Renaissance of Kaon Flavour Physics

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Beauty 2016, Marseille, May 2016

Plan for next 28 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.

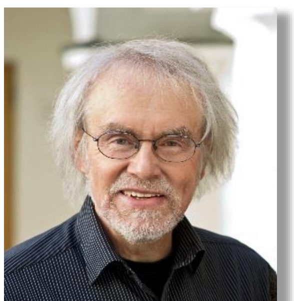
Highlights from 331, LHT, Vector-Like Quark Models

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)

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, 1512.02869,1604.02344)
New Strategy (AJB, 1601.00005)
Vector-like Quarks (Bobeth, AJB, Celis, Jung, 1605.xxxx)

Four dominant contributions to ε′/ε in the SM

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

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

From ReA_0 → −3.6; From ReA_2 → 1.2

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

Assumes that ReA_0 and ReA_2 (ΔI=1/2 Rule) fully described by SM (includes isospin breaking corrections)

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

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

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

Meson evolution $m_\pi \to \mu = 0(1\,\text{GeV})$ suppresses $B_6^{(1/2)}$ and $B_8^{(3/2)}$ below 1 and $B_6^{(1/2)}$ stronger than $B_8^{(3/2)}$ in accordance with quark evolution for $\mu > 1\,\text{GeV}$

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)

ε'/ε within SM

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

$$\left\{ \frac{\mathrm{Re}\,A_2}{\mathrm{Re}\,A_0} \approx \frac{1}{22} \qquad \frac{\mathrm{Im}\,C_6}{\mathrm{Im}\,C_8} \approx 90 \qquad \frac{\langle Q_8 \rangle_2}{\langle Q_6 \rangle_0} \approx 2 \right\} \Rightarrow \text{strong cancellations}$$

ε'/ε beyond SM

$$\left(Q_6, Q_8, Q_6', Q_8' \right)$$

1. Generally Q_8 wins over Q_6 because $\left(\frac{\mathrm{Im}\,C_6}{\mathrm{Im}\,C_8} \right)^{NP} \approx 0(1)$ but can provide $\Delta(\varepsilon'/\varepsilon) > 0$

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

3. Chromomagnetic operators (not in this talk)

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

$$\left\{ \begin{array}{l} F_{B_s}\sqrt{\hat{B}_{B_s}} = (276.0 \pm 8.5\ \mathrm{MeV}) \\ F_{B_d}\sqrt{\hat{B}_{B_d}} = (229.4 \pm 9.3\ \mathrm{MeV}) \end{array} \right\} \Rightarrow$$

Their ratio $\xi = 1.203 \pm 0.019$

Similar but less precise results from ETM (1308.1851)

Blanke + AJB (1602.04020)

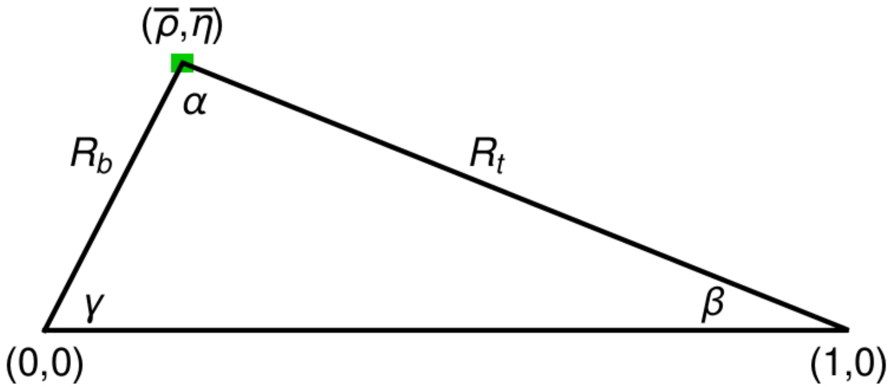
$$\left\{ \frac{\Delta M_d}{\Delta M_s},\ S_{\psi K_S} \right\} \Rightarrow \left\{ \begin{array}{l} \left|\frac{V_{ub}}{V_{cb}}\right| = 0.0864 \pm 0.0025 \\ \gamma = (62.7 \pm 2.1)^\circ \end{array} \right\}$$

S_1: Strategy 1: ΔM_s determines V_{cb} $\Rightarrow$ $|V_{cb}| = (39.5 \pm 1.3)\cdot 10^{-3}$

S_2: Strategy 1: ε_K determines V_{cb} $\Rightarrow$ $|V_{cb}| = (43.4 \pm 1.2)\cdot 10^{-3}$

$\Rightarrow$ Tension between ΔM_K and ε_K

Universal Unitarity Triangle 2016

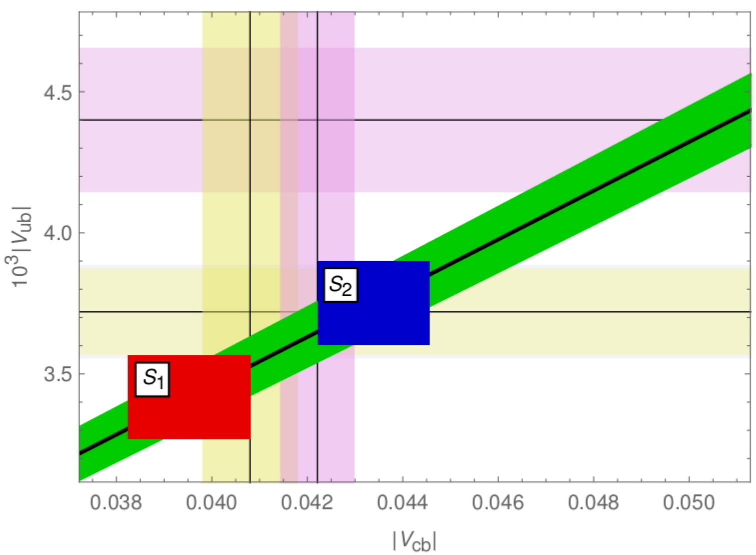


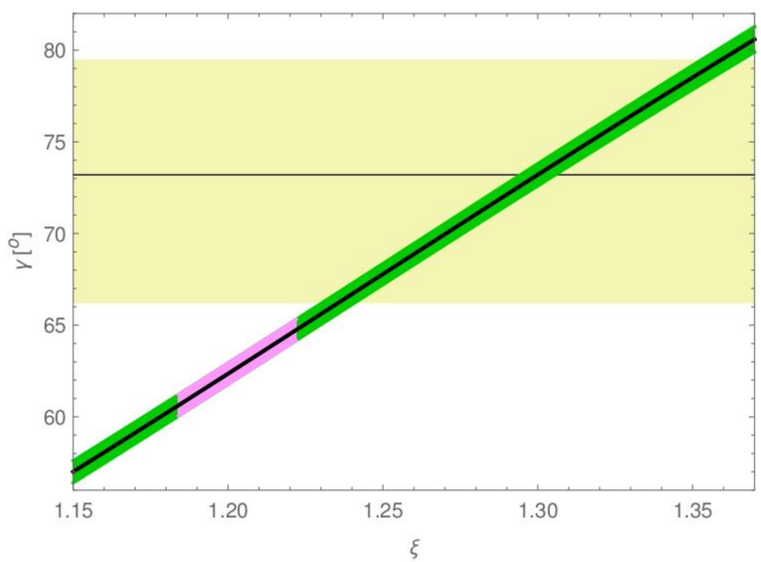
CMFV :

$$\bar{\rho} = 0.172 \pm 0.013$$
$$\bar{\eta} = 0.332 \pm 0.011$$

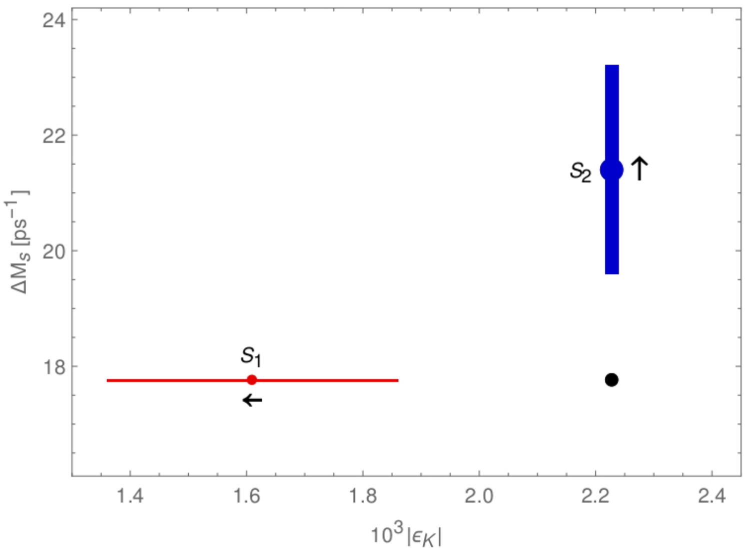
UT fit :

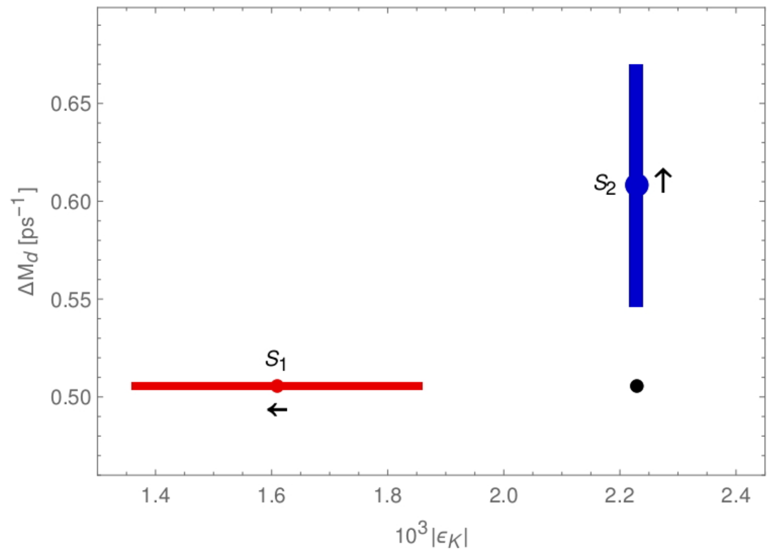
$$\bar{\rho} = 0.137 \pm 0.022$$
$$\bar{\eta} = 0.349 \pm 0.014$$





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





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

$$S_1:\quad |\varepsilon_K| \le (1.61 \pm 0.25)\cdot 10^{-3} \qquad |\varepsilon_K^{exp}| = 2.23\cdot 10^{-3}$$

$$S_2:\quad \Delta M_s \ge (21.4 \pm 1.8)\text{ps}^{-1} \qquad (\Delta M_s)^{exp} = 17.56\,/\,\text{ps}$$

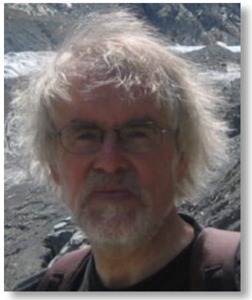
$$\Delta M_d \ge (0.608 \pm 0.062)\text{ps}^{-1} \qquad (\Delta M_d)^{exp} = 0.506\,/\,\text{ps}$$

Intermezzo

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

in the Standard Model

1503.02693



AJB

D.Buttazzo

J.Girrbach-Noe

R.Knegjens

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

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

CKM Uncertainties

AJB, Buttazzo, Girrbach-Noe, Knegjens
1503.02693

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

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

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

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

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

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

Section 3

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

beyond SM

AJB (1601.00005)

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 ?

Strategy

AJB (1601.00005)

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

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

(Im)

$$\varepsilon_K^{NP} = \kappa_\varepsilon \cdot 10^{-3}$$

$$0.1 \leq \kappa_\varepsilon \leq 0.4$$

(Im, Re)

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

Re and Im Parts: Z and Z´ Couplings

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

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

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

Basic Structure of NP Contributions

AJB (1601.00005)

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

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

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

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

(large)

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

(small)

⇩

Implications for

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

(Re, Im)

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

(Im)

Lessons on ε'/ε, ε_K, $K \to \pi\nu\bar{\nu}$: BSM

AJB: 1601.00005

Lesson 1

Do not expect much from MFV
(tensions cannot be removed) 1507.08672

Lesson 2

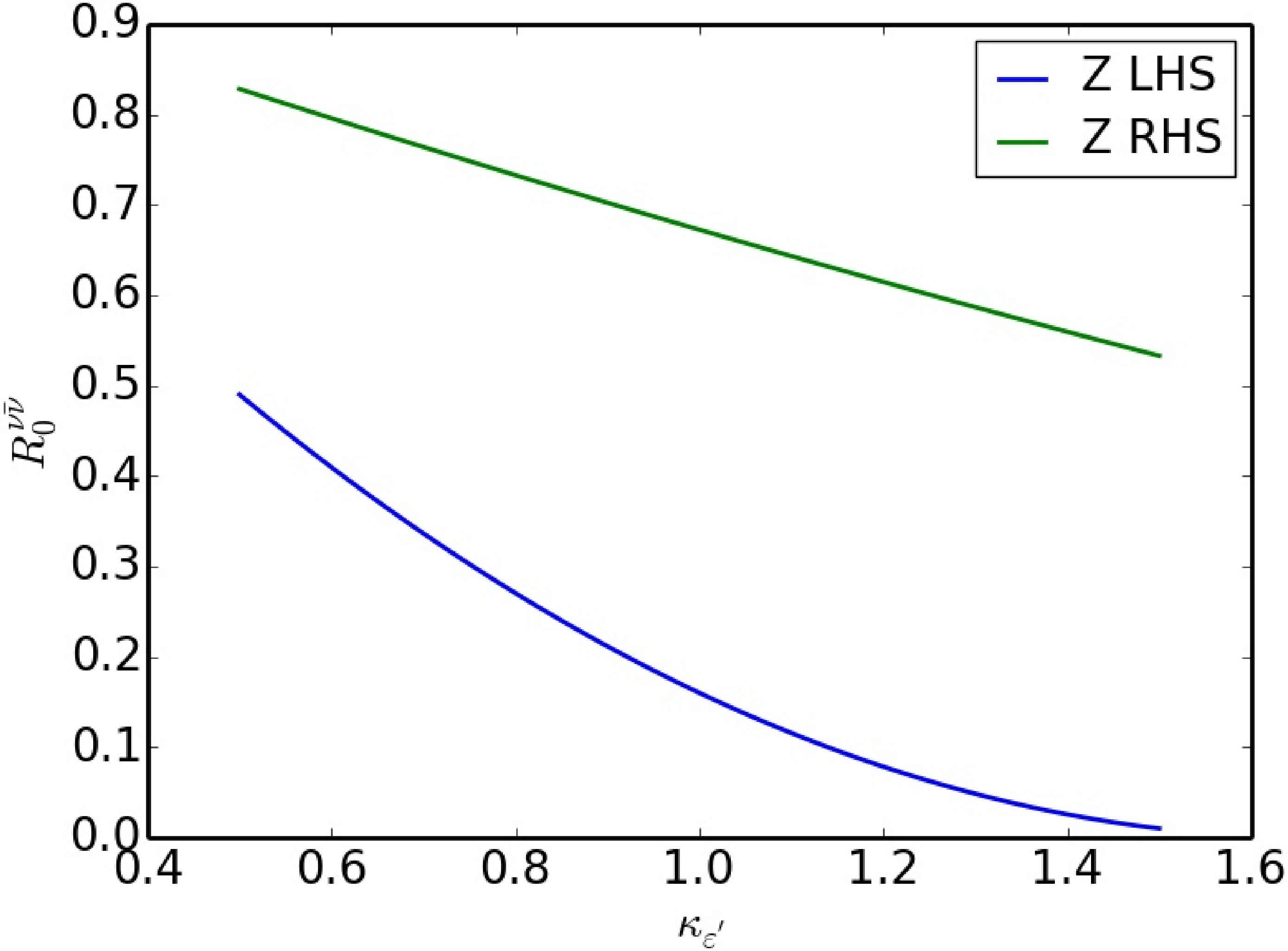
Tree-Level Z with LH or RH FCNC currents
(Anticorrelation of ε'/ε and $K_L \to \pi^0 \nu\bar{\nu}$)
$K^+ \to \pi^+ \nu\bar{\nu}$ can be significantly enhanced

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

Q_8

Q_8'

Z with LH or RH Flavour Violating Couplings



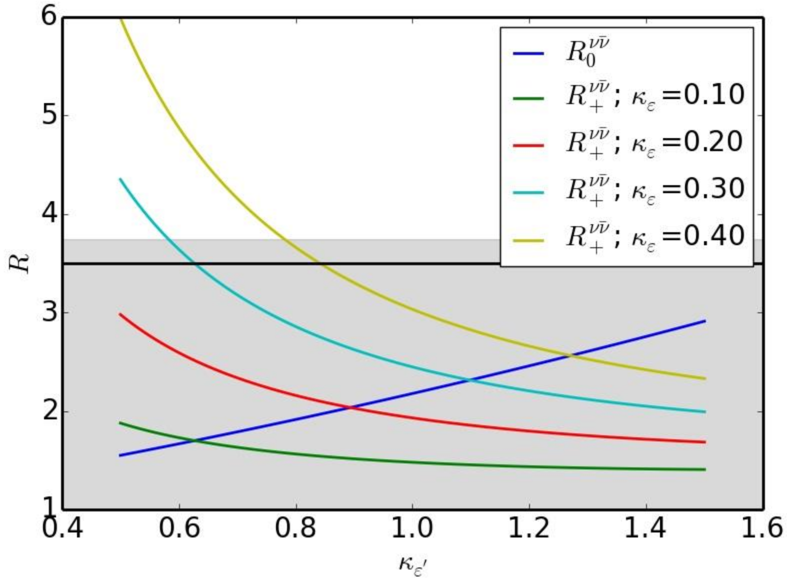
Lesson 3

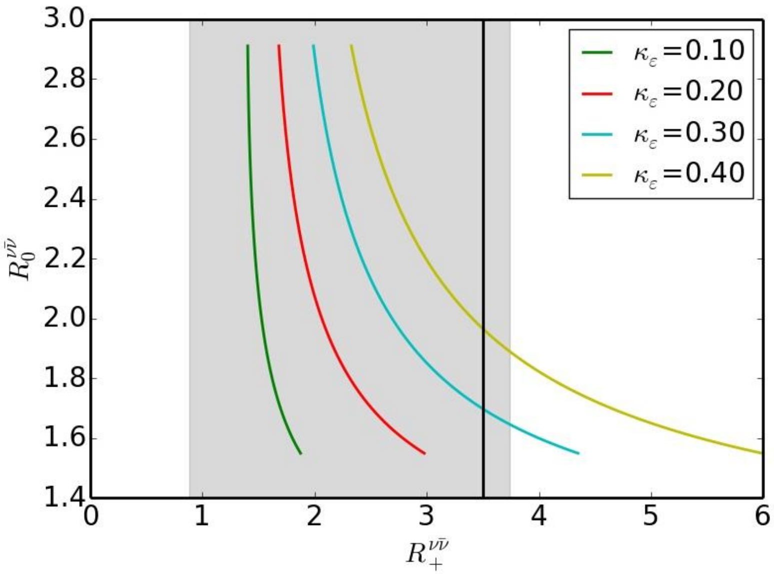
Tree-Level Z with LH + RH FCNC currents
ε'/ε, ε_K, $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$
can be simultaneously enhanced

Correlation depends on hierarchy between $\mathrm{Re}\Delta_{L,R}$ and $\mathrm{Im}\Delta_{L,R}$

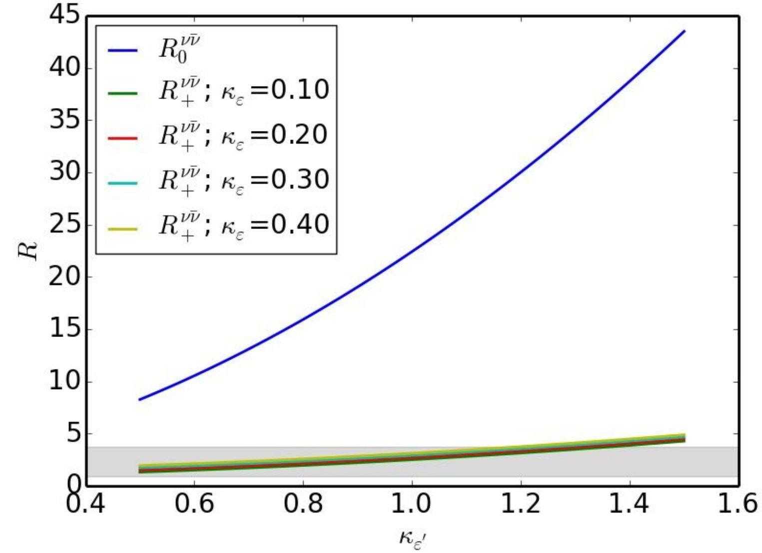
Z with LH and RH Flavour Violating Couplings

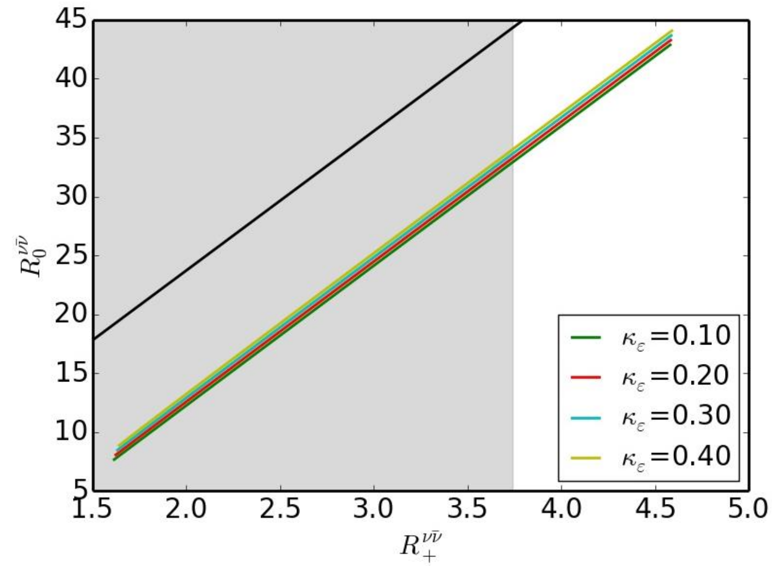
Example 1 $\mathrm{Im}\,\Delta_{L,R} < \mathrm{Re}\,\Delta_{L,R}$





Example 2 $\mathrm{Im}\,\Delta_{L,R} \gg \mathrm{Re}\,\Delta_{L,R}$





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

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

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

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

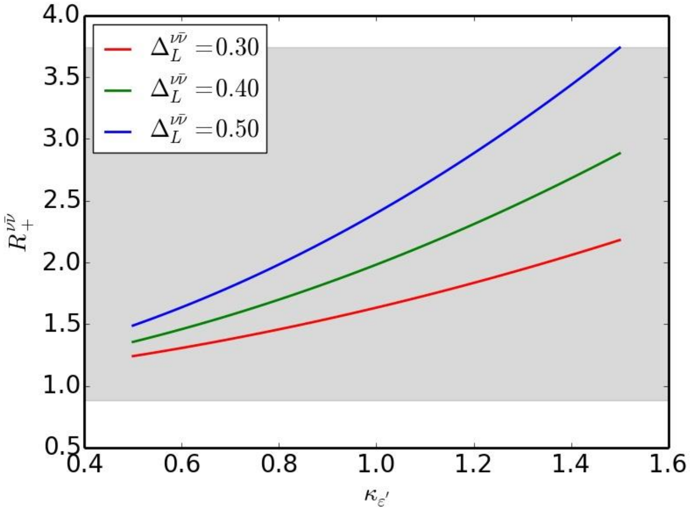
- $(\Delta M_K)^{NP} > 0$ (below 10%)

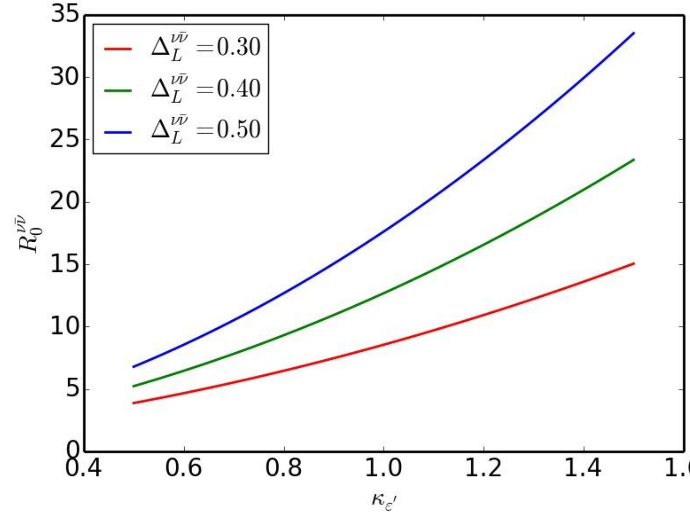
ε_K anomaly can be solved

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

$M_{Z'} = 3$ TeV

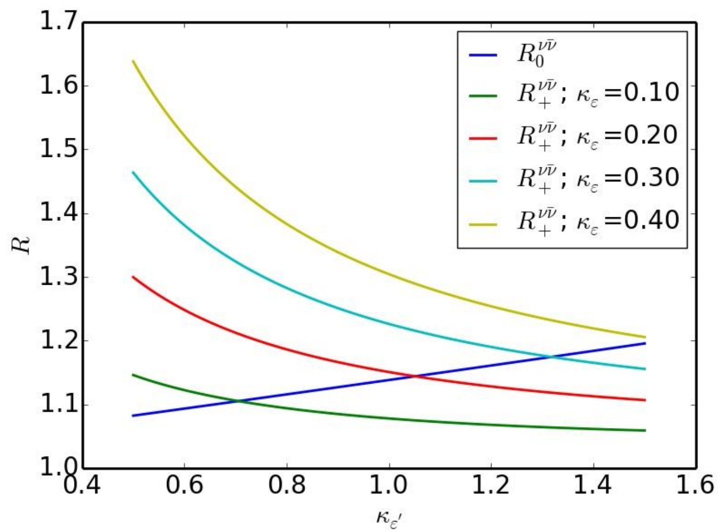
QCD Penguin (Q_6)



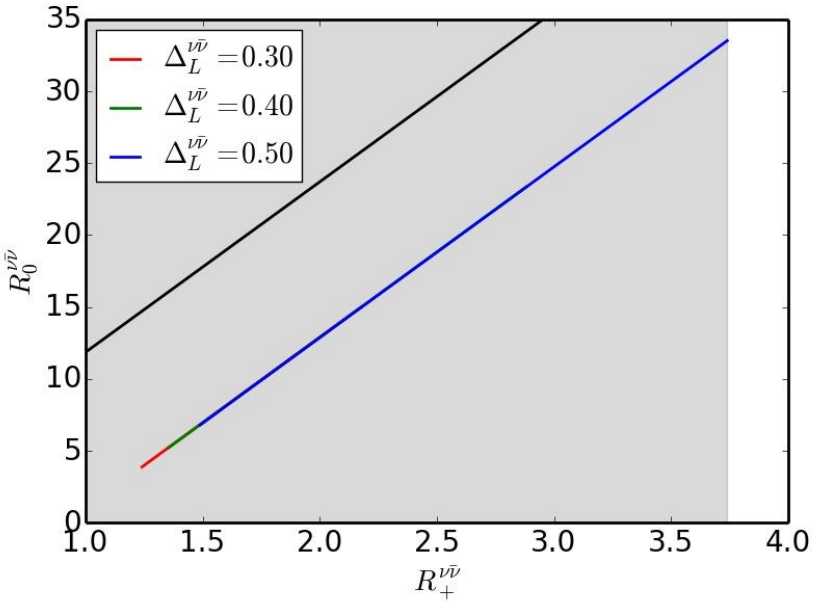


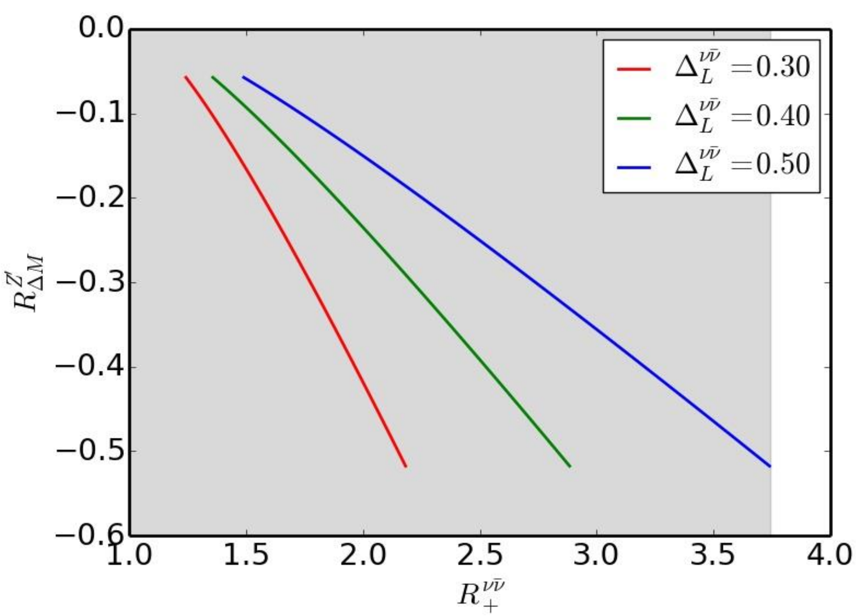
Electroweak Penguin (Q_8)

(Z′)

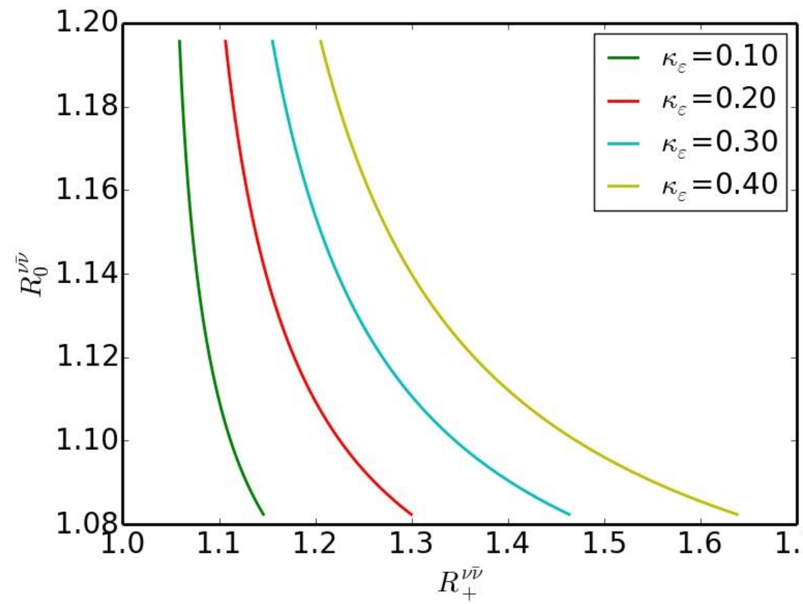


QCDP (Q_6)





EWP (Q_8)



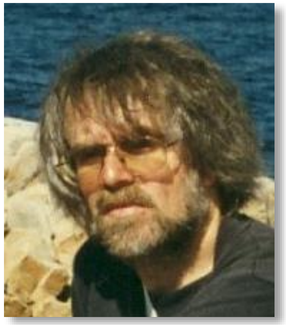
($R_{\Delta M}^{Z'} > 0$ but small)

(Z′)

Section 4

Highlights from 331, LHT, Vector-Like Quark 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

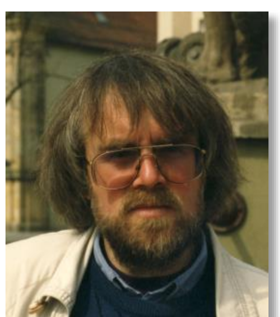

AJB


Dario Buttazzo


Rob Knegjens

Simplified NP Models
1507.08672


Monika Blanke


AJB


Stefan Recksiegel

LHT
1507.0631

Most Recent

AJB

Fulvia de Fazio

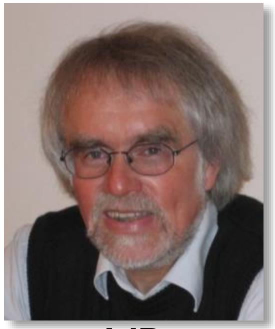
331 models facing $\Delta M_{s,d} \leftrightarrow \varepsilon_K$ tension

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

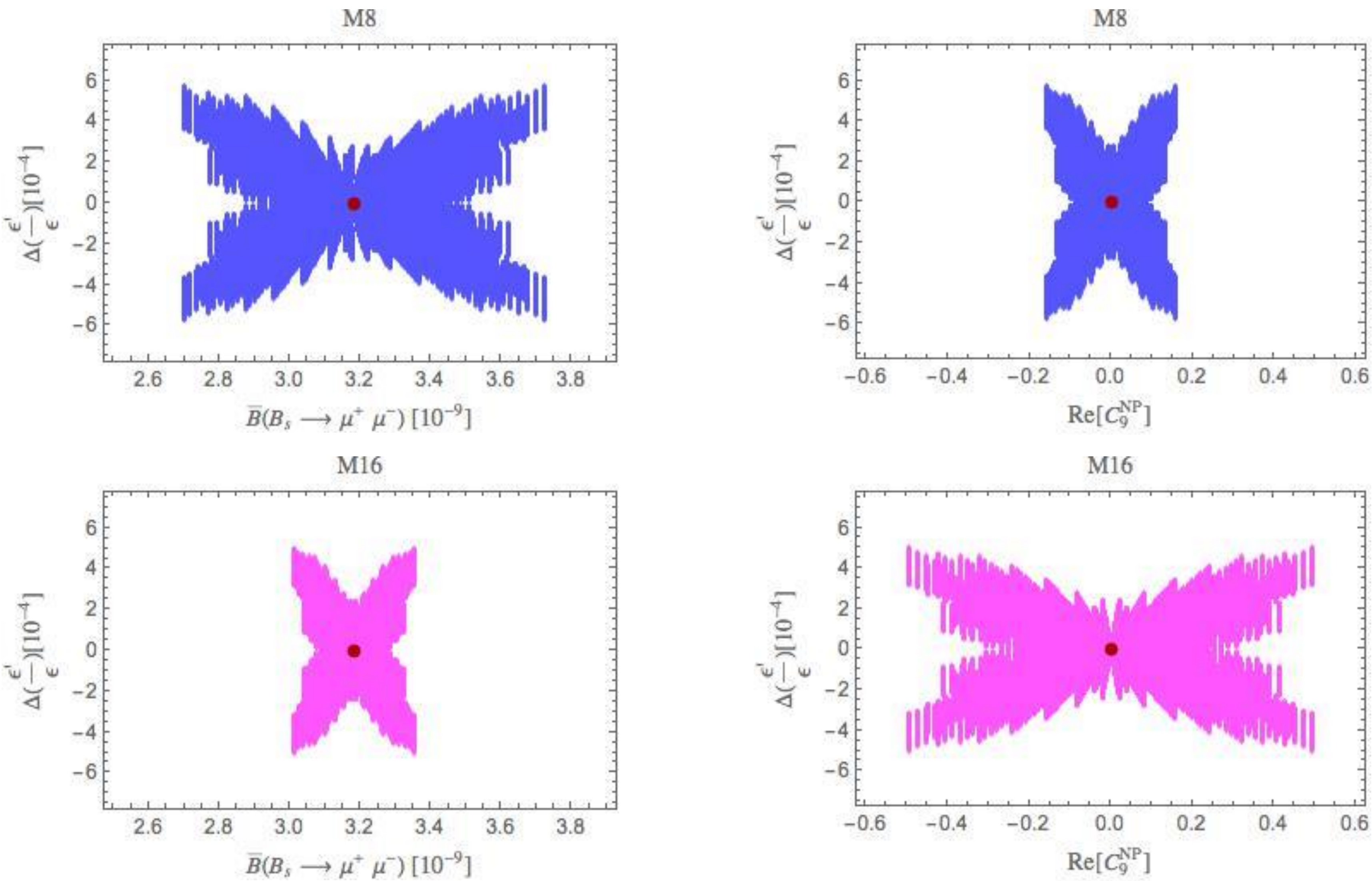
1. $\kappa_{\varepsilon'} \leq 0.8$ (only 3 models can reach upper bound)

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

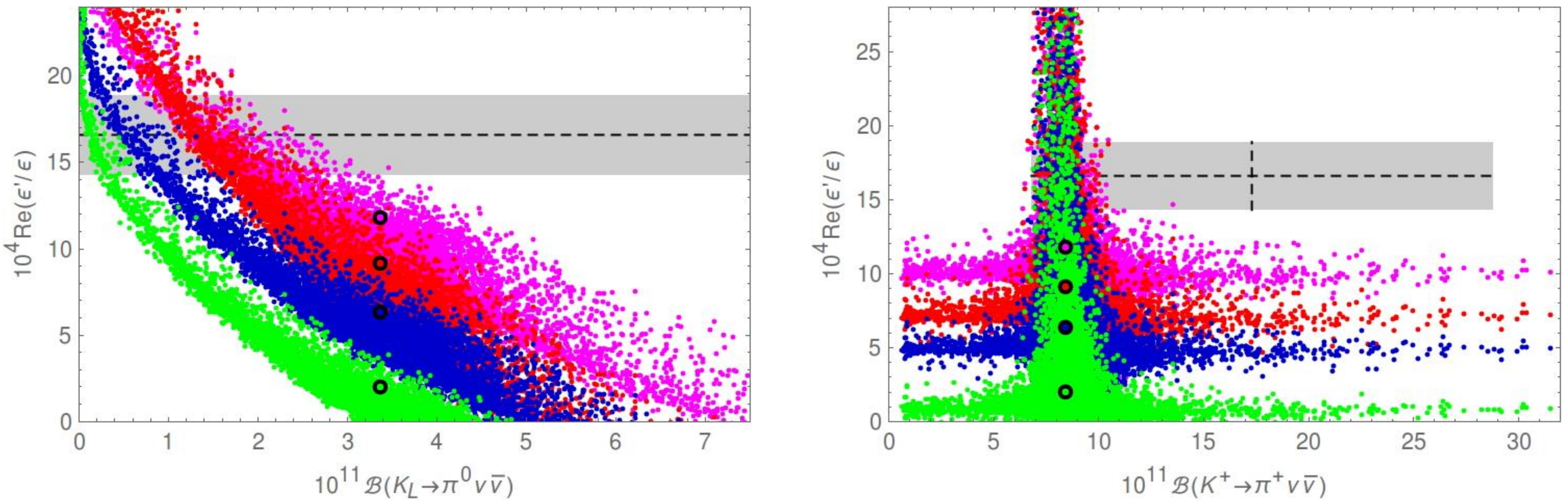
3. Small NP effects in $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$

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)

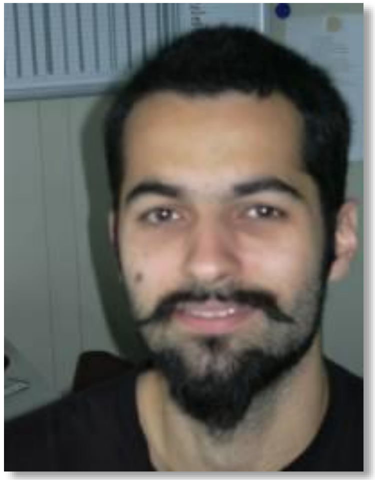
$\left(B_6^{(1/2)} = 1.0, \quad B_8^{(3/2)} = 1.0\right)$

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

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

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.

2018 Vision

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

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

Would point towards :

Z with LH + RH couplings

$$Z'\left(QCDP\right) \text{ with } Z'q\bar{q} \approx 0(1)$$

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

Open Questions to be answered hopefully in this Decade

1. What is $Br(K^+ \to \pi^+ \nu\bar{\nu})$ from NA62?
2. What is $Br(K_L \to \pi^0 \nu\bar{\nu})$ 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 $(\Delta M_K)^{SM}$? (Lattice)
6. Does NP contribute to ReA_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

RBC-UK QCD

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

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

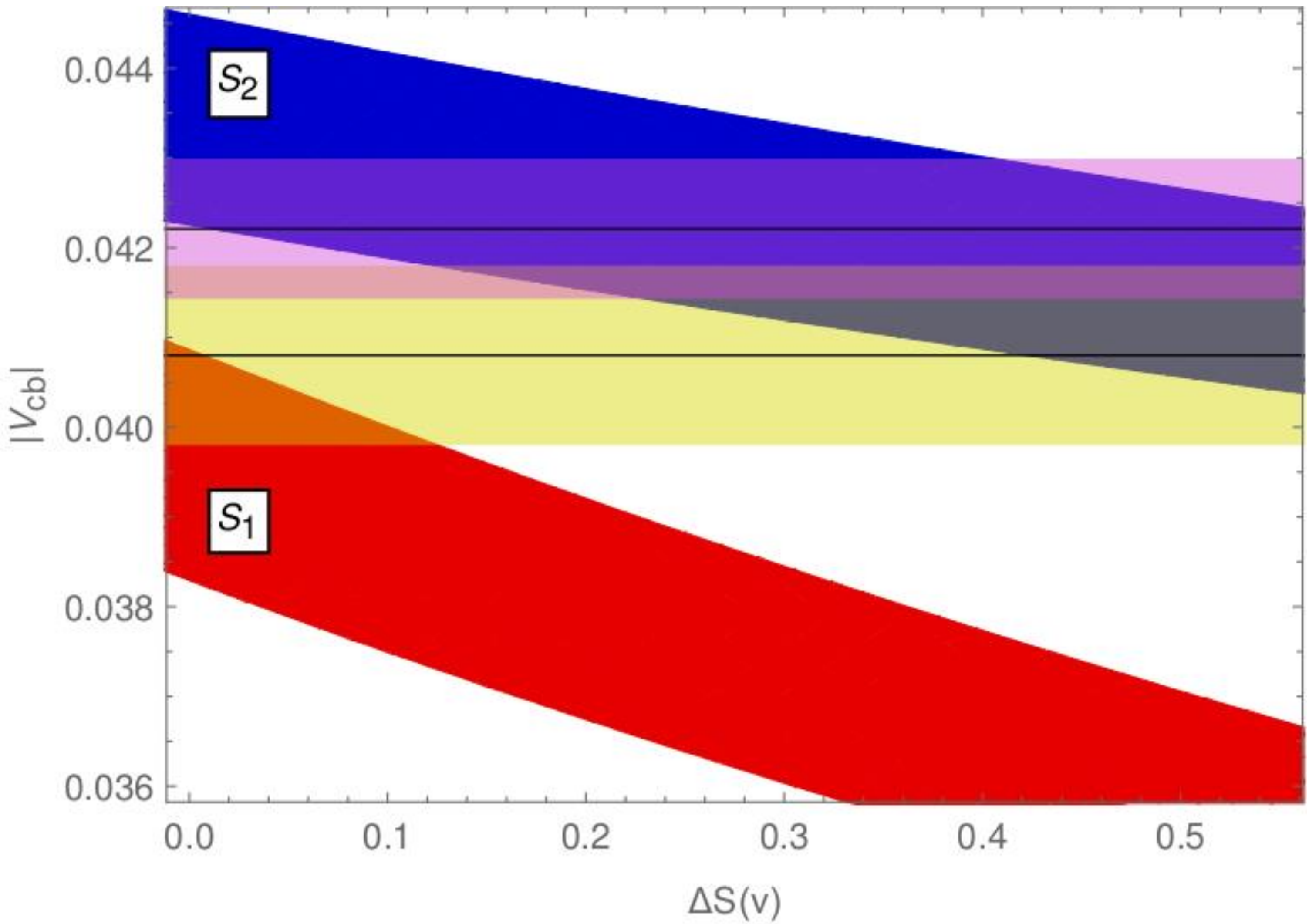
$$(\varepsilon'/\varepsilon)_{\mathrm{exp}} = (16.6 \pm 2.3) \cdot 10^{-4}$$

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

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

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

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

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

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

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

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

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

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

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

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

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

(will go down with new results)

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

RBC-UKQCD

Motivations for New Analysis

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

2. Stress CKM uncertainties in

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right), \quad Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)$$

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

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

Basically no CKM uncertainties

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

5. Use most recent lattice input for CKM

6. Provide the present best value in SM

$K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ 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 $B_s \to \mu^+\mu^-$ constraint
No MFV :	Correlation depends on the presence or absence of ε_K constraint, size on ε'/ε , $K_L \to \mu^+\mu^-$
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 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 $\kappa_\varepsilon \Uparrow$)

NP Effects in ΔM_K small

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)

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

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

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

Since 1955

Gell-Mann
Pais

1986, 2014

Large N including I/N corredtions : Quark Evolution $1\,GeV \leq \mu \leq M_W$
Meson Evolution $0 \leq \mu \leq 1\,GeV$

Correct value of ReA_2

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

Dominance of current-current operators

RBC-QCD (2013, 2015)

Correct value of ReA_2

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

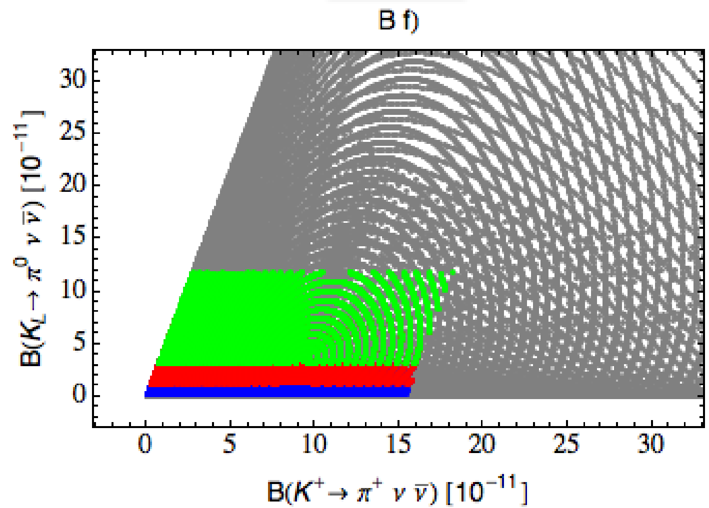
*) G´ with particular couplings ($M_{G'} \approx 3.5$ TeV) could be responsible for the missing piece

AJB
De Fazio
Girrbach-Noe
1404.3824

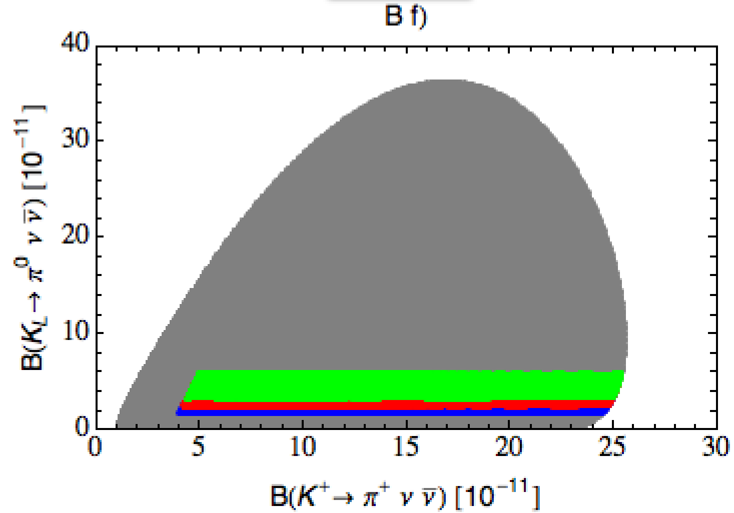
Z with FCNCs at Work

AJB, de Fazio, Girrbach-Noe 1404.3824

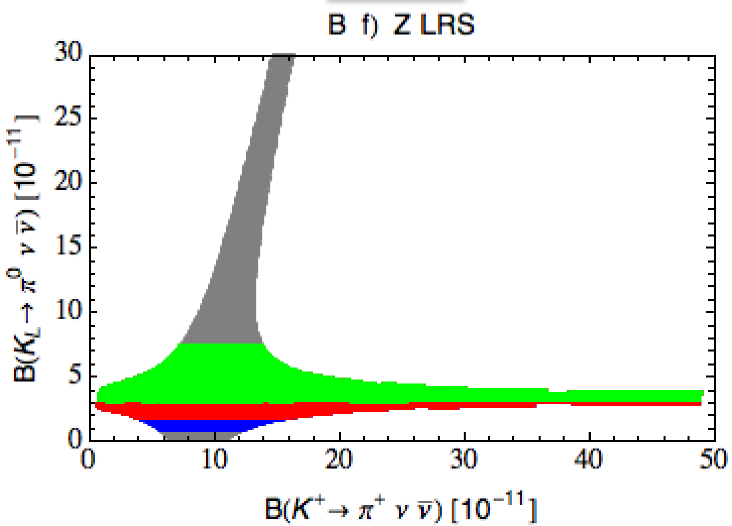
LHS



RHS



LRS



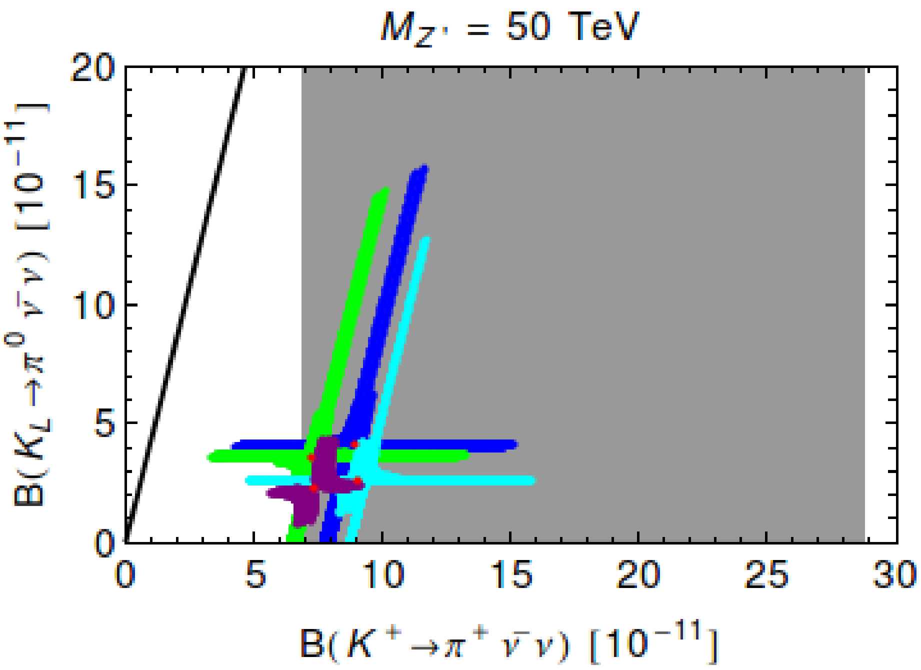
ε_K, ΔM_K constraint

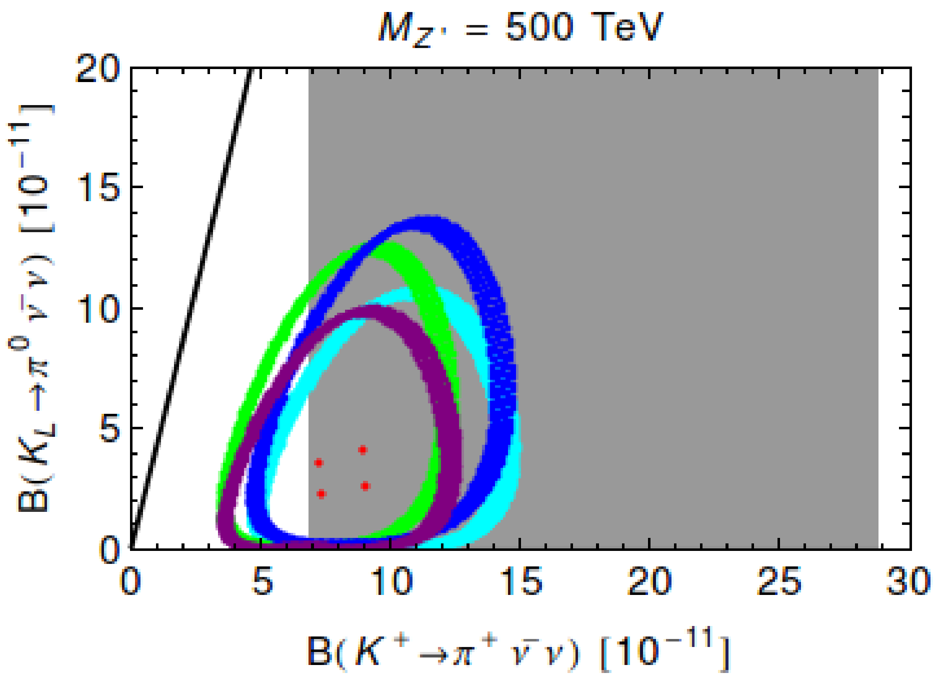
ε'/ε + $K_L \to \mu^+\mu^-$

- $B_6 = 1.25$
- $B_6 = 1.00$
- $B_6 = 0.75$

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 $g_L^{ij} \ll g_R^{ij}$ or $g_L^{ij} \gg g_R^{ij}$:

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

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

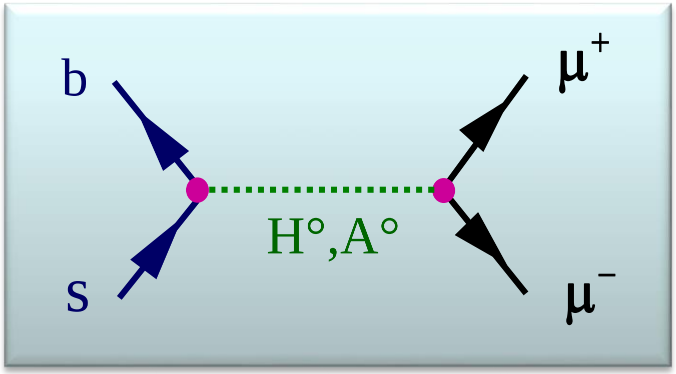
$$B_s : \Lambda_{NP}^{max} \simeq 160\ \text{TeV}$$

Yes we can !!

Can we reach Zeptouniverse through S and P

AJB, Buttazzo, Girrbach-Noe, Knegjens, 1407.0728

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



S : ≈ 350 TeV

P : ≈ 700 TeV

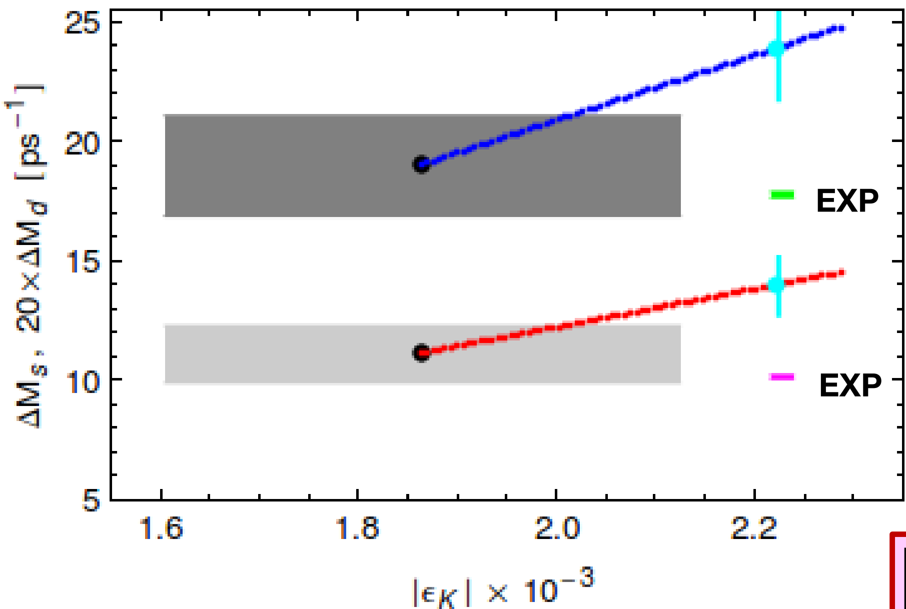
Pseudoscalars more powerful than scalars because of the interference with SM contribution

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

S=H° P=A°

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

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



AJB + Girrbach 1306.3755

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

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

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

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

$|V_{cb}|$

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

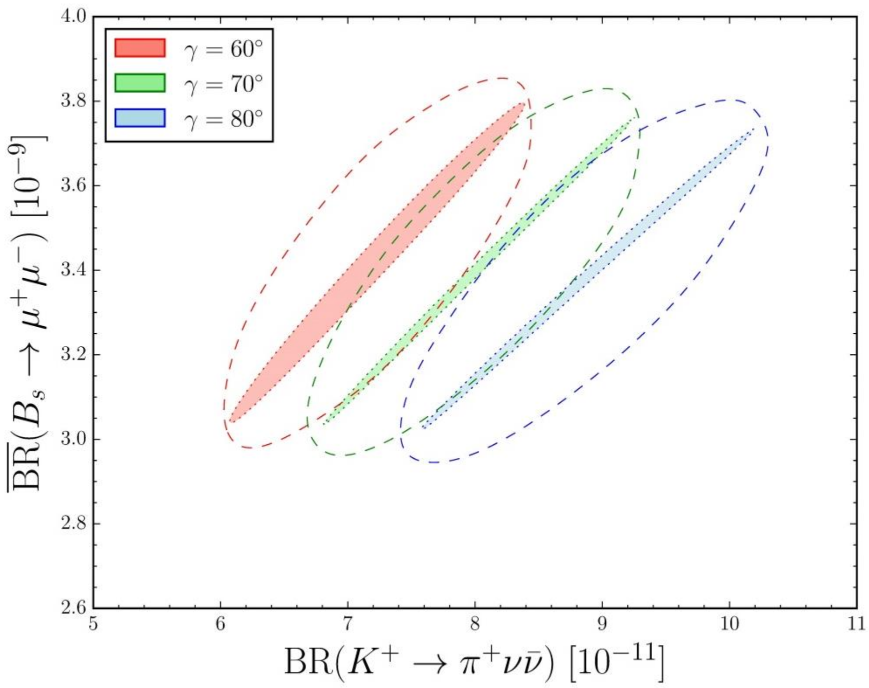
*) Can still work within MFV ($\Delta\varepsilon_K > 0$ in MFV) Blanke + AJB (2006)

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

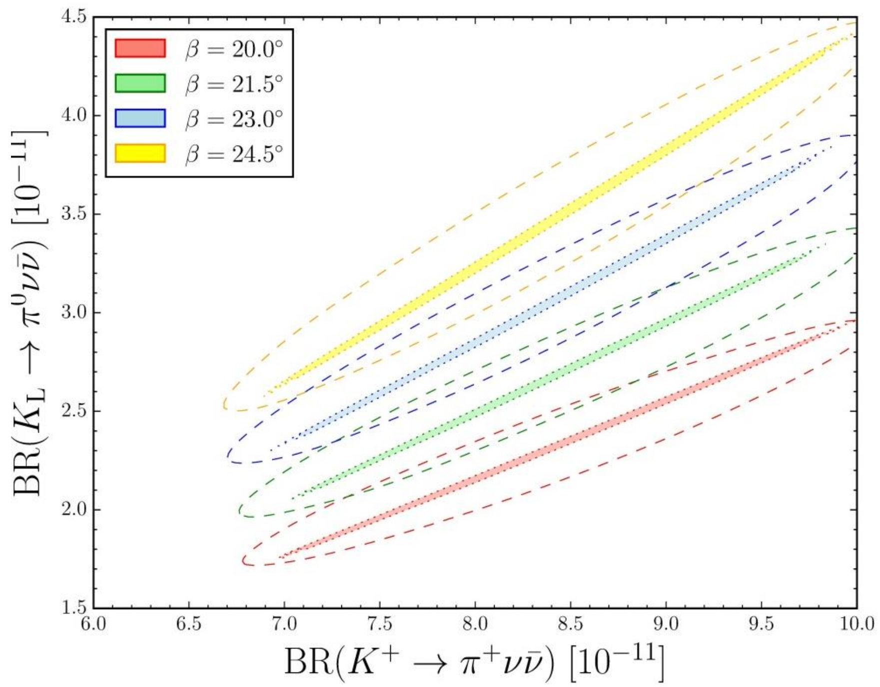
$B_s \to \mu^+\mu^-$, $K^+ \to \pi^+\nu\bar{\nu}$, γ

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

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

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

AJB + Gérard 1507.06326

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

Using BGJJ formula

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

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

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

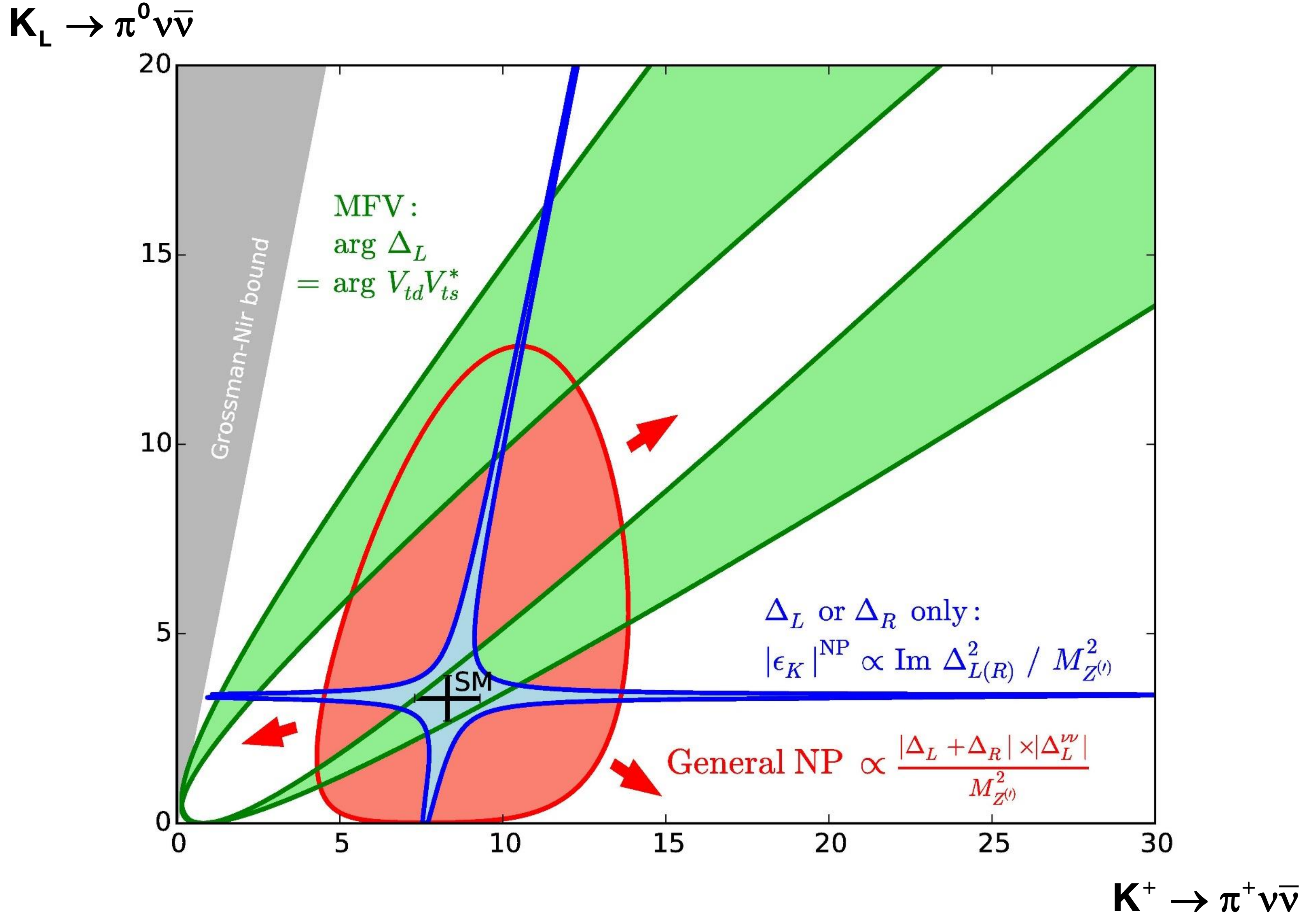
For $\mathrm{Im}\left(V_{ts}V_{td}^{*}\right) = 1.4 \cdot 10^{-4}$

Below data but positive

Yet still large uncertainties

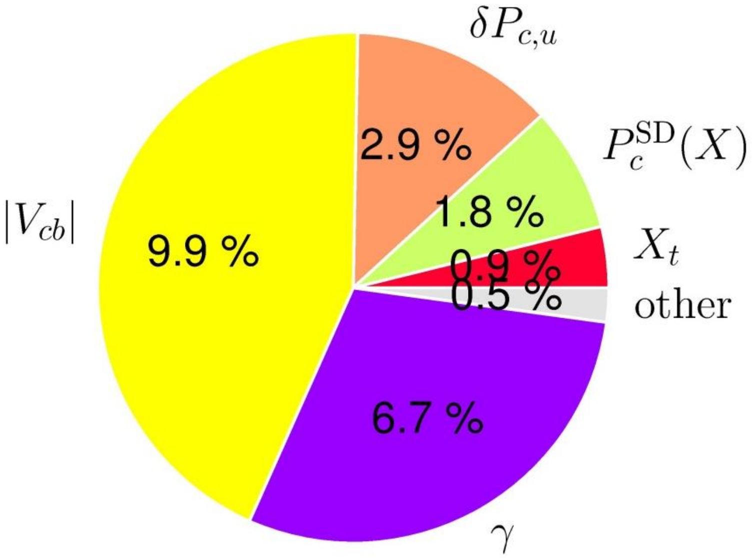
$K_L \to \pi^0\nu\bar{\nu}$ versus $K^+ \to \pi^+\nu\bar{\nu}$

AJB, Buttazzo, Knegjens, 1507.08672

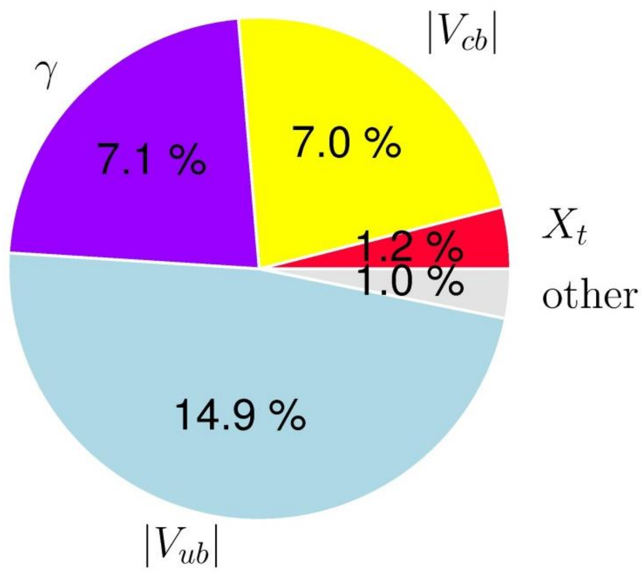


Error Budgets

$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$



$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$



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

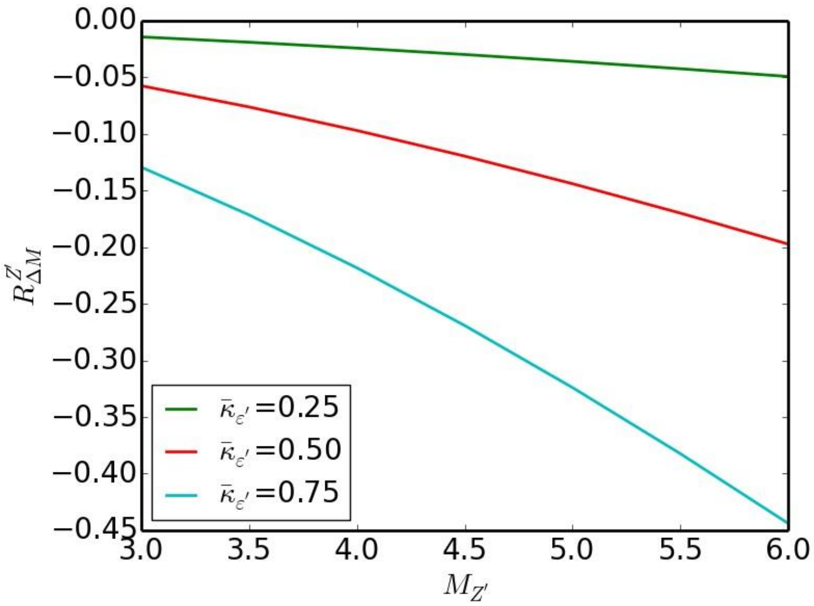
QCD Penguin

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 $M_{Z'}$

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



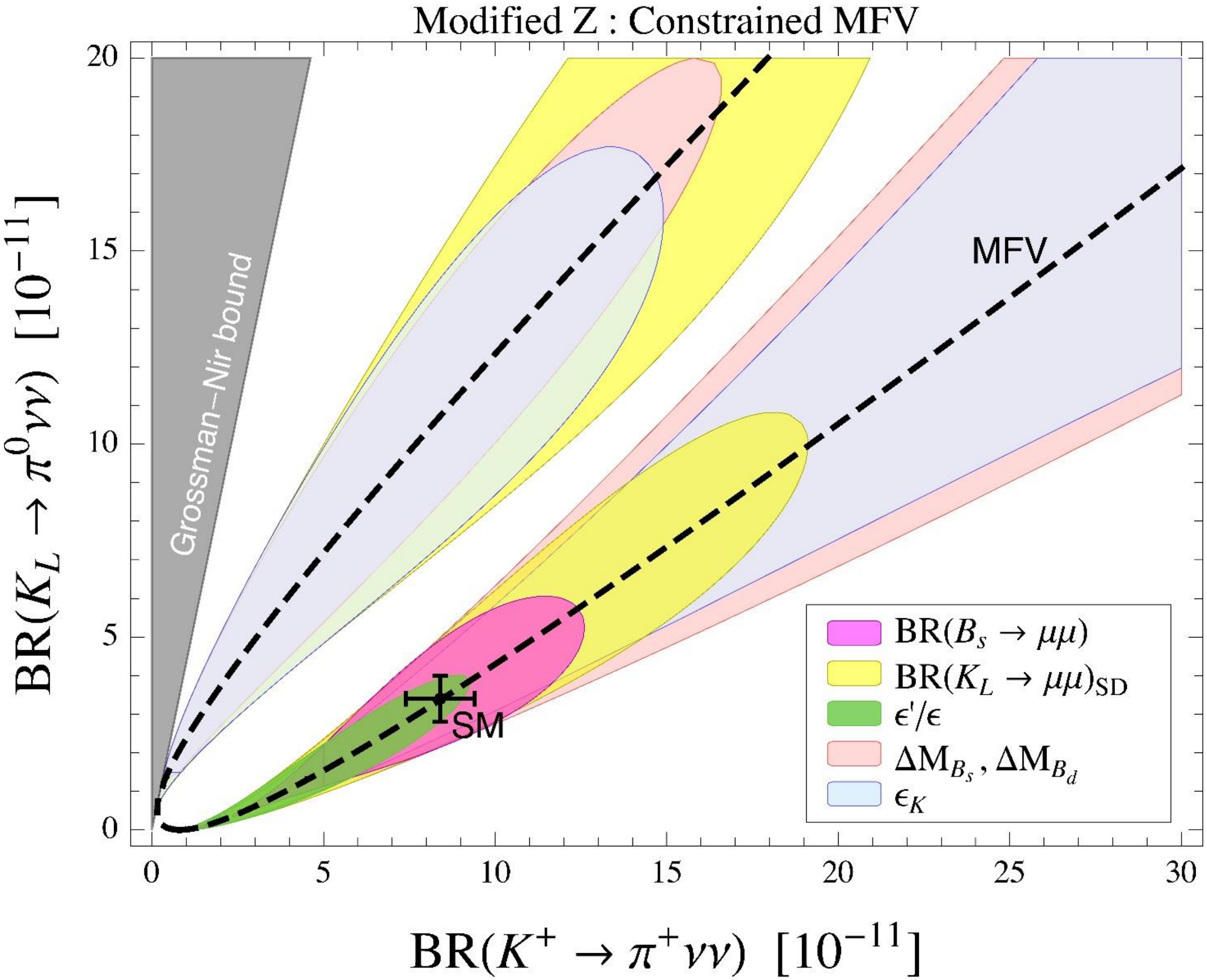
$$\bar{\kappa}_{\varepsilon'} \equiv \left[\frac{\kappa_{\varepsilon'}}{\Delta_R^{\rho\bar{\rho}}(Z')} \right]$$

EWP Penguin

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

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

Using Tree Level Determination of CKM

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

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

$$\Downarrow$$

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

$$\gamma = \left(73.2 \begin{array}{l} +6.3 \\ -7.0 \end{array}\right)^{\circ}$$

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

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

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

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

★ **AJB, Buttazzo, Girrbach-Noe, Knegjens 1503.02693**