Kaon Flavour Physics strikes back

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KAON 2016, Sept. 2016

Overture

Stars of KAON Flavour Physics

$\varepsilon_K, \Delta M_K$

ε'/ε

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

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

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

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

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

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. $B_{s,d} \rightarrow \mu^+\mu^-$
   $B_{s,d} \rightarrow \tau^+\tau^-$
5. $B^+ \rightarrow \tau^+\nu_\tau$
   $B \rightarrow D(D^*)\tau\nu$
6. $B \rightarrow X_s\gamma$
   $B \rightarrow K^*\gamma$
7. $B \rightarrow X_s l^+l^-$
   $B \rightarrow K^*(K) l^+l^-$
8. $B \rightarrow X_s\nu\bar{\nu}$
   $B \rightarrow K^*(K)\nu\bar{\nu}$
9. $K^+ \rightarrow \pi^+\nu\bar{\nu}$
   $K_L \rightarrow \pi^0\nu\bar{\nu}$
10. ε'/ε
11. Charm
    Top
12. LFV, EDMs
    $(g-2)_{\mu,e}$

AJB, Girrbach-Noe 1306.3775

B Physics Anomalies

1. $$R_{D^{(*)}} = \frac{Br\left(B \to D^{(*)}\tau\nu_\tau\right)}{Br\left(B \to D^{(*)}\mu\nu_\mu\right)} \qquad \left(3.5 - 4\sigma\right)$$

BaBar, LHCb, Belle

2. $$R_K = \frac{\Gamma\left(B \to K\mu\mu\right)}{\Gamma\left(B \to Kee\right)} = 0.745 \begin{matrix} +0.090 \\ -0.074 \end{matrix} \pm 0.036$$

$\left(2.6\sigma\right)$

LHCb

3. $$B \to K\left(K^*\right)\mu^+\mu^- \qquad (3\sigma)$$

$\left(B \to \varphi\mu^+\mu^-\right)$

(hadronic uncertainties)

4. $$Br\left(B_s \to \mu^+\mu^-\right)_{SM} = \left(3.65 \pm 0.23\right) \cdot 10^{-9}$$

$$\text{CMS} + \text{LHCb} \quad \left(2.8 \begin{matrix} +0.7 \\ -0.6 \end{matrix}\right) \cdot 10^{-9}; \quad \text{ATLAS} \quad \left(0.9 \begin{matrix} +1.1 \\ -0.9 \end{matrix}\right) \cdot 10^{-9}$$

B Physics Anomalies

Many papers:

Violation of lepton flavour universality

New flavour violating interactions:

Z´, Leptoquarks, Vector-like quarks, General 2HDM, U(2), ..W´, H^+,…

But no particular signs of new sources of CP-violation!

But: Anomaly in CP-violation in K-physics (ε'/ε)

ε' = CP-violation in Decay ($K_L \rightarrow \pi\pi$)

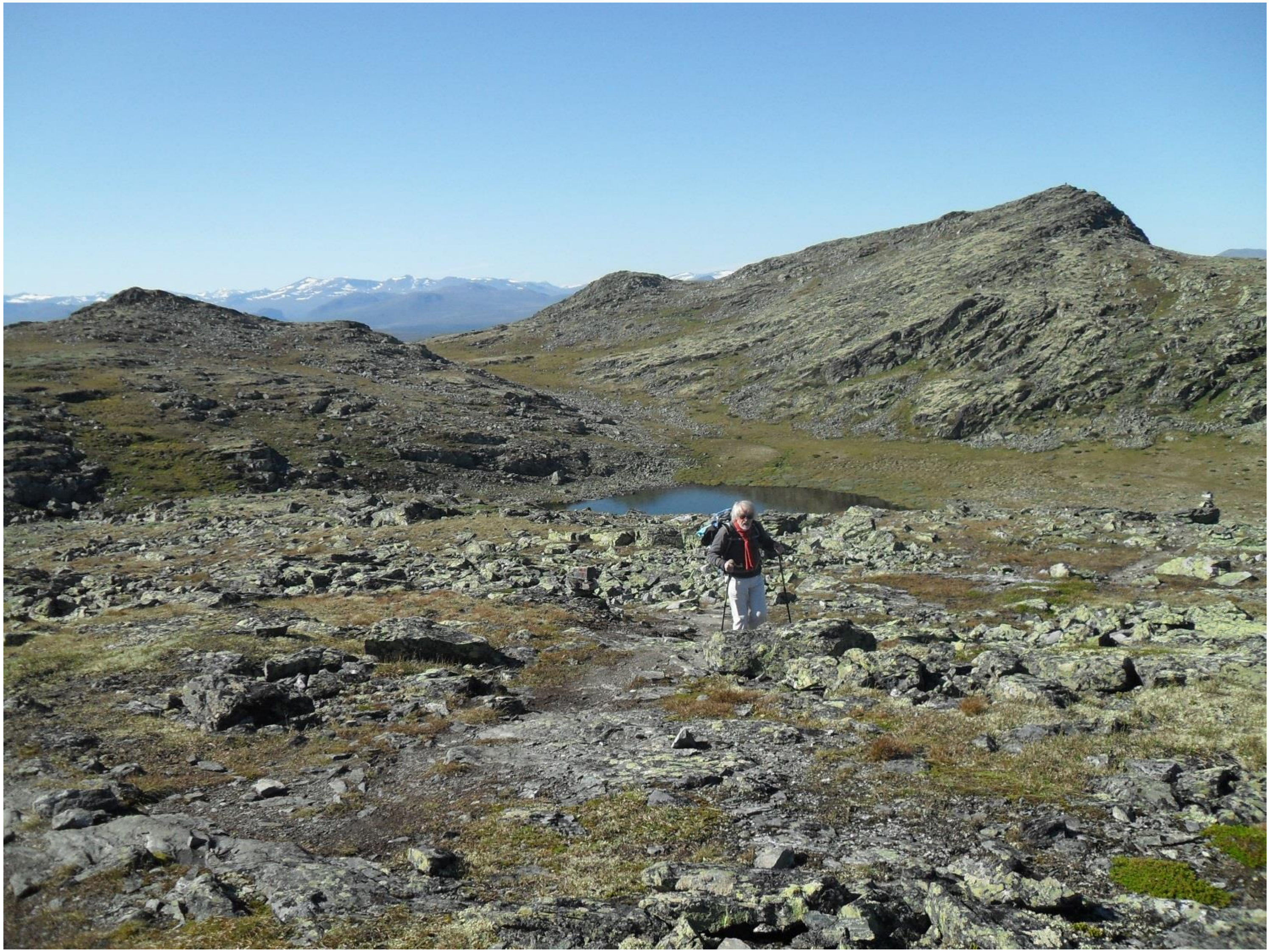
ε = CP-violation in $K^0 - \bar{K}^0$ Mixing

B-Physics Flavour Anomalies

Zugspitze

750 GeV Resonance

Kaon Flavour Physics



Plan for next 33 min

1.

ε'/ε strikes back

2.

$\varepsilon_K \leftrightarrow \Delta M_{s,d}$ tension in SM and CMFV

Intermezzo: $K \to \pi\nu\bar{\nu}$ in the Standard Model

3.

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

4.

Highlights from 331, LHT, Vector-Like Quark Models

5.

Outlook

Section 1
ε´/ε strikes back

2015 Anatomy of ε´/ε : 1507.06345

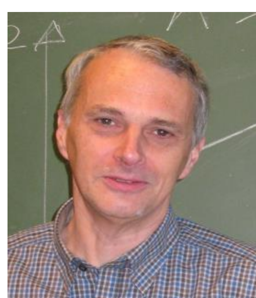
AJB

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 $B_6 = B_8 = 0.76$

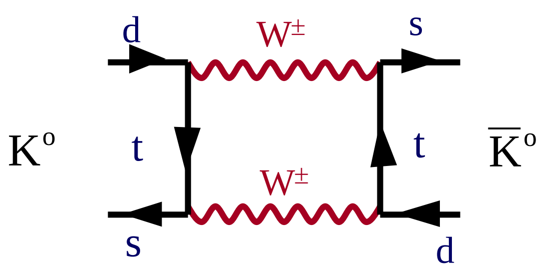
$(8.6 \pm 3.2) \cdot 10^{-4}$ for $B_6 = B_8 = 1.0$

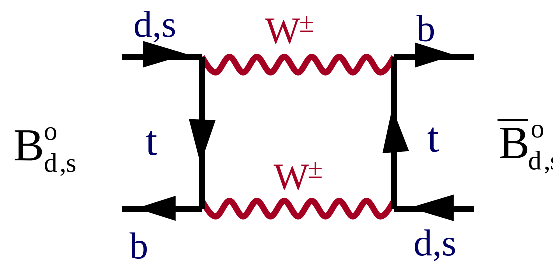
$(\varepsilon'/\varepsilon)_{exp} = (16.6 \pm 2.3) \cdot 10^{-4}$ — Possible New Physics

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.xxxx)

Loop Induced FCNC Processes





~~CP~~ ε_K-Parameter
ΔM (K_L-K_S)

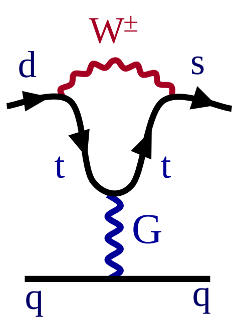
$B^o_d - \overline{B}^o_d$ Mixing

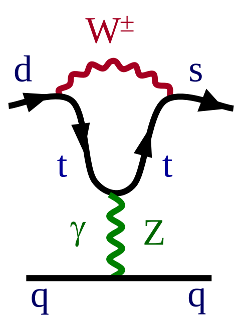
$B^0_s - \overline{B}^0_s$ Mixing

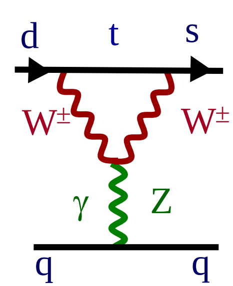
Discovered in 2006

(CDF, DØ)

ε'







(B_6)

(B_8)

Four dominant contributions to ε′/ε in the SM

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

From ReA_0 From ReA_2

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

(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)

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

Extracted from

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

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

Meson evolution $m_{\pi,K} \to \mu = 0(1\text{ GeV})$ 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 $\mu > 1\text{ GeV}$

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,…)

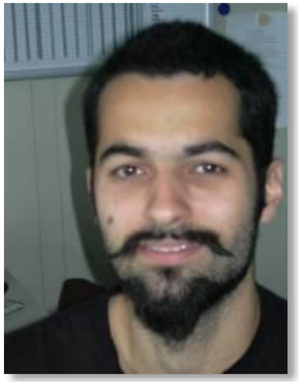
New application of dual QCD to $K \to \pi l^+ l^-$
(Caluccio-Leskow, D´Ambrosio, Greynat, Nath, 1604.09721)

2016 Standard Model Results

Teppei Kitahara

Ulrich Nierste

Paul Tremper



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

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

Maria Cerda-Sevilla

Martin Gorbahn

Sebastian Jäger

Ahmet Kokulu

Section 2

$\varepsilon_K \leftrightarrow \Delta M_{s,d}$ tension in SM and CMFV

(1602.04020)

Monika Blanke

AJB

Universal Unitarity Triangle 2016 (CMFV)

AJB, Gambino, Gorbahn, Jäger, Silvestrini 0007085

New Results from Fermilab Lattice + MILC 1602.03560

$$\left\{ \begin{array}{l} F_{B_s}\sqrt{\hat{B}_{B_s}} = (274.6 \pm 8.8\ \text{MeV}) \\ F_{B_d}\sqrt{\hat{B}_{B_d}} = (227.7 \pm 9.8\ \text{MeV}) \end{array} \right\} \Rightarrow$$

Their ratio

$$\xi = 1.206 \pm 0.019$$

Similar but less precise results from ETM (1308.1851)

Blanke + AJB

(1602.04020)

$$\left\{ \frac{\Delta M_d}{\Delta M_s},\ S_{\psi K_s}^{CP} \right\} \Rightarrow \left\{ \begin{array}{l} \left|\frac{V_{ub}}{V_{cb}}\right| = 0.0864 \pm 0.0025 \\ \gamma = (63.0 \pm 2.1)^\circ \end{array} \right\}$$

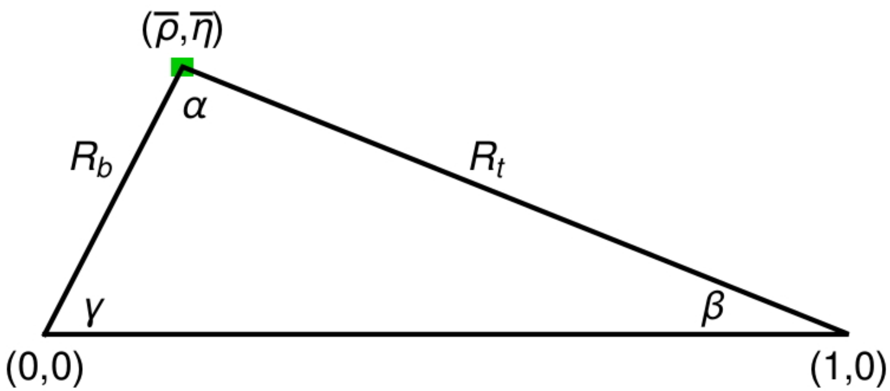
$(71 \pm 6)^\circ$ from Trees

S_1: Strategy 1: ΔM_s determines V_{cb} $\Rightarrow$ $|V_{cb}| = (39.7 \pm 1.3)\cdot 10^{-3}$

S_2: Strategy 1: ε_K determines V_{cb} $\Rightarrow$ $|V_{cb}| = (43.3 \pm 1.1)\cdot 10^{-3}$

$\Rightarrow$ Tension between ΔM_s and ε_K

Universal Unitarity Triangle 2016

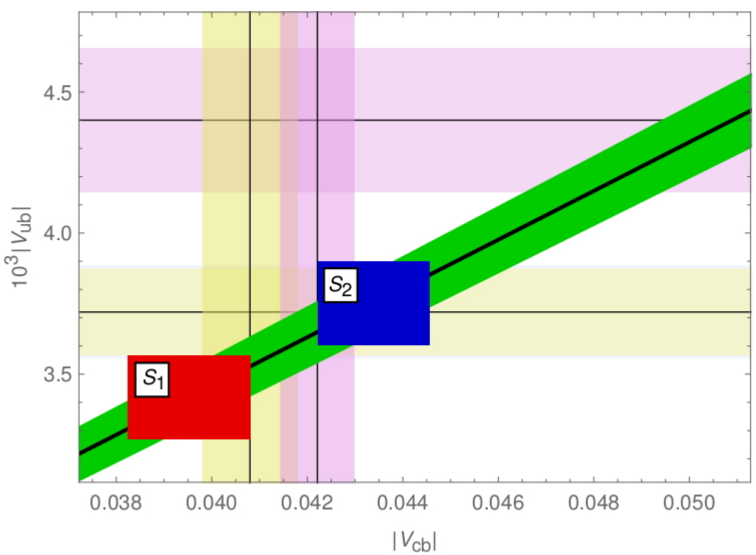


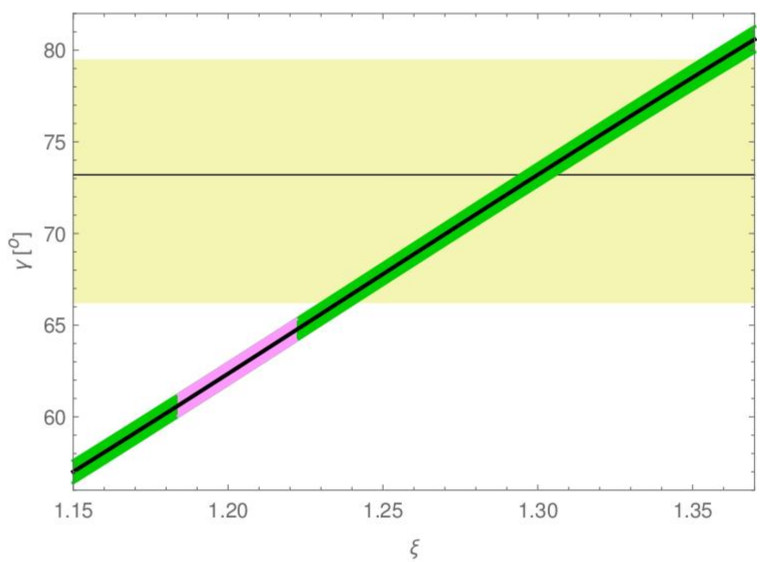
CMFV :

$$\bar\rho = 0.170 \pm 0.013$$
$$\bar\eta = 0.333 \pm 0.011$$

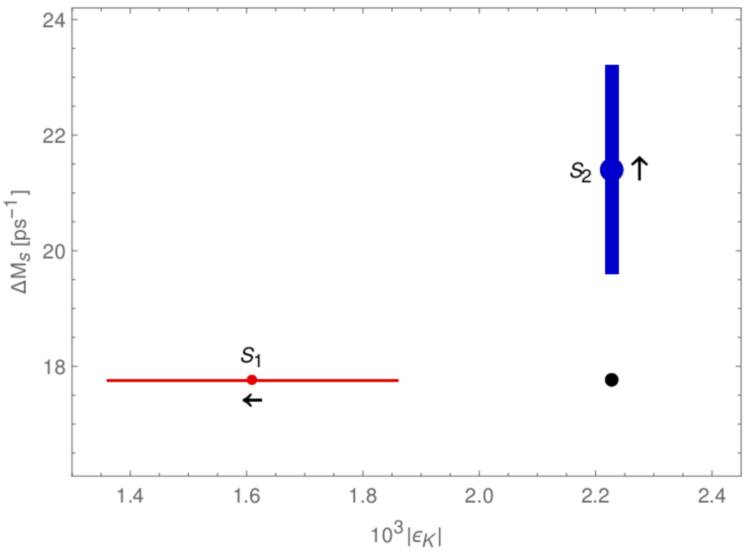
UT fit :

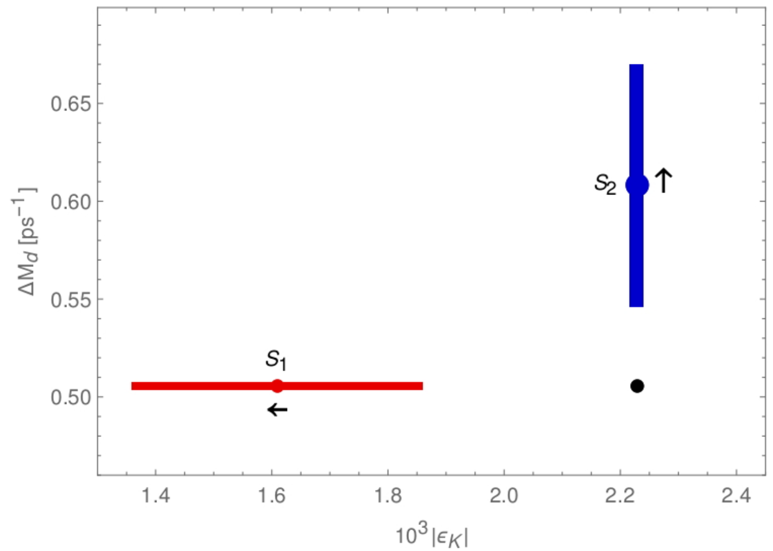
$$\bar\rho = 0.137 \pm 0.022$$
$$\bar\eta = 0.349 \pm 0.014$$





Tensions between $\Delta M_{d,s}$ and ε_K





Constrained MFV CKM + SM Operators $S_{Box} > S_{Box}^{SM}$ (Blanke, AJB 0610037)

S_1: $|\varepsilon_K| \leq (1.64 \pm 0.25) \cdot 10^{-3}$ $\quad |\varepsilon_K^{exp}| = 2.23 \cdot 10^{-3}$

S_2: $\Delta M_s \geq (21.1 \pm 1.8) ps^{-1}$ $\quad (\Delta M_s)^{exp} = 17.56 / ps$

$\Delta M_d \geq (0.600 \pm 0.064) ps^{-1}$ $\quad (\Delta M_d)^{exp} = 0.506 / ps$

Intermezzo

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

in the Standard Model

1503.02693

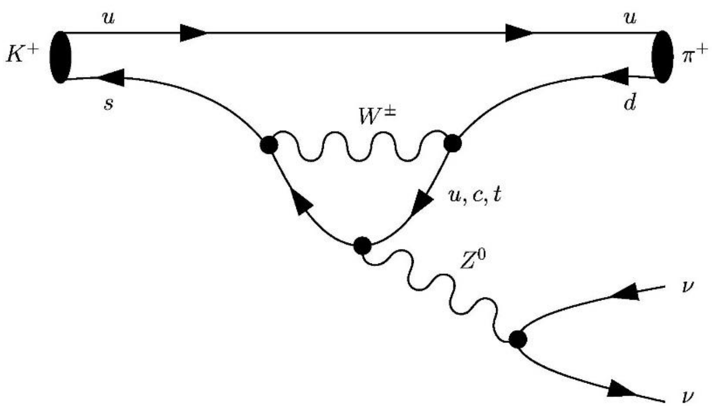

AJB

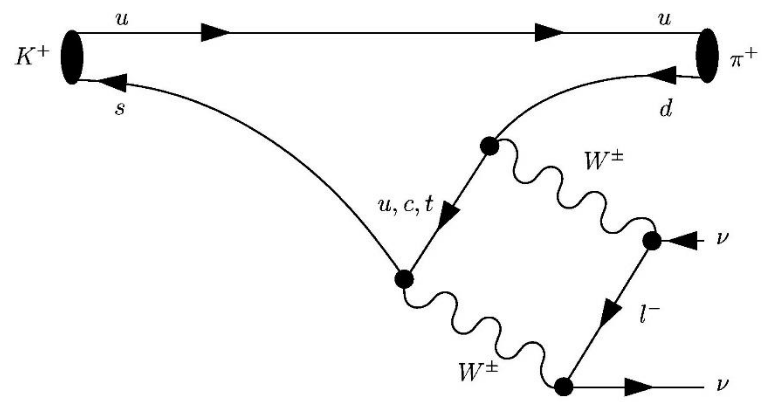

D.Buttazzo

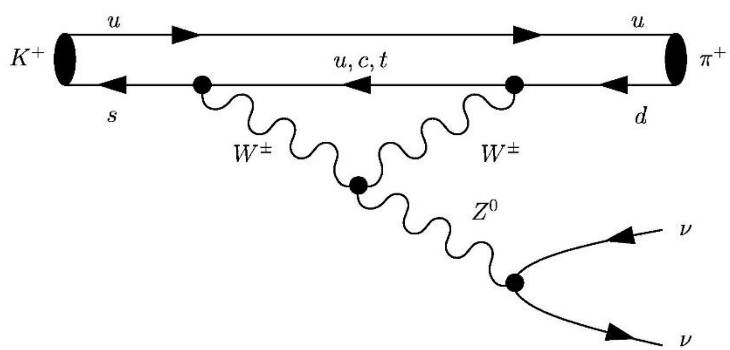

J.Girrbach-Noe


R.Knegjens

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







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

Data

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

CKM Uncertainties

AJB, Buttazzo, Girrbach-Noe, Knegjens 1503.02693

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

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

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

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

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

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

Can we reach Zeptouniverse through Rare K and B Decays?

(Z´)

AJB, Buttazzo, Girrbach-Noe, Knegjens, 1408.0728

If only left-handed or only right-handed couplings present in NP : Only with rare K Decays $B_s \sim 15$ TeV, $B_d \sim 15$ TeV

If both LH and RH present but $g_L^{ij} \ll g_R^{ij}$ or $g_L^{ij} \gg g_R^{ij}$:

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

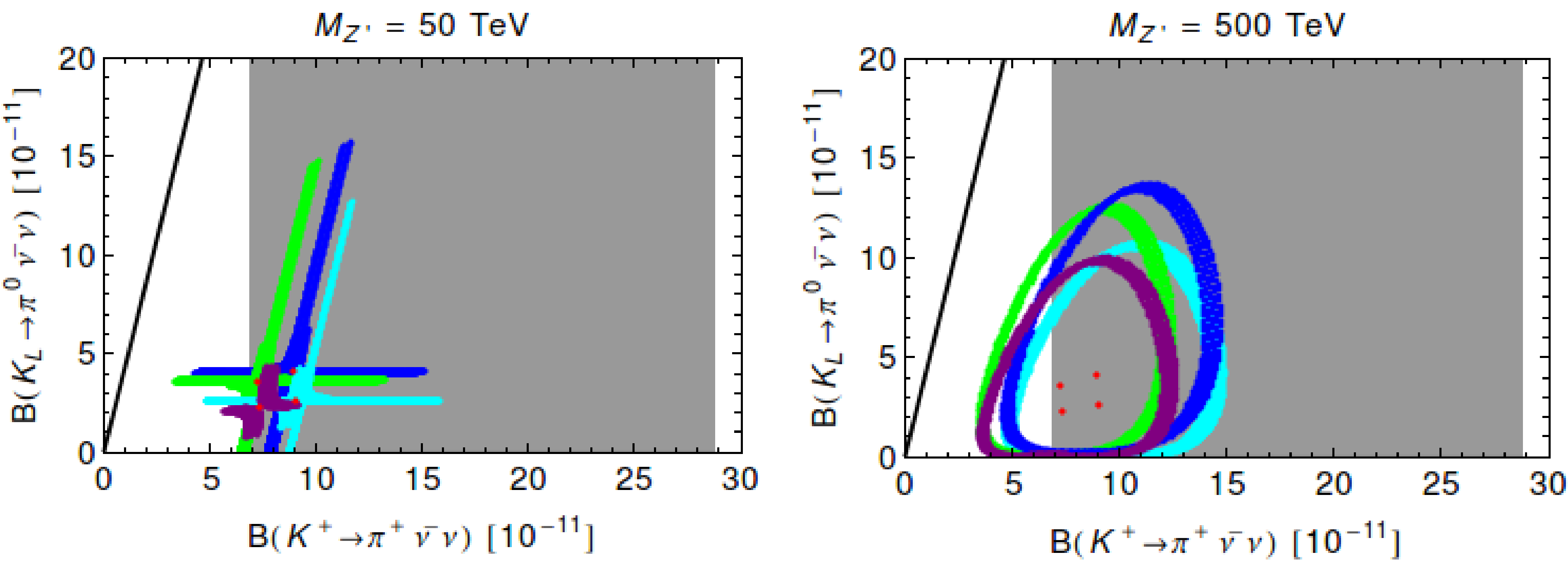
B_d : $\Lambda_{NP}^{max} \simeq 160$ TeV

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

Yes we can !!

Heavy Z´ at Work

AJB, Buttazzo, Girrbach-Noe, Knegjens, 1408.0728



ε_K constraint

General discussion: Blanke 0904.2528

No ε_K constraint

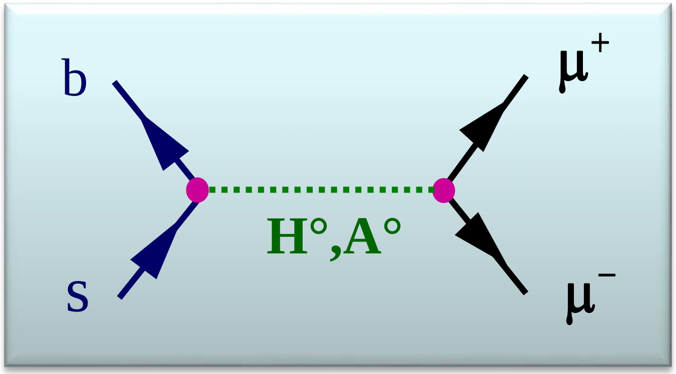
Colours: different CKM input

● SM

Can we reach Zeptouniverse through S and P

AJB, Buttazzo, Girrbach-Noe, Knegjens, 1408.0728

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



S : ≈ 350 TeV

P : ≈ 700 TeV

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

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

S=H° **P=A°**

Section 3

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

beyond SM

AJB (1601.00005)

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)

Strategy

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)

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

Re and Im Parts: Z and Z´ Couplings

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

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

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

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

Basic Structure of NP Contributions

AJB (1601.00005)

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

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

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

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

Dominance of $Q_8\,(Q_8')$ $\Rightarrow$ $\mathrm{Re} \gg \mathrm{Im}$ $\Rightarrow$ $\{\Delta M_K^{NP} > 0\}$ (small) (Z/Z′)

Implications for

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

(Re, Im)

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

(Im)

Lesson 1

We need new sources of CP violation!
1508.08672

Lesson 2

Tree-Level Z with LH or RH FCNC currents
(Anticorrelation of ε'/ε and $K_L \to \pi^0 \nu\bar{\nu}$)
$K^+ \to \pi^+ \nu\bar{\nu}$ can be significantly enhanced

LH	$R_+^{\nu\bar{\nu}} < 2$	Q_8
RH	$R_+^{\nu\bar{\nu}} < 5.7$	Q_8'

Only small effects in ε_K, ΔM_K allowed because of $K_L \to \mu^+\mu^-$ upper bounds

⇨ Isidori, Unterdorfer 0311084

Lesson 3

Tree-Level Z with LH + RH FCNC currents
ε'/ε, ε_K, $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$
can be simultaneously enhanced

Lesson 4

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

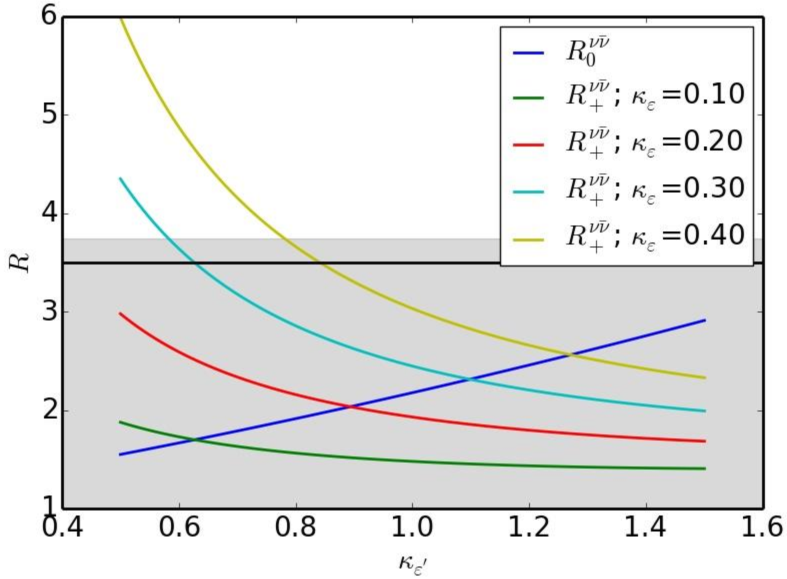
$$\text{Dominance of } Q_6\left(Q'_6\right) \Rightarrow \text{Im} >> \text{Re} \Rightarrow \left\{\Delta M_K^{NP} < 0\right\}$$

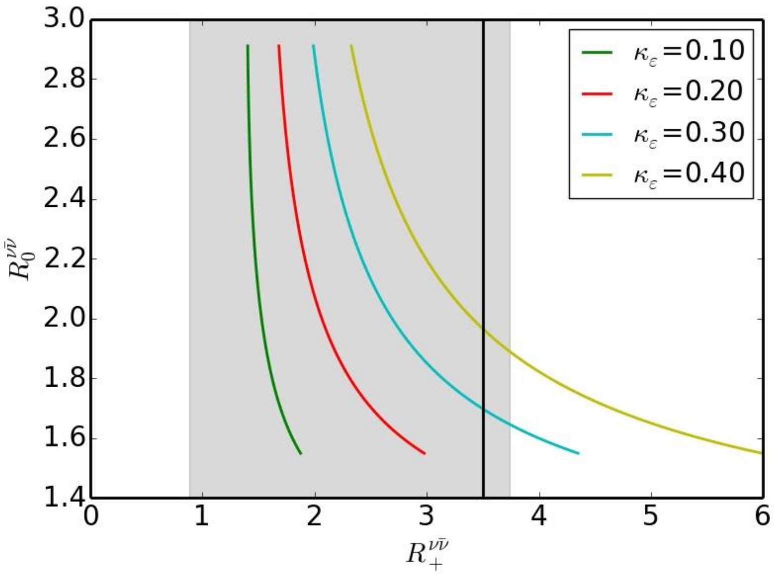
$$\text{Dominance of } Q_8\left(Q'_8\right) \Rightarrow \text{Re} >> \text{Im} \Rightarrow \left\{\Delta M_K^{NP} > 0\right\}$$

Z with LH and RH Flavour Violating Couplings

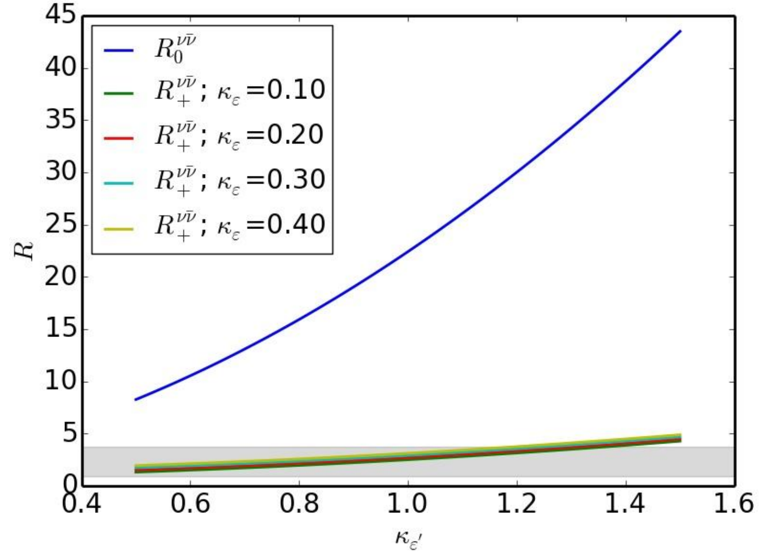
$Q_8 \left(Q'_8\right)$

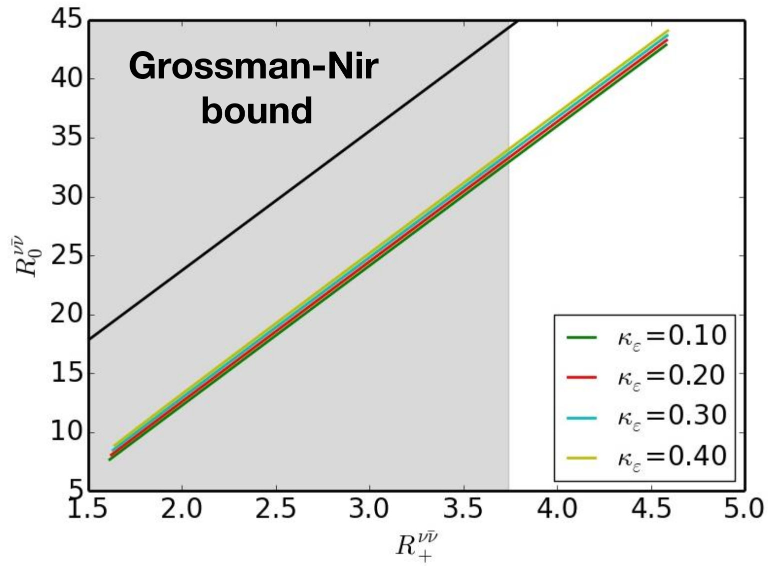
Example 1 $\text{Im}\,\Delta_{L,R} < \text{Re}\,\Delta_{L,R}$



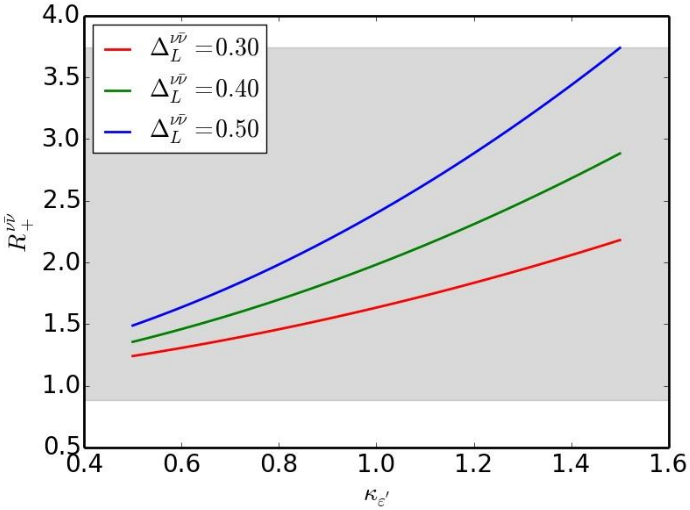


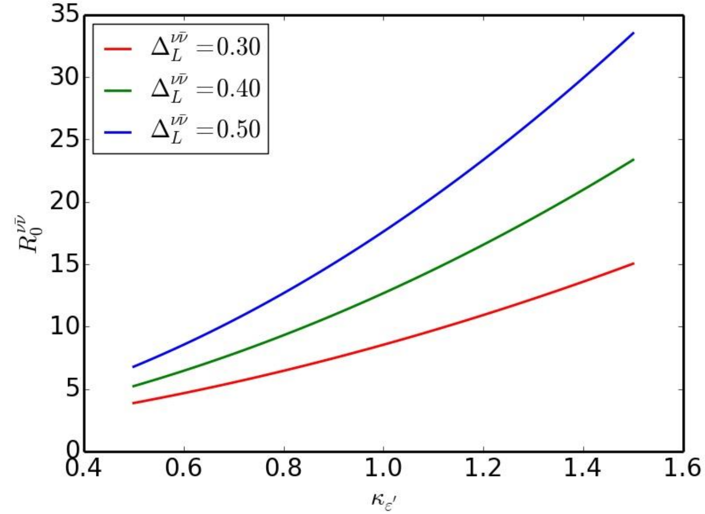
Example 2 $\text{Im}\,\Delta_{L,R} >> \text{Re}\,\Delta_{L,R}$





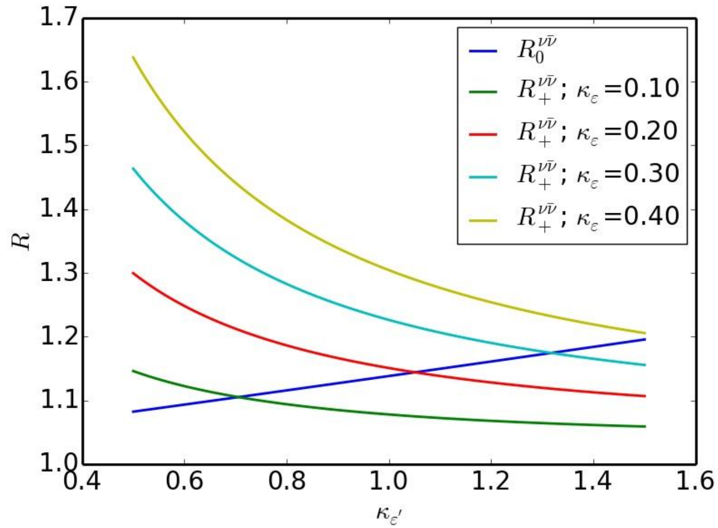
QCD Penguin (Q_6)



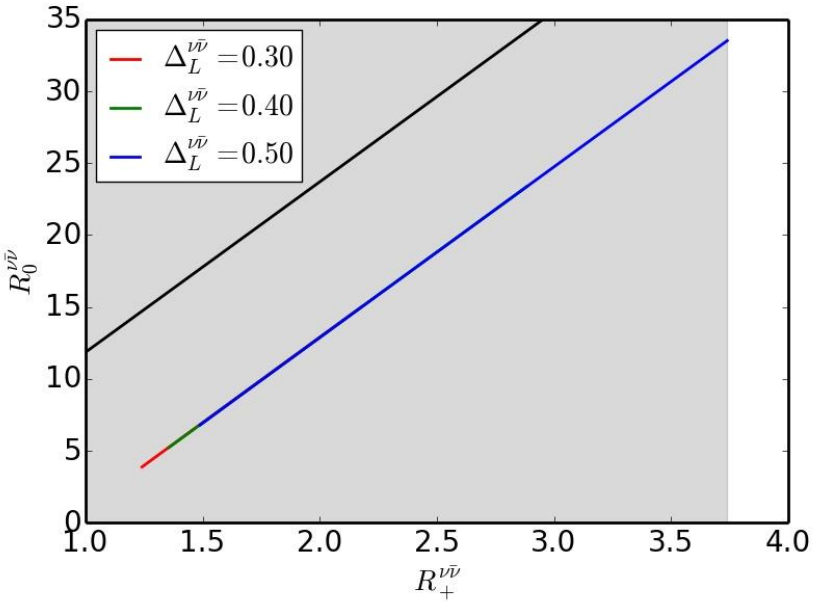


Electroweak Penguin (Q_8)

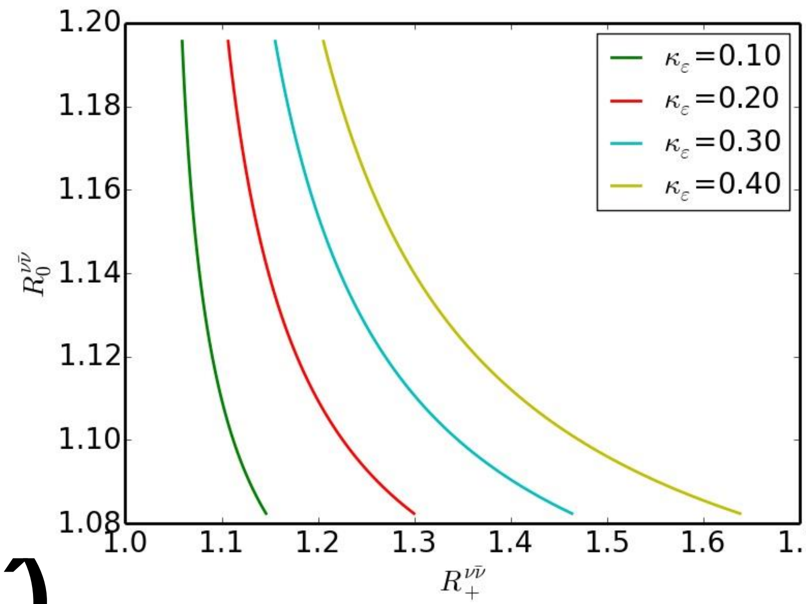
(Z´)



QCDP (Q_6)

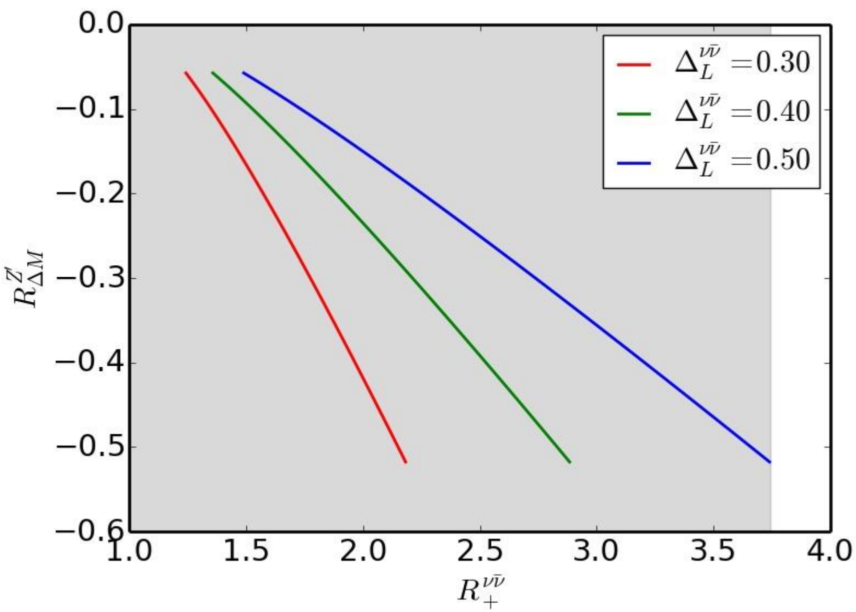


EWP (Q_8)



(Z′)

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



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

Section 4

Highlights from 331, LHT,
Vector-Like Quark Models,
SUSY Models

ε'/ε + $K \to \pi\nu\bar{\nu}$ 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


Monika Blanke


AJB


Stefan Recksiegel

LHT
1507.0631

Most Recent

AJB

Fulvia de Fazio

331 models facing

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

ε'/ε, $B_s \to \mu^+\mu^-$,

$B \to K^*\mu^+\mu^-$

Model with Vektor-like Quarks

Christoph Bobeth

AJB

Alejandro Celis

Martin Jung

331 Models Facing ε'/ε Anomaly

AJB, De Fazio 1512.02869, 1604.02344

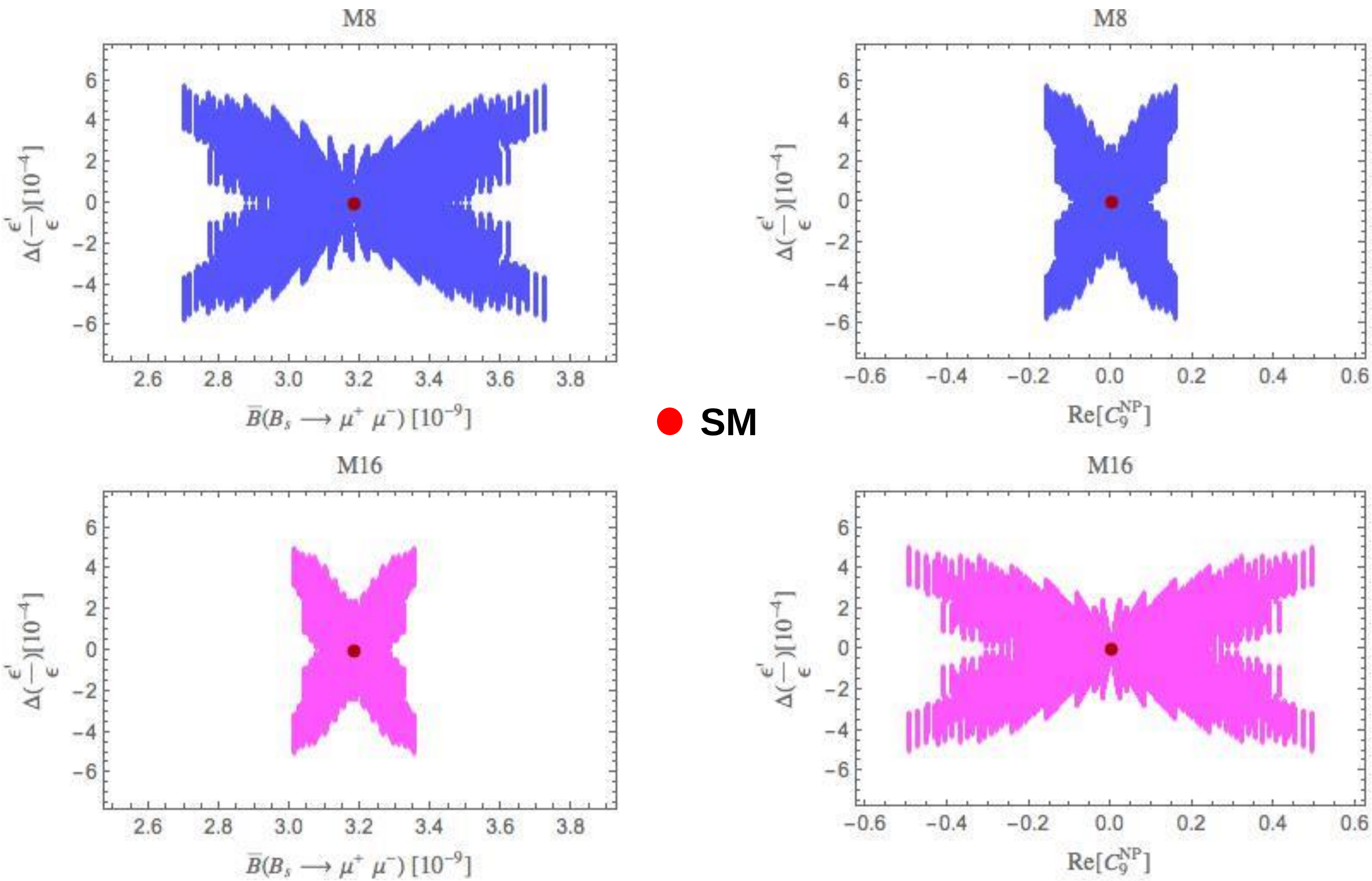
1. $\kappa_{\varepsilon'} \leq 0.8$ (only 3 among 24 models can reach upper bound)

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

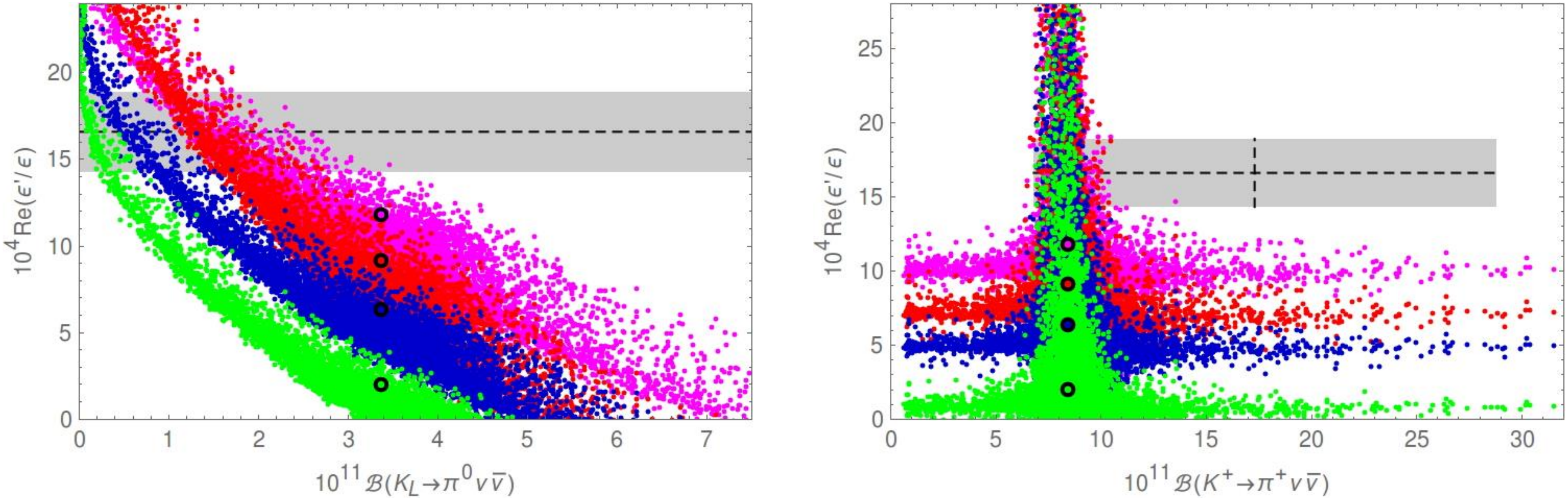
3. Small NP effects in $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$

Correlations in Favorite 331 Models

(AJB+De Fazio, 1604.02344)



LHT : Blanke, AJB, Recksiegel (1507.06316)



~~$\left(B_6^{(1/2)} = 1.0, \quad B_8^{(3/2)} = 0.76\right)$~~ **(Violates Large N bound)**

$\left(B_6^{(1/2)} = 1.0, \quad B_8^{(3/2)} = 1.0\right)$

$\left(B_6^{(1/2)} = 0.75, \quad B_8^{(3/2)} = 0.76\right)$

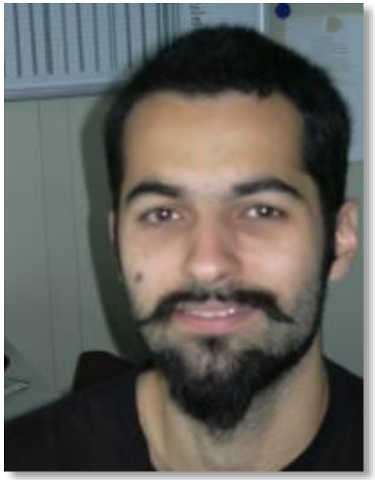
$\left(B_6^{(1/2)} = 0.57, \quad B_8^{(3/2)} = 0.76\right)$

Supersymmetric Explanation of ε'/ε and ε_K

Teppei Kitahara

Ulrich Nierste

Paul Tremper

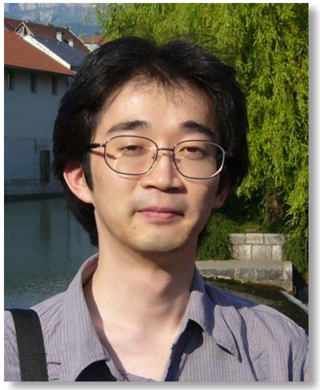


1604.07400

ε'/ε anomaly can be explained in the MSSM with squark masses above 3 TeV being consistent with ε_K without fine-tuning of CP phases or other parameters.

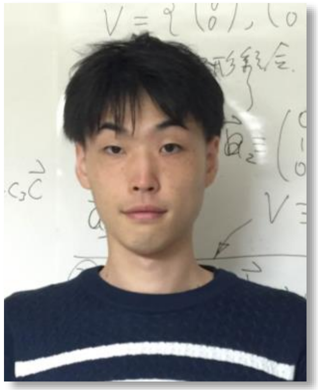
Other recent Studies of ε′/ε, Rare K Decays

Motoi Endo



Satoshi Mishima

Daiki Ueda



Kei Yamamoto

1603.07960

10 TeV Stop

1608.01444

: Superpartners lighter than 4-6 TeV
Correlations with other observables

Morimitsu Tanimoto

11 Vector-like Quark (VLQ) Models

Bobeth, AJB, Celis, Jung
1609.xxxx

(5) $G_{SM} = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ $\begin{bmatrix} \text{tree level Z } (\Delta F = 1) \\ \text{Boxes } (\Delta F = 2), \text{ VLQ} \end{bmatrix}$

(2) $G'_{SM}(S) = G_{SM} \otimes U(1)_{L_\mu - L_\tau}$ (Z´, boxes) Altmannshofer et al. (1403.1269)

(4) $G'_{SM}(\Phi) = G_{SM} \otimes U(1)_{L_\mu - L_\tau}$

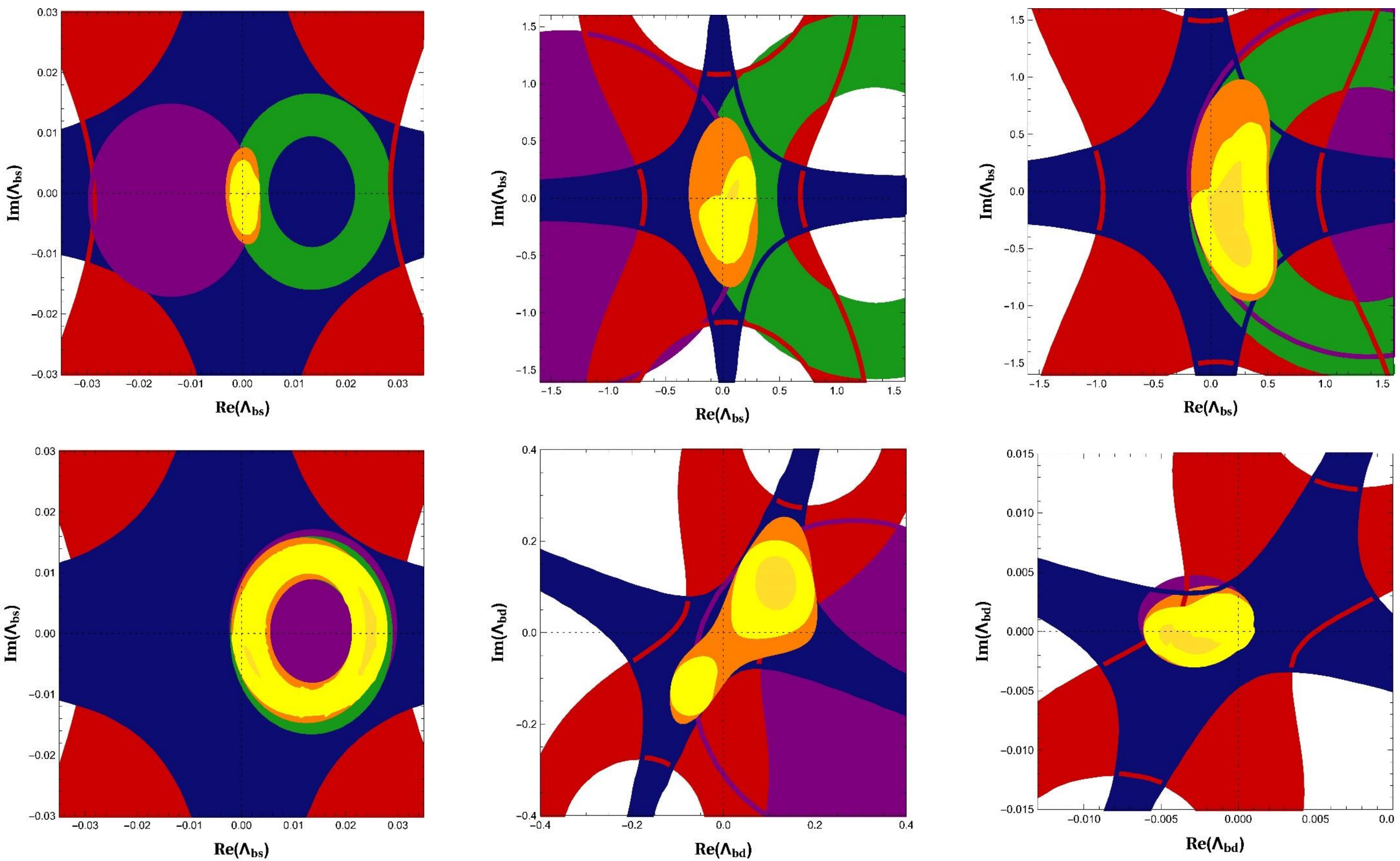
Most interesting effects in G_{SM} models:

5 free parameters in Yukawa couplings: Y_i + M_{VLQ}

- ★ Large NP effects in ε'/ε, $K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$
- Smaller but significant in $B_{s,d} \to \mu^+\mu^-$
- ε_K, $\Delta M_{s,d}$ tensions removed
- ★ Combination of $\Delta F=2$ and $\Delta F=1$ observables allows to determine M_{VLQ} independently of Y_i
- Unable to explain $B \to K^* l^+ l^-$ anomalies (possible in $G'_{SM}(S)$ but then other NP small)

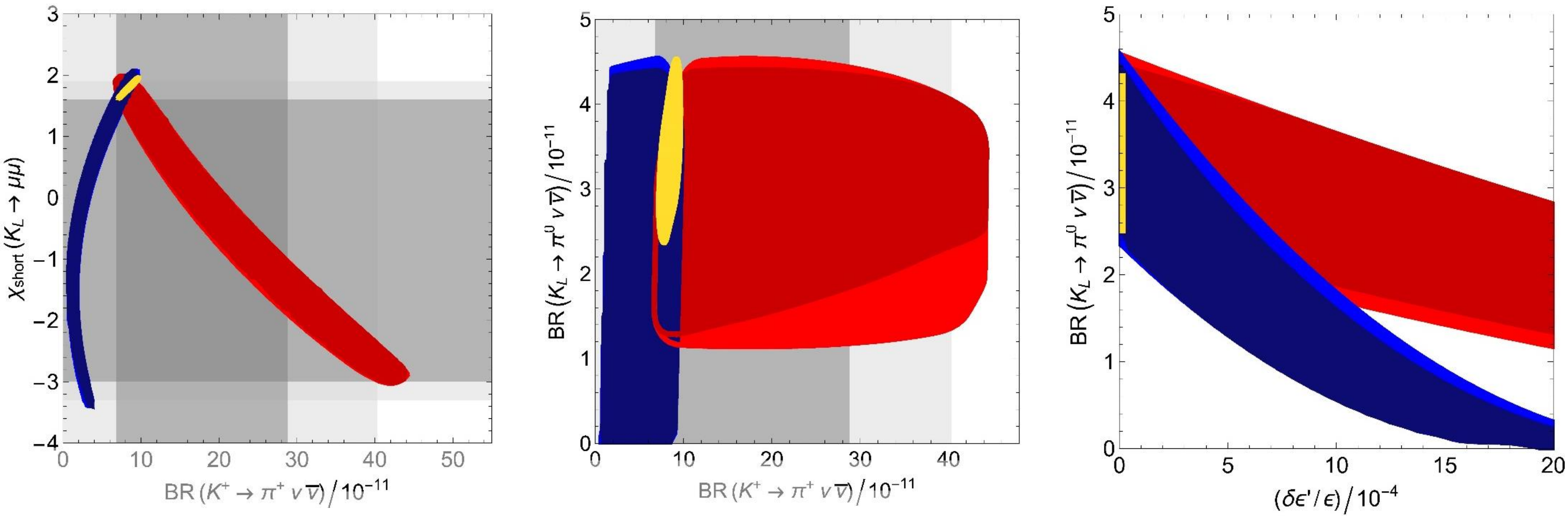
Patterns dependent on LH and RH currents

Constraints on Yukawa Couplings (VLQ-Art)



Correlations between Observables in G_{SM}

(VLQ Models)
BBCJ



- Left-handed FCNCs
- Right-handed FCNCs
- Standard Model

ε´/ε - anomaly easily solved

$K_L \to \pi^0\nu\bar{\nu}$ suppressed because of ε´/ε

$K^+ \to \pi^+\nu\bar{\nu}$ only enhanced In the presence of RH currents (because of $K_L \to \mu^+\mu^-$)

Open Questions for Coming Years

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

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

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

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

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

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

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

New Particles discovered at the LHC?

What about $\Delta I=1/2$ Rule?

What about $\Delta I = 1/2$ Rule?

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

Since 1955

Gell-Mann
Pais

1986, 2014

Large N including
1/N corredtions

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

Correct value of $\mathrm{Re}A_2$

$$\left(\frac{\mathrm{Re}\,A_0}{\mathrm{Re}\,A_2}\right)_{1/N} \approx 16.0 \pm 1.5 \quad {}^{*)}$$

Dominance of current-current operators

RBC-QCD
(2013, 2015)

Correct value of $\mathrm{Re}A_2$

$$\left(\frac{\mathrm{Re}\,A_0}{\mathrm{Re}\,A_2}\right)_{\mathrm{Lattice}} \approx 31 \pm 11$$

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

AJB
De Fazio
Girrbach-Noe
1404.3824

Exciting Times are just ahead of us !!!

Exciting Times are just ahead of us !!!

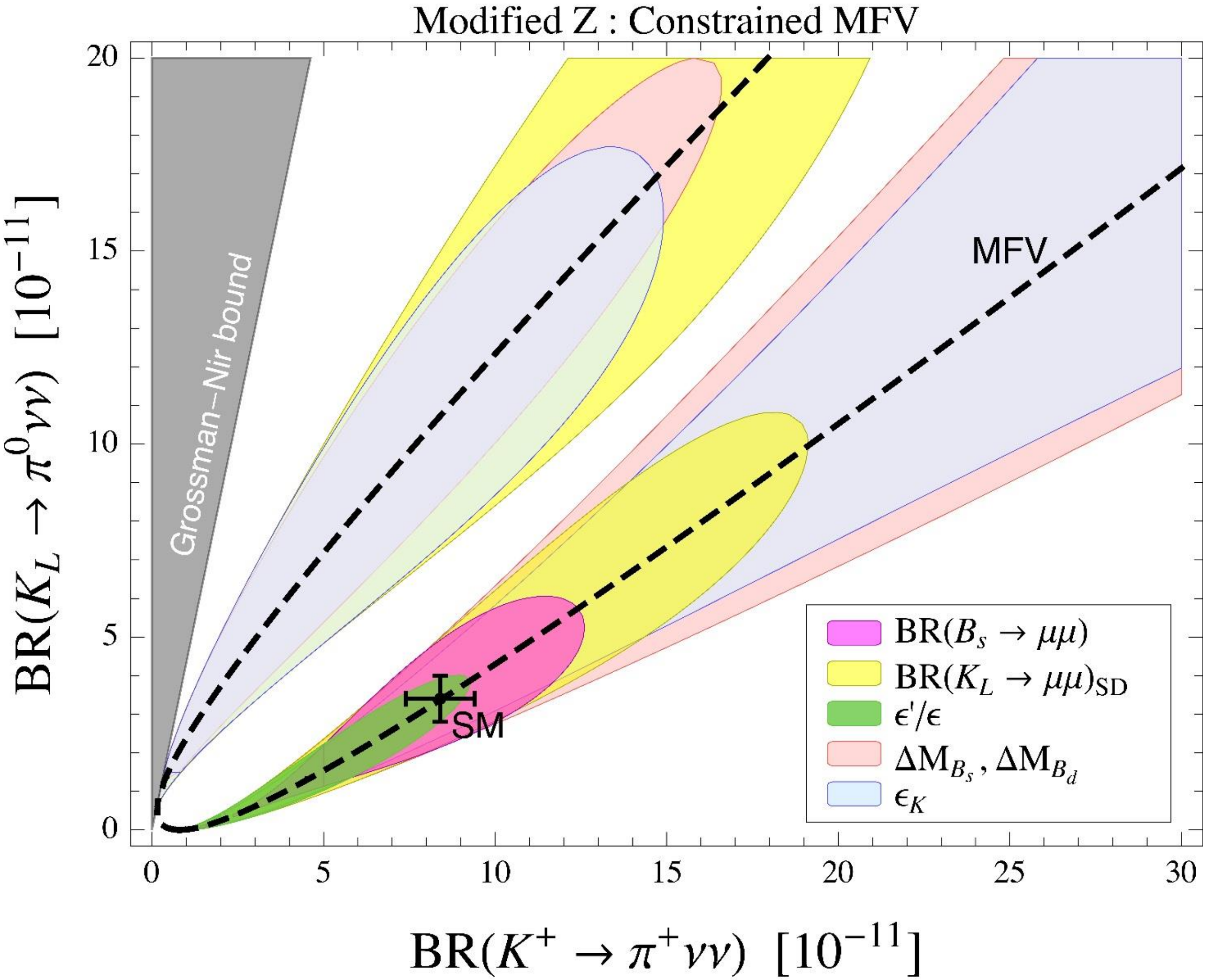
Thank You !

Anomalies in Kaon Flavour Physics

Backup

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

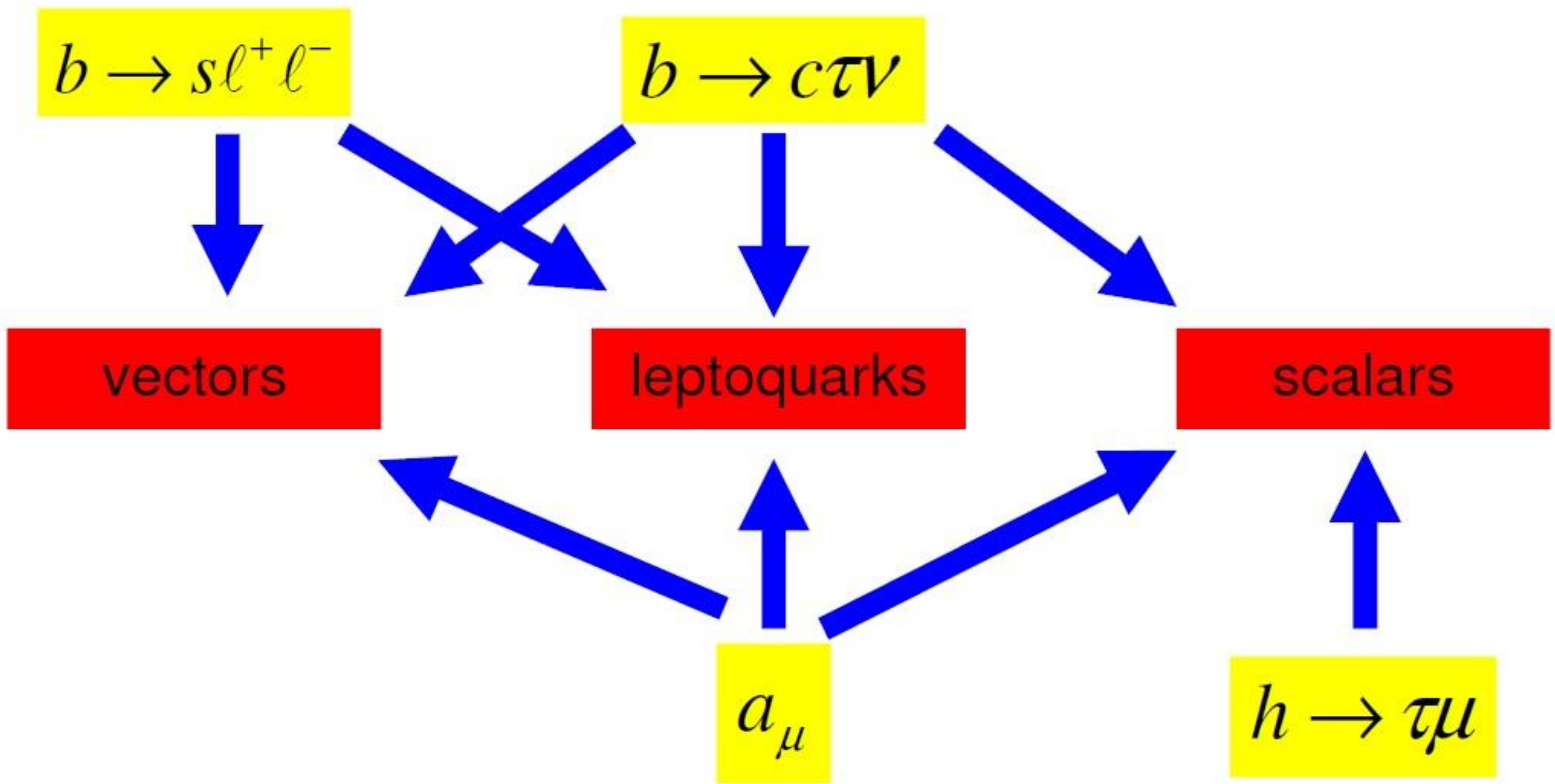
AJB + Fleischer (MFV)
0104238



AJB, Buttazzo, Knegjens: hep-ph-1507.08672

New Physics Explanations of Anomalies

Andreas Crivellin, 1605.02934



RBC-UK QCD

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

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

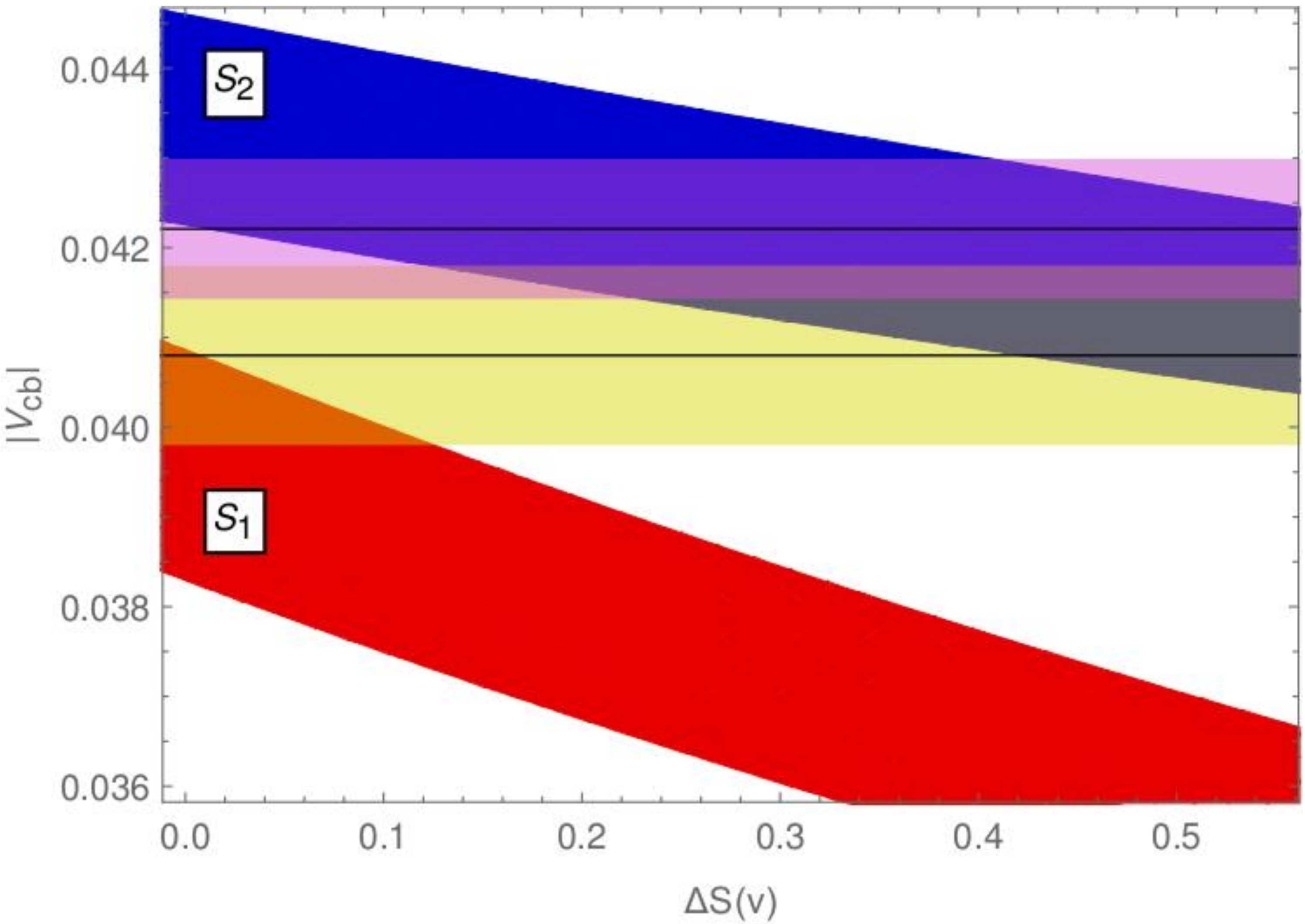
$$(\varepsilon'/\varepsilon)_{\mathrm{exp}} = (16.6 \pm 2.3) \cdot 10^{-4}$$

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

Large N

$$(\varepsilon'/\varepsilon) < (8.6 \pm 3.2) \cdot 10^{-4}$$

$$\left(\frac{\mathrm{Re}\,A_0}{\mathrm{Re}\,A_2}\right) = 16.0 \pm 1.5$$



0.044
0.042
0.040
0.038
0.036
$|V_{cb}|$
S_2
S_1
0.0
0.1
0.2
0.3
0.4
0.5
ΔS(v)

Bardeen
AJB
Gérard
(1986,
2014)

Large N Approach

AJB, Gérard (2015)

vs

Lattice

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

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

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

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

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

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

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

(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

Exp
22.4

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

Bardeen
AJB
Gérard
(1986,
2014)

Large N Approach

AJB, Gérard (2015)

vs

Lattice

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

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

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

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

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

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

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

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

Motivations for New Analysis

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

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

3. Point out correlation between
$$K^+ \to \pi^+ \nu\bar{\nu},\quad B_s \to \mu^+\mu^- \quad \text{and} \quad \gamma$$
(NA62) (LHCb+CMS) (LHCb)

4. Update correlation between
$$K^+ \to \pi^+ \nu\bar{\nu},\quad K_L \to \pi^0 \nu\bar{\nu} \quad \text{and} \quad \beta$$
(Buchalla, AJB, 94)
(AJB, Fleischer, 00)

Basically no CKM uncertainties

5. Use most recent lattice input for CKM

6. Provide the present best value in SM

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

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 $Br(K_L \to \pi^0 \nu\bar{\nu})$
- $Br(K^+ \to \pi^+ \nu\bar{\nu}) \leq 2\, Br(K^+ \to \pi^+ \nu\bar{\nu})^{SM}$
- 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 $Br(K_L \to \pi^0 \nu\bar{\nu})$
- $Br(K^+ \to \pi^+ \nu\bar{\nu}) \leq 6\, Br(K^+ \to \pi^+ \nu\bar{\nu})^{SM}$
- NP effects in ΔM_K and ε_K very small

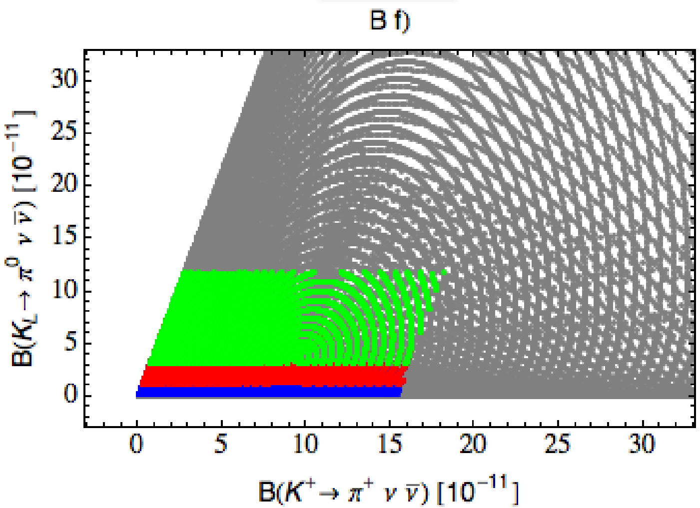
Unless Loop effects important

$Q_{8'}$ EWP

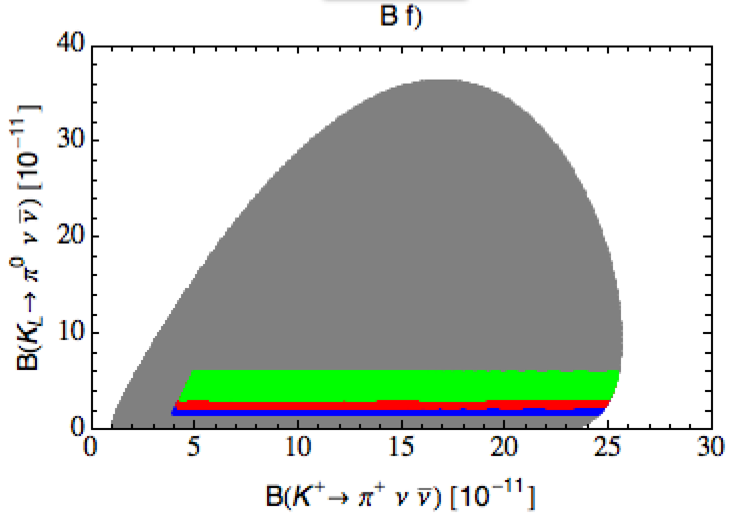
Z with FCNCs at Work

AJB, de Fazio,
Girrbach-Noe
1404.3824

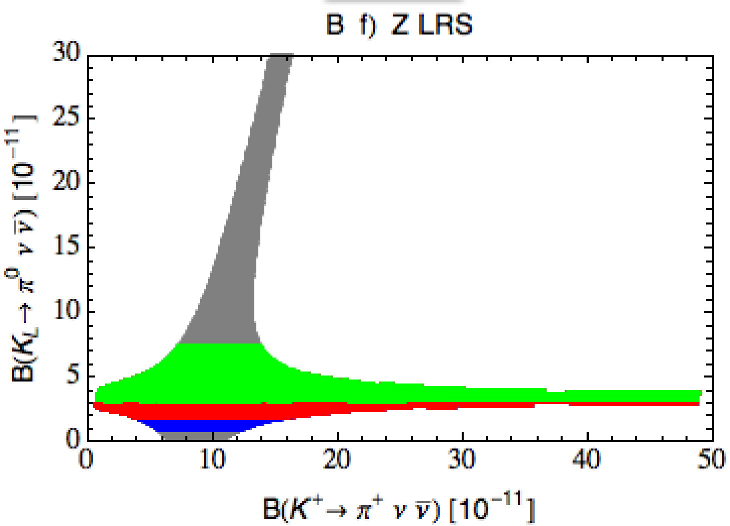
LHS



RHS



LRS



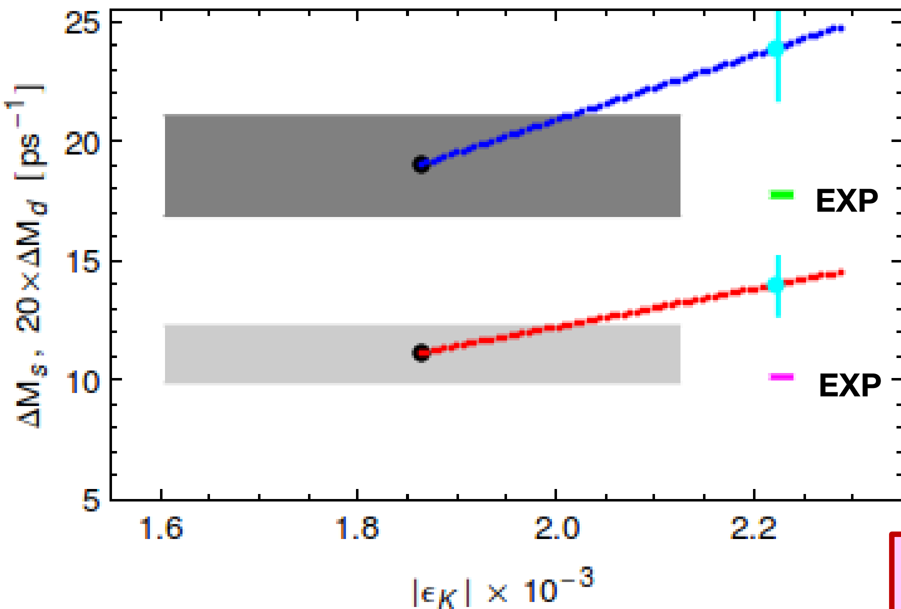
Grey: ε_K, ΔM_K constraint

ε'/ε + $K_L \to \mu^+\mu^-$:

- Green: $B_6 = 1.25$
- Red: $B_6 = 1.00$
- Blue: $B_6 = 0.75$

2 Tensions in $\Delta F=2$ within MFV

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



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

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

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

$|V_{cb}|$

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

AJB + Girrbach 1306.3755

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

*) 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 $S_{\psi K_s}$

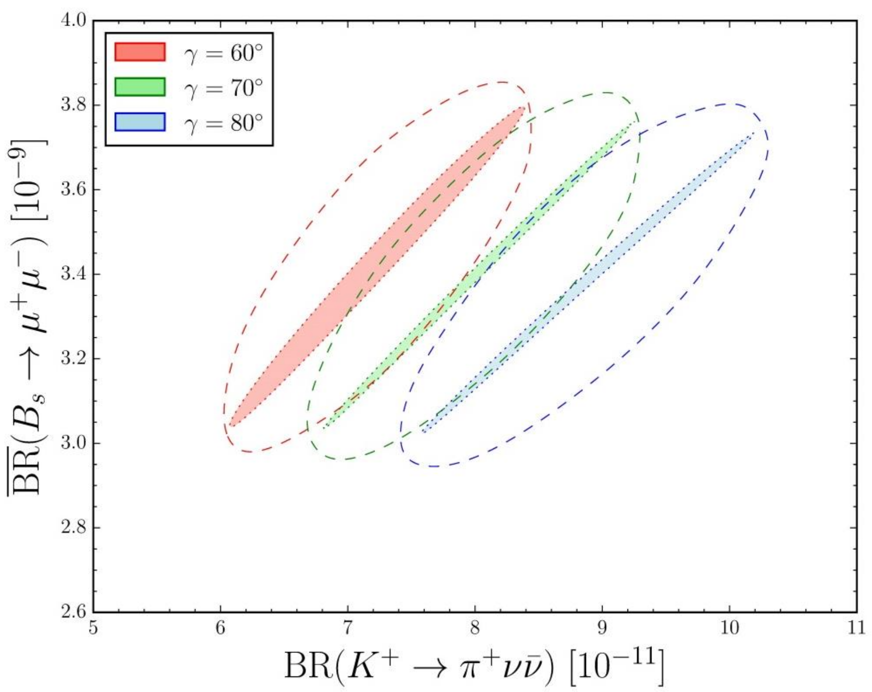
Correlations within SM

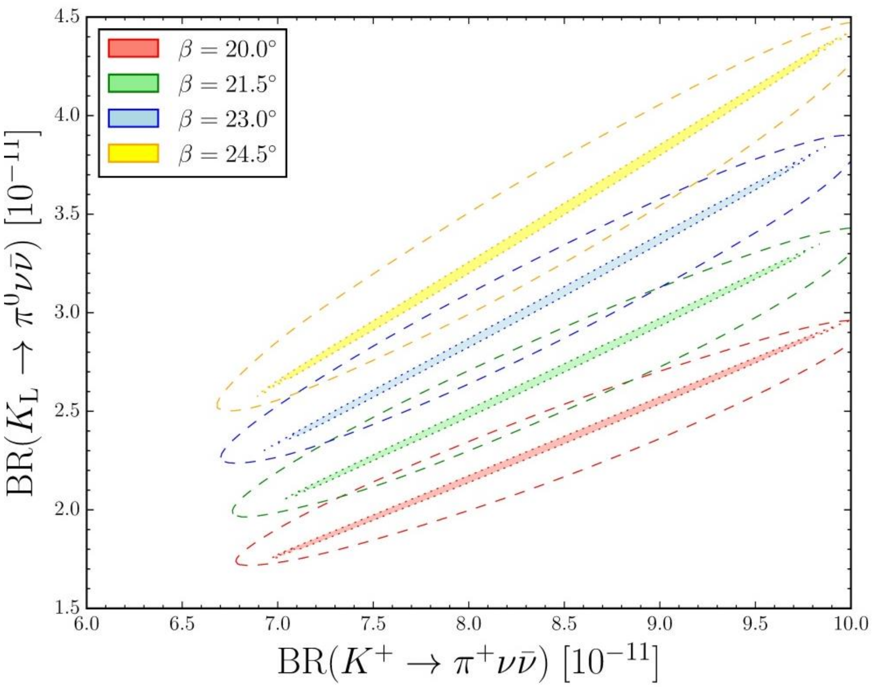
$B_s \to \mu^+\mu^-$, $K^+ \to \pi^+\nu\bar{\nu}$, γ

BBGK (2015)

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

Buchalla, AJB (94)





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.**

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

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

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

$$\gamma = (69.5 \pm 5.0)^\circ \Rightarrow \gamma = (70.8 \pm 2.3)^\circ$$

(after new lattice results for ξ)

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

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

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

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

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

AJB + Gérard   1507.06326

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

Using BGJJ formula

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

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

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

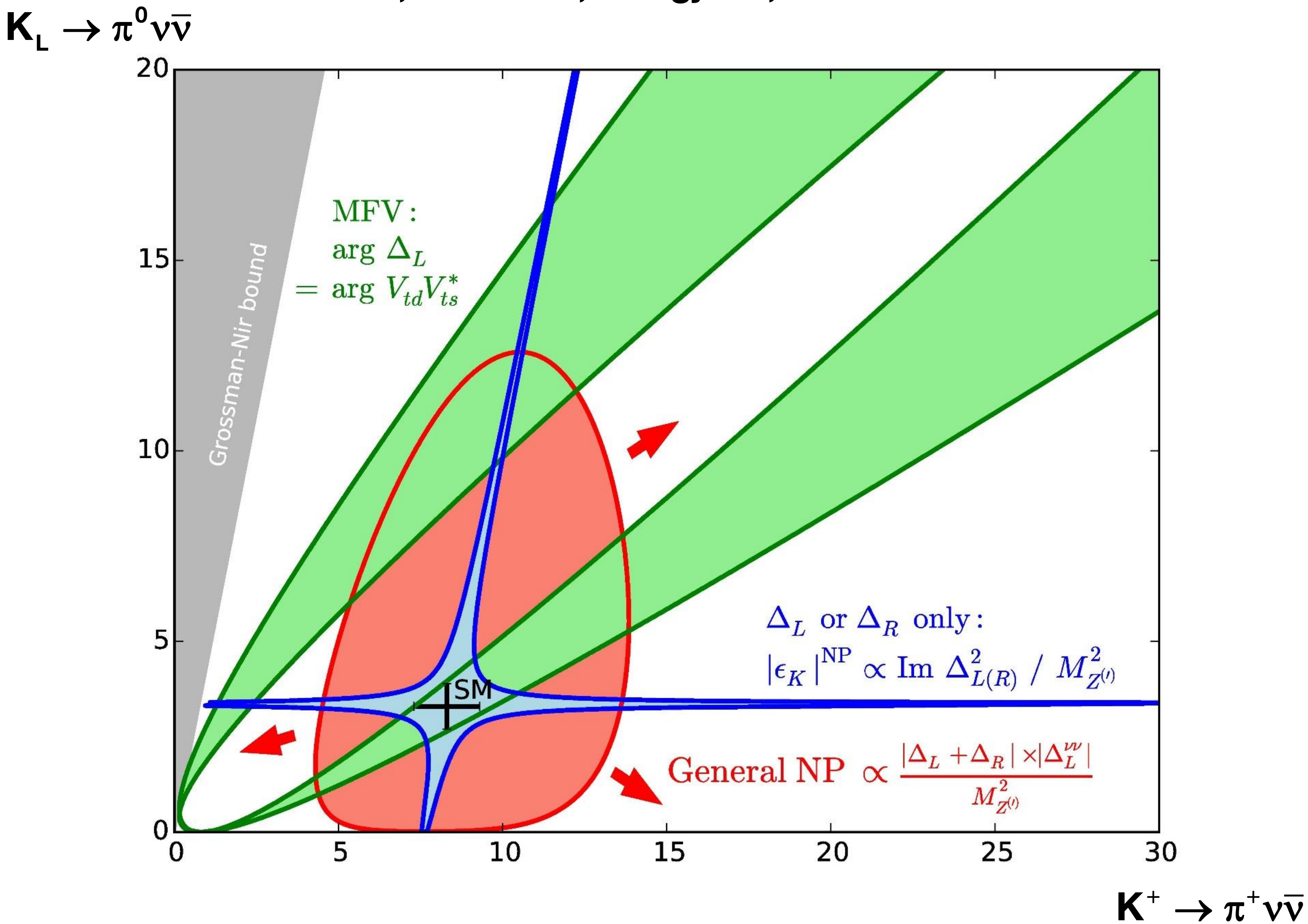
For $\mathrm{Im}\left(V_{ts}V_{td}^*\right) = 1.4 \cdot 10^{-4}$

Below data but positive

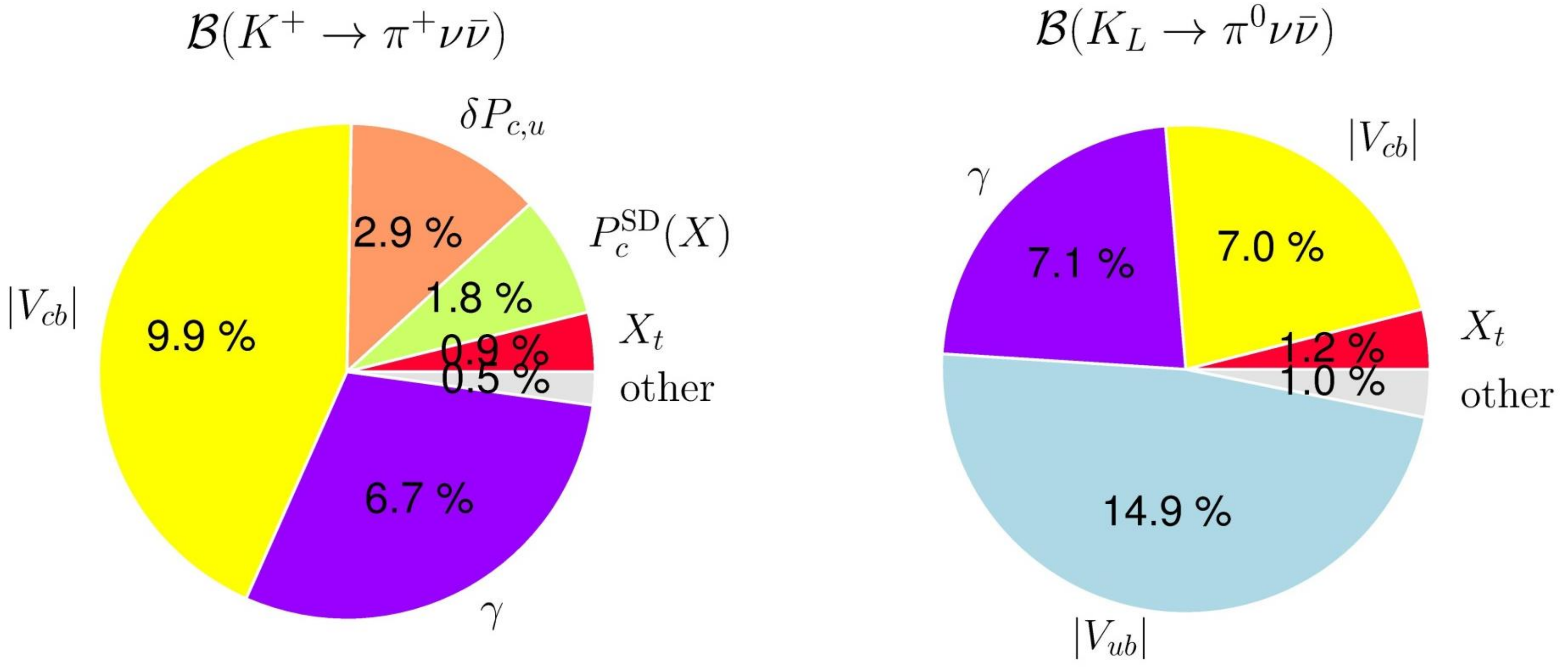
Yet still large uncertainties

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

AJB, Buttazzo, Knegjens, 1507.08672



Error Budgets



Update: 1503.02693

$P_c = 0.404 \pm 0.024$

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

Z´ outside the reach of the LHC

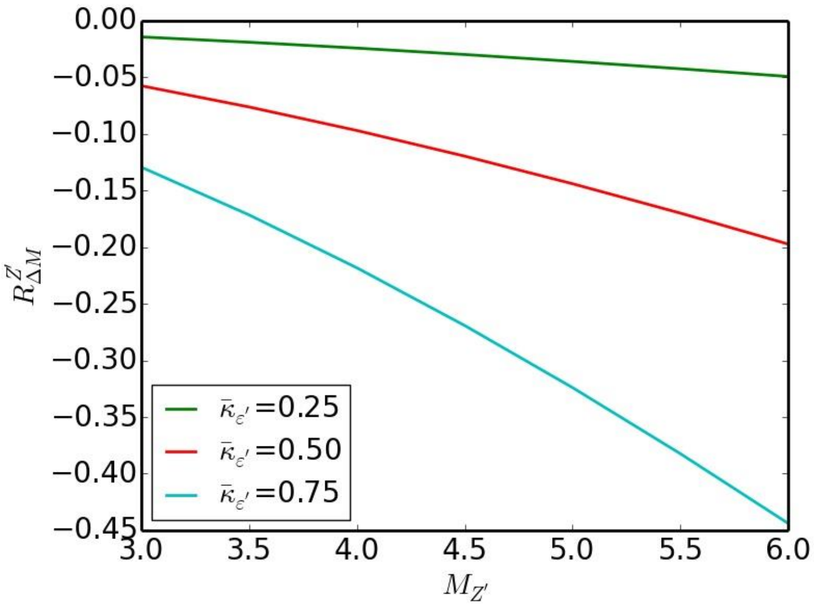
QCD Penguin

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

But constraint from ΔM_K

Independent of $M_{Z'}$

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



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

EWP Penguin

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

Using Tree Level Determination of CKM

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

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

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

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

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

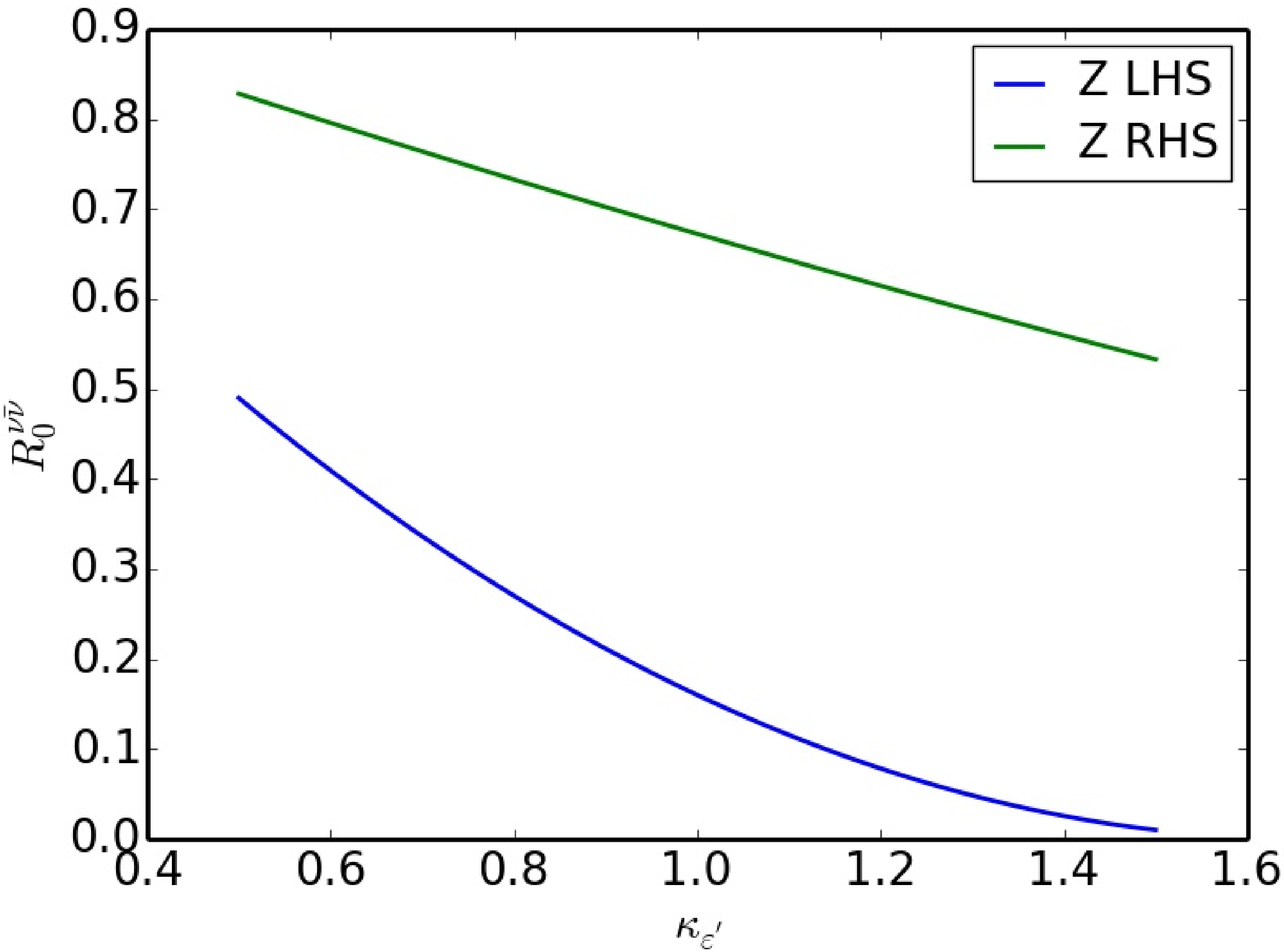
$$\overline{Br}(B_s \to \mu^+\mu^-)_{exp} = (2.8 \pm 0.7)\cdot 10^{-9}$$

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

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

AJB, Buttazzo, Girrbach-Noe, Knegjens 1503.02693

Z with LH or RH Flavour Violating Couplings



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

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

($K^+ \Uparrow$ with $\kappa_\varepsilon \Uparrow$) Only (20-40)% effects

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

ε_K anomaly can be solved

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

$M_{Z'} = 3$ TeV

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

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

ε'/ε, ε_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

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

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

Example 2

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

$K_L \Uparrow$ $K^+ \Uparrow$ 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