Dual QCD and Flavour Kaon Physics

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Quark Confinement
Dublin, August 2018

Overture

Present Superstars of K Physics

[NA48 KTev] $$\frac{\varepsilon'}{\varepsilon} = (16.6 \pm 2.3) \cdot 10^{-4}$$

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

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

[1964] $$\varepsilon = e^{i\varphi_\varepsilon} (2.23 \pm 0.01) \cdot 10^{-3}$$

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

$(\Delta I = 1/2 \text{ Rule})$ $$\frac{\mathrm{Re}\, A_0}{\mathrm{Re}\, A_2} = 22.35$$

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

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

[1955]

[NA62] [2019] $$K^+ \to \pi^+ \nu\bar{\nu},\ K_L \to \pi^0 \nu\bar{\nu}$$

ΔM_K

[1959]

$K_L - K_S$ Mass difference

Effective Hamiltonian and OPE

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

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

Wilson Coefficients

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:

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

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

$\mu \approx 1-3$ 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) (Munich, Rome + Gorbahn, Brod,
Including BSM (early 1990s) Haisch, Jäger,
Nierste, Cerda-Sevilla)

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

2.

ε´/ε strikes back

3.

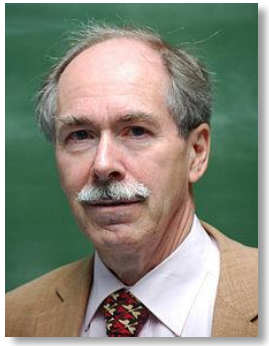
ε´/ε Beyond SM

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.

⇩

Factorization of hadronic matrix elements ★

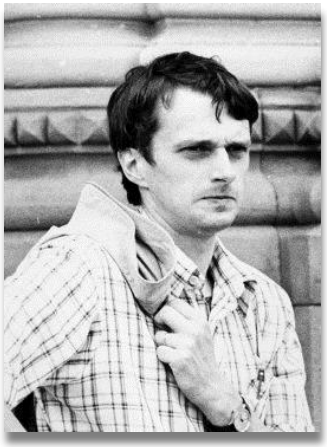
Dual QCD Approach for Weak Decays

Successful low energy approximation of QCD

1985

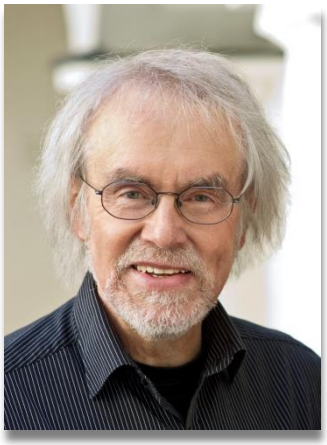
W. Bardeen

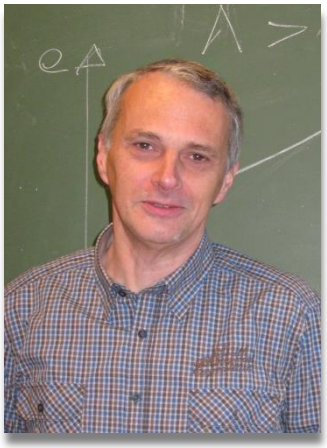
AJB



J.-M. Gérard

2014





Basics of Dual QCD

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

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

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

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

$\Pi =$ octet of pseudoscalar mesons

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

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

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

Meson representation of

quark-currents

quark-densities

Hadronic Matrix Elements (Large N Limit)

Simply products of quark currents
or quark densities
or tensor structures

$$P_L = (1-\gamma_5)/2$$

Example :

$$\left\langle \pi\pi(I=0)\left|(\bar{s}P_L d)(\bar{u}P_L u)\right|K\right\rangle = -\frac{F_\pi}{24}\left[\frac{2m_K^2}{m_s(\mu)+m_d(\mu)}\right]^2$$

SD Scale

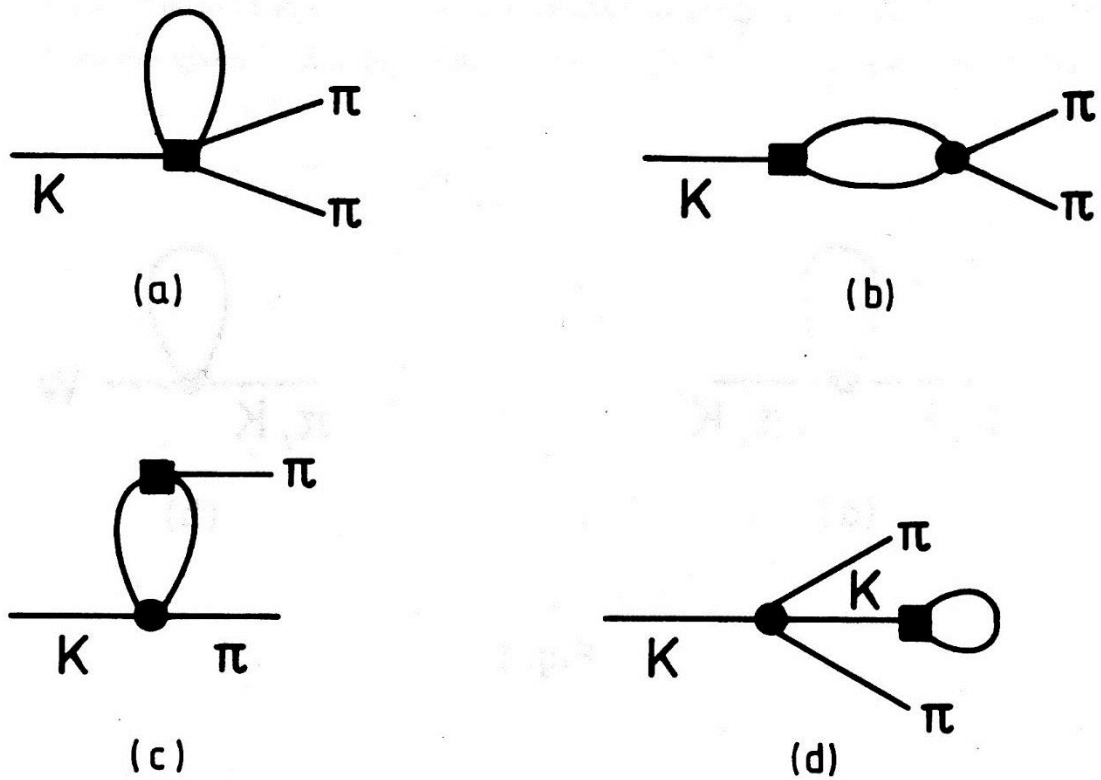
This is <u>tree-level</u> calculation in meson theory: factorizable <u>contributions</u>

In order to match with short-distance Wilson coefficients <u>non-factorizable</u> contributions must be included: <u>loops</u> in meson theory

They vanish at factorization scale: 0 (m_π, m_K) ≠ μ

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

$(\varepsilon'/\varepsilon,\ \varepsilon,\ \Delta I = 1/2$ Rule, $\Delta M_K)$

SM and BSM Operators

Reviews: 1401.1385, 1408.4820

Λ_{NP}

EW

1 GeV

$\Lambda_{DQCD} \approx 0.8$ GeV

m_π, m_K

SMEFT with SM and BSM Operators

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

DQCD: Meson Evolution (1/N)
$0(m_\pi, m_K) \to \Lambda_{DQCD} \approx 0.8$ GeV

RG Evolution
α_s, α_2, α_1
top Yukawa

α_s, α_{QED}

Non-Factorizable contributions

SM and BSM operators

Factorization Scale

$(N \to \infty)$

for hadronic matrix elements

★ 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.

ΔI = ½ Rule

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

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

1986

Dual QCD (BBG)

(Main Dynamics Behind ΔI = ½ 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:	$\hat{B}_K = 0.763 \pm 0.010$	

Gérard: $\hat{B}_K < 0.75$

$$\langle \bar{K}^0 | Q(\mu) | K^0 \rangle = \frac{4}{3} F_K^2 m_K B_K(\mu) \qquad \hat{B}_K = B_K(\mu)\alpha_s^P(\mu)$$

$$Q = \left[\bar{s}\gamma_\mu(1-\gamma_5)d\right]^2$$

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

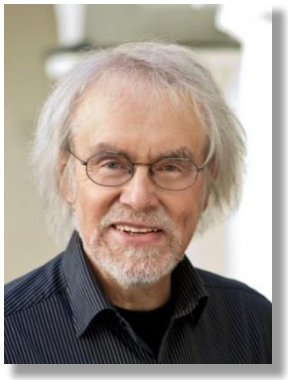
$B_{CMO} \approx 1/3$

Much smaller than early estimates in chiral quark model

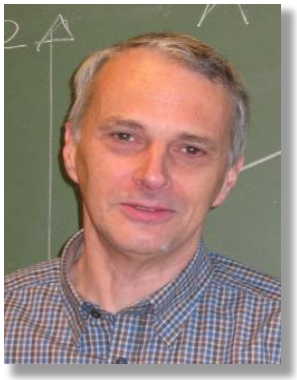
2. Explanation of BSM B_i parameters ($K^0 - \bar{K}^0$ Mixing) obtained by Lattice QCD 1804.02401 (AJB + Gérard)

3. $K \to \pi\pi$ matrix elements of <u>all</u> BSM 4-quark operators

Jason Aebischer



AJB



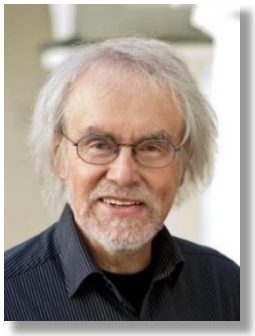
J.-M. Gérard

(1807.01709)

4. Master Formula for ε´/ε Beyond SM (1807.02520)


Jason Aebischer


Christoph Bobeth


AJB

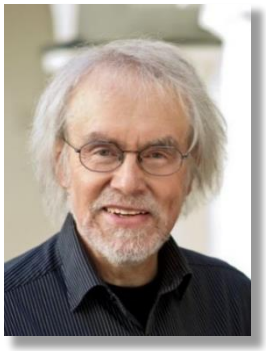

Jean-Marc Gérard


David Straub

5. Anatomy of ε´/ε Beyond SM (1808.xxxxx) First SMEFT analysis


Jason Aebischer


Christoph Bobeth


AJB


David Straub

Section 2

ε'/ε strikes back

Main Actors in ε´/ε in SM

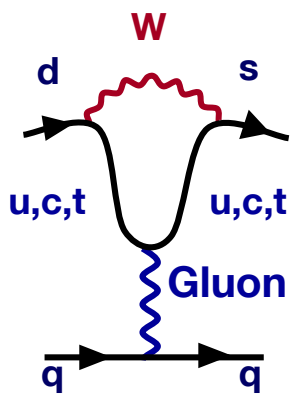
Q_6 – QCD Penguin operator

Q_8 – Electroweak Penguin operator

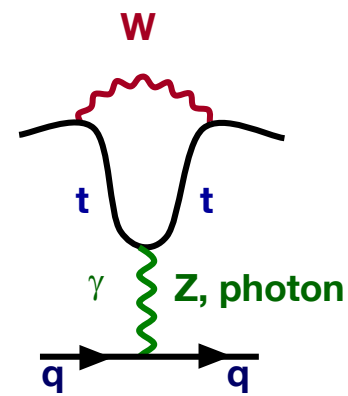
$$Q_6 = \left(\bar{s}_\alpha d_\beta\right)_{V-A} \sum_q \left(\bar{q}_\beta q_\alpha\right)_{V+A}$$

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

$Q_6 =$



$Q_8 =$



QCD and Electroweak Penguin Matrix Elements

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

$$\langle Q_6(\mu)\rangle_0 = -4\left[\frac{m_K^2}{m_s(\mu)}\right]^2 (F_K - F_\pi) B_6^{(1/2)}(\mu)$$

$$\langle Q_8(\mu)\rangle_2 = \sqrt{2}\left[\frac{m_K^2}{m_s(\mu)}\right]^2 F_\pi B_8^{(1/2)}(\mu)$$

$B_6(\mu)$, $B_8(\mu)$: very weak μ dependence for $\mu > 1\text{GeV}$

Four dominant contributions to ε´/ε in the SM

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

From ReA_0 — From ReA_2

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

(NLO) (Q_4)

(V-A) ⊗ (V-A) QCD Penguins	(V-A) ⊗ (V+A) QCD Penguins	(V-A) ⊗ (V-A) EW Penguins	(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)

Extracted from

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

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

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 $\mu = m_\pi$ <u>not</u> $\mu = 0(1\ \text{GeV})$

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 $\mu > 1$ GeV

QCD and Electroweak Penguin Matrix Elements (DQCD)

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

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 $\mu \geq 1\text{GeV}$

RBC-UKQCD

$$B_6^{(1/2)} = 1 - 0.66 \ln\left(1 + \frac{\Lambda^2}{\tilde{m}_6^2}\right) \Rightarrow B_6^{(1/2)} < 0.7$$

$$B_8^{(3/2)} = 1 - 0.17 \ln\left(1 + \frac{\Lambda^2}{\tilde{m}_8^2}\right) \Rightarrow B_8^{(3/2)} \approx 0.8 \pm 0.1$$

$$B_6^{(1/2)} = 0.57 \pm 0.19$$

$$B_8^{(3/2)} = 0.76 \pm 0.05$$

$\tilde{m}_{6,8} < \Lambda$

$$(\varepsilon'/\varepsilon)_{SM} < (6.0 \pm 2.4) \cdot 10^{-4}$$ (2015)

(NLO)

Present Status of ε´/ε in the SM

July 25th 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)	$(\varepsilon'/\varepsilon)^{exp} = (16.6 \pm 2.3) \cdot 10^{-4}$	

NNLO : Maria Cerda-Sevilla, Martin Gorbahn, Sebastian Jäger, Ahmet Kokulu

In progress

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

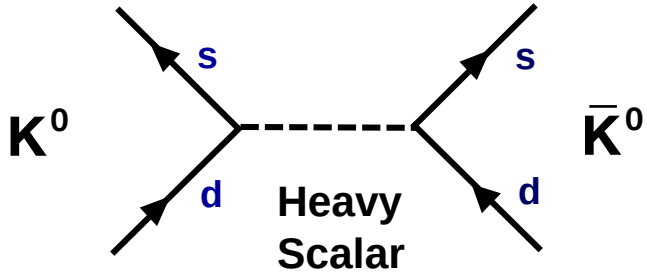
BSM $\Delta S = 2$ Operators $K^0 - \bar{K}^0$ Mixing

$$P_{L,R} = \frac{1}{2}\left(1 \pm \gamma_5\right)$$

BSM

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

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



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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(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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1 GeV	0.62	1.10	0.90	0.45	
					} gap : Vector mesons
(0.70) GeV					
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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	← $N \to \infty$

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 (DQCD)

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

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

Dual QCD

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

AJB Expectation (May 2018) 1805.11096

$$(\varepsilon'/\varepsilon)_{SM} = (5 \pm 2) \cdot 10^{-4}$$

Will new RBC-UKQCD results support this claim?

Section 3

ε′/ε Beyond the SM

Review: AJB (1805.11096) (update soon)

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

$\mu \approx 1 - 3$ GeV

Renormalization scale

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

Already calculated by Lattice + DQCD

Calculated in July 2018 in DQCD

(1807.01709)

All Dimension 6 BSM Four-Quark Operators (linearly independent)

ABG (1807.01709) ABBS (1808.xxxxx)

QCD x QED invariant

SM : 7

BSM : 33 = 7´+ 13 + 13´

Obtained from SM : L ↔ R Matrix Elements reverse sign

Operators unrelated to SM operators

Matrix Elements only calculated in DQCD

SMEFT invariant under SM gauge Group

BSM : 21 = 7´+ 7 + 7´

Magnificant Seven

ABG (1807.01709)

Allowed by SMEFT : $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$

$$A = \left(\bar{s}\gamma^{\mu}P_L d\right)\left(\bar{d}\gamma_{\mu}P_L d\right) - \left(\bar{s}\gamma^{\mu}P_L d\right)\left(\bar{s}\gamma_{\mu}P_L s\right)$$

★ $$B_2 = \left(\bar{s}P_R d\right)\left(\bar{d}P_L d\right) - \left(\bar{s}P_R d\right)\left(\bar{s}P_L d\right)$$

$$C_2 = \left(\bar{s}\gamma^{\mu}P_L d\right)\left(\bar{d}\gamma_{\mu}P_R d\right) - \left(\bar{s}\gamma^{\mu}P_L d\right)\left(\bar{s}\gamma_{\mu}P_R s\right)$$

$$D_1 = \left(\bar{s}P_L u\right)\left(\bar{u}P_L d\right)$$

★ $$D_1^* = -\left(\bar{s}\sigma^{\mu\nu}P_L u\right)\left(\bar{u}\sigma_{\mu\nu}P_L d\right)$$

$$D_2 = \left(\bar{s}P_L d\right)\left(\bar{u}P_L u\right)$$

★ $$D_2^* = -\left(\bar{s}\sigma^{\mu\nu}P_L d\right)\left(\bar{u}\sigma_{\mu\nu}P_L u\right)$$

All colour singlet quark bilinears

★ **Largest Matrix Elements**

NP Models and ε´/ ε Anomaly

(Only SM operators)

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, 1806.03424)
Leptoquark Models	Bobeth, AJB (1712.01295)

Master Formula for ε´/ ε Beyond SM

$$\left(\frac{\varepsilon'}{\varepsilon}\right) = \left(\frac{\varepsilon'}{\varepsilon}\right)_{SM} + \left(\frac{\varepsilon'}{\varepsilon}\right)_{NP}$$

Valid in ANY extension of SM

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

$(P_L \leftrightarrow P_R)$

i = 1,…40 4-quark operators + 1 dipole operator

Model independent: $P_i(\mu_{ew})$ - Include hadronic elements + renormalization group effects from $\mu \approx 0$ (1 GeV) to $\mu_{ew} \approx 0$ (M_W)

All listed in

J. Aebischer, C. Bobeth, AJB, J.-M. Gérard, D. Straub 1807.02520

Section 4

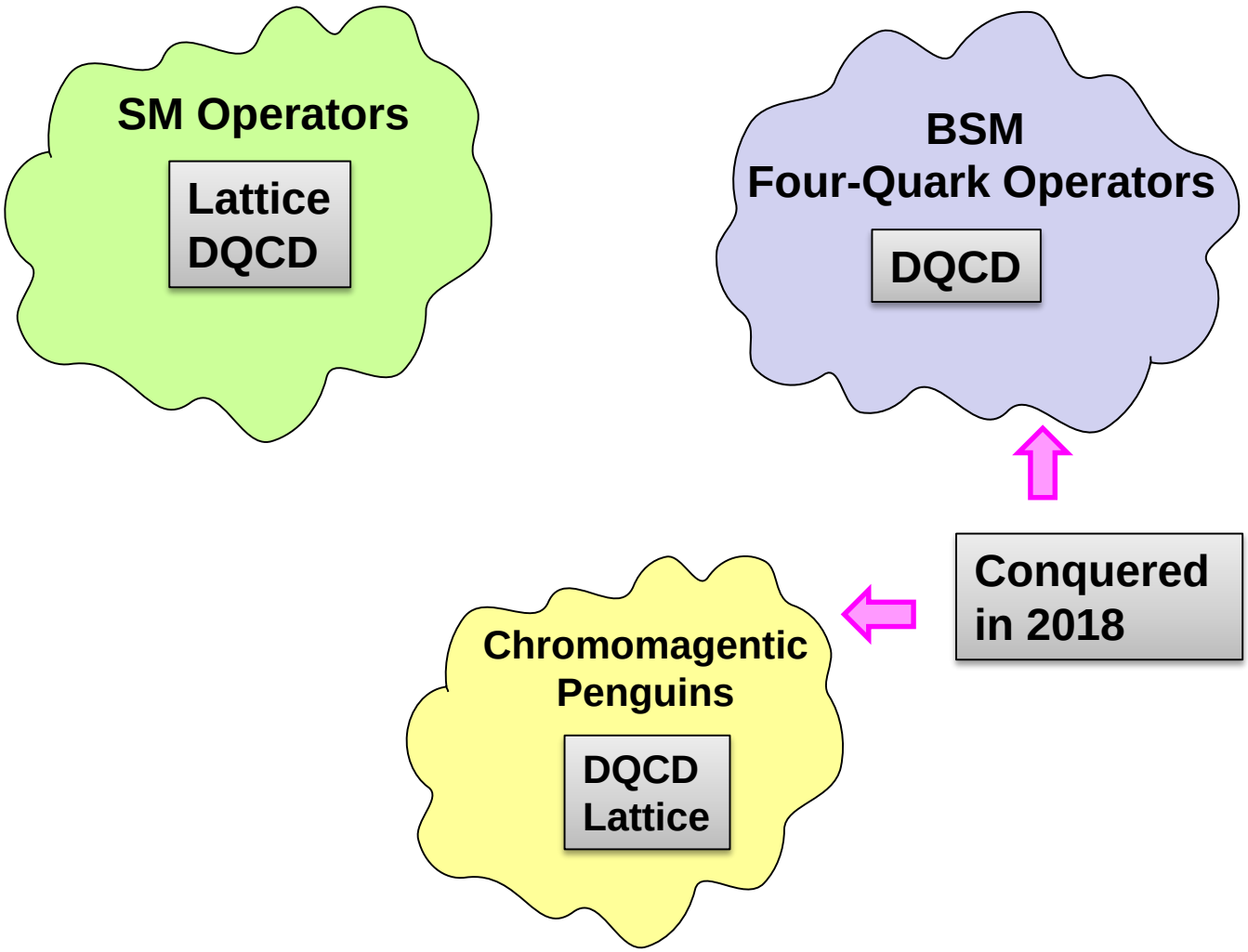
Summary

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.

Islands of K $\rightarrow \pi\pi$ Matrix Elements



Most important for ε´/ε Anomaly

Left-Right Operators

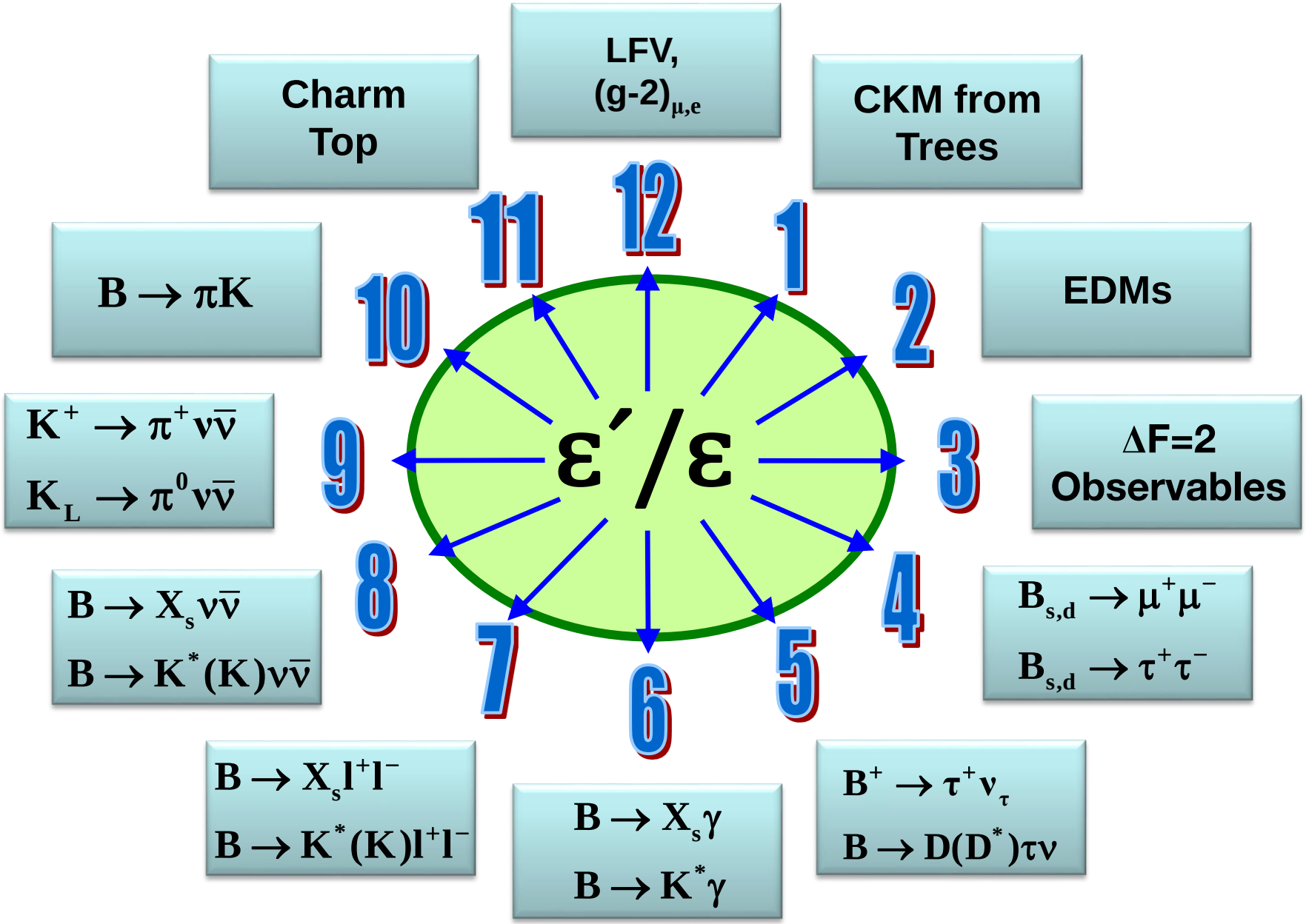
Z´, W´

Vector-like Quarks

Scalar and Tensor Operators

Heavy Scalars

BSM anatomy of ε´/ε : Aebischer, Bobeth, AJB, Straub (1808.xxxxx) SMEFT analysis


ε′/ε
12
LFV, (g-2)μ,e
1
CKM from Trees
2
EDMs
3
ΔF=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
$B \to \pi K$
11
Charm Top

Open Questions for Coming Years

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

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

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

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

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

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

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

New Particles discovered at the LHC?

What about $\Delta I=1/2$ 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 $K \to \pi\nu\bar{\nu}$

More papers later

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) (1703.04753)
Leptoquarks (Bobeth, AJB, 1712.01295)

General Z´ at Work

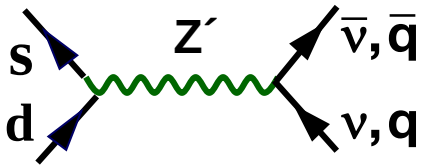
Can solve anomalies in R_K, R_{K^*}, P_5' (many papers)

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

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

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

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

Basic Structure of NP Contributions

AJB (1601.00005)

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

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

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

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

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

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.

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!)

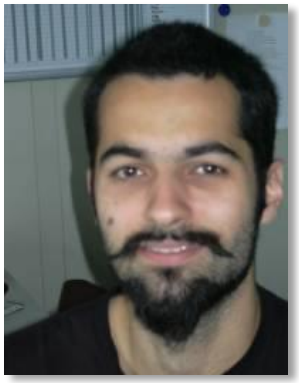
In contrast to most explanations of B-anomalies

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 $(\varepsilon'/\varepsilon)_{SM}$

Maria Cerda-Sevilla

Martin Gorbahn

Sebastian Jäger

Ahmet Kokulu

New IAS Postdoc

New TUM Postdoc

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)

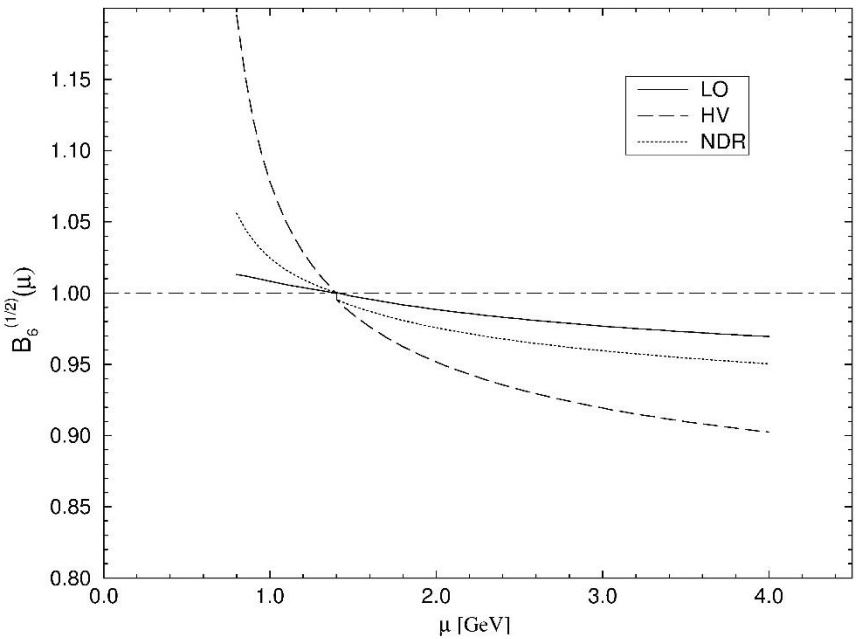
No more work for DQCD :

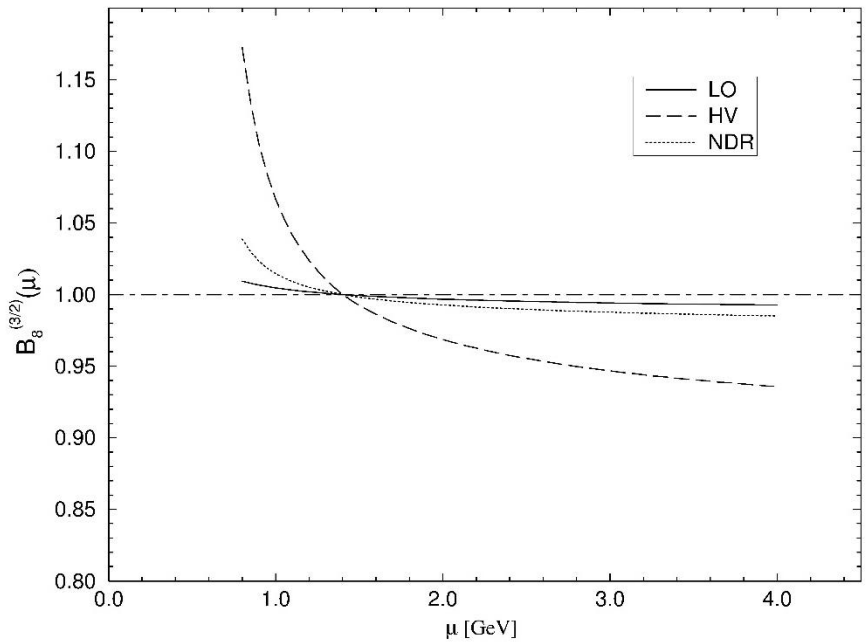
Aebischer, AJB, Gérard (1807.xxxxx)

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

B_6 and B_8 in the Perturbative Regime (1993!)

AJB, Jamin, Lautenbacher, (9303284)



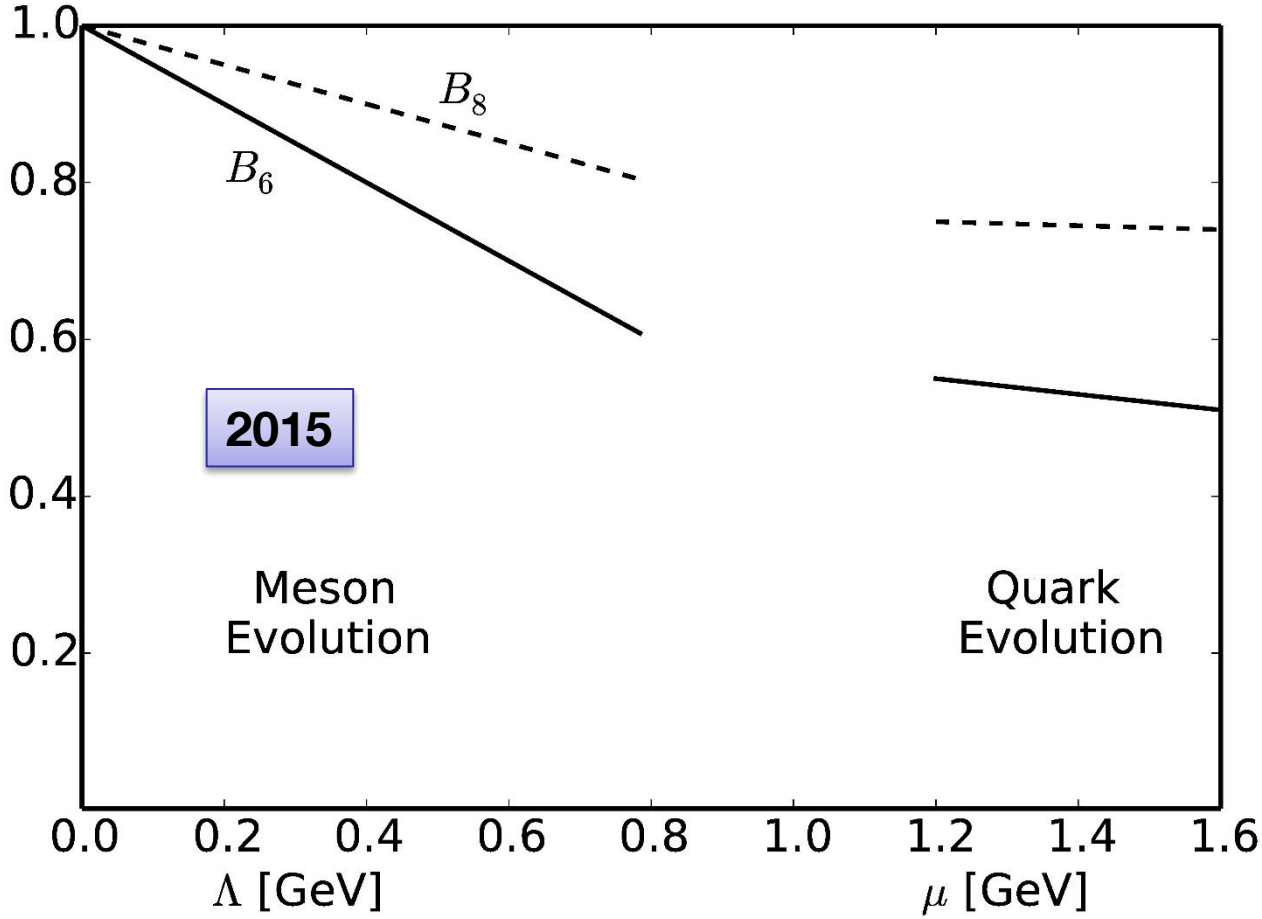


B_6 and B_8 decrease with increasing μ!

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

Scale Dependence of B_6 and B_8

AjB+ Gerard (1507.06326)



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

★ **The most likely new particles behind These operators are heavy scalars (colourless + coloured)**

But new heavy gauge bosons, Z´, W´ Could also be important

BSM Anatomy : Aebischer, Bobeth, AJB, Straub (1808.xxxxx)

Forbidden by SMEFT but allowed by QCD∗QED

ABG (1807.01709)

★ $$B_1 = \left(\bar{s}P_R d\right)\left(\bar{u}P_L u\right)$$

$$C_1 = \left(\bar{s}\gamma^\mu P_L u\right)\left(\bar{u}\gamma_\mu P_R d\right)$$

$$D_3 = \left(\bar{s}P_L d\right)\left(\bar{d}P_L d\right)$$

★ $$D_3^* = -\left(\bar{s}\sigma^{\mu\nu}P_L d\right)\left(\bar{d}\sigma_{\mu\nu}P_L d\right)$$

$$D_4 = \left(\bar{s}P_L d\right)\left(\bar{s}P_L s\right)$$

$$D_4^* = -\left(\bar{s}\sigma^{\mu\nu}P_L d\right)\left(\bar{s}\sigma_{\mu\nu}P_L s\right)$$

★ **Largest Matrix Elements**