KAON Physics strikes back

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NA62, Mainz, January 2016

Overture

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)

Confirmed 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 : $(\varepsilon'/\varepsilon) = (1.9 \pm 4.5) \cdot 10^{-4}$

AJB, Gorbahn,
Jäger, Jamin
(1507.06345)

$(\varepsilon'/\varepsilon) = (6.0 \pm 2.4) \cdot 10^{-4}$ 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)
New Strategy (AJB, 1601.00005)

Next 45 min

1. News on $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L \rightarrow \pi^0 \nu \bar{\nu}$ (Standard Model and Beyond) without ε'/ε

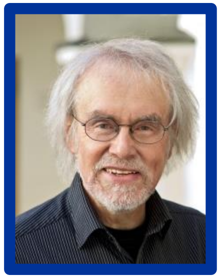
2. ε'/ε strikes back

3. Outlook

Section 1

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

1503.02693 1507.08672



AJB

D.Buttazzo

J.Girrbach-Noe

R.Knegjens

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ and $K_L \rightarrow \pi^0 \nu\bar{\nu}$ 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 $|V_{ub}|, |V_{cb}|, \gamma$

Data

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

General Properties

1. $K^+ \to \pi^+ \nu\bar{\nu}$ CP-conserving

2. $K_L \to \pi^o \nu\bar{\nu}$ CP-violating

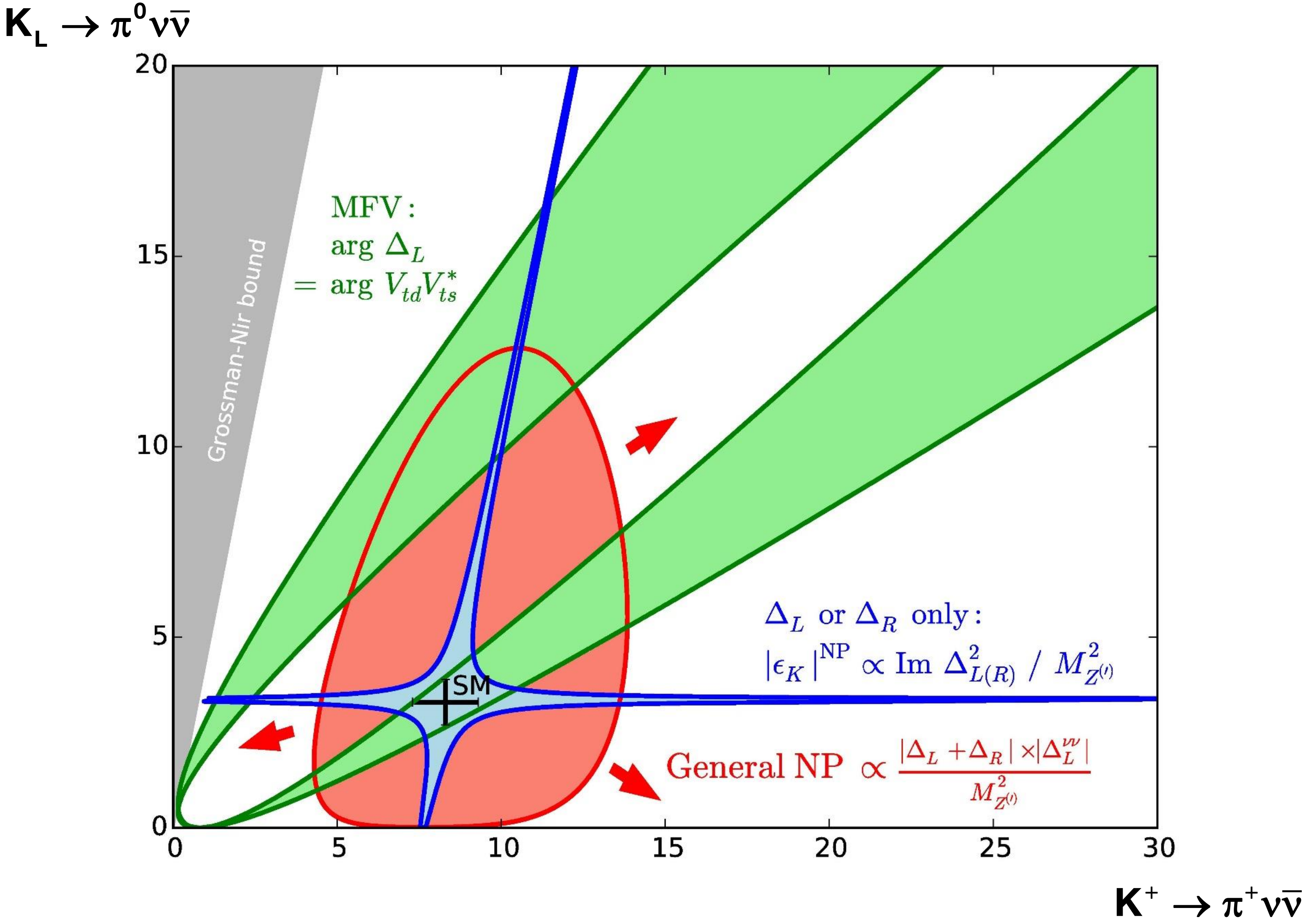
3. Both sensitive to New Physics (NP)
   $K^+ \to \pi^+ \nu\bar{\nu}$ bounded by $K_L \to \mu^+\mu^-$
   $K_L \to \pi^0 \nu\bar{\nu}$ bounded by ε'/ε

4. The correlation between $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ depends on the ε_K constraint (Blanke 0904.2528)

5. Can probe scales far above LHC.

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

AJB, Buttazzo, Knegjens, 1507.08672



Motivations for New Analysis

1. NA62 in progress: 10% measurement of $K^+ \to \pi^+ \nu\bar{\nu}$ in 2018.

2. Stress CKM uncertainties in $\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$, $\mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right)$

3. Point out correlation between

   $$\boxed{K^+ \to \pi^+ \nu\bar{\nu}, \quad B_s \to \mu^+\mu^- \quad \text{and} \quad \gamma}$$

   (NA62) (LHCb+CMS) (LHCb)

4. Update correlation between

   $$\boxed{K^+ \to \pi^+ \nu\bar{\nu}, \quad K_L \to \pi^0 \nu\bar{\nu} \quad \text{and} \quad \beta}$$

   (Buchalla, AJB, 94)
   (AJB, Fleischer, 00)

5. Use most recent lattice input for CKM

6. Provide the present best value in SM

Basically no CKM uncertainties

Using Tree Level Determination of CKM (A)

$$\left|V_{ub}\right|_{excl} = (3.72 \pm 0.14) \cdot 10^{-3} \qquad \left|V_{cb}\right|_{excl} = (39.36 \pm 0.75) \cdot 10^{-3}$$

$$\left|V_{ub}\right|_{incl} = (4.40 \pm 0.25) \cdot 10^{-3} \qquad \left|V_{cb}\right|_{incl} = (42.21 \pm 0.78) \cdot 10^{-3}$$

$$\left|V_{ub}\right|_{avg} = (3.88 \pm 0.29) \cdot 10^{-3} \qquad \left|V_{cb}\right|_{avg} = (40.7 \pm 1.4) \cdot 10^{-3}$$

$$\gamma = \left(73.2\ {}^{+6.3}_{-7.0}\right)^{\circ}$$

$$\overline{\mathrm{Br}}\left(B_s \to \mu^+\mu^-\right) = \left(3.4 \pm 0.3\right) \cdot 10^{-9}$$

$$\overline{\mathrm{Br}}\left(B_s \to \mu^+\mu^-\right)_{exp} = \left(2.8 \pm 0.7\right) \cdot 10^{-9}$$

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

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

AJB, Buttazzo, Girrbach-Noe, Knegjens 1503.02693

CKM Uncertainties

AJB, Buttazzo,
Girrbach-Noe,
Knegjens
1503.02693

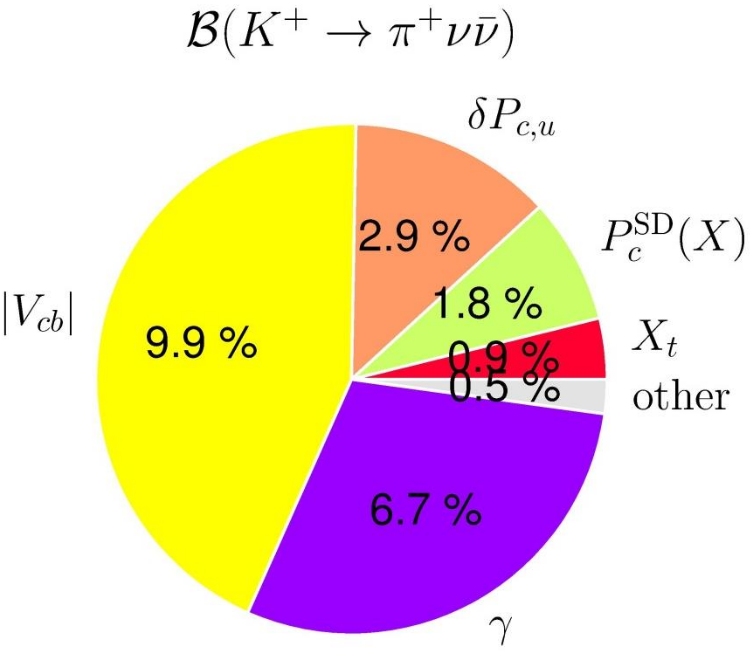
$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(8.39 \pm 0.30\right)\cdot 10^{-11}\left[\frac{|V_{cb}|}{0.0407}\right]^{2.8}\left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

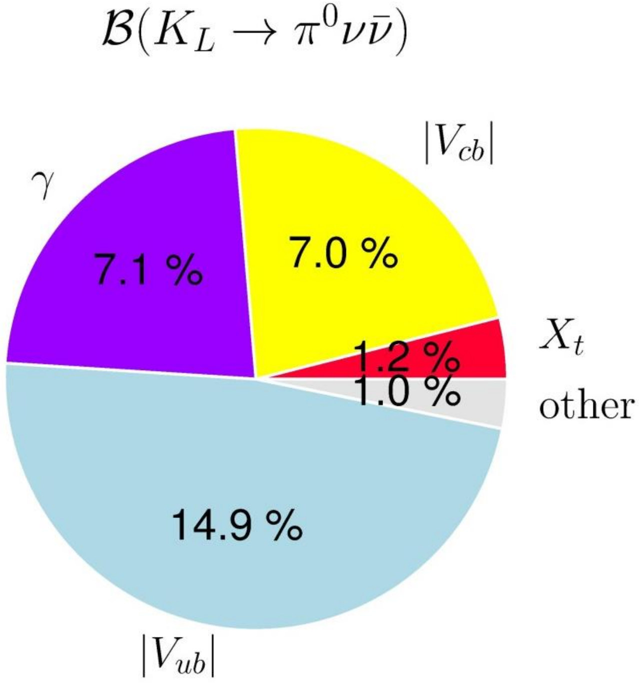
$$Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) = \left(3.36 \pm 0.05\right)\cdot 10^{-11}\left[\frac{|V_{ub}|}{3.88\cdot 10^{-3}}\right]^{2}\left[\frac{|V_{cb}|}{0.0407}\right]^{2}\left[\frac{\sin\gamma}{\sin(73.2)}\right]^{2}$$

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

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

Error Budgets





Update: 1503.02693

$P_c = 0.404 \pm 0.024$

$X_t = 1.481 \pm 0.005_{th} \pm 0.008_{exp}$

Strategy B: use ε_K, ΔM_s, ΔM_d, $S_{\psi K_s}$

$$|V_{cb}| = (42.4 \pm 1.0) \cdot 10^{-3}$$

$$|V_{ub}| = (3.61 \pm 0.13) \cdot 10^{-3}$$

$$\gamma = \left(69.5 \pm 5.0\right)^{\circ} \Rightarrow \gamma = \left(70.8 \pm 2.3\right)^{\circ}$$

(after new lattice results for ξ)

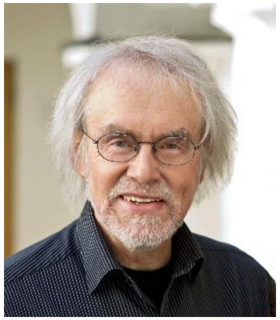
$$Br\left(K^{+} \to \pi^{+}\nu\bar{\nu}\right) = \left(9.1 \pm 0.7\right) \cdot 10^{-11}$$

$$Br\left(K_{L} \to \pi^{0}\nu\bar{\nu}\right) = \left(3.0 \pm 0.3\right) \cdot 10^{-11}$$

$$\text{UTfit}: |V_{cb}| = \left(41.7 \pm 0.6\right) \cdot 10^{-3} \qquad |V_{ub}| = (3.63 \pm 0.12) \cdot 10^{-3}$$

$$\text{CKMfitter}: |V_{cb}| = \left(41.2 \pm 1.0\right) \cdot 10^{-3} \qquad |V_{ub}| = \left(3.55 \pm 0.16\right) \cdot 10^{-3}$$

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



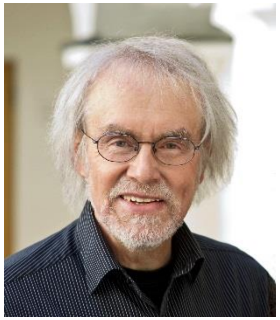
AJB

Fulvia de Fazio

Jennifer Girrbach-Noe

Z, Z´ 331

1404.3824,…
1311.6729



AJB

Dario Buttazzo

Rob Knegjens

Simplified NP Models
1507.08672

$K^+ \rightarrow \pi^+\nu\bar{\nu}$ and $K_L \rightarrow \pi^0\nu\bar{\nu}$ in simplified NP Models

Review Mod. Phys.: AJB, Schwab, Uhlig (2008) (0405132)
AJB, Buttazzo, Knegjens: hep-ph-1507.08672

MFV : 20-30% effects, strong correlation between K^+ and K_L (Z, Z´)

$U(2)^3$: Larger effects in the absence of $B_s \rightarrow \mu^+\mu^-$ constraint

No MFV : Correlation depends on the presence or absence of ε_K constraint, size on ε'/ε , $K_L \rightarrow \mu^+\mu^-$

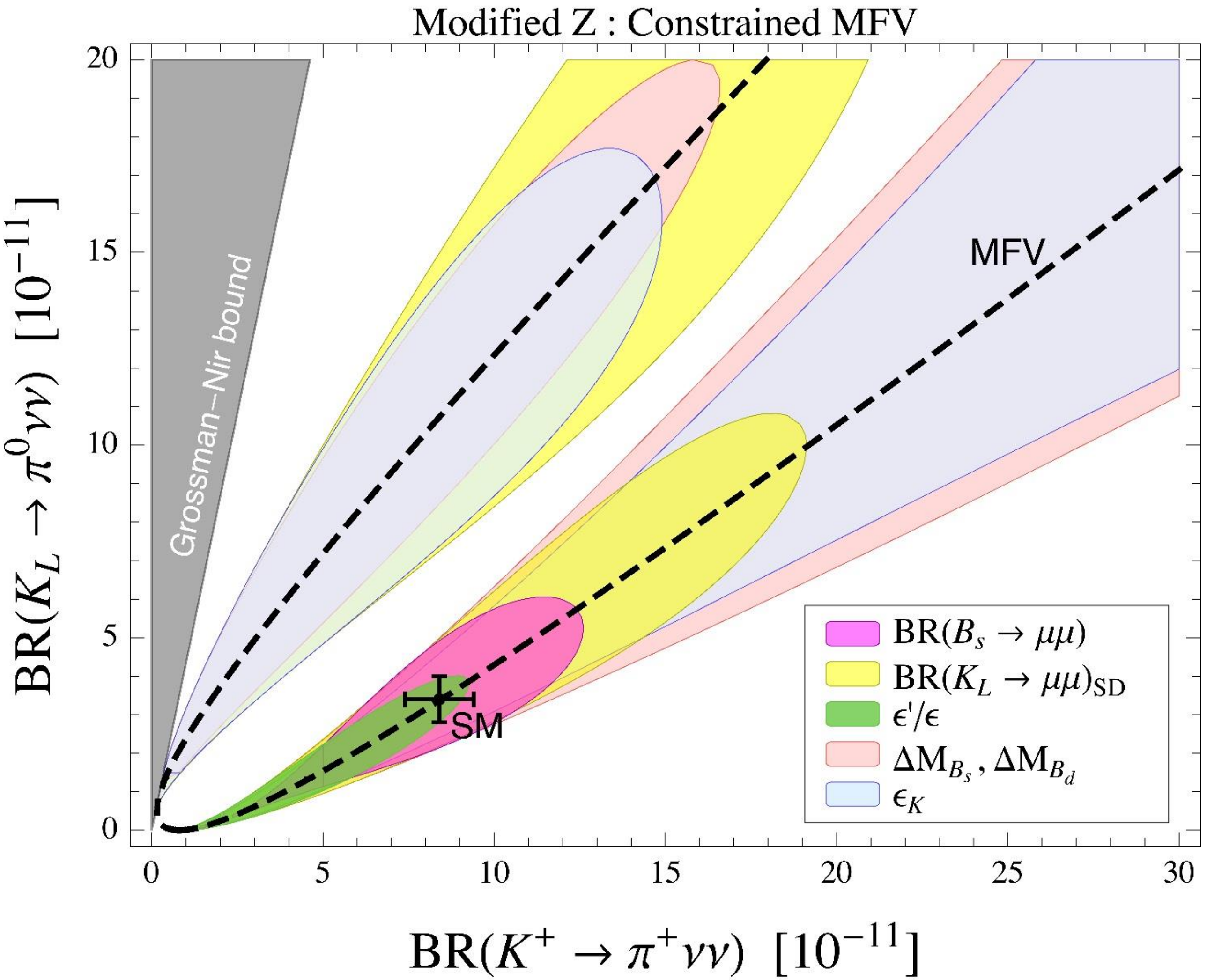
FCNCs Z : Enhancements by factors 2-3 over SM still possible (ε'/ε constraint important)

FCNCs Z´ : Still larger enhancements possible as ε'/ε constraint can be eliminated in a model independent analysis but not in specific models with known flavour diagonal quark couplings.

More info in BBK

see Rob Knegjens (Moriond) 1505.04928

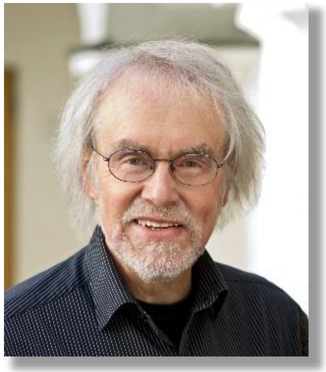
$K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ in MFV and U(2)^3



AJB, Buttazzo, Knegjens: hep-ph-1507.08672

Section 3
ε´/ε strikes back

2015 Anatomy of ε´/ε : 1507.06345

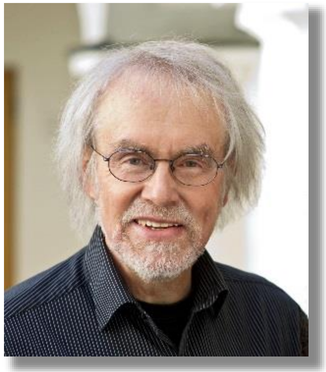


AJB

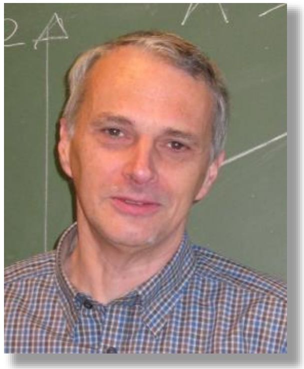
Martin Gorbahn

Sebastian Jäger

Matthias Jamin



AJB



Jean-Marc Gérard

Large N news
1507.06326

RBC-UK QCD

$$\varepsilon'/\varepsilon = \left(1.4 \pm 7.0\right) \cdot 10^{-4}$$

$$\left(\frac{\mathrm{Re}\,A_0}{\mathrm{Re}\,A_2}\right) = 31.0 \pm 6.6$$

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

$$\left(\frac{\mathrm{Re}\,A_0}{\mathrm{Re}\,A_2}\right)_{\mathrm{exp}} = 22.4$$

Four dominant contributions to ε'/ε in the SM

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

From ReA_0

From ReA_2

$$\mathrm{Re}\left(\varepsilon'/\varepsilon\right)=\left[\frac{\mathrm{Im}\left(V_{td}V_{ts}^{*}\right)}{1.4\cdot10^{-4}}\right]10^{-4}\left[-3.6+21.4\cdot B_6^{(1/2)}+1.2-10.4\cdot B_8^{(3/2)}\right]$$

(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 ($\Delta I=1/2$ Rule) fully described by SM (includes isospin breaking corrections)

ε'/ε from RBC-UKQCD

Calculate all contributions directly (no isospin breaking corrections)

$$\left[-\left(6.5\pm3.2\right)+25.3\cdot B_6^{(1/2)}+\left(1.2\pm0.8\right)-10.2\cdot B_8^{(3/2)}\right]$$

ε´/ε from RBC-UKQCD

Anatomy: AJB, Gorbahn, Jäger, Jamin (2015)

Calculate all contributions directly

$$\mathrm{Re}\left(\varepsilon'/\varepsilon\right)=\left[\frac{\mathrm{Im}\left(V_{td}V_{ts}^{*}\right)}{1.4\cdot 10^{-4}}\right]10^{-4}\left[-6.5+25.3\cdot B_6^{(1/2)}+1.2-10.2\cdot B_8^{(3/2)}\right]$$

(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

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

Extracted from

⇩

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

EW penguins in full agreement with BGJJ but

+ third term very similar to BGJJ

$(\mathrm{ReA}_2)_{\mathrm{Lattice}}\approx(\mathrm{ReA}_2)_{\mathrm{exp}}$

$$\left[\frac{(\mathrm{Re}\,A_0)}{(\mathrm{Re}\,A_0)_{\mathrm{exp}}}\approx 1.4\right]$$

⇨

The negative contribution of Q_4 overestimated

⇨

$$\left(\frac{\varepsilon'}{\varepsilon}\right)_{\mathrm{Lattice}}=(1.4\pm 7.0)\cdot 10^{-4}$$

New Bound on $B_6^{(1/2)}$ and $B_8^{(3/2)}$ from Large N

AJB + Gérard 1507.06326

$$\boxed{B_6^{(1/2)} \leq B_8^{(3/2)} < 1}$$

Using BGJJ formula

$$B_6^{(1/2)} = 1.0 \qquad B_8^{(3/2)} = 1.0 \quad \Rightarrow \quad (\varepsilon'/\varepsilon)_{SM} = 8.6 \cdot 10^{-4}$$

$$B_6^{(1/2)} = 0.8 \qquad B_8^{(3/2)} = 0.8 \quad \Rightarrow \quad (\varepsilon'/\varepsilon)_{SM} = 6.4 \cdot 10^{-4}$$

$$B_6^{(1/2)} = 0.6 \qquad B_8^{(3/2)} = 0.8 \quad \Rightarrow \quad (\varepsilon'/\varepsilon)_{SM} = 2.2 \cdot 10^{-4}$$

For $\boxed{\mathrm{Im}\left(V_{ts}V_{td}^{*}\right) = 1.4 \cdot 10^{-4}}$

Below data but positive

Yet still large
uncertainties

Bardeen
AJB
Gérard
(1986,
2014)

Large N Approach

AJB, Gérard (2015)

vs

Lattice

$$\hat{B}_K = 0.73 \pm 0.02$$

$$\left(\hat{B}_K \leq 0.75\right)$$

$$B_6^{(1/2)} = 1 - 0\left(1/N\right)$$

$$B_8^{(3/2)} = 1 - 0\left(1/N\right)$$

$$\frac{\mathrm{Re}\,A_0}{\mathrm{Re}\,A_2} = 16.0 \pm 1.5$$

$$B_8^{(1/2)} = 1 - 0\left(1/N^2\right)$$

Exp
22.4

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

$$\hat{B}_K = 0.766 \pm 0.010 \quad \text{(FLAG)}$$

(will go down with new results)

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

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

$$\frac{\mathrm{Re}\,A_0}{\mathrm{Re}\,A_2} = 31.0 \pm 6.6$$

$$B_8^{(1/2)} = 1.0 \pm 0.2$$

RBC-UKQCD

Bardeen
AJB
Gérard
(1986,
2014)

Large N Approach

AJB, Gérard (2015)

vs

Lattice

$$\hat{B}_K = 0.73 \pm 0.02$$

$$\left(\hat{B}_K \leq 0.75\right)$$

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

$$B_8^{(3/2)} = 0.80 \pm 0.10$$

$$\frac{\mathrm{Re}\,A_0}{\mathrm{Re}\,A_2} = 16.0 \pm 1.5$$

$$B_8^{(1/2)} = 1 - 0\left(1/N^2\right)$$

Exp
22.4

$$\hat{B}_K = 0.766 \pm 0.010 \quad \text{(FLAG)}$$

(will go down with new results)

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

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

$$\frac{\mathrm{Re}\,A_0}{\mathrm{Re}\,A_2} = 31.0 \pm 6.6$$

$$B_8^{(1/2)} = 1.0 \pm 0.2$$

RBC-UKQCD

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

Strategy

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)

In some models
$K_L \to \mu^+\mu^-$
More important
than ε_K

Re and Im Parts: Z and Z´ Couplings

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

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

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 but can provide $\kappa_{\varepsilon'} > 0$

$$\left(\frac{\mathrm{Im}\,C_6}{\mathrm{Im}\,C_8}\right)^{NP} \approx 0(1)$$

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

3° Chromomagnetic operators (not in this talk)

Basic Structure of NP Contributions

AJB (1601.00005)

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

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

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

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

(large)

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

(small)

⇩

Implications for

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

(Re, Im)

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

(Im)

Different Patterns of Flavour Violation

Z with LH couplings: $\Delta_L^{sd}(Z)$

Q_8 EWP

AJB (1601.00005)

- Anticorrelation of ε'/ε and $K_L \to \pi^0 \nu\bar{\nu}$
- Strong suppression of $\mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right)$
- $\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) \leq 2\ \mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)^{SM}$
- NP effects in ΔM_K and ε_K very small

$\}$ No specific correlation

($K_L \to \mu^+\mu^-$ constraint more important)

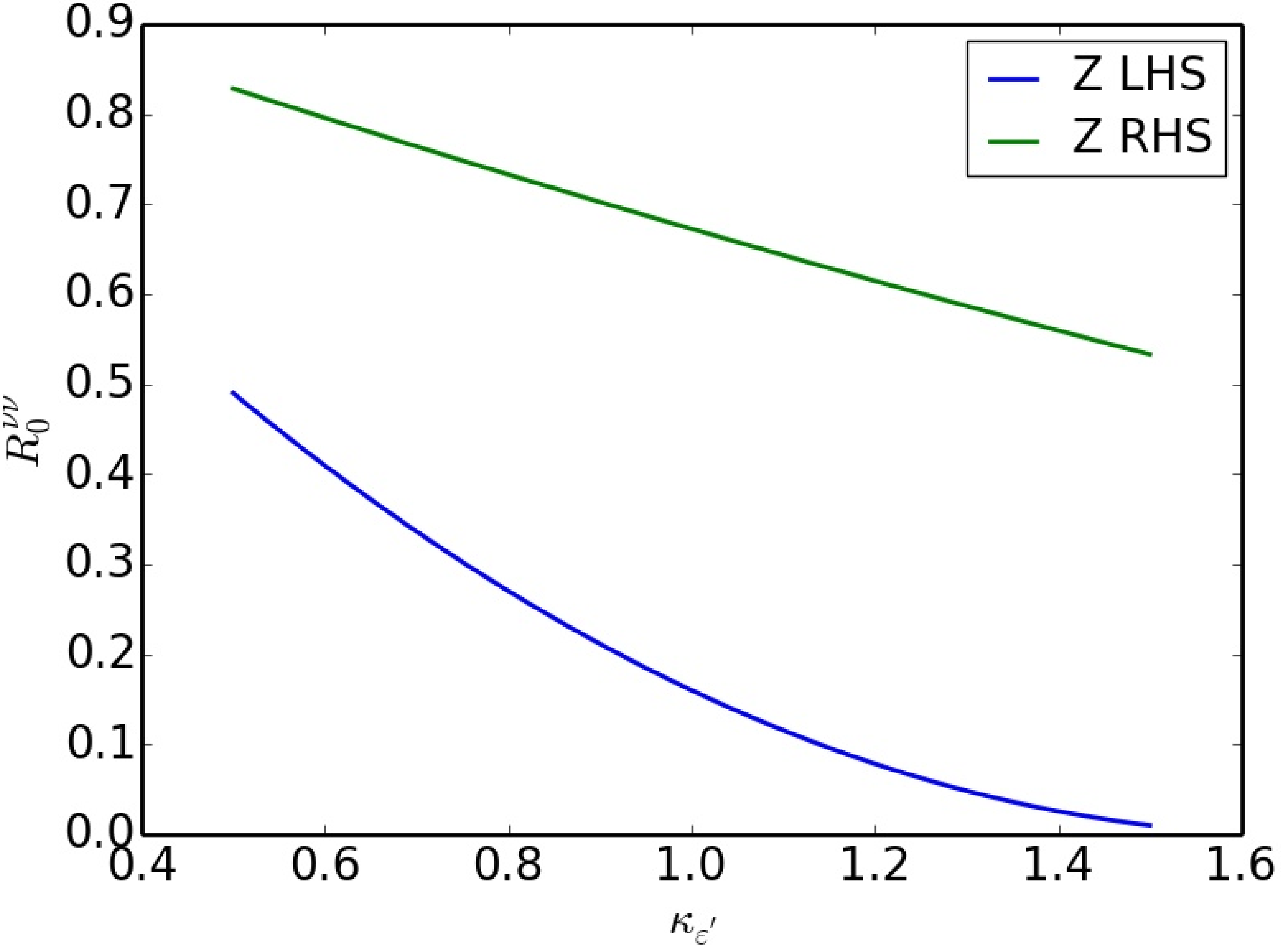
Z with RH couplings: $\Delta_R^{sd}(Z)$

- Anticorrelation of ε'/ε and $K_L \to \pi^0 \nu\bar{\nu}$
- Moderate suppression of $\mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right)$
- $\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) \leq 6\ \mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)^{SM}$
- NP effects in ΔM_K and ε_K very small

Unless Loop effects important

$Q_{8'}$ EWP

Z with LH or RH Flavour Violating Couplings



Z with LH and RH Couplings $\Delta^{sd}_{L,R}(Z)$

AJB (1601.00005)

New Features

ε_K constraint dominates over $K_L \to \mu^+\mu^-$
because of LR operators $\to$ "ε_K anomaly"
can be resolved.

Possibility of simultaneous enhancements of

$\varepsilon'/\varepsilon,\ \varepsilon_K,\ K_L \to \pi^0\nu\bar{\nu},\ K^+ \to \pi^+\nu\bar{\nu}$

Example 1

$\mathrm{Im}\,\Delta_{L,R} < \mathrm{Re}\,\Delta_{L,R}$

Both $K_L \to \pi^0\nu\bar{\nu}$ and $K^+ \to \pi^+\nu\bar{\nu}$ enhanced
but anticorrelated

$K_L \Uparrow \quad K^+ \Downarrow \quad$ with $\kappa_{\varepsilon'} \Uparrow$

($K^+ \Uparrow$ with $\kappa_\varepsilon \Uparrow$)

Example 2

$\mathrm{Im}\,\Delta_{L,R} >> \mathrm{Re}\,\Delta_{L,R}$

$K_L \Uparrow \quad K^+ \Uparrow \quad$ with $\kappa_{\varepsilon'} \Uparrow$

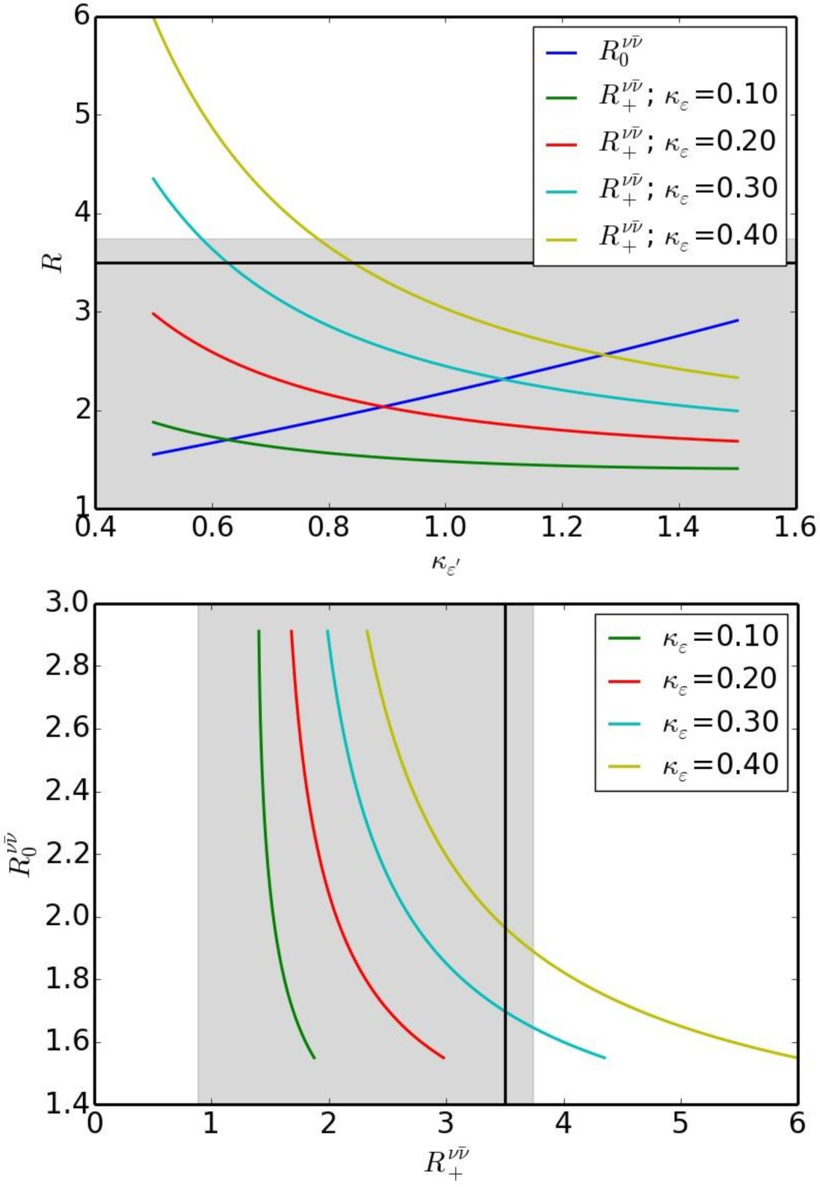
(no depencence on κ_ε)

NP Effects
in ΔM_K
small

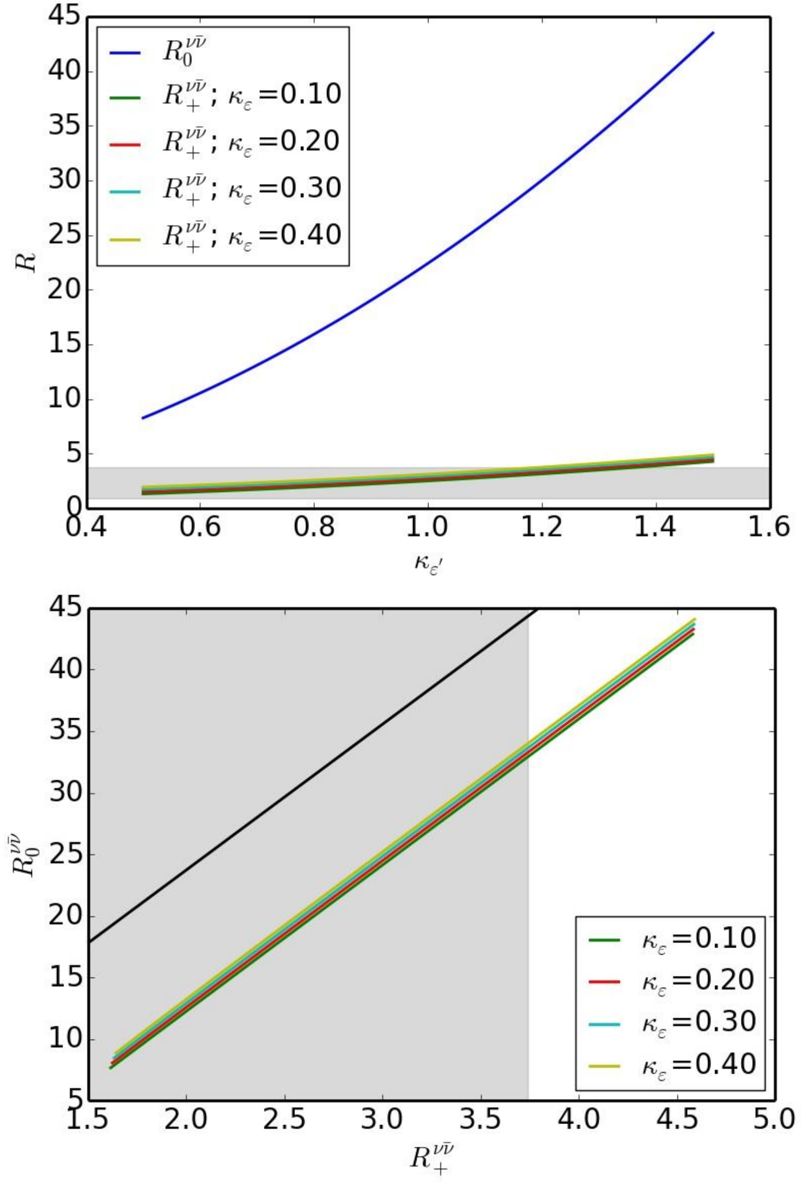
Correlation between K_L and K^+
On the branch parallel to Grossmann-Nir Bound

Z with LH and RH Flavour Violating Couplings

Example 1



Example 2



Z´ Scenarios with LH Couplings $\Delta_L^{sd}(Z')$

AJB (1601.00005)

Dominance of QCD Penguins (Q_6) in ε'/ε

- Strong correlation between K^+ and K_L on the branch parallel to GN bound
- Very large effects in K_L, moderate in K^+
- $(\Delta M_K)^{NP} < 0$ (could be 20%)

ε_K anomaly
can be solved

Dominance of electroweak Penguins (Q_8) in ε'/ε

- Both enhanced but anticorrelated

$K_L \Uparrow \quad K^+ \Downarrow$ with $\kappa_{\varepsilon'} \Uparrow$

($K^+ \Uparrow$ with $\kappa_\varepsilon \Uparrow$)

Only (20-40)% effects

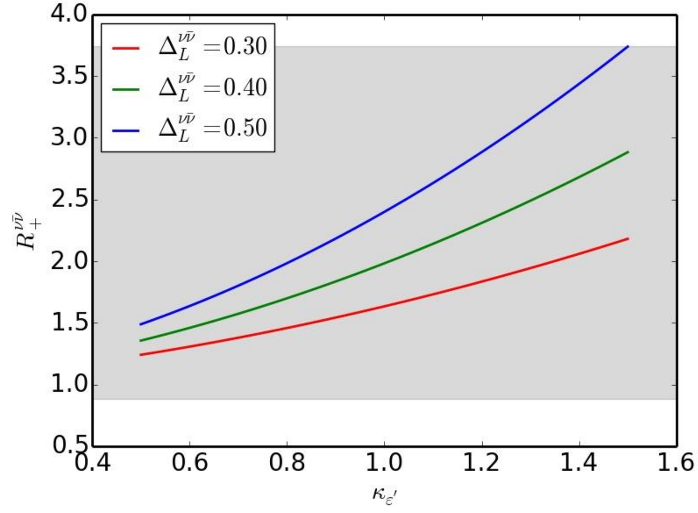
Pattern for $\Delta_R^{q\bar{q}}(Z') \approx 0(1)$ in ε'/ε

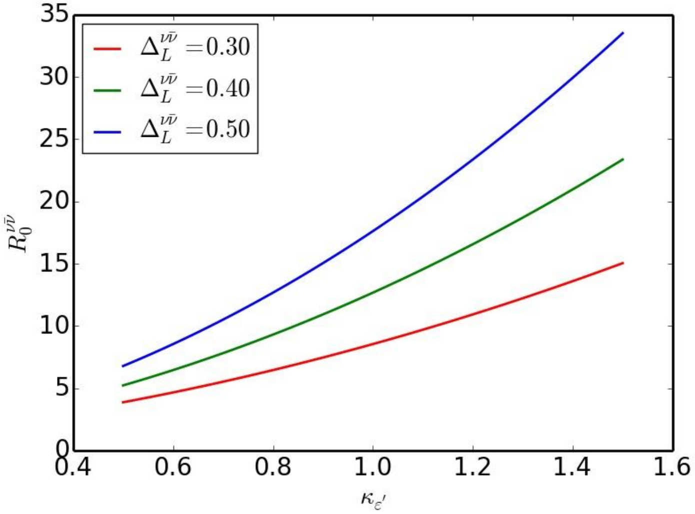
- $(\Delta M_K)^{NP} > 0$ (below 10%)

ε_K anomaly
can be solved

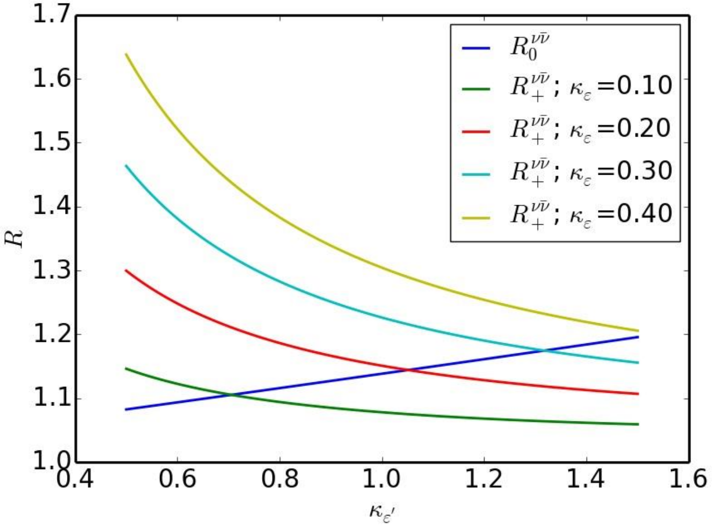
$M_{Z'} = 3$ TeV

QCD Penguin (Q_6)

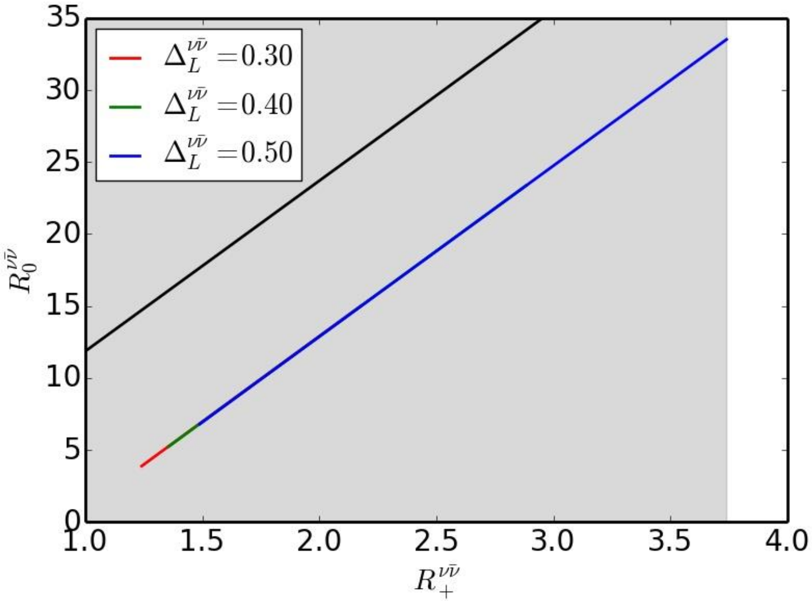


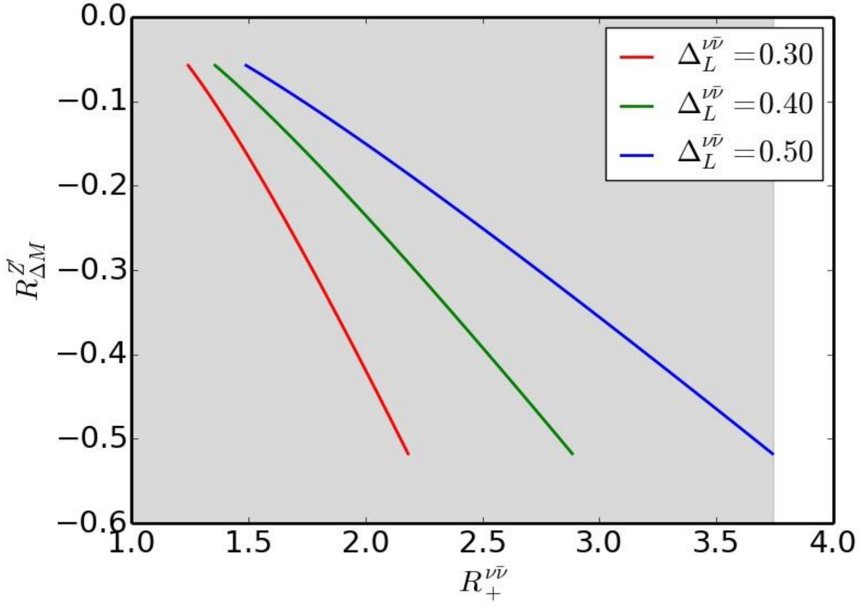


Electroweak Penguin (Q_8)

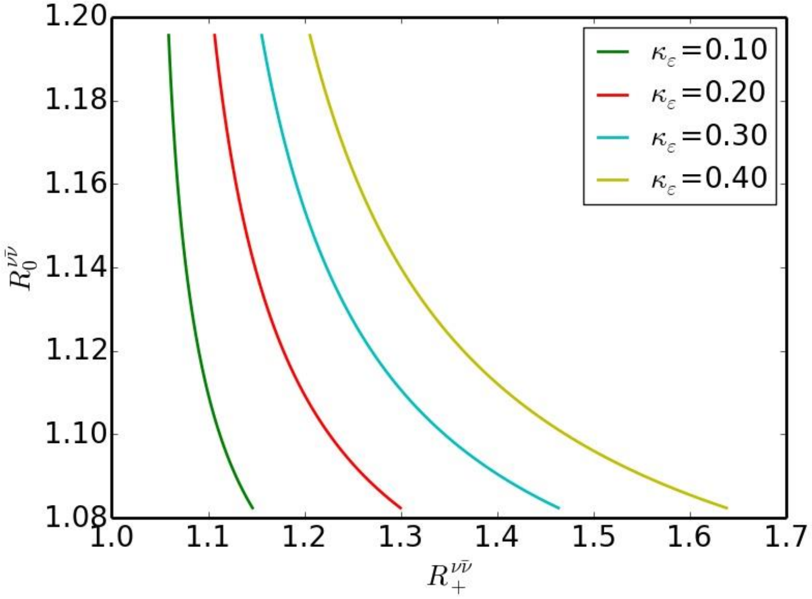


QCDP (Q_6)





EWP (Q_8)



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

Z´ outside the reach of the LHC

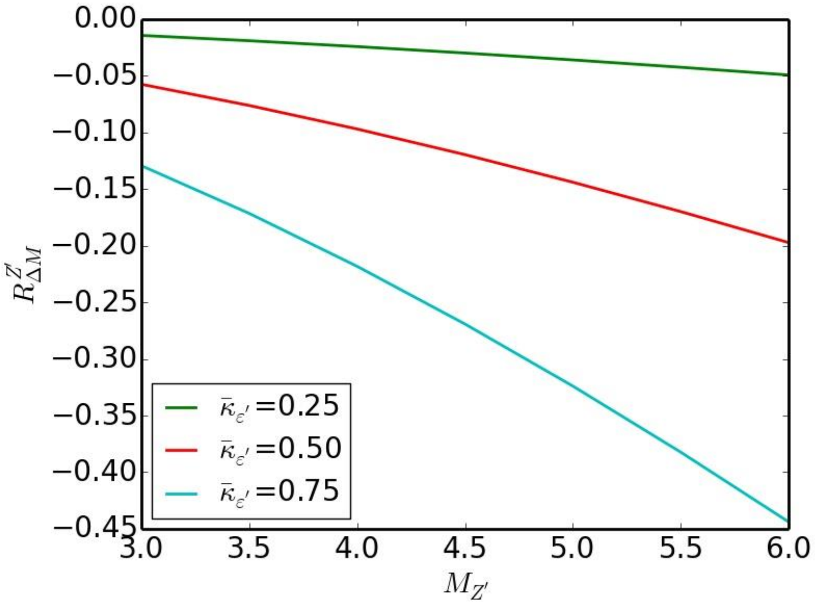
QCD Penguin

For fixed $\kappa_{\varepsilon'}$: $\mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right)$, $\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$

But constraint from ΔM_K

Independent of $M_{Z'}$

$Z' q\bar{q} \approx 0(1)$



$$\bar{\kappa}_{\varepsilon'} \equiv \left[\frac{\kappa_{\varepsilon'}}{\Delta_R^{\rho\bar{\rho}}\left(Z'\right)}\right]$$

EWP Penguin : Significant effects in rare decays only for $q\bar{q}Z' \approx 0(10^{-2})$

331 Models Facing ε'/ε Anomaly

AJB, De Fazio 1512.02869

1. $\kappa_{\varepsilon'} \leq 0.8$ (only 3 models can reach upper bound)

2. None of them can explain suppressions of C_9 $\left(B \to K\left(K^*\right)\mu^+\mu^-\right)$ and $B_s \to \mu^+\mu^-$ simultaneously.
   None R_K

3. Small NP effects in $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$

LHT : Blanke, AJB, Recksiegel (1507.06316) (see Monika)

2018 Vision

$$\boxed{\mathrm{Br}\left(K^+ \rightarrow \pi^+ \nu\bar{\nu}\right) = \left(18.0 \pm 2.0\right) \cdot 10^{-11}}$$ (NA62)

$$\boxed{\kappa_{\varepsilon'} \approx 1.0}$$

Would point towards :

Z with LH + RH couplings

$Z'(\mathrm{QCDP})$ with $Z'q\bar{q} \approx 0(1)$

$Z'(\mathrm{EWP})$ with $Z'q\bar{q} \approx 10^{-2}$

Open Questions to be answered hopefully in this Decade

1. What is $\mathrm{Br}\left(K^+ \rightarrow \pi^+\nu\bar{\nu}\right)$ from NA62?
2. What is $\mathrm{Br}\left(K_L \rightarrow \pi^0\nu\bar{\nu}\right)$ from KOPIO?
3. What is the value of $\kappa_{\varepsilon'}$? (Lattice, CKM, NNLO)
4. What is the value of κ_{ε} ? (CKM, η_1)
5. What is $\left(\Delta M_K\right)^{SM}$? (Lattice)
6. Does NP contribute to $\mathrm{Re}A_0$ at 10-20% level? (Lattice)
   (see AJB, De Fazio, Girrbach: 1404.3824)
7. Do Z´, G´ or other new particles exist?

Exciting Times are just ahead of us !!!

Exciting Times are just ahead of us !!!

Thank You !

Backup

What about ΔI = 1/2 Rule?

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

Since 1955

Gell-Mann
Pais

1986, 2014

Large N including
I/N corredtions

: Quark Evolution $1\,\mathrm{GeV} \leq \mu \leq M_W$
Meson Evolution $0 \leq \mu \leq 1\,\mathrm{GeV}$

Correct value
of ReA_2

$$\left(\frac{\mathrm{Re}\,A_0}{\mathrm{Re}\,A_2}\right)_{\mathrm{I/N}} \approx 16.0 \pm 1.5 \quad *)$$

Dominance
of current-
current
operators

RBC-QCD

(2013, 2015)

Correct value
of ReA_2

$$\left(\frac{\mathrm{Re}\,A_0}{\mathrm{Re}\,A_2}\right)_{\mathrm{Lattice}} \approx 31 \pm 7$$

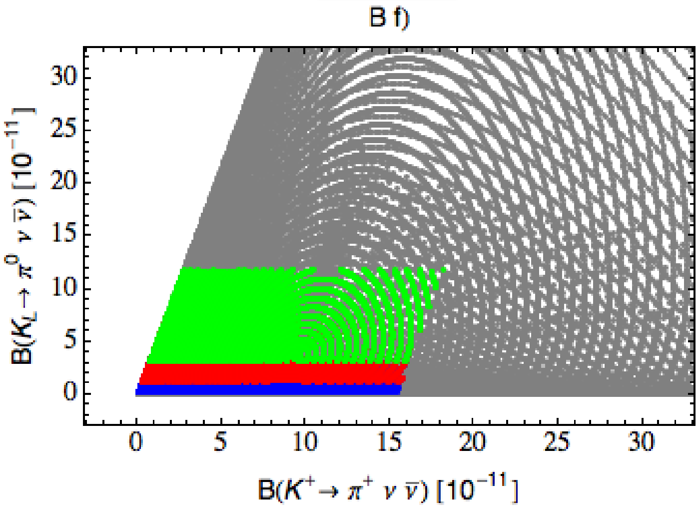
*) G´ with particular couplings ($M_{G'} \approx 3.5$ TeV)
could be responsible for the missing piece

AJB
De Fazio
Girrbach-Noe
1404.3824

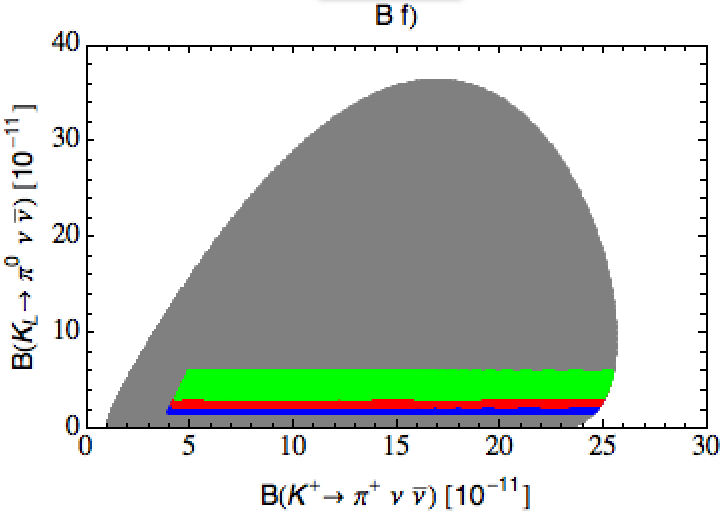
Z with FCNCs at Work

AJB, de Fazio,
Girrbach-Noe
1404.3824

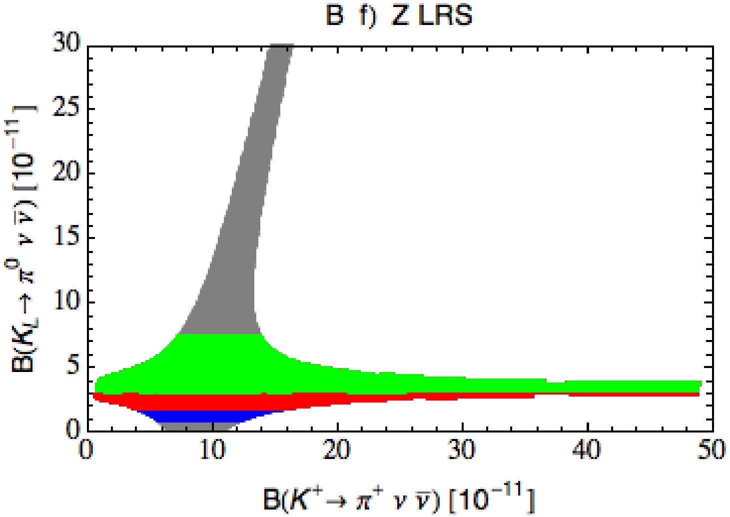
LHS



RHS



LRS



■ ε_K, ΔM_K **constraint**

ε'/ε

+

$K_L \to \mu^+\mu^-$

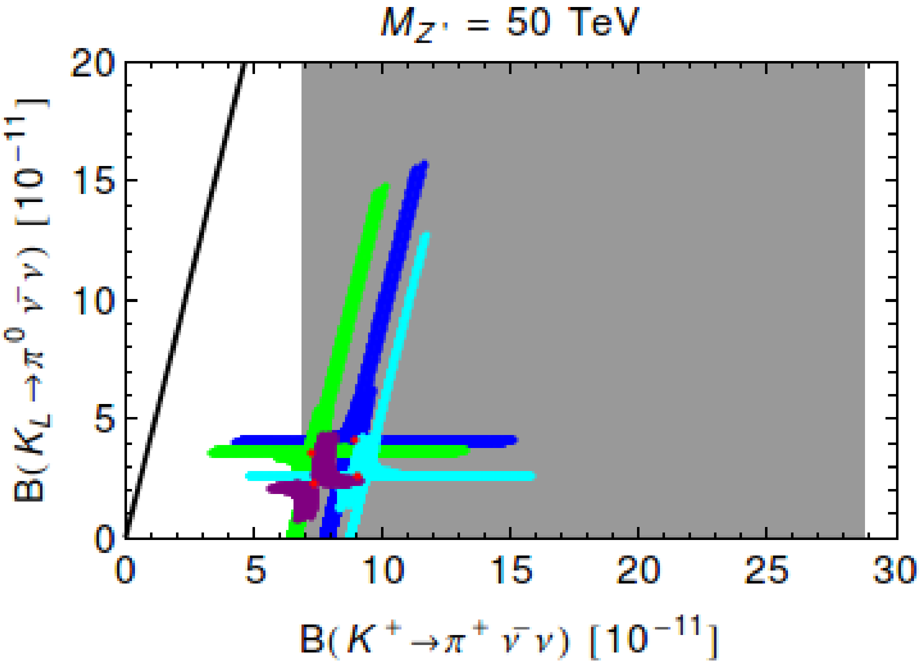
🟩 $B_6 = 1.25$

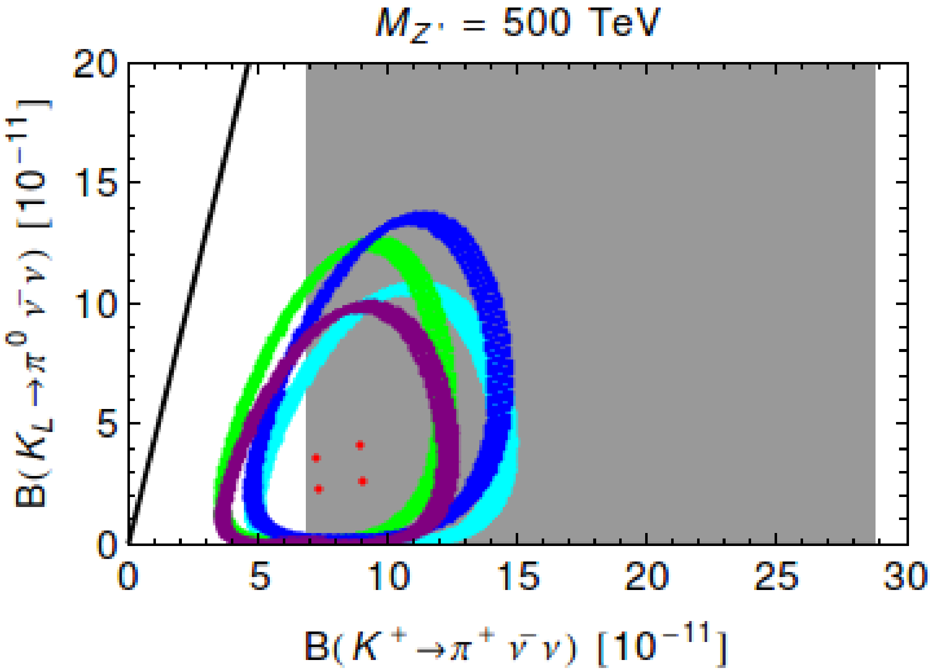
🟥 $B_6 = 1.00$

🟦 $B_6 = 0.75$

Heavy Z´ at Work

AJB, Buttazzo, Girrbach-Noe, Knegjens, 1407.0728





ε_K constraint

General discussion:
Blanke 0904.2528

No ε_K constraint

Can we reach Zeptouniverse through Quark Flavour Physics ?

(Z´)

AJB, Buttazzo, Girrbach-Noe, Knegjens, 1407.0728

If only left-handed or only right-handed couplings present in NP

:

Only with K rare Decays

$B_s \sim$ **15 TeV,** $B_d \sim$ **15 TeV**

If both LH and RH present but

$g_L^{ij} << g_R^{ij}$ **or** $g_L^{ij} >> g_R^{ij}$

:

$K \to \pi\nu\bar{\nu}: \ \Lambda_{NP}^{max} \simeq$ **2000 TeV**

$B_d \ : \Lambda_{NP}^{max} \simeq$ **160 TeV**

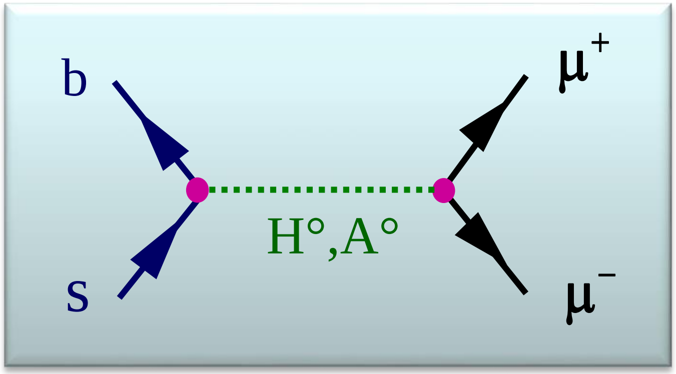
$B_s \ : \Lambda_{NP}^{max} \simeq$ **160 TeV**

Yes we can !!

Can we reach Zeptouniverse through S and P

AJB, Buttazzo, Girrbach-Noe, Knegjens, 1407.0728

Yes : $\mathbf{B_{s,d} \to \mu^+\mu^-}$



S : ≈ 350 TeV
P : ≈ 700 TeV

Pseudoscalars more powerful than scalars because of the interference with SM contribution

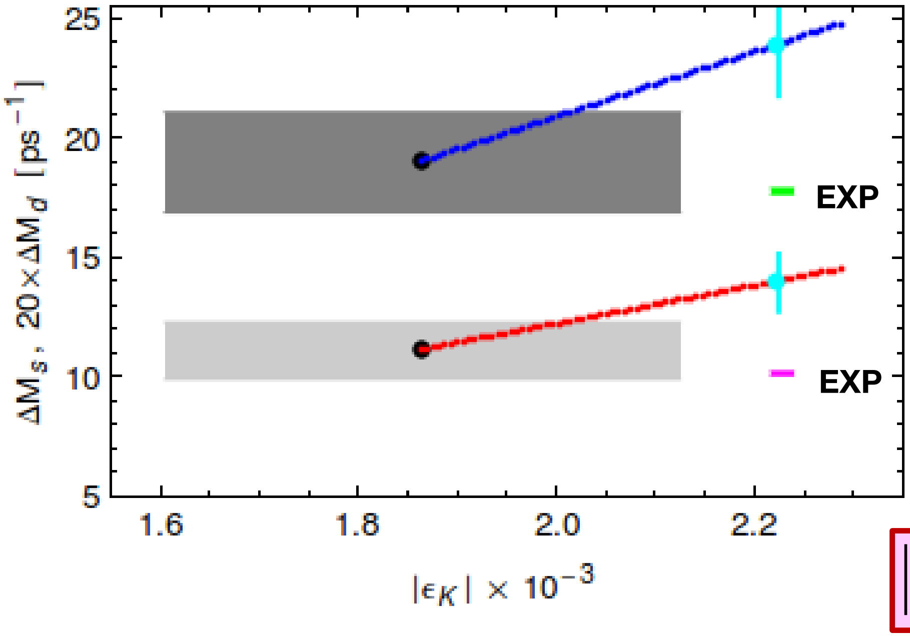
Similar to $\mathbf{K \to \pi\nu\bar{\nu}}$ **(Z´):**
No tuning neccessary to reach Zeptouniverse

S=H°

P=A°

2 Tensions in ΔF=2 within MFV

$\varepsilon_K \leftrightarrow \Delta M_{s,d}$



AJB + Girrbach 1306.3755

Similar tension in Gauged Flavour Models: AJB, Merlo, Stamou (2011)

$\varepsilon_K \leftrightarrow S_{\psi K_s}$

$$\left\{|V_{ub}|_{\rm excl}\right\} \Rightarrow \left\{\begin{array}{l} \varepsilon_K^{\rm SM} < \varepsilon_K^{\rm exp} \\ S_{\psi K_s}^{\rm SM} \approx S_{\psi K_s}^{\rm exp} \end{array}\right\}^{*)} \quad (2\sigma)$$

$$\left\{|V_{ub}|_{\rm incl}\right\} \Rightarrow \left\{\begin{array}{l} \varepsilon_K^{\rm SM} \approx \varepsilon_K^{\rm exp} \\ S_{\psi K_s}^{\rm SM} > S_{\psi K_s}^{\rm Data} \end{array}\right\} \quad (3\sigma)$$

$$\boxed{|V_{cb}|}$$

Lunghi + Soni (2008)
AJB + Guadagnoli (2008)

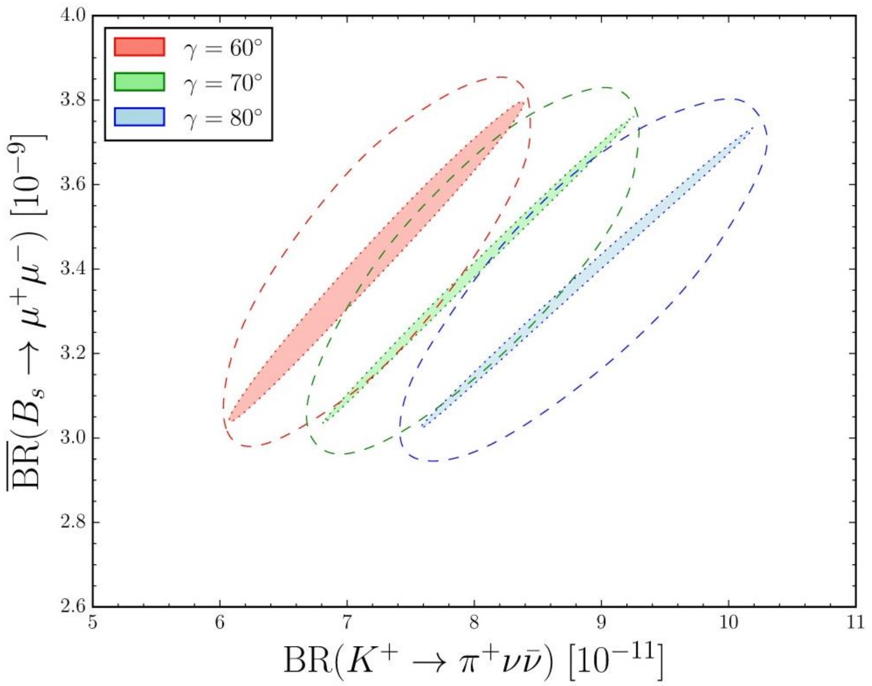
*) **Can still work within MFV ($\Delta\varepsilon_K > 0$ in MFV) Blanke + AJB (2006)**

Both tensions can only be clarified through improved $|V_{ub}|$, $|V_{cb}|$ + Lattice Input and improved measurement of $S_{\psi K_s}$

Correlations within SM

$B_s \to \mu^+\mu^-$, $K^+ \to \pi^+\nu\bar{\nu}$, γ

BBGK (2015)



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

Buchalla, AJB (94)