explanations of B-anomalies

Section 4

Summary

Main Messages from this Talk

The inclusion of meson evolution in the phenomenology of any non-leptonic transition like $K^0-\bar{K}^0$ mixing, $K\to\pi\pi$ decays ($\Delta I=1/2$ Rule, ε'/ε) is mandatory !

Meson Evolution is hidden in LQCD results but among analytic approaches only DQCD takes this important QCD dynamics into account.

DQCD Prediction : **ε'/ε anomaly will be confirmed by RBC-UKQCD this summer !**

★ **$K \to \pi\pi$ hadronic matrix elements of all DIM=6 BSM operators will be available soon (DQCD)**

★ **Tensor-Tensor and scalar-scalar operators could be behind the ε'/ε anomaly**

Open Questions for Coming Years

$\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$?
NA62

$\mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right)$?
KOTO

$B \to K\left(K^*\right)\nu\bar{\nu}$?
Belle

$\left(\varepsilon'/\varepsilon\right)_{SM}, \kappa_{\varepsilon'}$?

$\left(\varepsilon_K\right)_{SM}, \kappa_{\varepsilon}$?

$\left(\Delta M_K\right)_{SM}$?

New Anomalies in Flavour Physics (B, D, LFV)?

New Particles discovered at the LHC?

What about ΔI=1/2 Rule?

(New Physics at 10-20% ?)

Lattice QCD
Can hopefully answer this question.

Coming Years : Flavour Precision Era

LHC Upgrade
E = 14 TeV
(CERN)

Precision
$B_{d,s}$ – Meson Decays
LHCb, CMS
KEK (Japan)

$K^+ \to \pi^+ \nu\bar{\nu}$ $(\sim 10^{-10})$ (CERN)

$K_L \to \pi^0 \nu\tilde{\nu}$ $(\sim 3 \cdot 10^{-11})$ J-PARC (Japan)

Lepton Flavour Violation
$\mu \to e\gamma$
$\mu \to eee$
$\tau \to \mu\gamma,\ \tau \to 3\mu$

Electric Dipole Moments

Improved Lattice Gauge Theory Calculations

Neutrinos

$(g\text{-}2)_\mu$

ε'/ε

$\Delta I = ½$ Rule, ΔM_K

Exciting Times are just ahead of us !!!

Exciting Times are just ahead of us !!!

Thank You !

Backup

ε'/ε strikes back (CP-Violation in $K_L \to \pi\pi$)

New results on hadronic matrix elements of QCD penguin (B_6) and electroweak penguin (B_8) operators

Large N approach to QCD : $B_6 < B_8 < 1$ ⇒ Upper Bound on ε'/ε in the Standard Model — AJB + Gérard (1507.06326)

Supported by Lattice QCD : $B_6 = 0.57 \pm 0.19$ | $B_8 = 0.76 \pm 0.05$ — RBC-UKQCD

Anatomy of ε'/ε in the Standard Model : NLO $(\varepsilon'/\varepsilon)_{SM} = (1.9 \pm 4.5) \cdot 10^{-4}$ — AJB, Gorbahn, Jäger, Jamin (1507.06345)

$(\varepsilon'/\varepsilon)_{SM} = (6.0 \pm 2.4) \cdot 10^{-4}$ for $B_6 = B_8 = 0.76$

$(\varepsilon'/\varepsilon)_{exp} = (16.6 \pm 2.3) \cdot 10^{-4}$ — Possible New Physics

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

Z´ general (AJB, Buttazzo, Knegjens, 1507.08672)
Littlest Higgs Model (Blanke, AJB, Recksiegel, 1507.06316)
331 Models (AJB, De Fazio, 1512.02869,1604.02344)
New Strategy (AJB, 1601.00005)
Vector-like Quarks (Bobeth, AJB, Celis, Jung, 1609.04783)
Leptoquarks (Bobeth, AJB, 1712.01295)

More papers later

(1703.04753)

General Z´ at Work

Can solve anomalies in R_K, R_{K^*}, $P_5{}'$ (many papers)

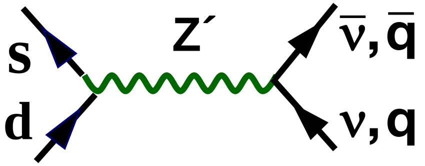
Here : ε'/ε, $K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$, ΔM_K

Q_6, Q_6' – QCD Penguin operators

Q_8, Q_8' – Electroweak Penguin operators

$$Q_6 = \left(\bar{s}_\alpha d_\beta\right)_{V-A} \sum_q \left(\bar{q}_\beta q_\alpha\right)_{V+A}$$

$$Q_8 = \left(\bar{s}_\alpha d_\beta\right)_{V-A} \sum_q e_q \left(\bar{q}_\beta q_\alpha\right)_{V+A}$$



Strategy (Z´)

AJB (1601.00005)

$$(\varepsilon'/\varepsilon)^{NP} = \kappa_{\varepsilon'} \cdot 10^{-3}$$

$$0.5 \le \kappa_{\varepsilon'} \le 1.5$$

(Im)

$$\varepsilon_K^{NP} = \kappa_\varepsilon \cdot 10^{-3}$$

$$0.1 \le \kappa_\varepsilon \le 0.4$$

(Im, Re)

ε_K more important than $K_L \to \mu^+\mu^-$ in Z´ models

↓

Re and Im Parts: Z´ Couplings

$\Delta_L^{sd}(Z')$, $\Delta_R^{sd}(Z')$

↓

$K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$, $K_L \to \mu^+\mu^-$, ΔM_K

(Re, Im) (Im) (Re) (Im, Re)

Basic Structure of NP Contributions

AJB (1601.00005)

$$\left(\varepsilon'/\varepsilon\right)^{NP} \to \mathrm{Im} \qquad \varepsilon_K^{NP} \to \mathrm{Im}\cdot\mathrm{Re}$$

$$\left(\kappa_{\varepsilon'} \geq 0.5\right) \qquad \left(\kappa_{\varepsilon} \geq 0.1\right)$$

$$\Delta M_K^{NP} \sim \left[(\mathrm{Re})^2 - (\mathrm{Im})^2\right]$$

Dominance of $Q_6\left(Q_6'\right) \Rightarrow \mathrm{Im} \gg \mathrm{Re} \Rightarrow \left\{\Delta M_K^{NP} < 0\right\}$ (large)

Dominance of $Q_8\left(Q_8'\right) \Rightarrow \mathrm{Re} \gg \mathrm{Im} \Rightarrow \left\{\Delta M_K^{NP} > 0\right\}$ (small)

Distinction between these scenarios

Main Message

Correlation between ε'/ε and $K \to \pi\nu\bar{\nu}$ in Z´ scenarios depends on whether QCP Penguin (Q_6) or EWP (Q_8) dominates NP in ε'/ε

Effects in $K \to \pi\nu\bar{\nu}$ much larger if Q_6 dominates NP

ε'/ε within SM

$$\varepsilon'/\varepsilon \sim \left[\frac{\mathrm{Re}\,A_2}{\mathrm{Re}\,A_0} \mathrm{Im}\,C_6 \langle Q_6 \rangle_0 - \mathrm{Im}\,C_8 \langle Q_8 \rangle_2 + \text{ smaller contributions} \right]$$

$$\left\{ \frac{\mathrm{Re}\,A_2}{\mathrm{Re}\,A_0} \approx \frac{1}{22} \qquad \frac{\mathrm{Im}\,C_6}{\mathrm{Im}\,C_8} \approx 90 \qquad \frac{\langle Q_8 \rangle_2}{\langle Q_6 \rangle_0} \approx 2 \right\} \Rightarrow \text{ strong cancellations}$$

ε'/ε beyond SM

$$\left(Q_6, Q_8, Q'_6, Q'_8 \right)$$

1. Generally Q_8 wins over Q_6 because $\left(\frac{\mathrm{Im}\,C_6}{\mathrm{Im}\,C_8} \right)^{NP} \approx 0(1)$ but can provide $\Delta(\varepsilon'/\varepsilon) > 0$

2. Q_6 wins over Q_8 in the presence of a flavour symmetry forbidding Q_8

3. Chromomagnetic operators

Stars of KAON Flavour Physics

$\varepsilon_K, \Delta M_K$

ε'/ε

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

$K_L \to \pi^0 \nu\bar{\nu}$

$K_{L,S} \to \mu^+\mu^-$

$K_L \to \pi^0 l^+ l^-$

$\Delta I = 1/2$ Rule

They all can give some information about very short distance scales but to identify new physics, correlations with $B_{s,d}$ and D observables, EDMs, Lepton physics crucial

In particular if we want to reach Zeptouniverse without any direct hints from the LHC

Towards Zeptouniverse in 12 Steps

12 LFV, EDMs $(g\text{-}2)_{\mu,e}$

1 CKM from Trees

2 Lattice

3 $\Delta F=2$ Observables

4 $B_{s,d} \to \mu^+\mu^-$
$B_{s,d} \to \tau^+\tau^-$

5 $B^+ \to \tau^+\nu_\tau$
$B \to D(D^*)\tau\nu$

6 $B \to X_s\gamma$
$B \to K^*\gamma$

7 $B \to X_s l^+l^-$
$B \to K^*(K)l^+l^-$

8 $B \to X_s\nu\bar{\nu}$
$B \to K^*(K)\nu\bar{\nu}$

9 $K^+ \to \pi^+\nu\bar{\nu}$
$K_L \to \pi^0\nu\bar{\nu}$

10 ε'/ε

11 Charm Top

AJB, Girrbach-Noe 1306.3775

AJB 1505.00618