Dual QCD @ Work

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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

[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

$(\Delta I = 1/2$ 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

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

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

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:

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

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

$\mu \approx 1-3$ 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 40 min

1. Dual QCD

2. ε'/ε strikes back

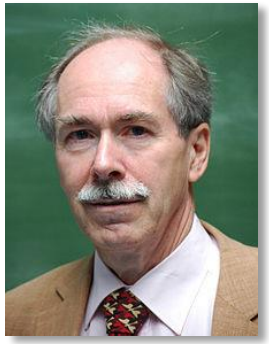
3. ε'/ε Beyond SM

4. ε'/ε vs $K \to \pi\nu\bar{\nu}$

5. 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.

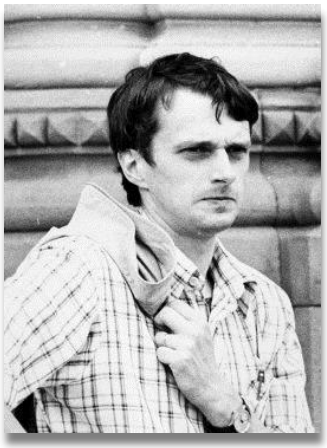
Dual QCD Approach for Weak Decays

Successful low energy approximation of QCD

1985

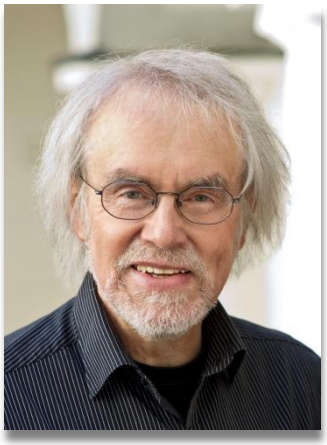
W. Bardeen

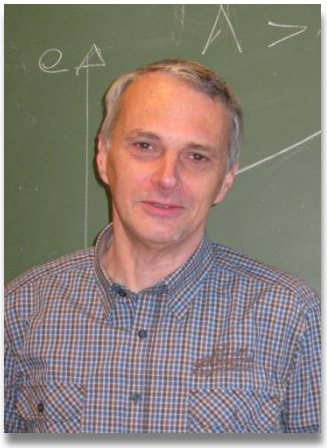
AJB



J.-M. Gérard

2014





Basics of Dual QCD

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

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

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

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

$\Pi =$ octet of pseudoscalar mesons

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

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

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

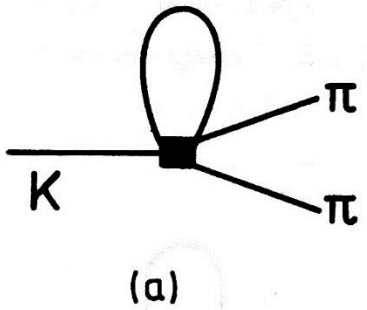
Meson representation of

quark-currents

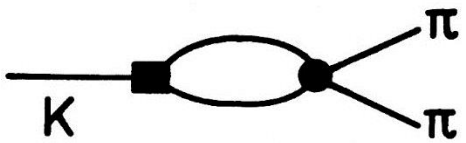
quark-densities

Meson Evolution

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



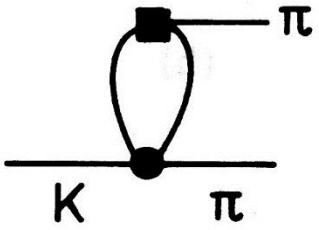
(a)



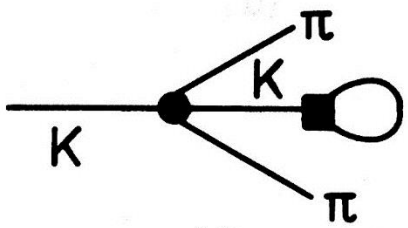
(b)

■ weak

● strong



(c)



(d)

Very different philosophy from Chiral PTh

No dimensional regularisation !!!

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

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

SM and BSM Operators

Reviews: 1401.1385, 1408.4820, 1809.02616

Λ_{NP}

EW

SMEFT with SM and BSM Operators

RG Evolution
α_s, α_2, α_1
top Yukawa

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

α_s, α_{QED}

1 GeV

$\Lambda_{DQCD} \approx 0.8$ GeV

Non-Factorizable contributions

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

$(N \to \infty)$

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.

★ Very different philosophy from Chiral PTh in which meson evolution not included.

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 QCD dynamics below 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

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

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

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 RBC-UKQCD $R = 31 \pm 11$

(2012) 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: $B_6^{1/2} = B_8^{3/2} = 1$ $(\mu \approx 0(m_\pi))$

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 $\mu \geq 1$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

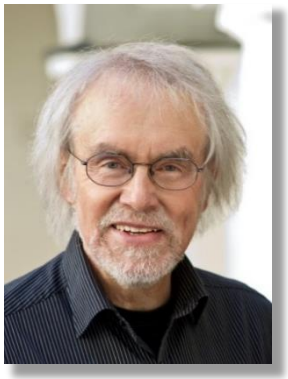
$B_{CMO} \approx 1/3$

Much smaller than early estimates in chiral quark model

2. Confirmation 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

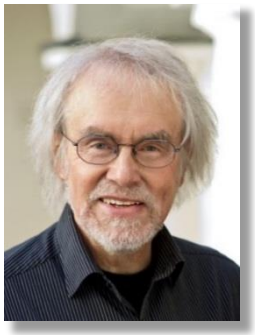
J.-M. Gérard

(1807.01709)

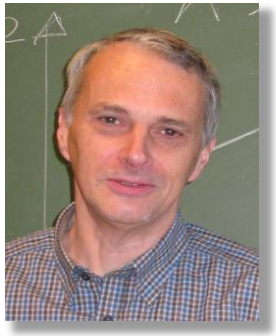
Master Formula for ε′/ε Beyond SM (1807.02520)

Jason Aebischer

Christoph Bobeth

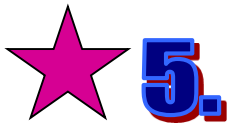


AJB



Jean-Marc Gérard

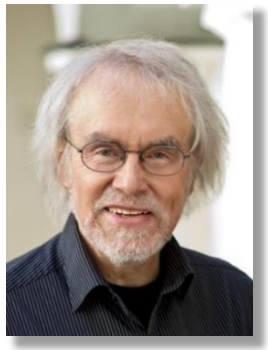
David Straub



Anatomy of ε′/ε Beyond SM (1808.00466) First SMEFT analysis

Jason Aebischer

Christoph Bobeth



AJB

David Straub

Section 2

ε'/ε strikes back

Main Actors in ε´/ε in SM

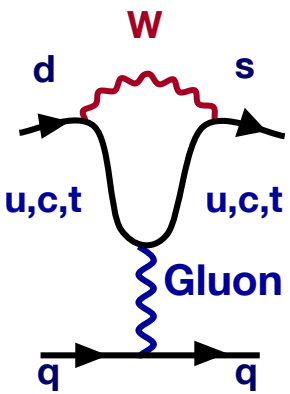
Q_6 – QCD Penguin operator

Q_8 – Electroweak Penguin operator

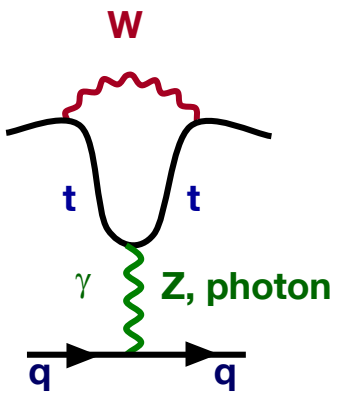
$$Q_6 = \left(\bar{s}_\alpha d_\beta\right)_{V-A} \sum_q \left(\bar{q}_\beta q_\alpha\right)_{V+A}$$

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

$Q_6 =$



$Q_8 =$



QCD and Electroweak Penguin Matrix Elements

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

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

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

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

Four dominant contributions to ε'/ε in the SM

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

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

From $\mathrm{Re}A_0$ → -3.6 term; From $\mathrm{Re}A_2$ → 1.2 term

(NLO) (Q_4)

-3.6	$21.4\cdot B_6^{(1/2)}$	1.2	$-10.4\cdot B_8^{(3/2)}$
(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 $\mathrm{Re}A_0$ and $\mathrm{Re}A_2$ ($\Delta I=1/2$ Rule) fully described by SM (includes isospin breaking corrections)

Extracted from ⇩ RBC-UKQCD :

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

$B_6^{(1/2)} = 0.57 \pm 0.19$ $\quad$ $B_8^{(3/2)} = 0.76 \pm 0.05$

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 $\mu \geq 1$GeV

RBC-UKQCD

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

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

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

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

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

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

(NLO)

Present Status of ε'/ε in the SM

Oct 2nd 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. (No meson evolution!!)
Experiment (NA48, KTeV)	$(\varepsilon'/\varepsilon)^{exp} = (16.6 \pm 2.3) \cdot 10^{-4}$	

Additional Messages

1. NNLO Corrections to **electroweak penguins**
(not included in any analysis yet)
AJB, Gambino, Haisch (1998)

$$\Delta(\varepsilon'/\varepsilon) \approx -1.3 \cdot 10^{-4}$$

Remove large renormalization scheme dependence from NLO + scale dependence in $m_t(\mu)$

2. NNLO Corrections to **QCD penguins**
Maria Cerda-Sevilla, Martin Gorbahn, Sebastian Jäger, Ahmet Kokulu

$$\Delta(\varepsilon'/\varepsilon) \approx \boxed{?} \cdot 10^{-4}$$

3. Meson Evolution suppressing ε'/ε significantly more important than enhancement through FSI (claimed by Pallante + Pich)

AJB + Gérard (1603.05686)

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

$$O_1 = \left(\bar{s}^\alpha \gamma_\mu P_L d^\alpha\right)\left(\bar{s}^\beta \gamma_\mu P_L d^\beta\right) \to B_1$$

BSM

$$\begin{cases} O_2 = \left(\bar{s}^\alpha P_L d^\alpha\right)\left(\bar{s}^\beta P_L d^\beta\right) \to B_2 \\ O_3 = \left(\bar{s}^\alpha P_L d^\beta\right)\left(\bar{s}^\beta P_L d^\alpha\right) \to B_3 \\ O_4 = \left(\bar{s}^\alpha P_L d^\alpha\right)\left(\bar{s}^\beta P_R d^\beta\right) \to B_4 \\ O_5 = \left(\bar{s}^\alpha P_L d^\beta\right)\left(\bar{s}^\beta P_R d^\alpha\right) \to B_5 \end{cases}$$

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

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

$N \to \infty$

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-UKQCD)

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					
					} 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

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

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1 GeV					
					} 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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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					
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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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 (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?

It looks like

Dual QCD congratulates NA48 + KTeV for the Discovery of New Sources of CP-Violation in ε′/ε (2002)

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 (1808.00466)

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´

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_t)

All listed in

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

Operators with Largest P_i

ABBGS (1808.00466)

(Most efficient in explaining ε'/ε anomaly)

$$O^u_{VLR} = \left(\bar{s}^i \gamma_\mu P_L d^i\right)\left(\bar{u}^j \gamma^\mu P_R u^j\right)$$

$$\tilde{O}^u_{VLR} = \left(\bar{s}^i \gamma_\mu P_L d^j\right)\left(\bar{u}^j \gamma^\mu P_R u^i\right)$$

$$O^d_{VLR} = \left(\bar{s}^i \gamma_\mu P_L d^i\right)\left(\bar{d}^j \gamma^\mu P_R d^j\right)$$

$$\tilde{O}^d_{VLR} = \left(\bar{s}^i \gamma_\mu P_L d^j\right)\left(\bar{d}^j \gamma^\mu P_R d^i\right)$$

$(+ P_L \leftrightarrow P_R)$

Present already in SM

(i, j = 1,2,3, colour) (generate Q_6, Q_8)

$$O^u_{TLL} = \left(\bar{s}^i \sigma_{\mu\nu} P_L d^i\right)\left(\bar{u}^j \sigma^{\mu\nu} P_L u^j\right)$$

$$\tilde{O}^u_{TLL} = \left(\bar{s}^i \sigma_{\mu\nu} P_L d^j\right)\left(\bar{u}^j \sigma^{\mu\nu} P_L u^i\right)$$

$$O^d_{TLL} = \left(\bar{s}^i \sigma_{\mu\nu} P_L d^i\right)\left(\bar{d}^j \sigma^{\mu\nu} P_L d^j\right)$$

$$O^u_{SLR} = \left(\bar{s}^i P_L d^i\right)\left(\bar{u}^j P_R u^j\right)$$

New Operators
(related to scalar-scalar operators by Fierz identities)

Forbidden in
SMEFT = $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
Allowed by $SU(3)_C \otimes U(1)_Q$

NP Models and ε'/ε Anomaly (Only SM operators)

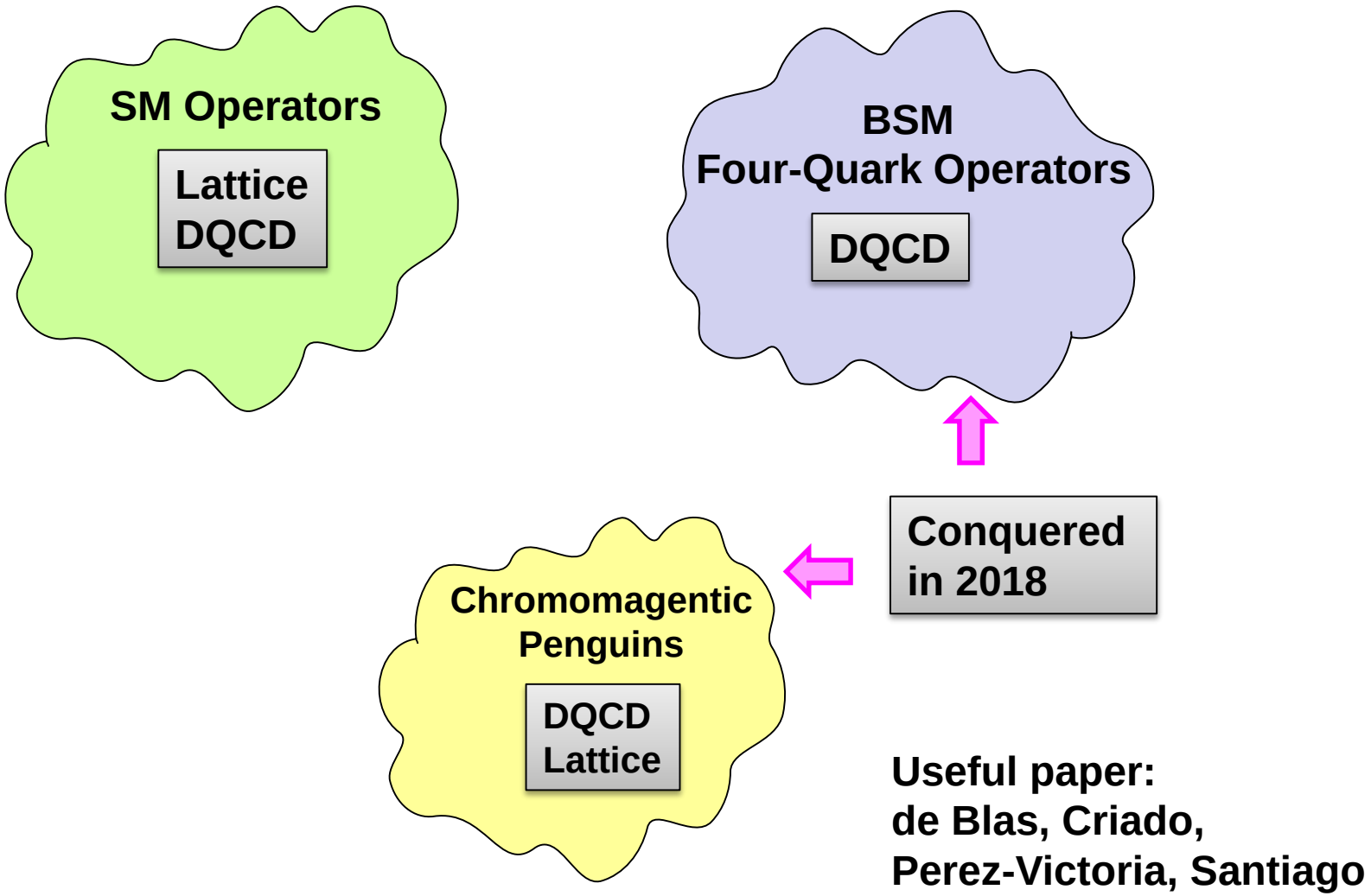
Littlest Higgs (T parity)	Blanke, AJB, Recksiegel (1507.06316)
Z-FCNC	AJB (1601.00005), Bobeth, AJB, Celis, Jung (1703.04753) Endo, Kitahara, Mishima, Yamamoto (1612.08839)
Z´-Models	AJB (1601.00005), AJB, Buttazzo, Knegjens (1507.08672)
331- Models	AJB, De Fazio (1512.02869, 1604.02344)
Vector-Like 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)

NP Models and ε′/ε Anomaly continued

2HDM	**Chen, Nomura (1804.06017, 1805.07522)**
SU(8)	**Matsuzaki, Nishiwaki, Yamamoto (1806.02312)**
Diquarks	**Chen, Nomura (1808.04097)**

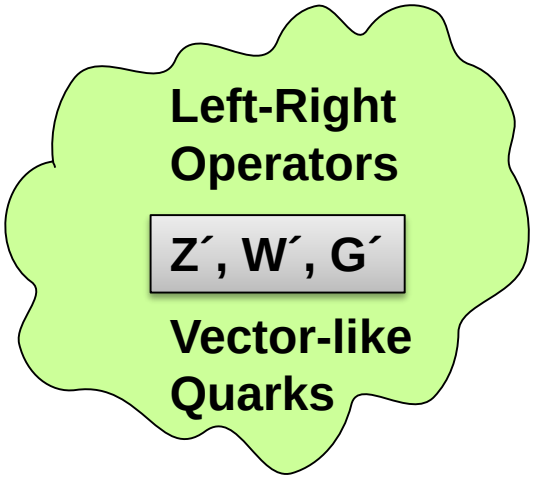
Islands of K $\to \pi\pi$ Matrix Elements

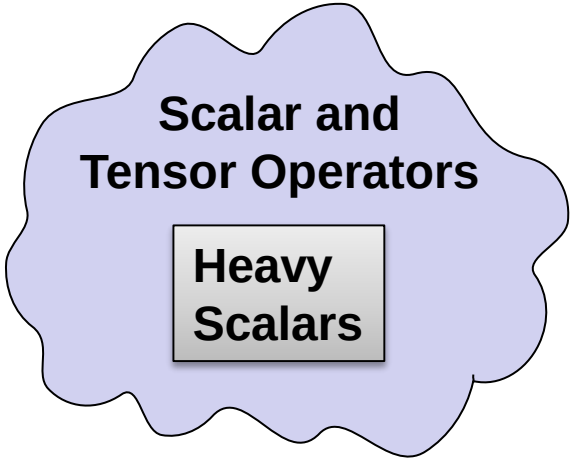
ABBS (1808.00466)



Useful paper:
de Blas, Criado,
Perez-Victoria, Santiago
(1711.10391)

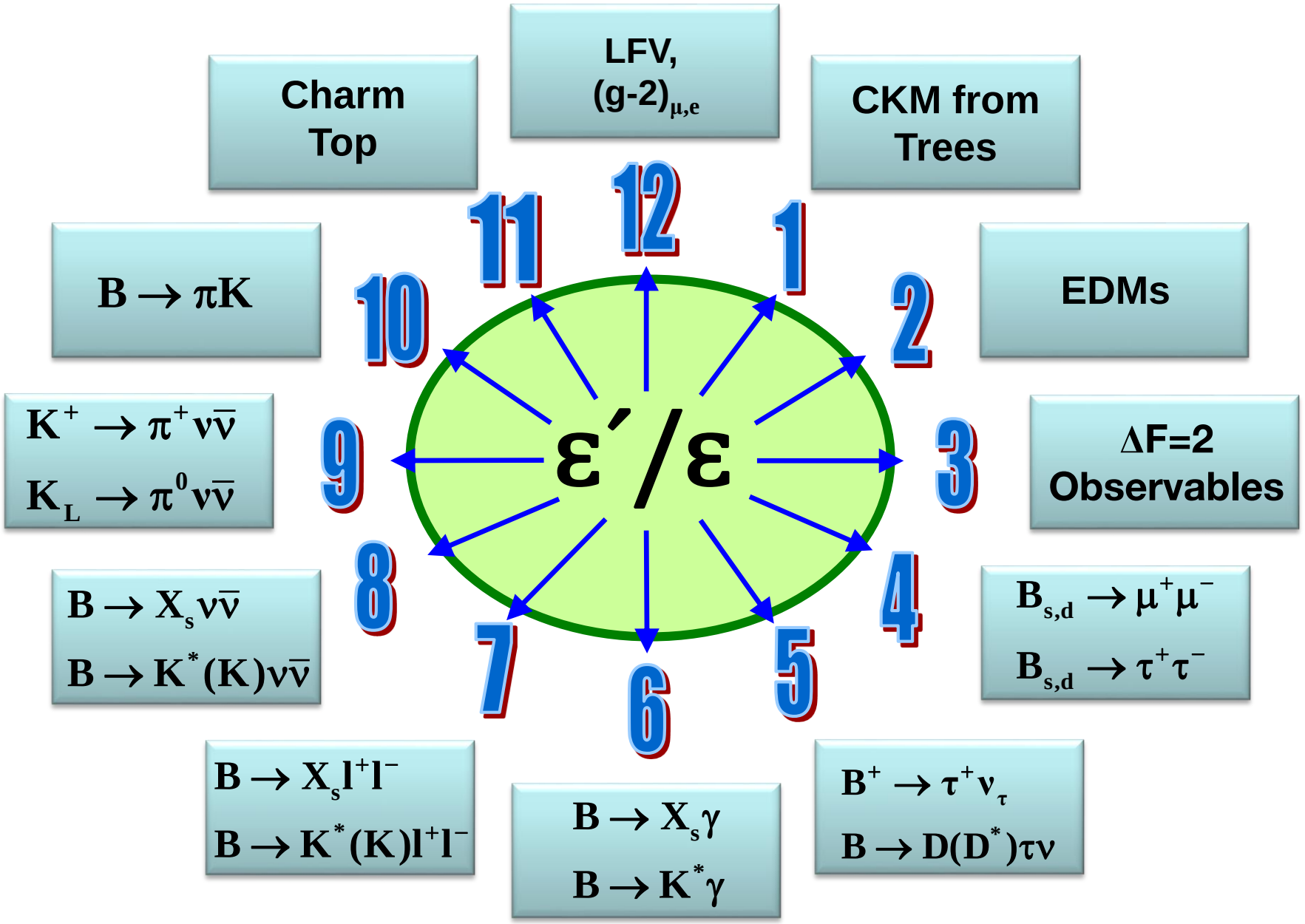
Most important for ε´/ε Anomaly





Unexplored island

BSM anatomy of ε´/ε : Aebischer, Bobeth, AJB, Straub (1808.00466) SMEFT analysis


LFV, $(g-2)_{\mu,e}$
Charm
Top
CKM from Trees
$B \to \pi K$
EDMs
$K^+ \to \pi^+ \nu\bar{\nu}$
$K_L \to \pi^0 \nu\bar{\nu}$
$\Delta F=2$ Observables
$B \to X_s \nu\bar{\nu}$
$B \to K^*(K) \nu\bar{\nu}$
$B_{s,d} \to \mu^+\mu^-$
$B_{s,d} \to \tau^+\tau^-$
$B \to X_s l^+ l^-$
$B \to K^*(K) l^+ l^-$
$B \to X_s \gamma$
$B \to K^* \gamma$
$B^+ \to \tau^+ \nu_\tau$
$B \to D(D^*) \tau\nu$
ε'/ε
12
1
2
3
4
5
6
7
8
9
10
11

Section 4

ε'/ε and $K \to \pi\nu\bar{\nu}$

Lessons beyond the SM

AJB: 1601.00005; 1805.11096
Aebischer, Bobeth, AJB, Straub: 1808.00466

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

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

\+ **Isospin breaking corrections**

→ **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

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(17.3 \pm 11\right) \cdot 10^{-11}$$
$$Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) \leq 3.0 \cdot 10^{-9}$$

(KOTO)

CKM Uncertainties

AJB, Buttazzo, Girrbach-Noe, Knegjens 1503.02693

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

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

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

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

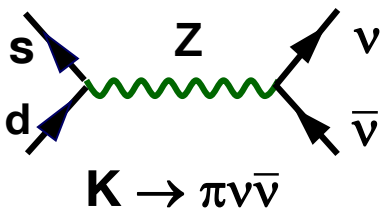
$$\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(8.4 \pm 1.0\right) \cdot 10^{-11}$$

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

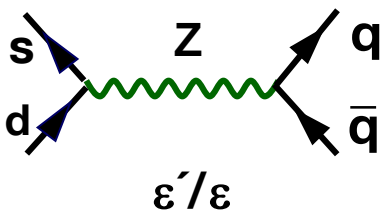
Links between $(\varepsilon'/\varepsilon)_{BSM}$ and $(K \to \pi\nu\bar{\nu})_{BSM}$

With few exceptions these links are not direct unless one makes specific assumptions about flavour diagonal couplings:

Examples



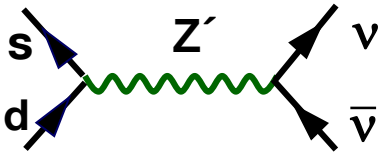
$K \to \pi\nu\bar{\nu}$

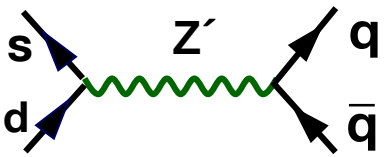


ε'/ε

$Z\nu\bar{\nu}$
$Zq\bar{q}$

known





$Z'\nu\bar{\nu}$
$Z'q\bar{q}$

arbitrary and unrelated to each other

In loop induced decays concrete models are required, but often in view of many parameters no strict relation.

(MSSM, L-R symmetric models)

RG Effects: $\varepsilon'/\varepsilon \leftrightarrow K \to \pi\nu\bar{\nu}$

(1808.00466)

In both directions governed by QED and EW effects

(Model independent)

1. **Large enhancement of ε'/ε does not imply large effects in $K \to \pi\nu\bar{\nu}$**

2. **Large enhancements of $K \to \pi\nu\bar{\nu}$ do not imply large enhancement of ε'/ε (Problem for leptoquark models)**

Induced Z-mediated FCNCs

LH FCNCs

Enhancement of ε'/ε implies
suppression of $K_L \to \pi^0 \nu\bar{\nu}$
$\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) \leq 2\ \mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)_{SM}$

($K_L \to \mu\bar{\mu}$ bound)

RH FCNCs

Suppression of $K_L \to \pi^0 \nu\bar{\nu}$
$\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) \leq 1.5\ \mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)_{SM}$

(ε_K bound SMEFT)

LH+RH FCNCs

$K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$
can be both enhanced if necessary
(no definite prediction)

Literature:

AJB (1601.00005), Bobeth, AJB, Celis, Jung (1703.04753)
Endo, Kitahara, Mishima, Yamamoto (1612.08839)

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. Scalar, Tensor, Chromomagnetic operators

Z´ mediated FCNCs

Strongly model-dependent

(Constraints from $\Delta S=2$, $\Delta C=2$ can be important)

1. In 331 models $(\varepsilon'/\varepsilon)_{BSM} \leq 8 \cdot 10^{-4}$
but negligible contributions to $K \to \pi\nu\bar{\nu}$

2. In general Z´ models with $Z'\nu\bar{\nu}$, $Z'q\bar{q}$ 0(1)

a) Dominance of Q_8 (EWP): Both $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$ in ε'/ε can be moderately enhanced

b) Dominance of Q_6 (QCDP): Enhancement of ε'/ε implies large enhancement of $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ (parallel to Grossman-Nir bound)

but (ΔM_K) strongly suppressed

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

General Z´ at Work

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

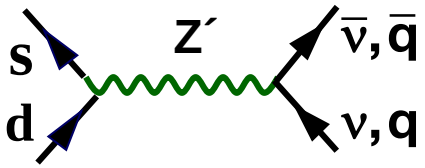
Here : $\varepsilon'/\varepsilon,\ K^+ \to \pi^+ \nu\bar{\nu},\ K_L \to \pi^0 \nu\bar{\nu},\ \Delta M_K$

$Q_6,\ Q_6'$ – QCD Penguin operators

$Q_8,\ Q_8'$ – Electroweak Penguin operators

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

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



Strategy (Z´)

AJB (1601.00005)

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

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

(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)

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

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

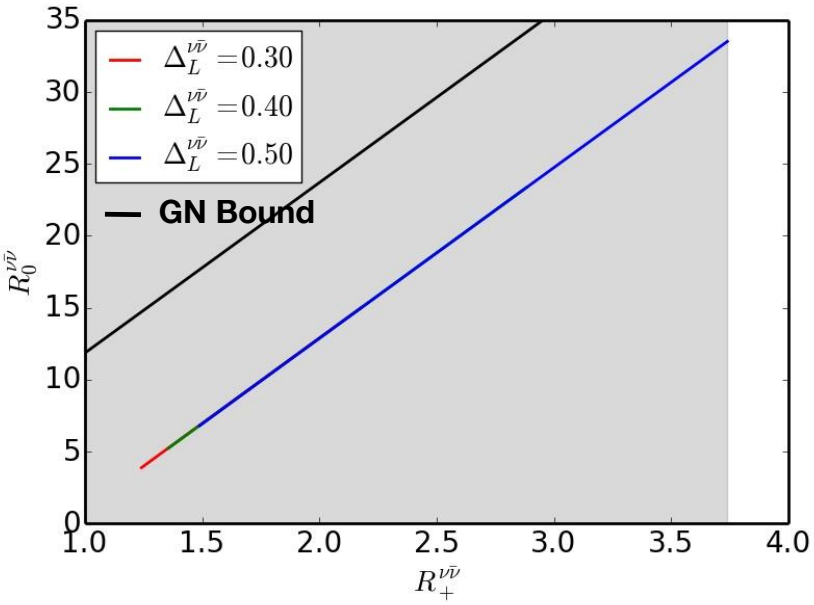
$$\Delta M_K^{NP} \sim \left[(\mathrm{Re})^2 - (\mathrm{Im})^2\right]$$

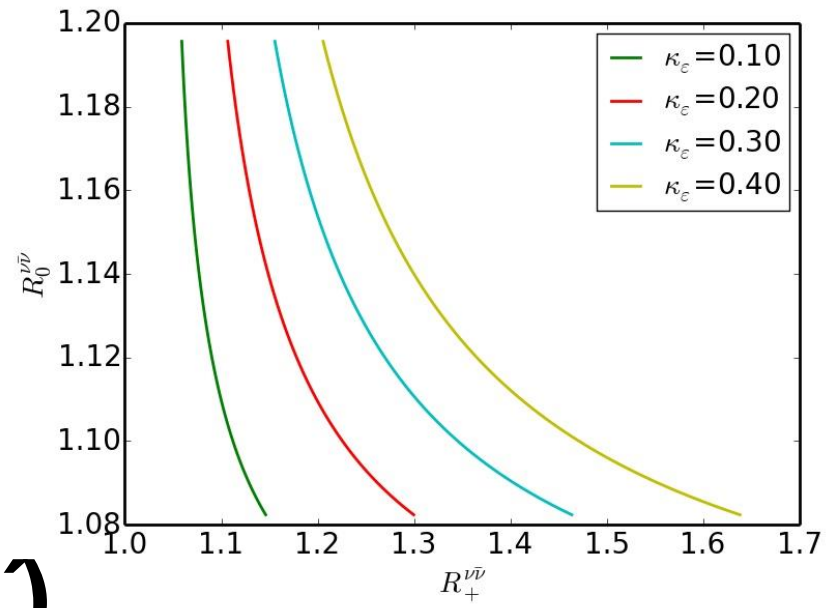
Dominance of $Q_6\left(Q_6'\right) \Rightarrow \mathrm{Im} \gg \mathrm{Re} \Rightarrow \left\{\Delta M_K^{NP} < 0\right\}$ (large)

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

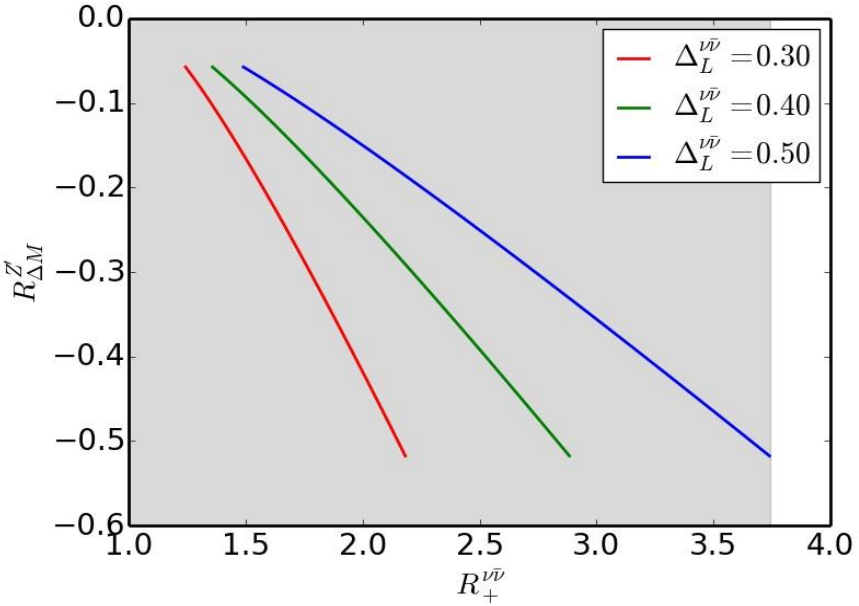
Distinction between these scenarios

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





(Z′)

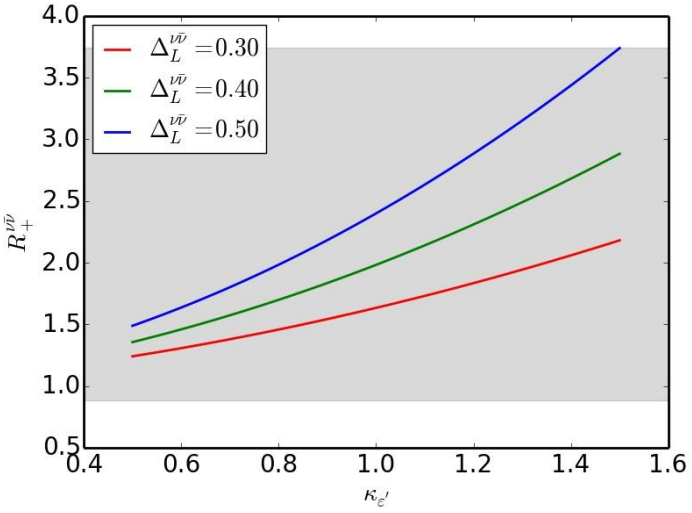


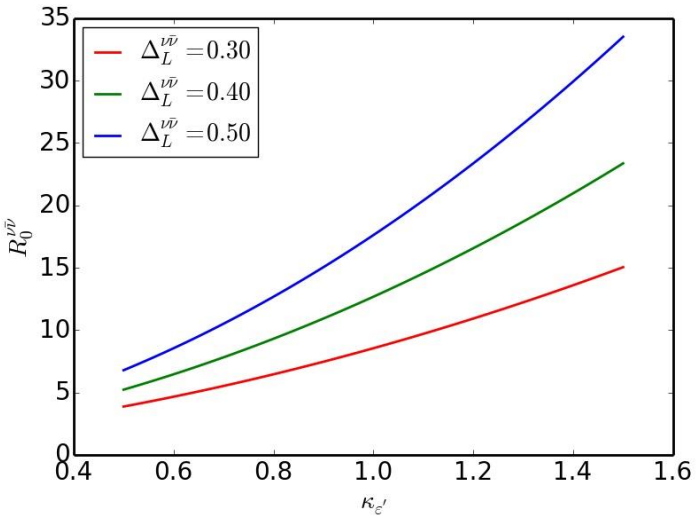
$\left(R_{\Delta M}^{Z'} > 0 \text{ but small}\right)$

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

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

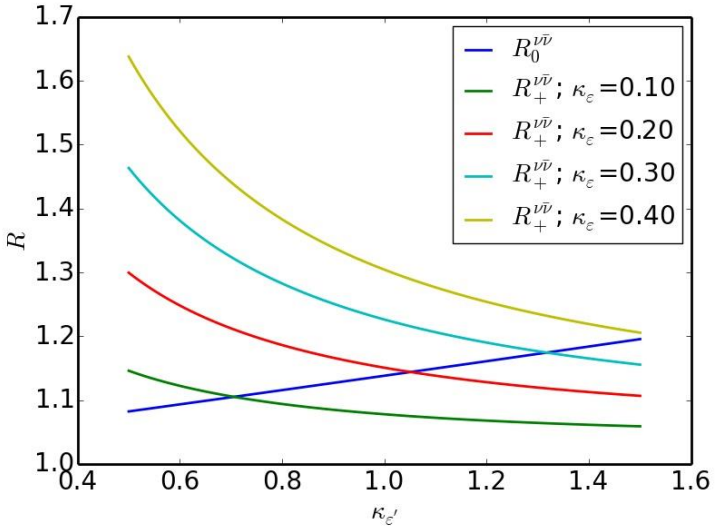
QCD Penguin (Q_6)





Electroweak Penguin (Q_8)

(Z')



ε'/ε and rare K Processes in Leptoquark Models

Bobeth, AJB (1712.01295)

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

Basically only U_1 model survives

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 $\kappa_\varepsilon, \approx 1.0$ +

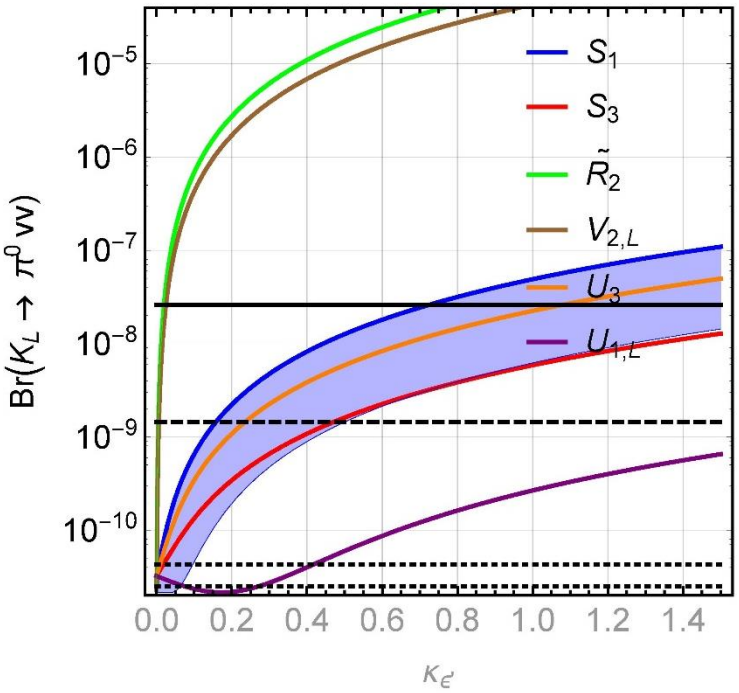
3. If only left-handed or right-handed couplings present ruled out through

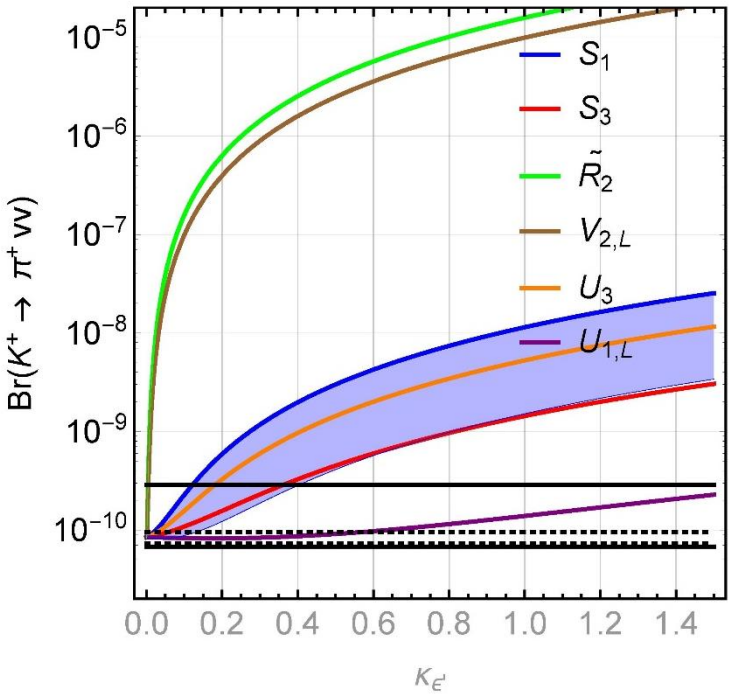
$$\left(K_L \to \pi^0 e^+ e^-,\ K_L \to \pi\mu^+\mu^+,\ K_S \to \mu^+\mu^-\right)$$

(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

U_1

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

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

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 5

Summary

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

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

$(\varepsilon_K)_{SM}$?

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

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

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

Improved Lattice Gauge Theory Calculations

ε'/ε

$\Delta I = ½$ Rule,
ΔM_K

Neutrinos

Exciting Times are just ahead of us !!!

Thank You !

Backup