Kaon Flavour News

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Lyon
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Overture

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

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

AJB, Girrbach-Noe 1306.3775

AJB 1505.00618

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, Haisch, Jäger, Nierste, Cerda-Sevilla)
(early 1990s)

LD

Lattice QCD (ETM, SWME, RBC-UKQCD, ...)

(Numerical sophisticated tedious calculations lasting many years)

Analytic

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

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 38 min

1. Dual QCD News

2. ε'/ε strikes back

3. $K \to \pi\nu\bar{\nu}$ in the Standard Model

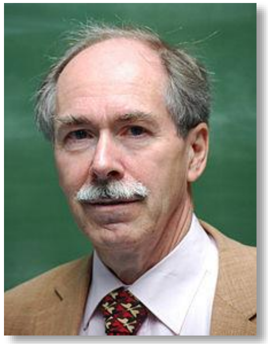
4. Implications for ε'/ε, ε_K, $K \to \pi\nu\bar{\nu}$, ΔM_K (Z´- FCNCs)

5. BSM for ε'/ε

6. Summary

1.
Dual QCD

Large N
QCD



Gerard ´t Hooft
(1974)

Edward Witten
(1979, 1980)

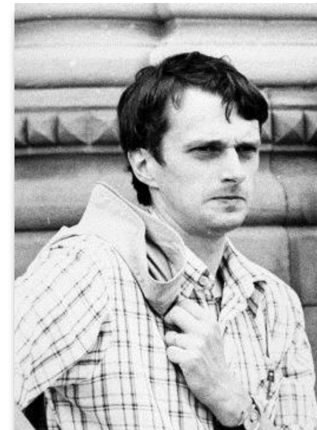
At Large N QCD becomes a theory of weakly interacting mesons

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

1985

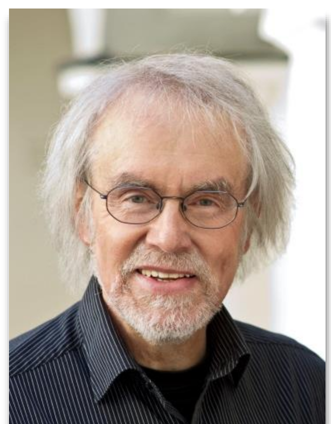


W. Bardeen

AJB

J.-M. Gérard

2014



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

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

Non-Factorizable contributions

SM and BSM operators

($N \to \infty$)

Factorization Scale

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. (1985-2012)

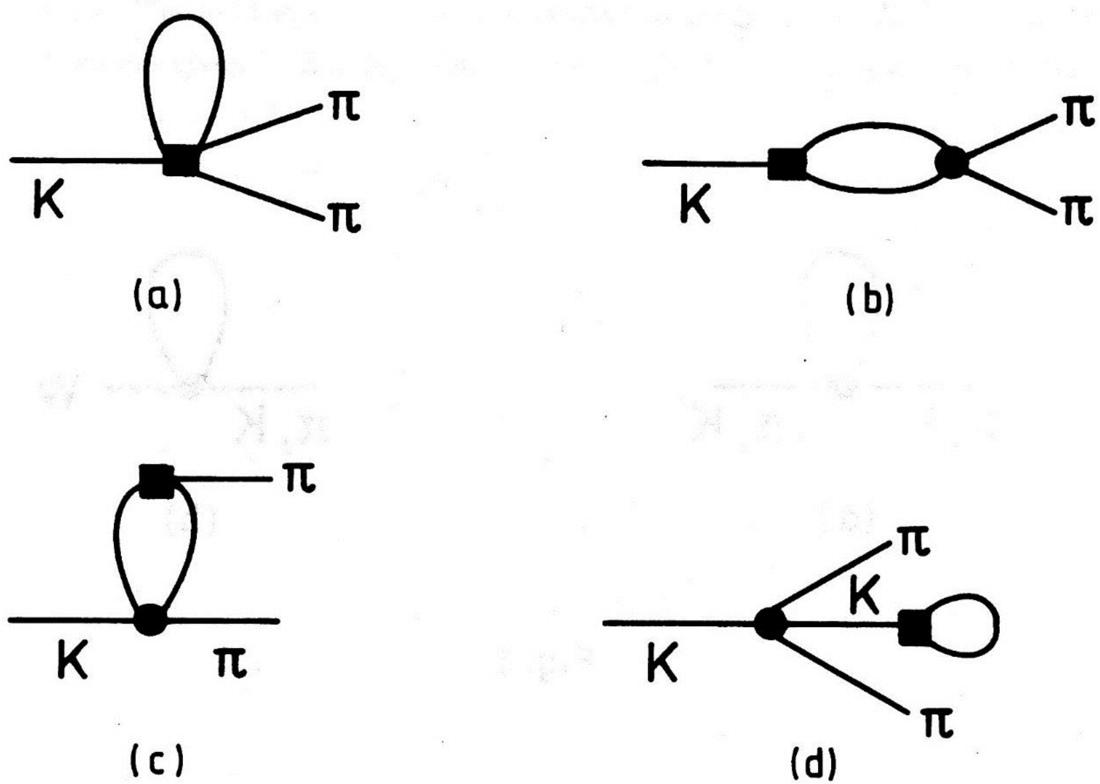
2. Giving insight in numerical results obtained by Lattice QCD at 2-3 GeV. Progress in LQCD ↓ (2012 →)

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.

Meson Evolution

Loops with a physical cutt-off Λ



Very different philosophy from Chiral PTh

No dimensional regularisation !!!

$\Delta I = 1/2$ 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 Donoghe 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

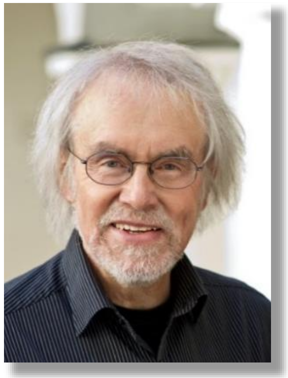
$B_{CMO} \approx 1/3$

Much smaller than early estimates in chiral quark model

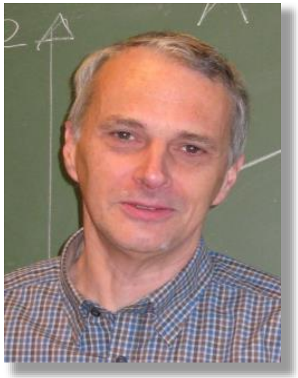
2. Explanation of BSM B_i parameters $(K^0 - \bar{K}^0$ Mixing)
obtained by Lattice QCD 1804.02401 (AJB + Gérard)

3. More Results this Summer

Jason Aebischer



AJB



J.-M. Gérard

Section 2
ε´/ε strikes back

2015 Anatomy of ε´/ε : 1507.06345

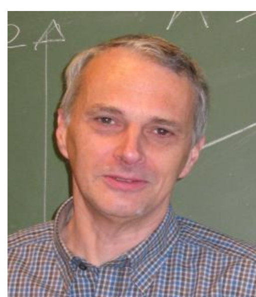
AJB

Martin Gorbahn

Sebastian Jäger

Matthias
Jamin

AJB



Jean-Marc Gérard

Large N news
1507.06326

FSI
1603.05686

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 $B_6 = B_8 = 0.76$

$(8.6 \pm 3.2) \cdot 10^{-4}$ for $B_6 = B_8 = 1.0$

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

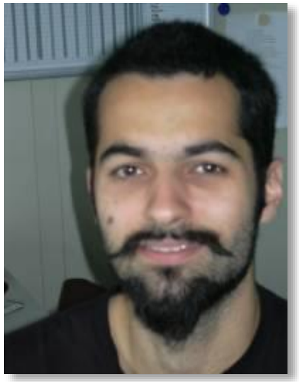
(1703.04753)

2016 Standard Model Results

Teppei Kitahara

Ulrich Nierste

Paul Tremper



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

2018

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

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 $\mathrm{Re}A_0$ (→ $-3.6 + 21.4\cdot B_6^{(1/2)}$) | From $\mathrm{Re}A_2$ (→ $+1.2 - 10.4\cdot B_8^{(3/2)}$)

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

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

Assumes that $\mathrm{Re}A_0$ and $\mathrm{Re}A_2$ ($\Delta I=1/2$ 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 : $B_6^{(1/2)} = 0.57 \pm 0.19$ $\quad B_8^{(3/2)} = 0.76 \pm 0.05$

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

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

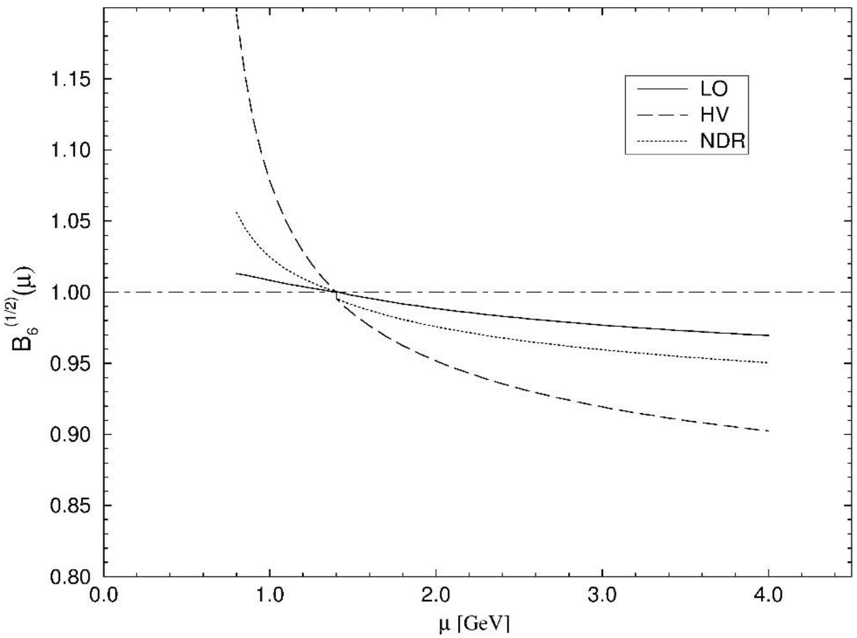
But $B_6^{(1/2)} = B_8^{(3/2)} = 1$ is large N prediction

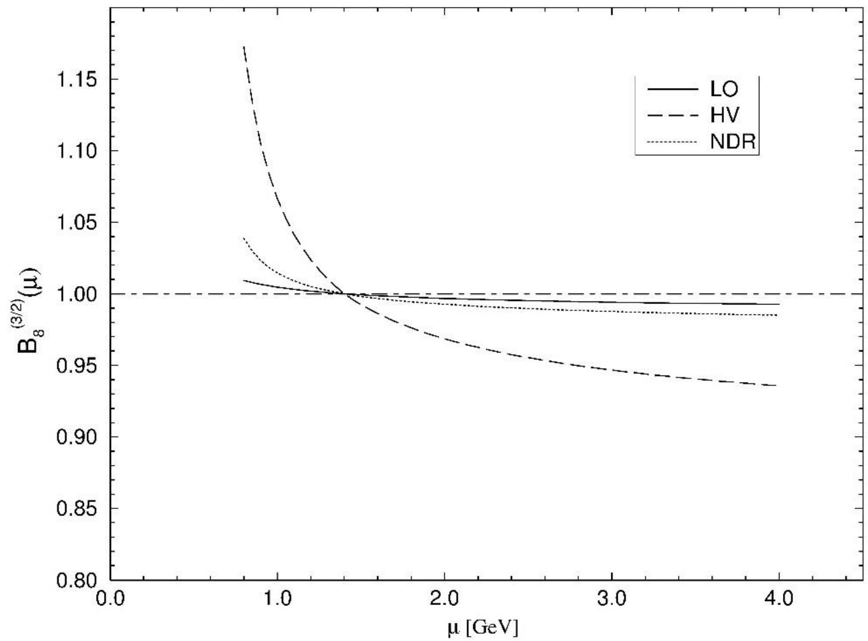
for $\mu = m_\pi$ not $\mu = 0(1\,\text{GeV})$

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)



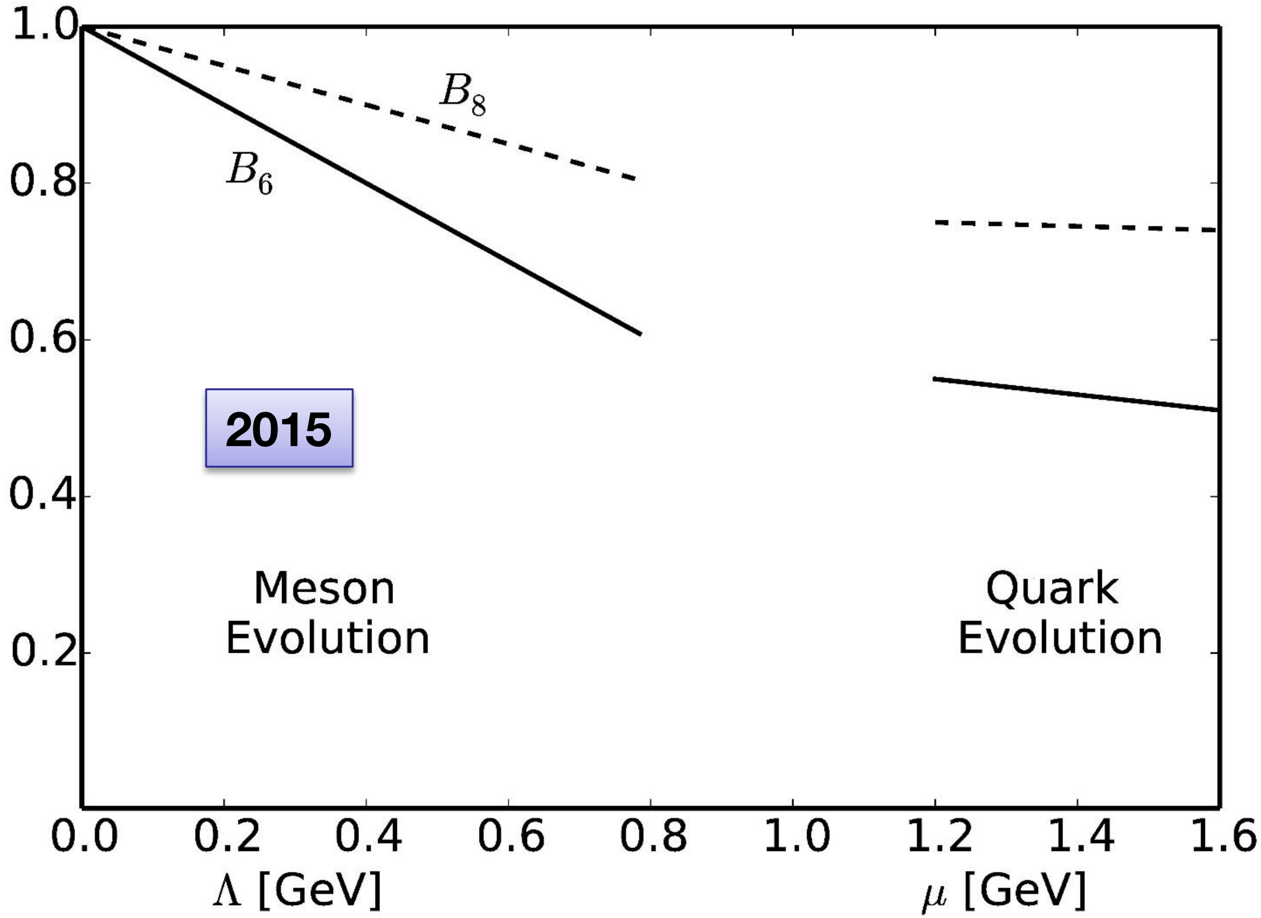


B_6 and B_8 decrease with increasing μ!

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,…)

New application of dual QCD to $K \to \pi l^+ l^-$
(Caluccio-Leskow, D´Ambrosio, Greynat, Nath, 1604.09721)

(see next talk)

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 controversial issue of Final State interactions is absent here !!!**

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

ΔS = 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

$$0_2 = \left(\bar{s}^\alpha P_L d^\alpha\right)\left(\bar{s}^\beta P_L d^\beta\right) \to B_2$$

$$0_3 = \left(\bar{s}^\alpha P_L d^\beta\right)\left(\bar{s}^\beta P_L d^\alpha\right) \to B_3$$

$$0_4 = \left(\bar{s}^\alpha P_L d^\alpha\right)\left(\bar{s}^\beta P_R d^\beta\right) \to B_4$$

$$0_5 = \left(\bar{s}^\alpha P_L d^\beta\right)\left(\bar{s}^\beta P_R d^\alpha\right) \to B_5$$

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

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

$N \to \infty$

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 ⇩					$B_2=B_3=B_4=B_5=1$ 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 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. ?

ε'/ε anomaly is the largest anomaly in flavour physics !

Based on DQCD, not Lattice yet !

(A.J. Buras)

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

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

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

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

Dual QCD

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

Section 3

$K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^o \nu\bar{\nu}$

in the Standard Model

1503.02693

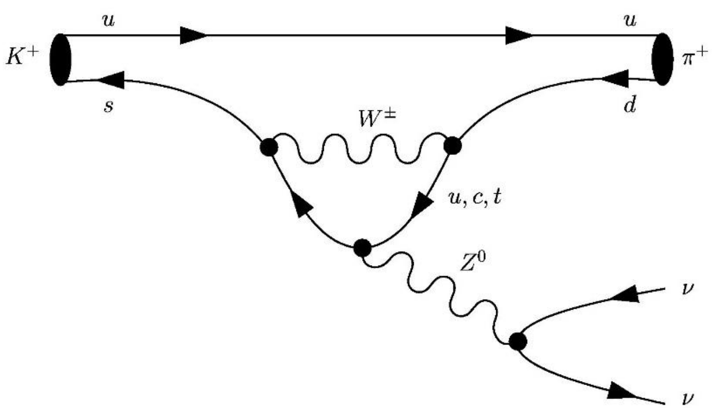
AJB

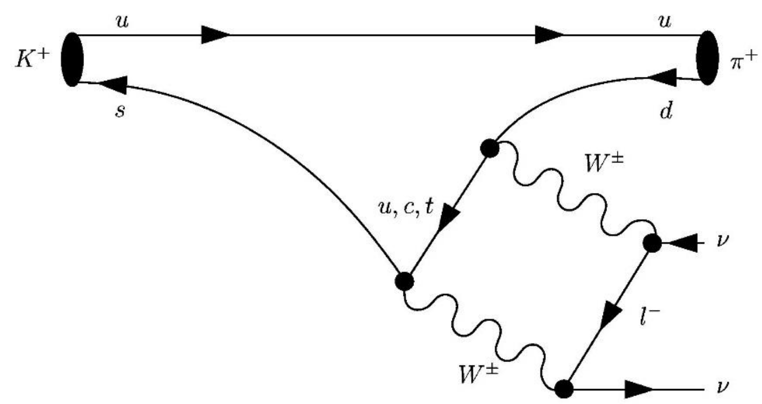
D.Buttazzo

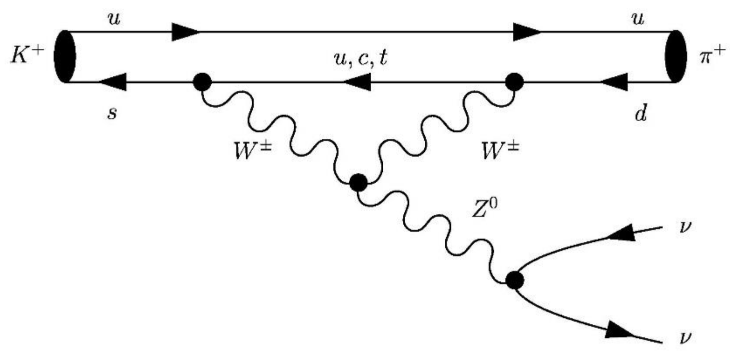
J.Girrbach-Noe

R.Knegjens

Waiting for $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi\nu\bar{\nu}$







NA62 (2018)
KOTO (2020)

AJB, M. Lautenbacher, G. Ostermaier (9303284)

AJB, F. Schwab, S. Uhlig (0405132)

$K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ in the SM

QCD Corrections:

NLO Buchalla, AJB; Misiak, Urban (93, 98)
NNLO AJB, Gorbahn, Haisch, Nierste (2005)

NLO EW Corrections:

Large m_t: Buchalla, AJB (1997)
Exact NLO (m_t): Brod, Gorbahn, Stamou (2010)
" " (m_c): Brod, Gorbahn (2008)

LD Effects:

\+ **Isospin breaking corrections**

Isidori, Mescia, Smith (2005)
Mescia, Smith (2007)

TH uncertainties at the level of 2% in BR

Unique in Flavour Physics !!

But significant parametric uncertainties

due to $|V_{ub}|, |V_{cb}|, \gamma$

NA62 : 1 Event !

Data

$$\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(17.3 \pm 11\right) \cdot 10^{-11}$$
$$\mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right) \le 2.6 \cdot 10^{-8}$$

CKM Uncertainties

AJB, Buttazzo, Girrbach-Noe, Knegjens 1503.02693

$$\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(8.39 \pm 0.30\right)\cdot 10^{-11}\left[\frac{|V_{cb}|}{0.0407}\right]^{2.8}\left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

$$\mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right) = \left(3.36 \pm 0.05\right)\cdot 10^{-11}\left[\frac{|V_{ub}|}{3.88\cdot 10^{-3}}\right]^{2}\left[\frac{|V_{cb}|}{0.0407}\right]^{2}\left[\frac{\sin\gamma}{\sin(73.2)}\right]^{2}$$

$$\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(8.39 \pm 0.58\right)\cdot 10^{-11}\left[\frac{\gamma}{73.2^\circ}\right]^{0.81}\left[\frac{\overline{\mathrm{Br}}\left(B_s \to \mu^+\mu^-\right)}{3.4\cdot 10^{-9}}\right]^{1.42}\left[\frac{227.7}{F_{B_s}}\right]^{2.84}$$

$$\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(8.39 \pm 1.11\right)\cdot 10^{-11}\left[\frac{|\varepsilon_K|}{2.23\cdot 10^{-3}}\right]^{1.07}\left[\frac{\gamma}{73.2^\circ}\right]^{-0.11}\left[\frac{V_{ub}}{3.88\cdot 10^{-3}}\right]^{-0.95}$$

$$\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(8.4 \pm 1.0\right)\cdot 10^{-11}$$

$$\mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right) = \left(3.4 \pm 0.6\right)\cdot 10^{-11}$$

Section 3

ε'/ε, ε_K, $K \to \pi\nu\bar{\nu}$, ΔM_K

beyond SM

AJB (1601.00005)

What are the implications of NP in ε'/ε and ε_K on $K \to \pi\nu\bar{\nu}$ and ΔM_K ?

ε'/ε within SM

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

$$\left\{\frac{\mathrm{Re}A_2}{\mathrm{Re}A_0}\approx\frac{1}{22}\qquad \frac{\mathrm{Im}C_6}{\mathrm{Im}C_8}\approx 90\qquad \frac{\langle Q_8\rangle_2}{\langle Q_6\rangle_0}\approx 2\right\}\Rightarrow$$ 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 (not in this talk)

General Z´ at Work

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

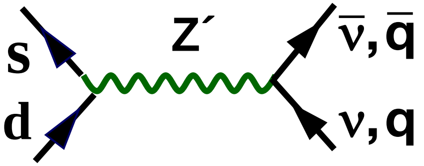
Here : $\varepsilon'/\varepsilon,\ K^+ \to \pi^+ \nu\bar{\nu},\ K_L \to \pi^0 \nu\bar{\nu},\ \Delta M_K$

Q_6, Q_6' – **QCD Penguin operators**

Q_8, Q_8' – **Electroweak Penguin operators**

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

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



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

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

↓

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

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

Basic Structure of NP Contributions

AJB (1601.00005)

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

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

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

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

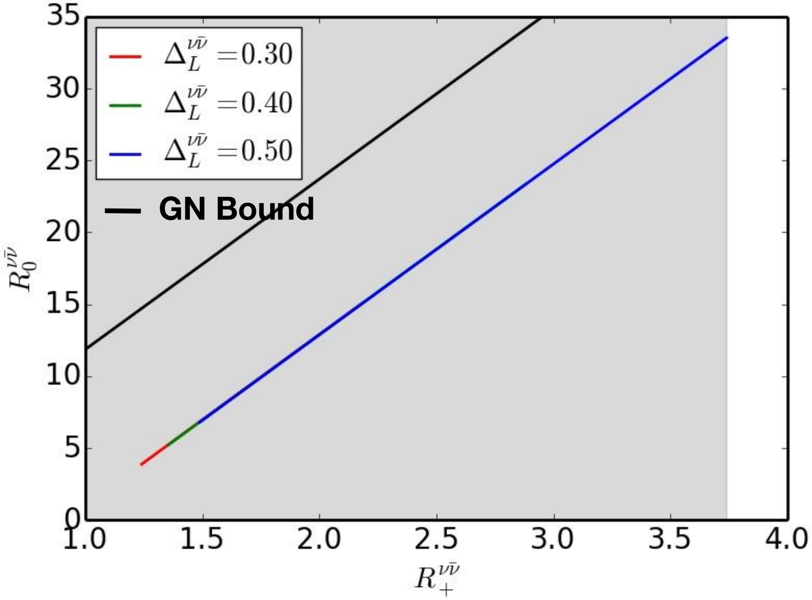
Dominance of $Q_8\left(Q_8'\right) \Rightarrow {\rm Re} \gg {\rm Im} \Rightarrow \left\{\Delta M_K^{\rm NP} > 0\right\}$ (small)

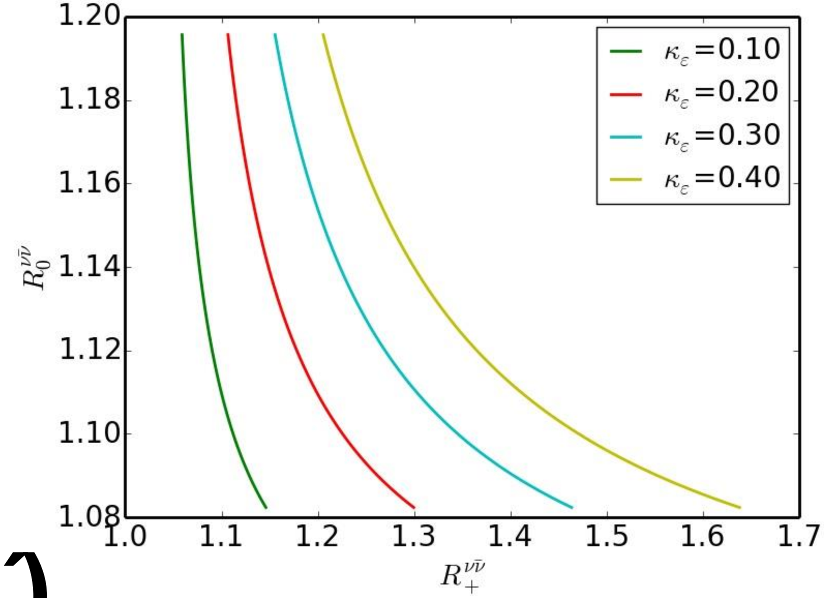
Distinction between these scenarios

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

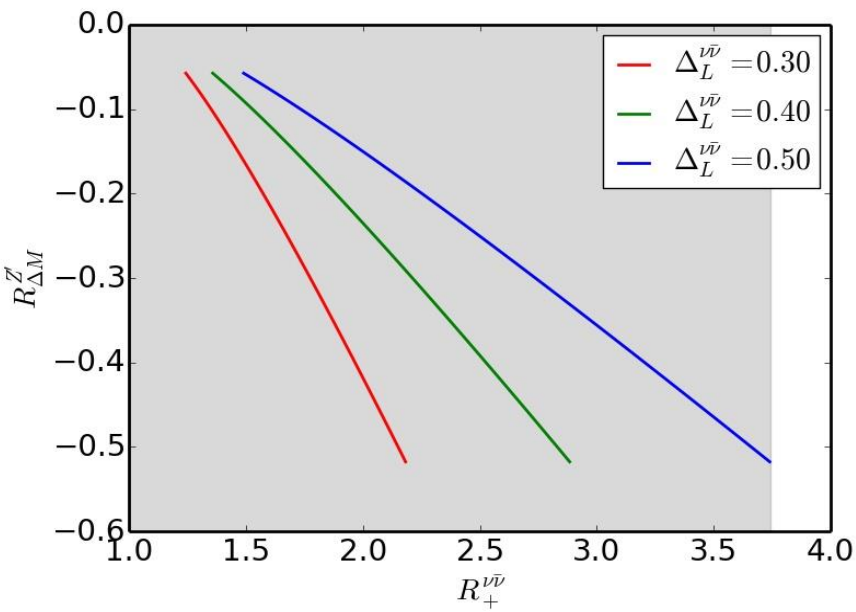
QCDP (Q_6) $(0.5 < \kappa_{\varepsilon'} < 1.5)$ **EWP (Q_8)**





(Z′)

$\left(R^{Z'}_{\Delta M} > 0 \text{ but small}\right)$

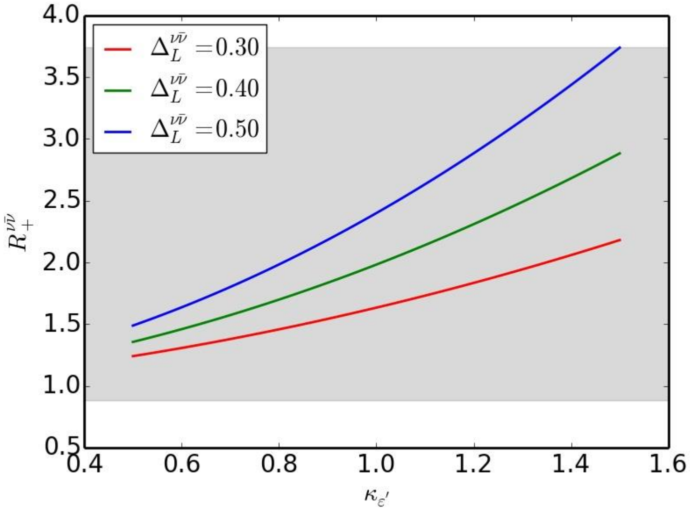


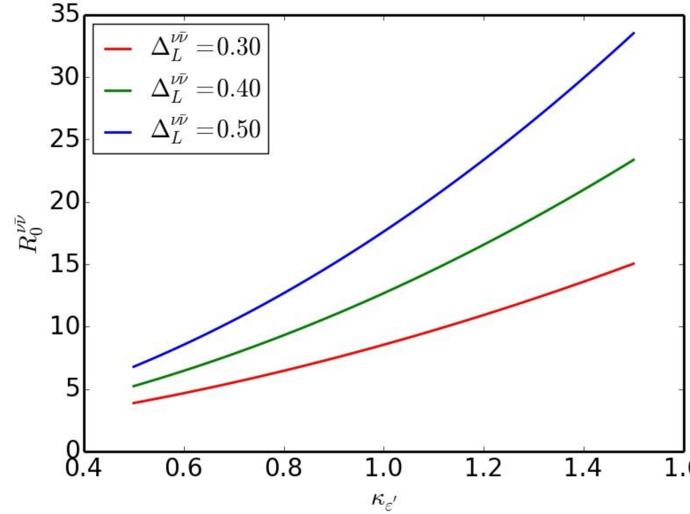
$$R_+^{\nu\bar\nu} = \frac{Br\left(K^+ \to \pi^+ \nu\bar\nu\right)}{Br\left(K^+ \to \pi^+ \nu\bar\nu\right)_{SM}}$$

$$R_0^{\nu\bar\nu} = \frac{Br\left(K_L \to \pi^0 \nu\bar\nu\right)}{Br\left(K_L \to \pi^0 \nu\bar\nu\right)_{SM}}$$

$$R^{Z'}_{\Delta M} = \frac{\left(\Delta M_K\right)^{NP}}{\left(\Delta M_K\right)^{exp}}$$

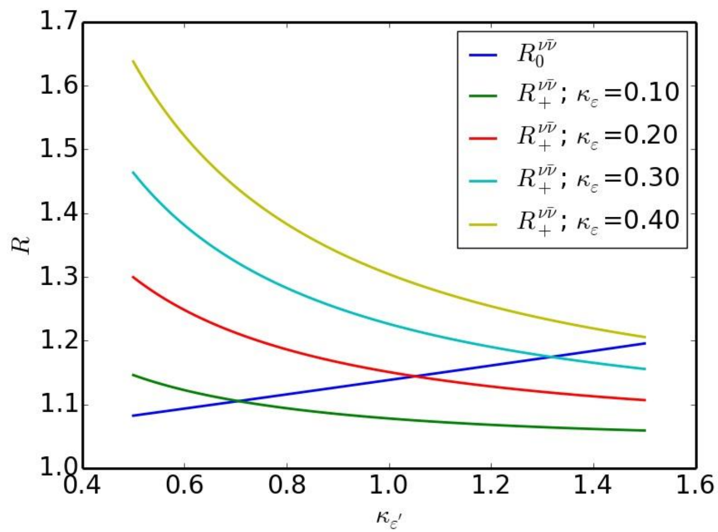
QCD Penguin (Q_6)





Electroweak Penguin (Q_8)

(Z´)



Section 5

BSM Models and ε′/ε

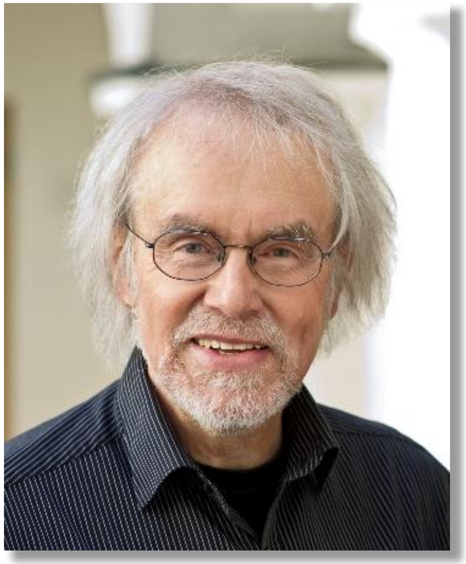
NP Models and ε´/ ε Anomaly

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)

Leptoquarks meet ε′/ ε and rare K Processes

1712.01295

Christoph Bobeth



AJB

ε'/ε and rare K Processes

1. Assuming that the upper bound on $(\varepsilon'/\varepsilon)_{SM}$ from Dual QCD is correct: Largest anomaly!

2. But in contrast to R_D, R_{D^*} (LQs contribute there at tree level) in ε'/ε leptoquarks contribute at one-loop (RG running and box contributions)

   ⇨ **Large Im(Y) couplings required**

3. Problems with rare decays

   $K \to \pi\nu\bar{\nu}$, $K_L \to \pi^0 l^+ l^-$, $K_S \to \mu^+\mu^-$ (tree – level)

   but also ΔM_K, ε_K

Leptoquark Models

Scalar Leptoquark	$SU(2)_L$	Vector Leptoquarks
S_1	singlet	U_1
$\tilde{S}_1$	singlet	$\tilde{U}_1$
R_2	doublet	V_2
$\tilde{R}_2$	doublet	$\tilde{V}_2$
S_3	triplet	U_3

Favoured by B-physics anomalies

U_1

Barbieri et al
Isidori et al
Crivellin et al

S_1, S_3

Crivellin et al (1703.09226)
Buttazzo et al (1706.07808)

$S_3, \tilde{R}_2$

Fajfer et al (1706.0779)

Eliminating Leptoquarks as origin of ε'/ε anomaly

Bobeth + AJB 1712.01295

Step 1 $\tilde{U}_1, \tilde{V}_2$ do not contribute to ε'/ε

Step 2 $\tilde{S}_1, \tilde{R}_2, S_3, U_3$

do not generate Q_8 operator through RG

Im (Yukawa) very large to get ε'/ε ⇒ Bounds on $K \to \pi\nu\bar{\nu}$, $K_L \to \pi^0 l^+ l^-$, ΔM_K strongly violated

Step 3 S_1, R_2, V_2, U_1 almost ruled out

Disfavoured (S_1, R_2, V_2)

$C_9^{NP} = C_{10}^{NP}$

Favoured by B-physics (U_1)

$\left(C_9^{NP} = -C_{10}^{NP}\right)$

Basic Dynamics for ε´/ ε in Leptoquark Models

Renormalization Electroweak Evolution from M_{LQ} to low-energy + QCD evolution enhancing Q_8

(SMEFT)

Semi-leptonic Operators of Leptoquark models ⇒ Non-leptonic Operators contributing to ε´/ ε

(log M_{LQ} / μ_{EW} enhanced)

Box-Diagrams in models with left-handed and right-handed couplings contributing directly to ε´/ ε (Q_8)

: selects S_1, R_2, U_1, V_2

↑ Favoured by B-physics anomalies

U_1 Model meets ε'/ε and rare K Decays

1. Generation of Q_8 through RG group! (+)

2. No tree-level contributions to $K \to \pi\nu\bar{\nu}$, generated through RG but still consistent with bounds even for $\kappa_{\varepsilon'} \approx 1.0$ (+)

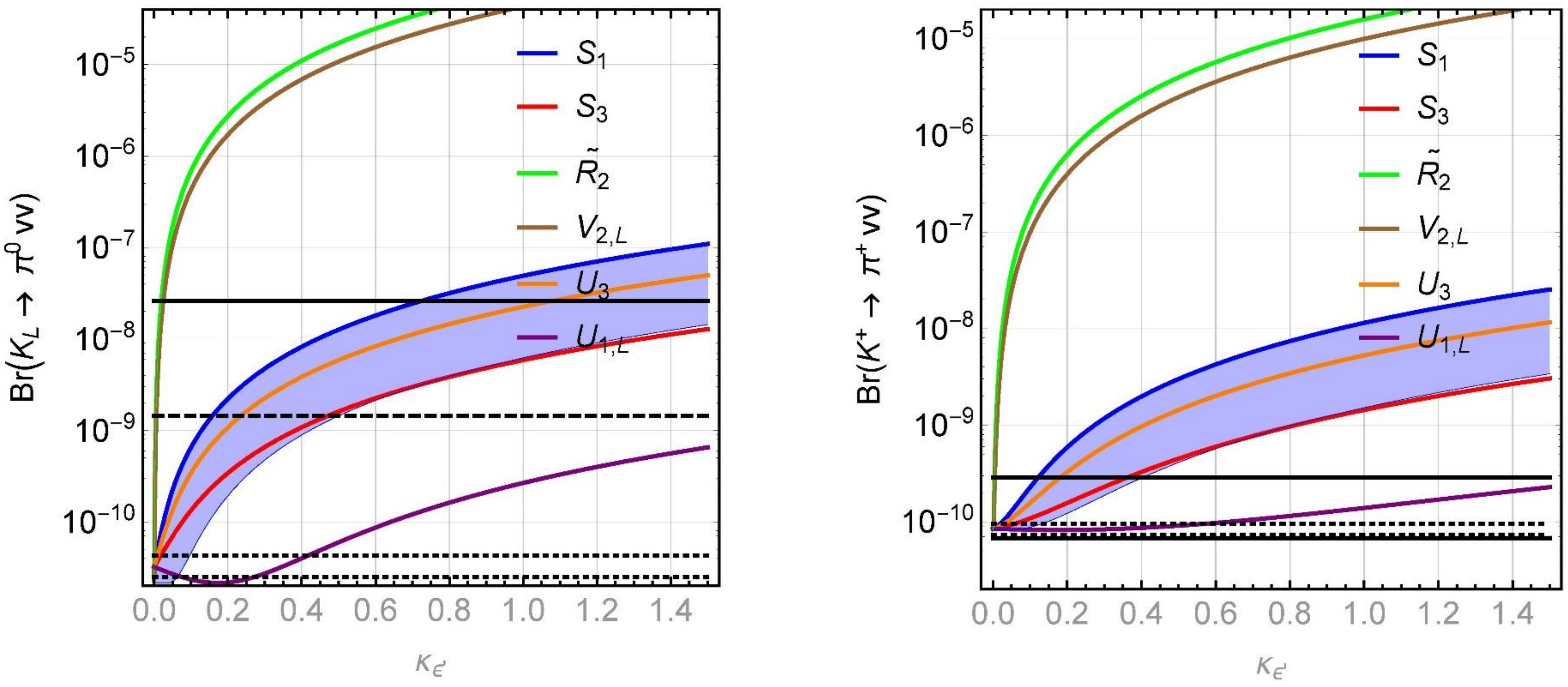
3. If only left-handed or right-handed couplings present ruled out through

$$\left(K_L \to \pi^0 e^+ e^-,\ K_L \to \pi\mu^+\mu^+,\ K_S \to \mu^+\mu^- \right)$$

(the only hope: couplings between τ and d, s) (-)

4. Box contributions with left- and right-handed couplings could help but UV completion needed to do the calculation. Would also generate LR contributions to ΔM_K, ε_K : very dangerous! (?)

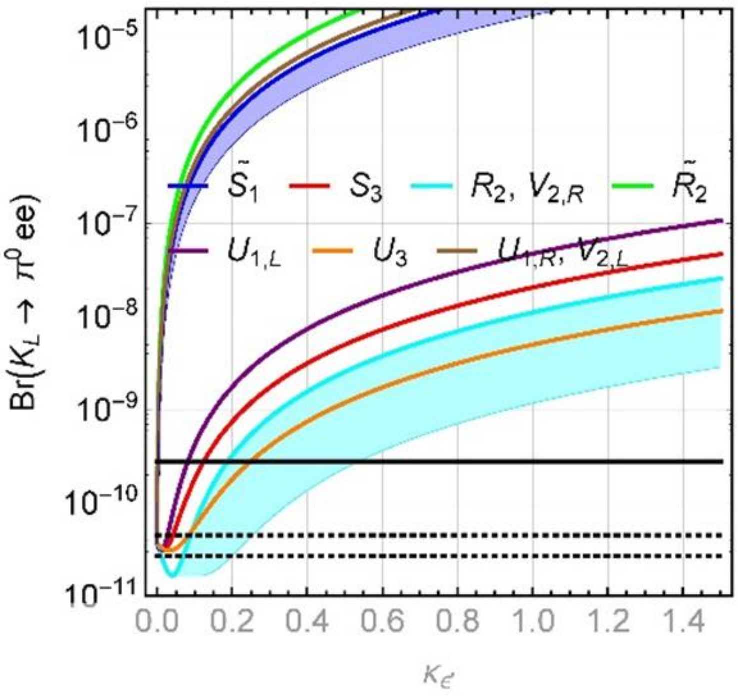
Leptoquarks facing ε'/ε and $K \to \pi\nu\bar{\nu}$

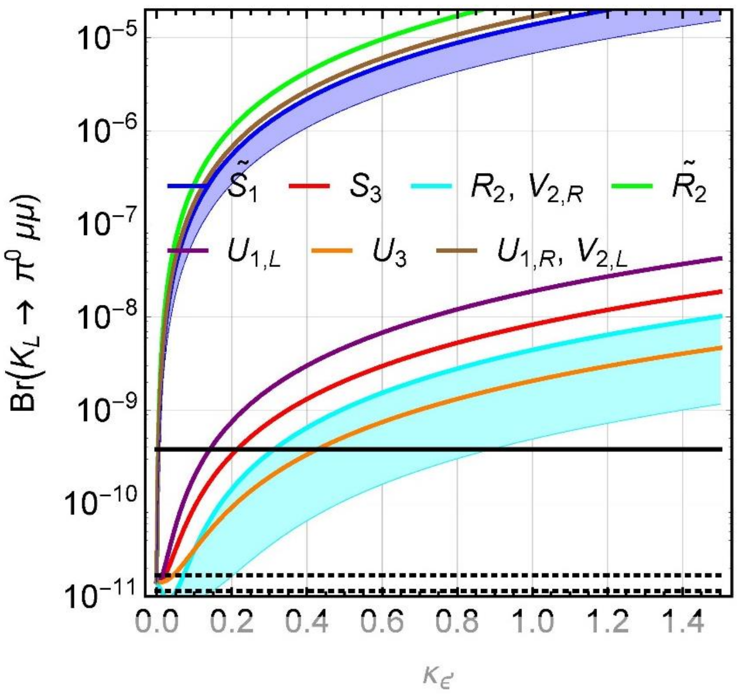


——— **Exp. Bound**

-------- **Grossman-Nir Bound**

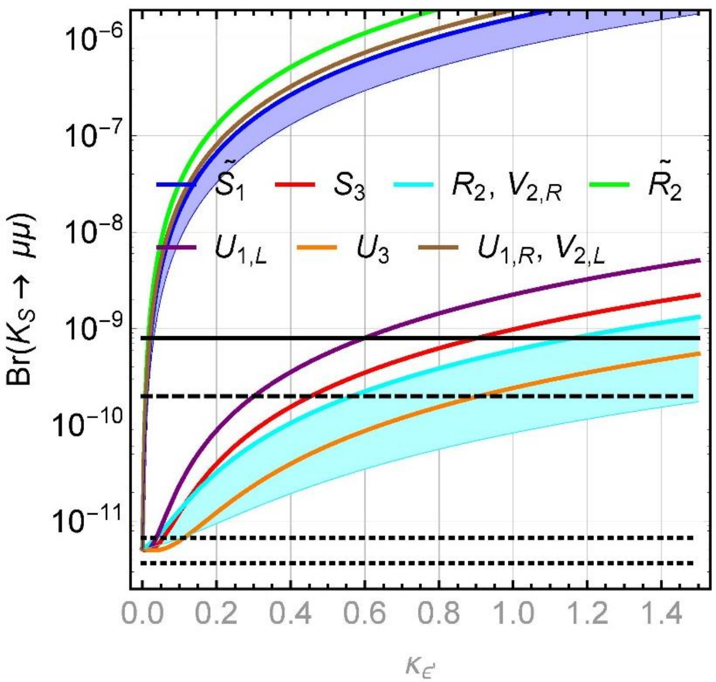
Leptoquarks facing ε'/ε and $K_L \to \pi^0 l^+ l^-$

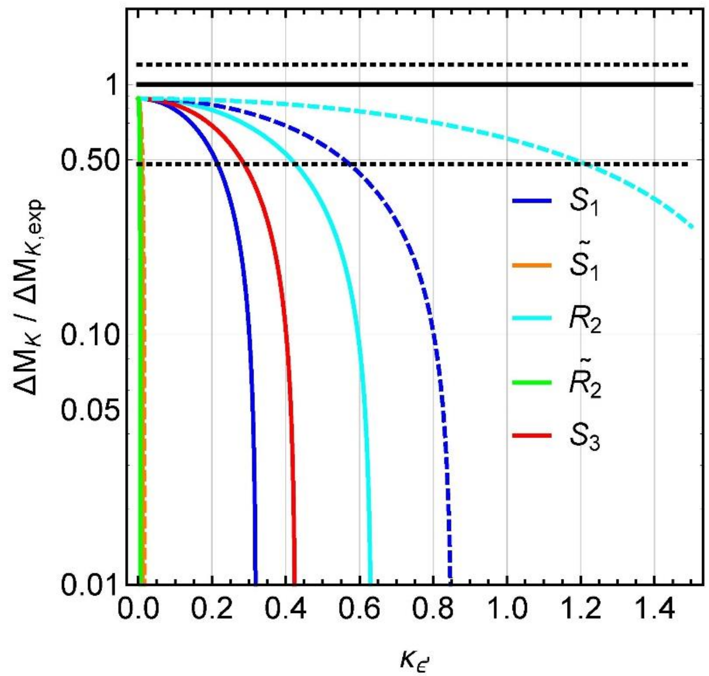




——— **Exp. Bound**

Leptoquarks facing ε'/ε and $K_S \to \mu\mu$





——— Exp. Bound (LHCb 2017)

-------- Future LHCb Bound

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

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 !**

Open Questions for Coming Years

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

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

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

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

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

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

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

$(g-2)_\mu$

ε'/ε

$\Delta I = 1/2$ Rule, ΔM_K

Exciting Times are just ahead of us !!!

Exciting Times are just ahead of us !!!

Thank You !

Finding Anomaly in ε′/ε
Norway: 2015