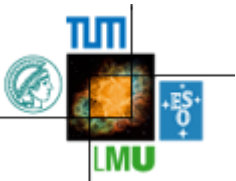


The Renaissance of Kaon Flavour Physics

Andrzej J. Buras
(Technical University Munich, TUM-IAS)

Zurich, May 2016



Overture

B Physics Anomalies

1.

$$R_{D^{(*)}} = \frac{\text{Br}(B \rightarrow D^{(*)} \tau \nu_\tau)}{\text{Br}(B \rightarrow D^{(*)} \mu \nu_\mu)} \quad (3.5 - 4\sigma)$$

2.

$$R_K = \frac{\Gamma(B \rightarrow K \mu \mu)}{\Gamma(B \rightarrow K e e)} = 0.745^{+0.090}_{-0.074} \pm 0.036 \quad (2.6\sigma)$$

3.

$$B \rightarrow K(K^*) \mu^+ \mu^- \quad (3\sigma)$$

$(B \rightarrow \phi \mu^+ \mu^-)$

(hadronic
uncertainties)

4.

$$\text{Br}(B_s \rightarrow \mu^+ \mu^-)_{\text{SM}} = (3.65 \pm 0.23) \cdot 10^{-9}$$

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

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!

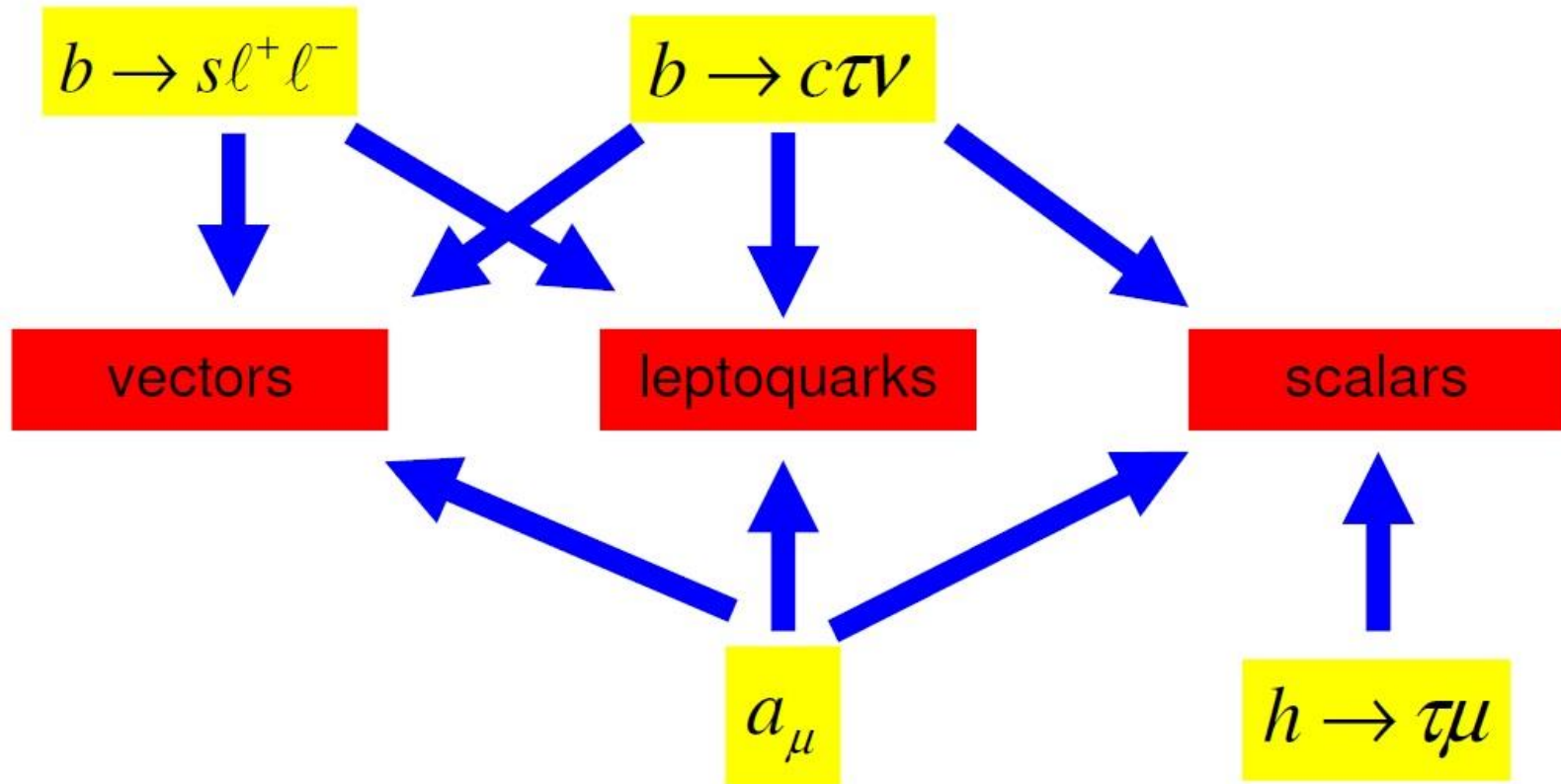
Here: Anomaly in CP-violation in K-physics (ε'/ε)

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

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

New Physics Explanations of Anomalies

Andreas Crivellin, 1605.02934



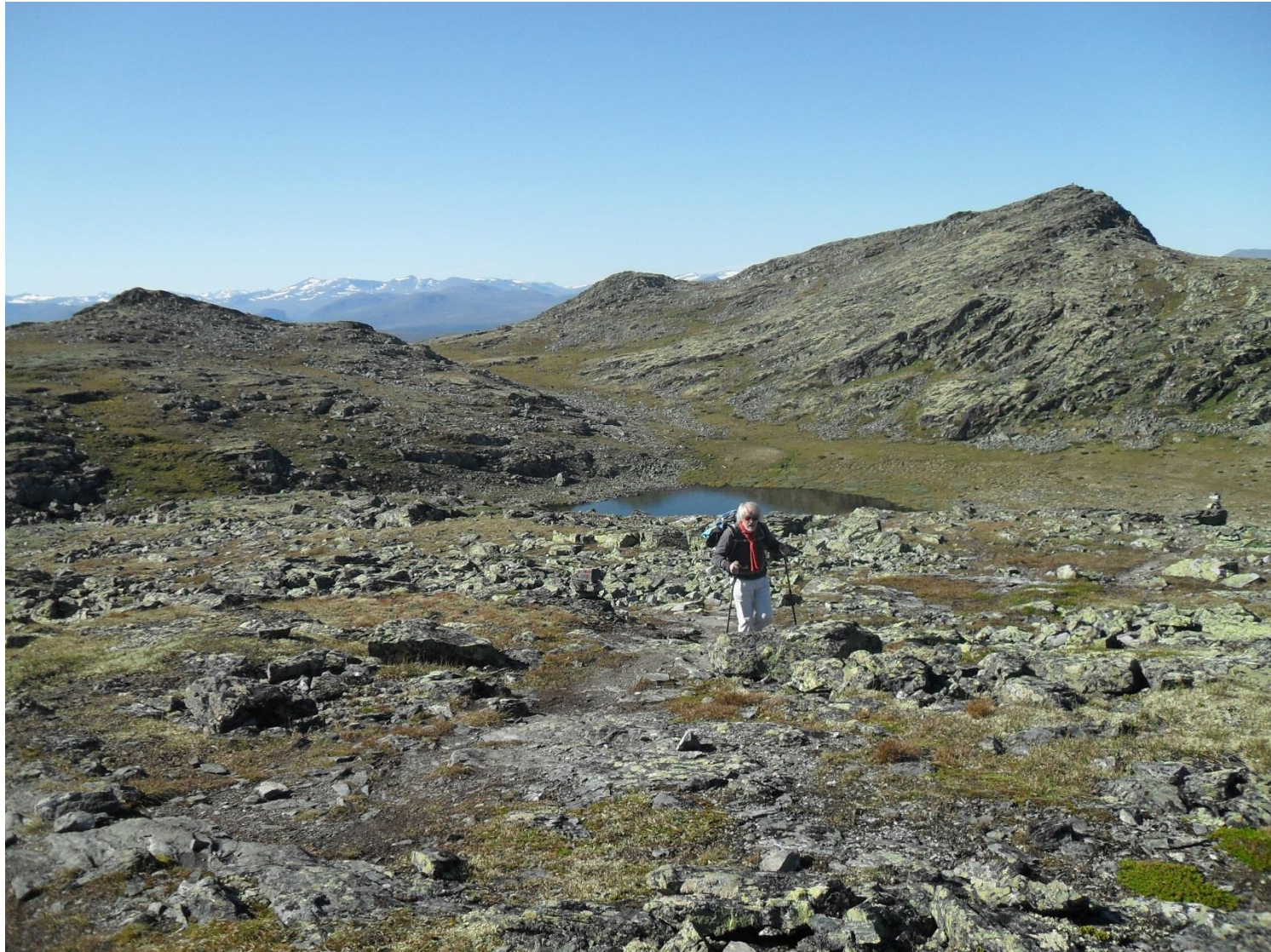
B-Physics Flavour Anomalies



750 GeV Resonance



Kaon Flavour Physics



Plan for next 45 min

1.

ε'/ε strikes back

2.

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

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

3.

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

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

$$: B_6 = 0.57 \pm 0.19 \quad B_8 = 0.76 \pm 0.05$$

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)

$$(\varepsilon'/\varepsilon) = (6.0 \pm 2.4) \cdot 10^{-4} \text{ for } B_6 = B_8 = 0.76$$

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

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

Possible New Physics

Implications for $K \rightarrow \pi\nu\bar{\nu}$

Z' general (AJB, Buttazzo, Knecht, 1507.08672)

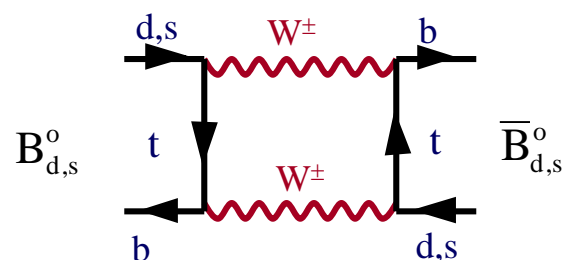
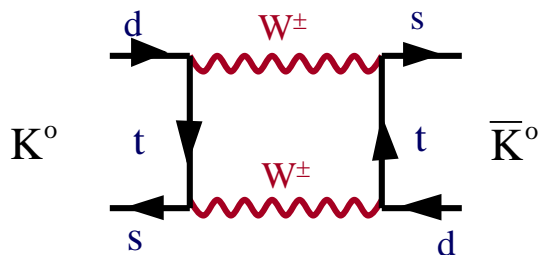
Littlest Higgs Model (Blanke, AJB, Recksiegel, 1507.06316)

331 Models (AJB, De Fazio, 1512.02869, 1604.02344)

New Strategy (AJB, 1601.00005)

Vector-like Quarks (Bobeth, AJB, Celis, Jung, 1605.xxxx)

Loop Induced FCNC Processes



\mathcal{CP} ϵ_K -Parameter
 $\Delta M (K_L - K_S)$

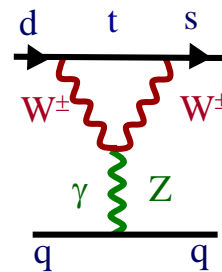
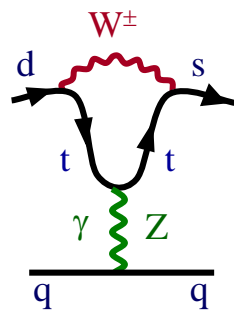
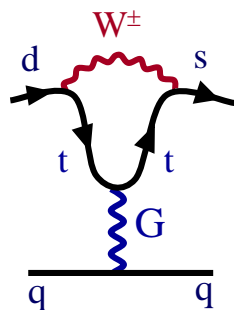
$B_d^0 - \bar{B}_d^0$ Mixing



$B_s^0 - \bar{B}_s^0$ Mixing



ϵ'



Discovered
 in 2006

(CDF, DØ)

Four dominant contributions to ε'/ε in the SM

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

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

From $\text{Re}A_0$
From $\text{Re}A_2$

(Q₄)

$(V-A) \otimes (V-A)$
QCD Penguins

$(V-A) \otimes (V+A)$
QCD Penguins

$(V-A) \otimes (V-A)$
EW Penguins

$(V-A) \otimes (V+A)$
EW Penguins

Assumes that $\text{Re}A_0$ and $\text{Re}A_2$ ($\Delta I=1/2$ Rule) fully described by SM (includes isospin breaking corrections)

Extracted from



RBC-UKQCD

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

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

Why $B_6^{(1/2)} < B_8^{(3/2)} < 1$?

and not $B_6^{(1/2)} > 1$, $B_8^{(3/2)} < 1$ (Pallante, Pich... FSI
2000)

Answer in Large N (Dual QCD) Approach

AJB + Gérard (1507.06326)

Before 2015 it was wrongly assumed that

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

But $B_6^{(1/2)} = B_8^{(3/2)} = 1$ is large N prediction
for $\mu = m_\pi$ not $\mu = 0(1 \text{ GeV})$

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

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 $K \rightarrow \pi^+\pi^-$
(Caluccio-Leskow, D'Ambrosio, Greynat, Nath, 1604.09721)**

ε'/ε within SM

$$\varepsilon'/\varepsilon \sim \left[\frac{\text{Re } A_2}{\text{Re } A_0} \text{Im } C_6 \langle Q_6 \rangle_0 - \text{Im } C_8 \langle Q_8 \rangle_2 + \text{smaller contributions} \right]$$
$$\left\{ \frac{\text{Re } A_2}{\text{Re } A_0} \approx \frac{1}{22} \quad \frac{\text{Im } C_6}{\text{Im } C_8} \approx 90 \quad \frac{\langle Q_8 \rangle_2}{\langle Q_6 \rangle_0} \approx 2 \right\} \Rightarrow \text{strong cancellations}$$

ε'/ε beyond SM (Q_6, Q_8, Q'_6, Q'_8)

- 1.** Generally Q_8 wins over Q_6 because $\left(\frac{\text{Im } C_6}{\text{Im } C_8} \right)^{\text{NP}} \approx 0(1)$ 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

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

Their ratio

$$\xi = 1.203 \pm 0.019$$

Similar but less precise
results from ETM
(1308.1851)

Blanke + AJB

(1602.04020)

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

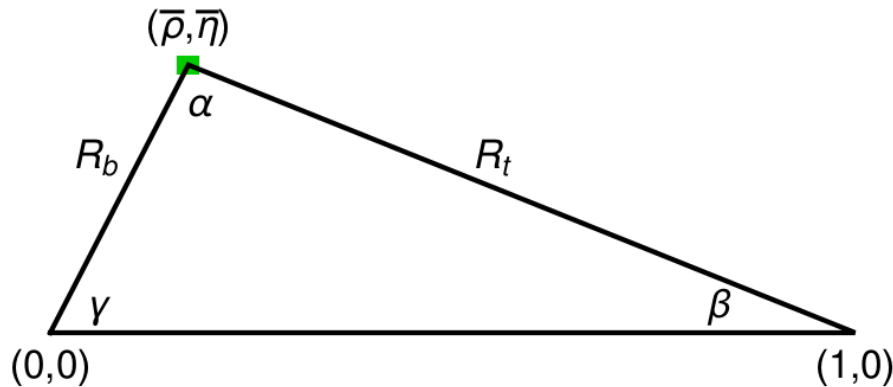
S₁: Strategy 1: ΔM_s determines $V_{cb} \Rightarrow |V_{cb}| = (39.5 \pm 1.3) \cdot 10^{-3}$

S₂: Strategy 1: ε_K determines $V_{cb} \Rightarrow |V_{cb}| = (43.4 \pm 1.2) \cdot 10^{-3}$



Tension between ΔM_K and ε_K

Universal Unitarity Triangle 2016



CMFV :

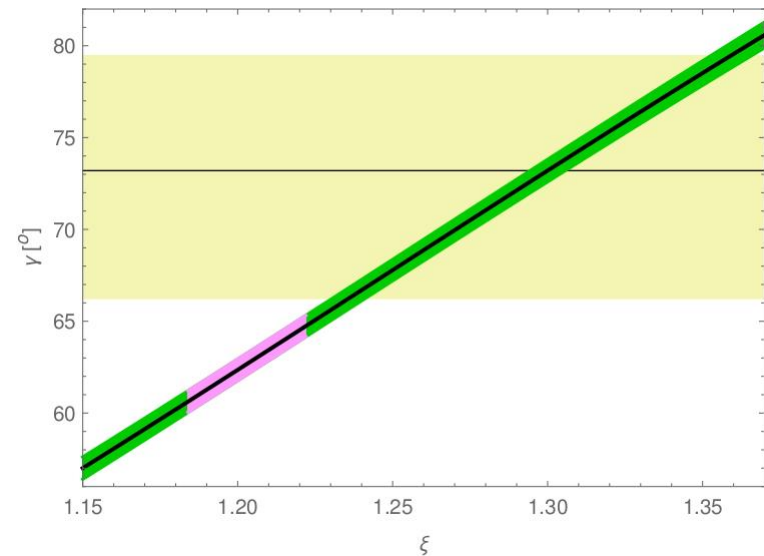
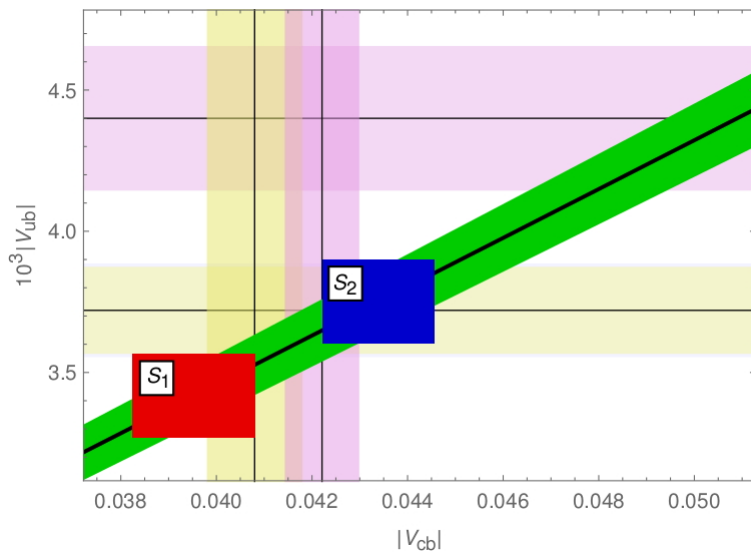
$$\bar{\rho} = 0.172 \pm 0.013$$

$$\bar{\eta} = 0.332 \pm 0.011$$

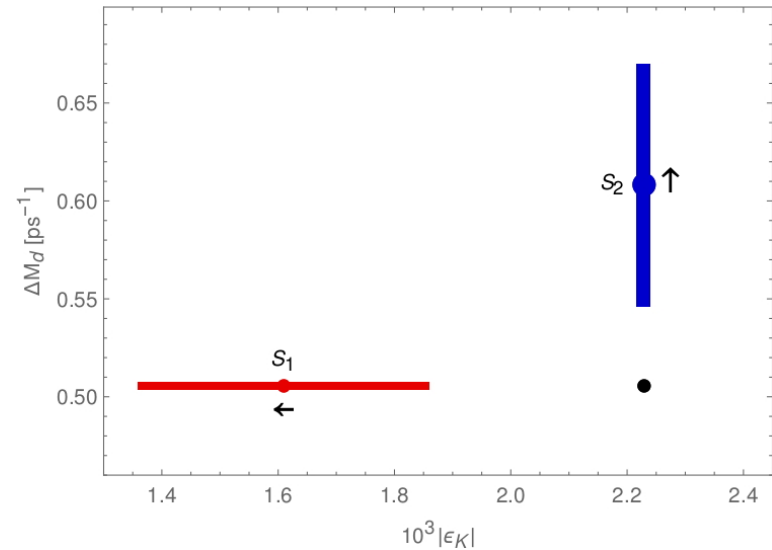
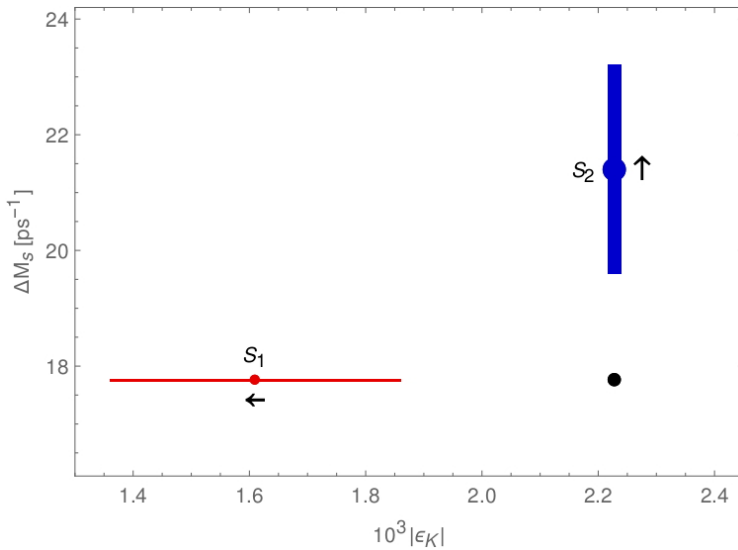
UT fit :

$$\bar{\rho} = 0.137 \pm 0.022$$

$$\bar{\eta} = 0.349 \pm 0.014$$



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



**Constrained
MFV
CKM +
SM Operators**
 $\mathbf{S}_{\text{Box}} > \mathbf{S}_{\text{Box}}^{\text{SM}}$
**(Blanke, AJB
0610037)**

$$\mathbf{S}_1: |\varepsilon_K| \leq (1.61 \pm 0.25) \cdot 10^{-3} \quad |\varepsilon_K^{\text{exp}}| = 2.23 \cdot 10^{-3}$$

$$\mathbf{S}_2: \Delta M_s \geq (21.4 \pm 1.8) \text{ps}^{-1} \quad (\Delta M_s)^{\text{exp}} = 17.56 / \text{ps}$$

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

Intermezzo

$$\mathbf{K}^+ \rightarrow \pi^+ \nu \bar{\nu} \text{ and } \mathbf{K}_L \rightarrow \pi^0 \nu \bar{\nu}$$

in the Standard Model

1503.02693



AJB



D. Buttazzo

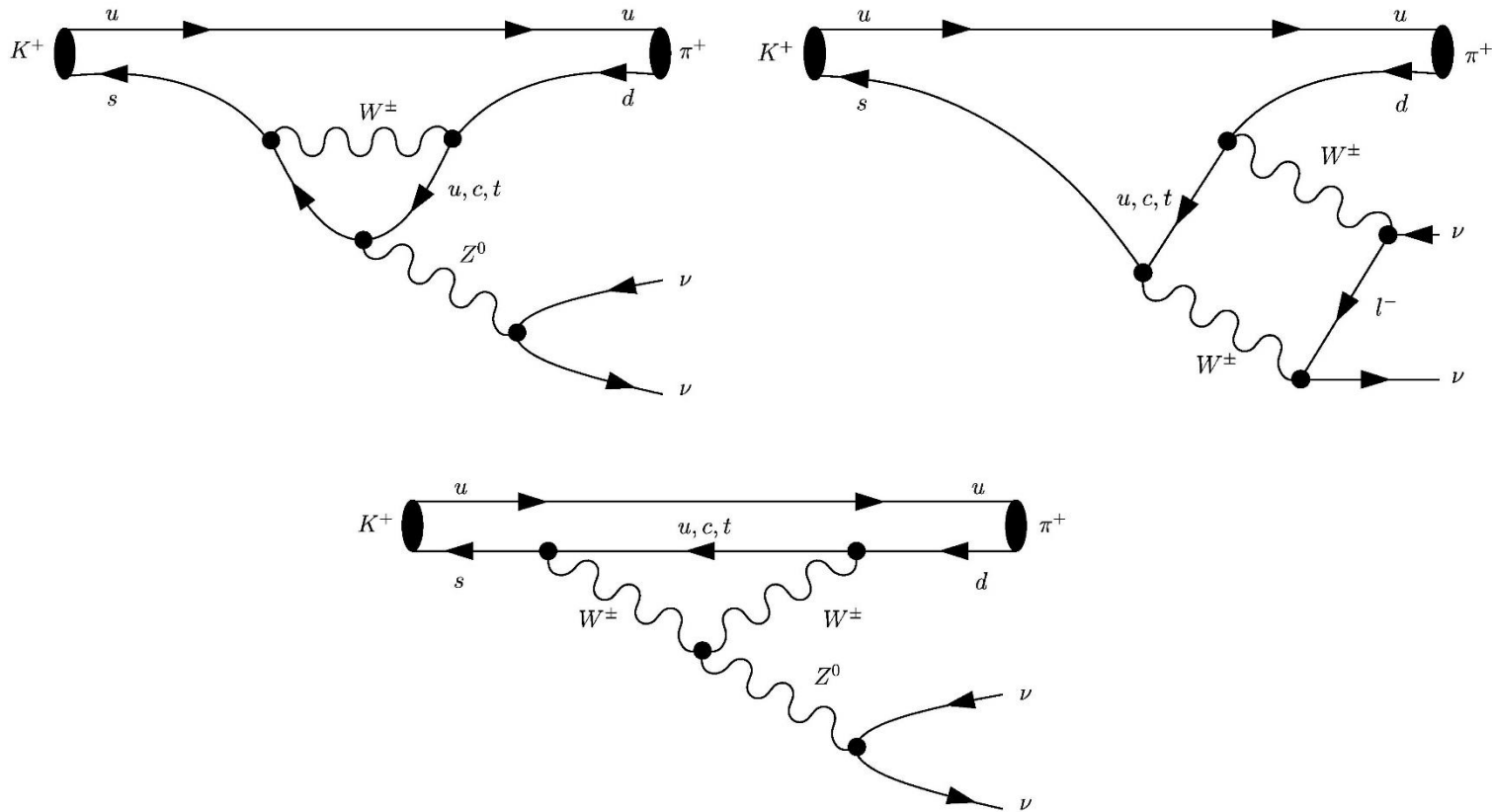


J. Girrbach-Noe



R. Kneijens

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



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

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

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

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

+ Isospin breaking corrections



TH uncertainties at the level of 2% in BR

Unique in
 Flavour
 Physics !!

But significant parametric uncertainties

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

Data

$$\begin{aligned} \text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) &= (17.3 \pm 11) \cdot 10^{-11} \\ \text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu}) &\leq 2.6 \cdot 10^{-8} \end{aligned}$$

CKM Uncertainties

AJB, Buttazzo,
Girrbach-Noe,
Knegjens
1503.02693

$$\text{Br}(\text{K}^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.39 \pm 0.30) \cdot 10^{-11} \left[\frac{|\mathbf{V}_{cb}|}{0.0407} \right]^{2.8} \left[\frac{\gamma}{73.2^\circ} \right]^{0.74}$$
$$\text{Br}(\text{K}_L \rightarrow \pi^0 \nu \bar{\nu}) = (3.36 \pm 0.05) \cdot 10^{-11} \left[\frac{|\mathbf{V}_{ub}|}{3.88 \cdot 10^{-3}} \right]^2 \left[\frac{|\mathbf{V}_{cb}|}{0.0407} \right]^2 \left[\frac{\sin \gamma}{\sin(73.2)} \right]^2$$

$$\text{Br}(\text{K}^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.39 \pm 0.58) \cdot 10^{-11} \left[\frac{\gamma}{73.2^\circ} \right]^{0.81} \left[\frac{\bar{\text{Br}}(\text{B}_s \rightarrow \mu^+ \mu^-)}{3.4 \cdot 10^{-9}} \right]^{1.42} \left[\frac{227.7}{F_{\text{B}_s}} \right]^{2.84}$$
$$\text{Br}(\text{K}^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.39 \pm 1.11) \cdot 10^{-11} \left[\frac{|\varepsilon_K|}{2.23 \cdot 10^{-3}} \right]^{1.07} \left[\frac{\gamma}{73.2^\circ} \right]^{-0.11} \left[\frac{|\mathbf{V}_{ub}|}{3.88 \cdot 10^{-3}} \right]^{-0.95}$$

$$\text{Br}(\text{K}^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \cdot 10^{-11}$$
$$\text{Br}(\text{K}_L \rightarrow \pi^0 \nu \bar{\nu}) = (3.4 \pm 0.6) \cdot 10^{-11}$$

Section 3

$$\varepsilon' / \varepsilon, \varepsilon_K, \mathbf{K} \rightarrow \pi v \bar{v}, \Delta \mathbf{M}_K$$

beyond SM

AJB (1601.00005)

Section 3

$$\varepsilon'/\varepsilon, \varepsilon_K, \mathbf{K} \rightarrow \pi v \bar{v}, \Delta \mathbf{M}_K$$

beyond SM

AJB (1601.00005)

**What are the implications
of NP in ε'/ε and ε_K on
 $\mathbf{K} \rightarrow \pi v \bar{v}$ and $\Delta \mathbf{M}_K$?**

Strategy

AJB (1601.00005)

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

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

(Im)

$$\varepsilon_{\text{K}}^{\text{NP}} = \kappa_{\varepsilon} \cdot 10^{-3}$$

$$0.1 \leq \kappa_{\varepsilon} \leq 0.4$$

(Im, Re)

In some models
 $\text{K}_L \rightarrow \mu^+ \mu^-$
 more important
 than ε_{K}

Re and Im Parts: \mathbf{Z} and \mathbf{Z}' Couplings

$$\Delta_{\text{L}}^{\text{sd}}(\mathbf{Z}), \Delta_{\text{R}}^{\text{sd}}(\mathbf{Z})$$

$$\Delta_{\text{L}}^{\text{sd}}(\mathbf{Z}'), \Delta_{\text{R}}^{\text{sd}}(\mathbf{Z}')$$

$$\text{K}^+ \rightarrow \pi^+ \nu \bar{\nu}, \text{K}_L \rightarrow \pi^0 \nu \bar{\nu}, \text{K}_L \rightarrow \mu^+ \mu^-, \Delta \mathbf{M}_{\text{K}}$$

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

Basic Structure of NP Contributions

AJB (1601.00005)

$$\begin{aligned}
 (\varepsilon'/\varepsilon)^{\text{NP}} &\rightarrow \text{Im} & \varepsilon_{\text{K}}^{\text{NP}} &\rightarrow \text{Im} \cdot \text{Re} \\
 (\kappa_{\varepsilon'} \geq 0.5) & & (\kappa_{\varepsilon} \geq 0.1) & \\
 \Delta M_{\text{K}}^{\text{NP}} &\sim \left[(\text{Re})^2 - (\text{Im})^2 \right]
 \end{aligned}$$

Dominance of $Q_6 (Q_6')$ \Rightarrow $\text{Im} \gg \text{Re} \Rightarrow \left\{ \Delta M_{\text{K}}^{\text{NP}} < 0 \right\}$ (Z)
 (large)

Dominance of $Q_8 (Q_8')$ \Rightarrow $\text{Re} \gg \text{Im} \Rightarrow \left\{ \Delta M_{\text{K}}^{\text{NP}} > 0 \right\}$ (Z/Z')
 (small)



Implications for

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

(Re, Im)

$$R_{0}^{\nu\bar{\nu}} = \frac{\text{Br}(\text{K}_L \rightarrow \pi^0 \nu\bar{\nu})}{\text{Br}(\text{K}_L \rightarrow \pi^0 \nu\bar{\nu})_{\text{SM}}}$$

(Im)

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

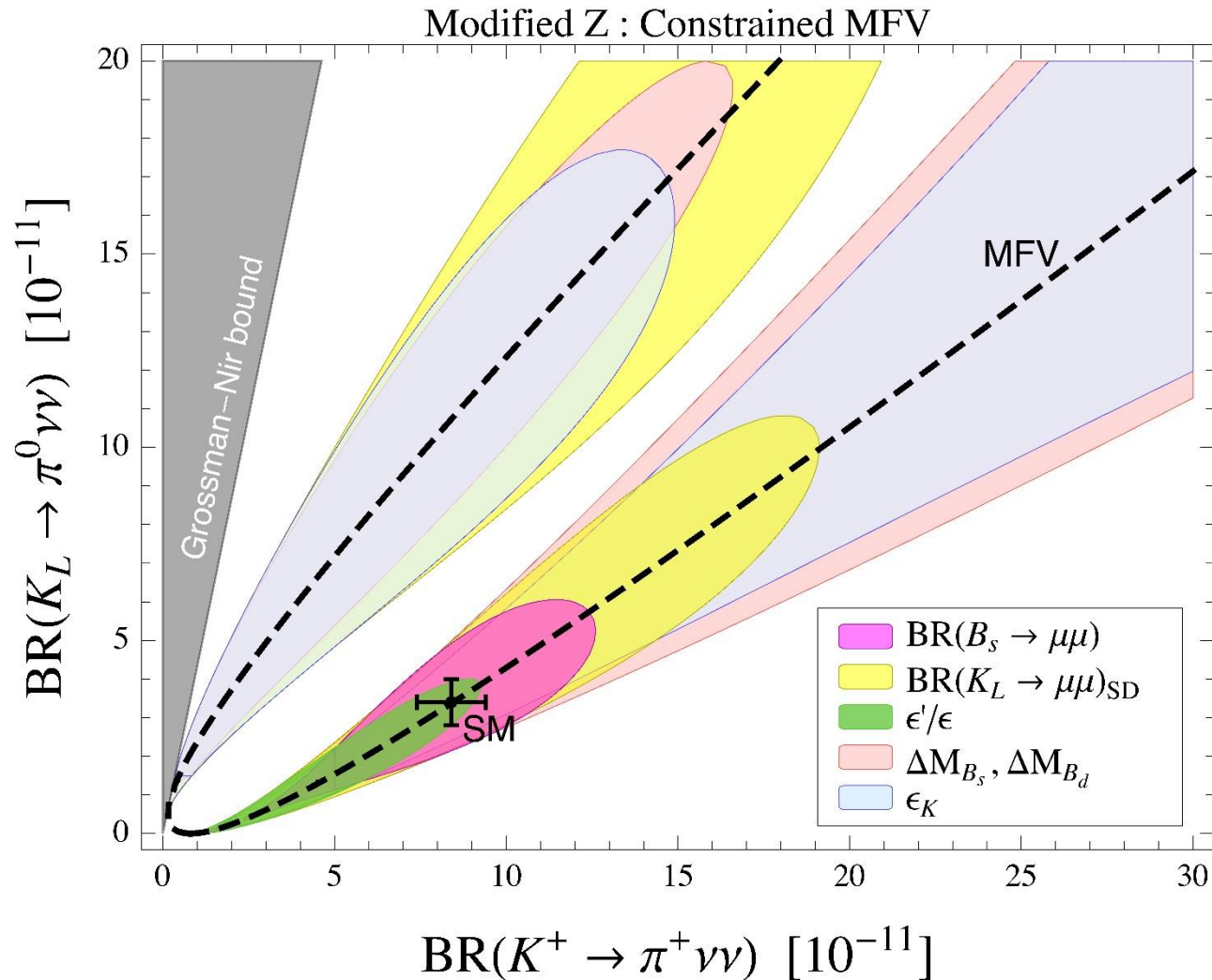
AJB: 1601.00005

Lesson 1

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

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

AJB + Fleischer (MFV)
0104238



AJB, Buttazzo, Kneijens: hep-ph-1507.08672

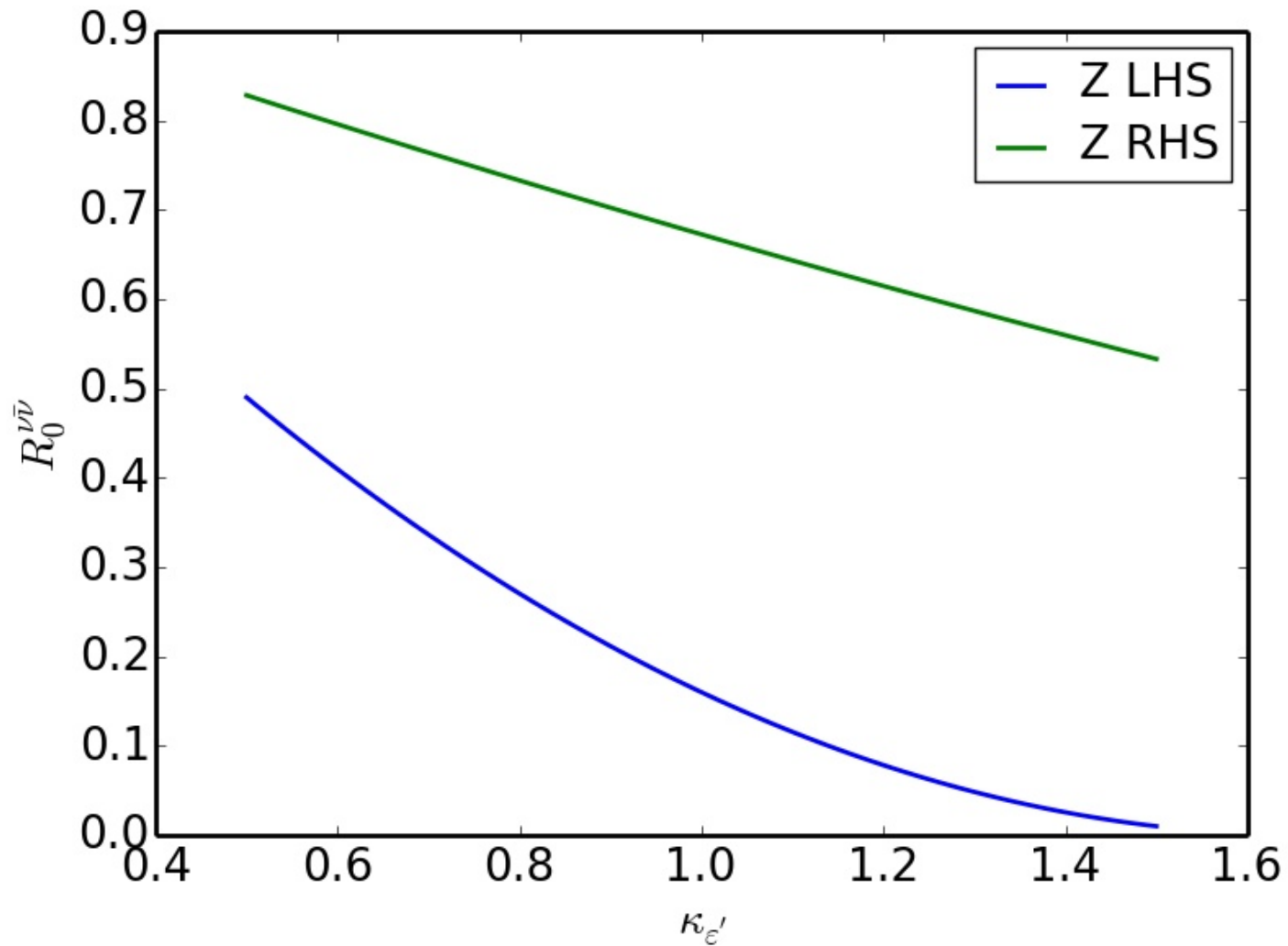
Lesson 2

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

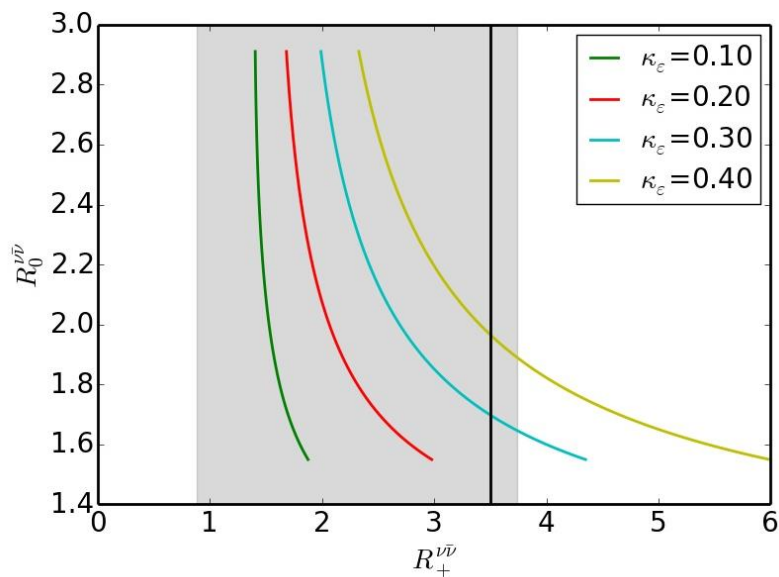
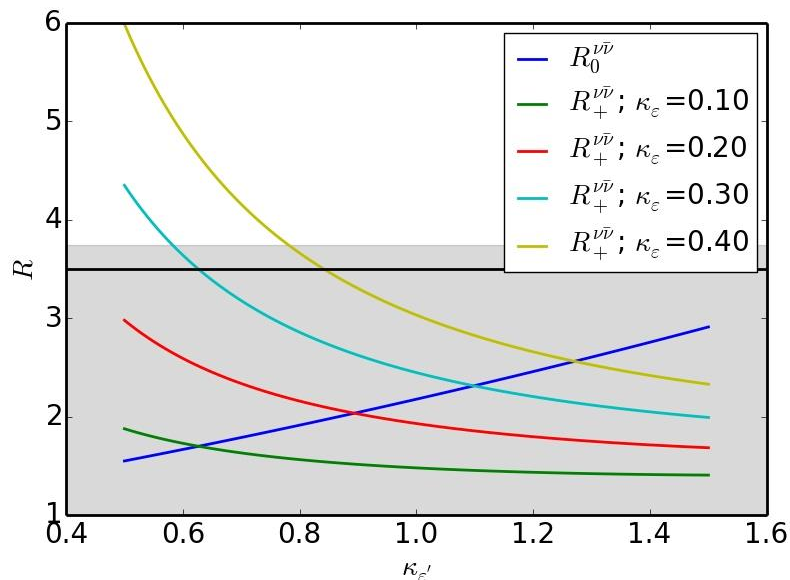
$\varepsilon'/\varepsilon, \varepsilon_K, K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L \rightarrow \pi^0 \nu \bar{\nu}$
can be simultaneously enhanced

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

Z with LH and RH Flavour Violating Couplings

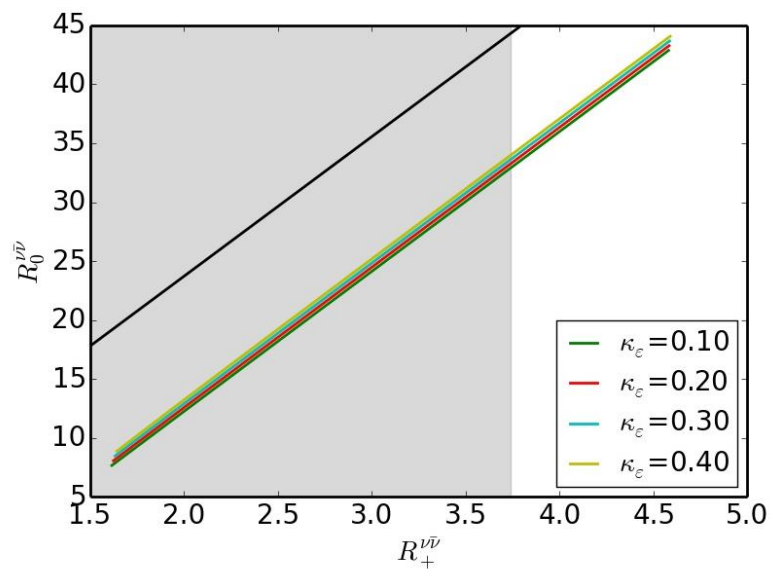
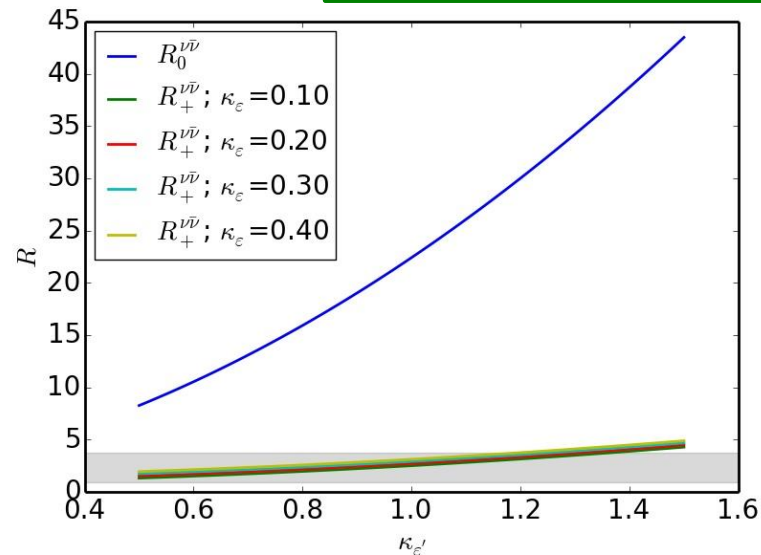
Example 1

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



Example 2

$\text{Im} \Delta_{L,R} \gg \text{Re} \Delta_{L,R}$



Lesson 4

Correlation between ε'/ε , $K \rightarrow \pi\nu\bar{\nu}$ 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**

$K_L \uparrow \uparrow \quad K^+ \downarrow \downarrow \quad \text{with } \kappa_{\varepsilon'} \uparrow \uparrow$

$(K^+ \uparrow \uparrow \text{ with } \kappa_\varepsilon \uparrow \uparrow)$ Only (20-40)% effects

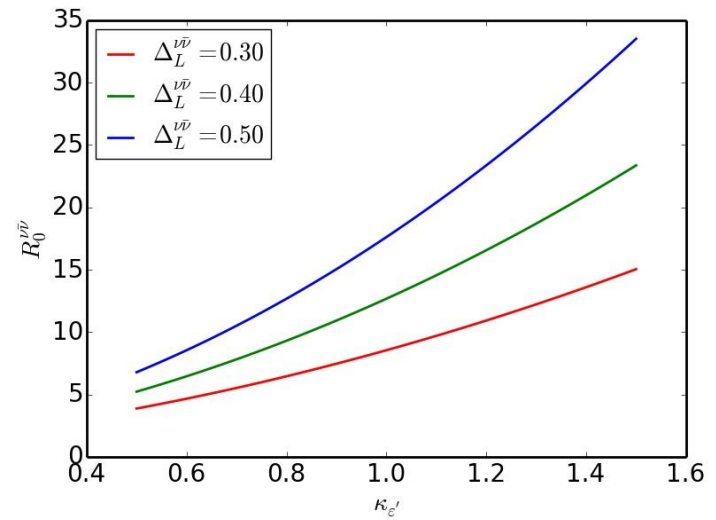
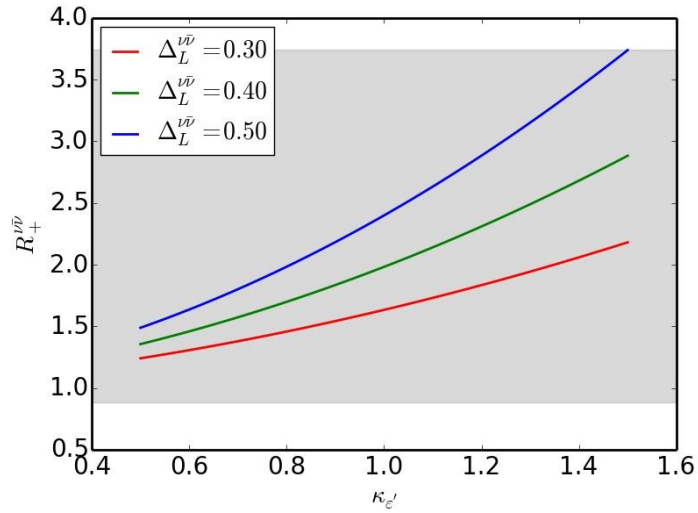
- **$(\Delta M_K)^{NP} > 0$ (below 10%)**

ε_K anomaly can be solved

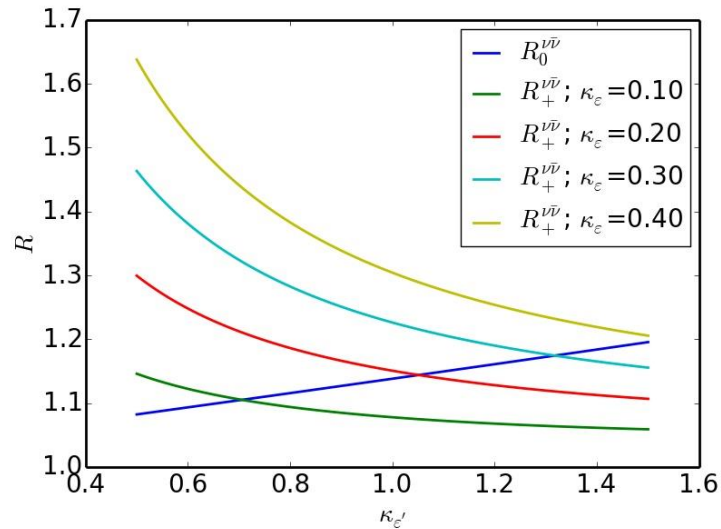
Pattern for $\Delta_R^{q\bar{q}}(Z') \approx 0(1)$ in ε'/ε

$M_{Z'} = 3 \text{ TeV}$

QCD Penguin (Q_6)

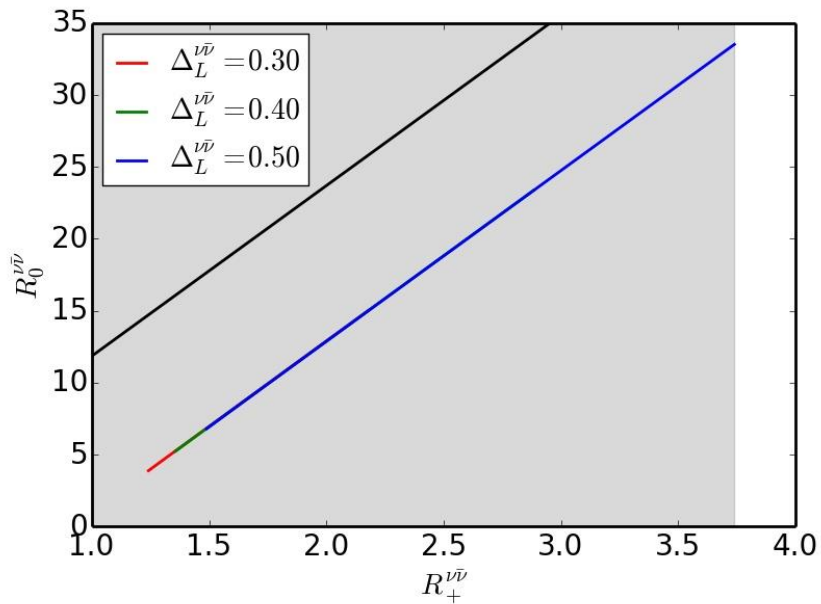


Electroweak Penguin (Q_8)

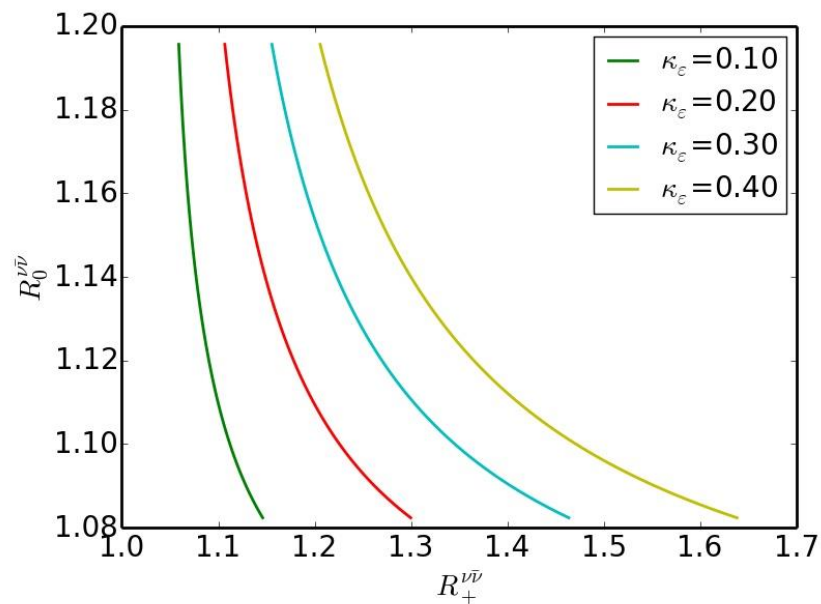


(Z)

QCDP (Q₆)

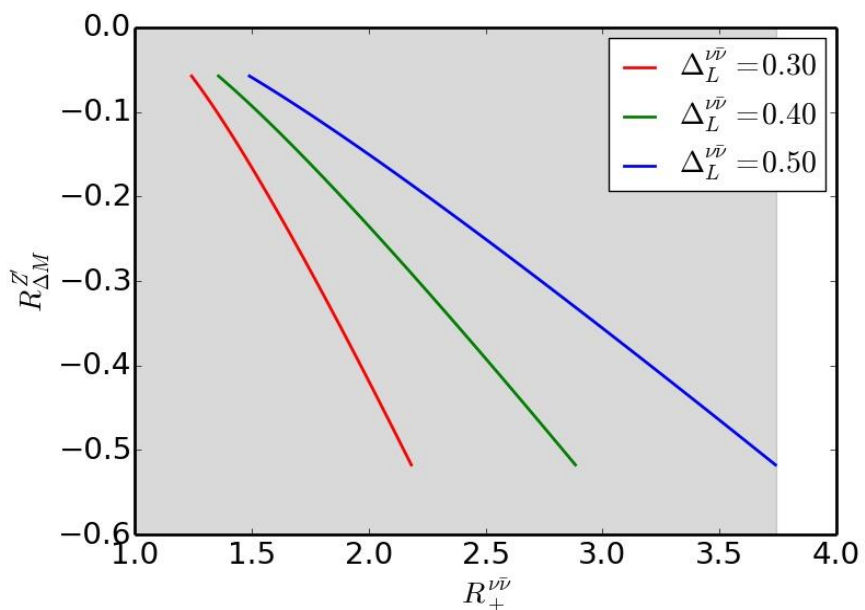


EWP (Q₈)



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

(Z)



Section 4

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

$\varepsilon'/\varepsilon + K \rightarrow \pi\nu\bar{\nu}$ beyond SM



AJB



Fulvia de Fazio



Jennifer Girrbach-Noe

Z, Z' 331

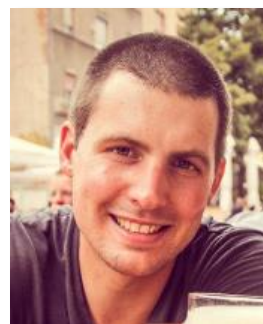
**1404.3824, ...
1311.6729**



AJB



Dario Buttazzo



Rob Kneijens

**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

$\varepsilon'/\varepsilon, B_s \rightarrow \mu^+ \mu^-$,

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

Model with Vektor-like Quarks



Christoph Bobeth



AJB



Alejandro Celis



Martin Jung

331 Models Facing ε'/ε Anomaly

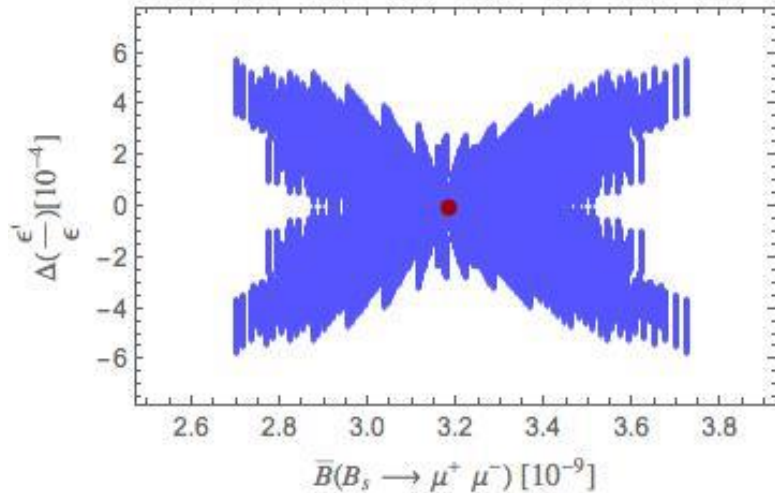
AJB, De Fazio 1512.02869, 1604.02344

- 1.** $\kappa_{\varepsilon'} \leq 0.8$ (only 3 models can reach upper bound)
- 2.** None of them can explain suppressions of C_9 ($B \rightarrow K(K^*)\mu^+\mu^-$) and $B_s \rightarrow \mu^+\mu^-$ simultaneously.
None R_K
- 3.** Small NP effects in $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ and $K_L \rightarrow \pi^0 \nu\bar{\nu}$

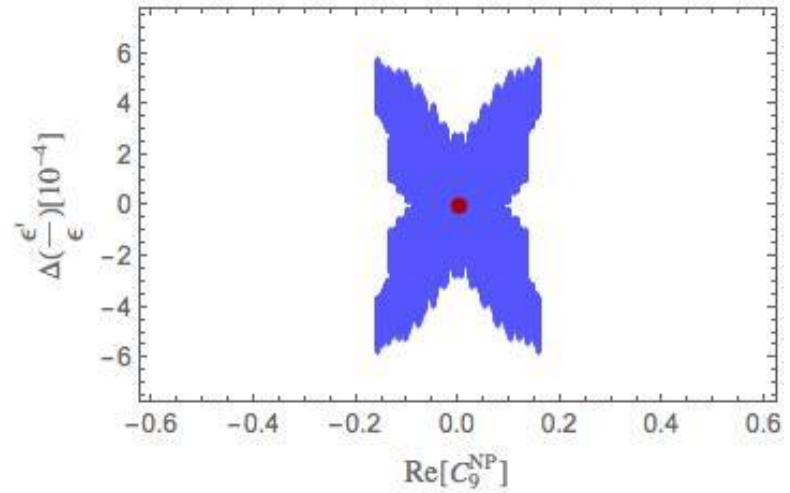
Correlations in Favorite 331 Models

(AJB+De Fazio, 1604.02344)

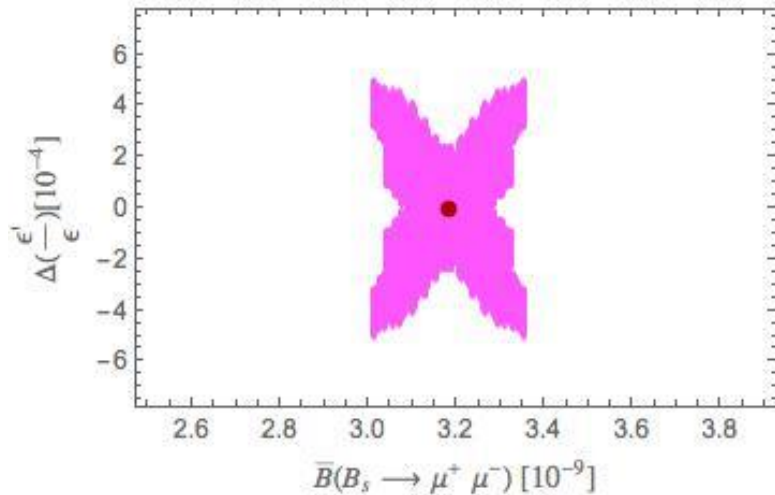
M8



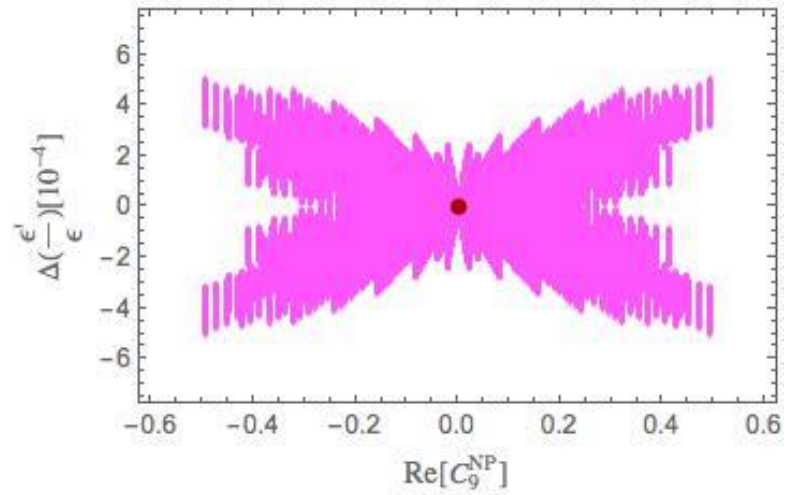
M8



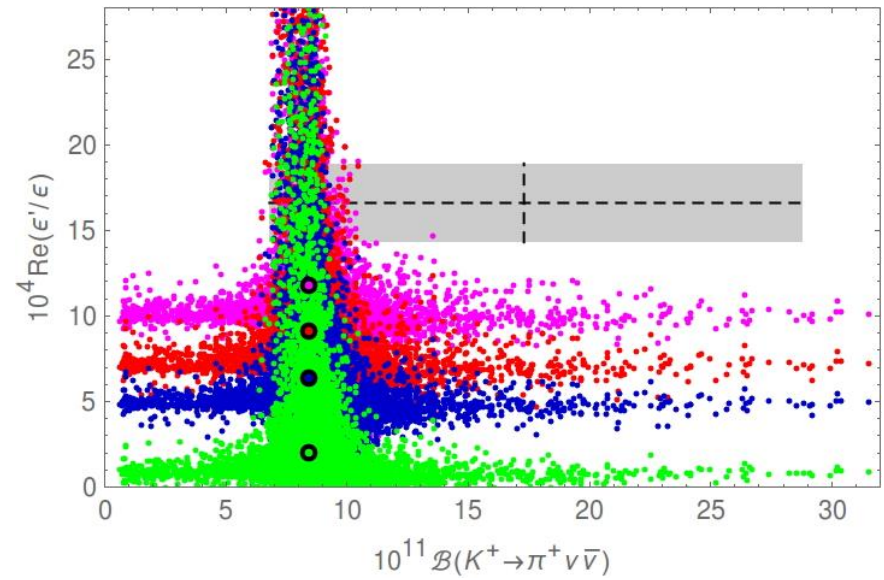
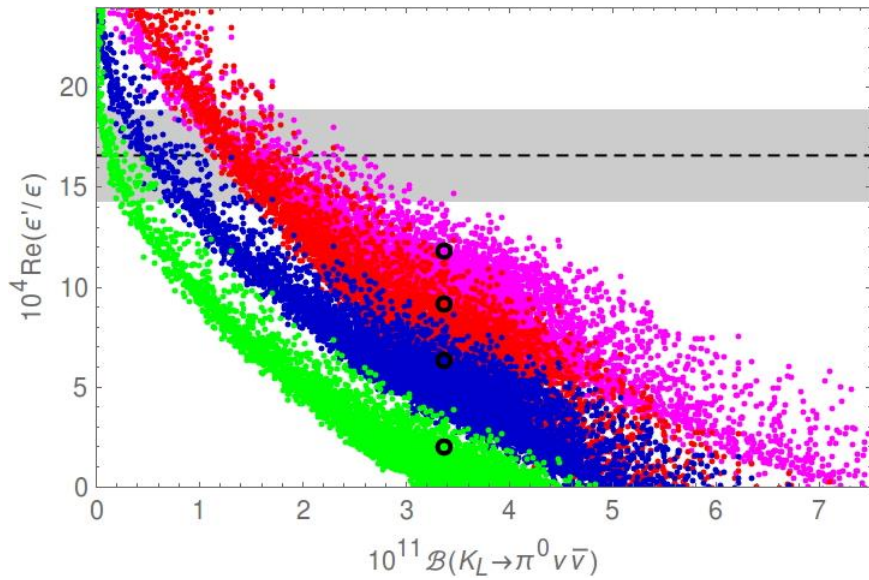
M16



M16



LHT : Blanke, AJB, Recksiegel (1507.06316)



~~$$\left(B_6^{(1/2)} = 1.0, B_8^{(3/2)} = 0.76 \right)$$~~

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

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

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

(Violates
Large N bound)

Supersymmetric Explanation of ε'/ε and ε_K

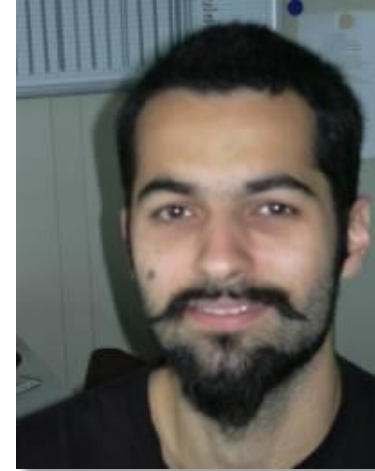
Teppei Kitahara



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

$$\text{Br}(\text{K}^+ \rightarrow \pi^+ \nu \bar{\nu}) = (18.0 \pm 2.0) \cdot 10^{-11} \quad (\text{NA62})$$

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

Would point
towards :

Z with LH + RH couplings
Z'(QCDP) with $Z' q \bar{q} \approx 0(1)$
Z'(EWP) with $Z' q \bar{q} \approx 10^{-2}$

Can we reach Zeptouniverse through Quark Flavour Physics ?

(Z')

AJB, Buttazzo, Girschbach-Noe, Kneijens, 1407.0728

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

:

Only with K rare Decays
 $B_s \sim 15 \text{ TeV}$, $B_d \sim 15 \text{ TeV}$

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

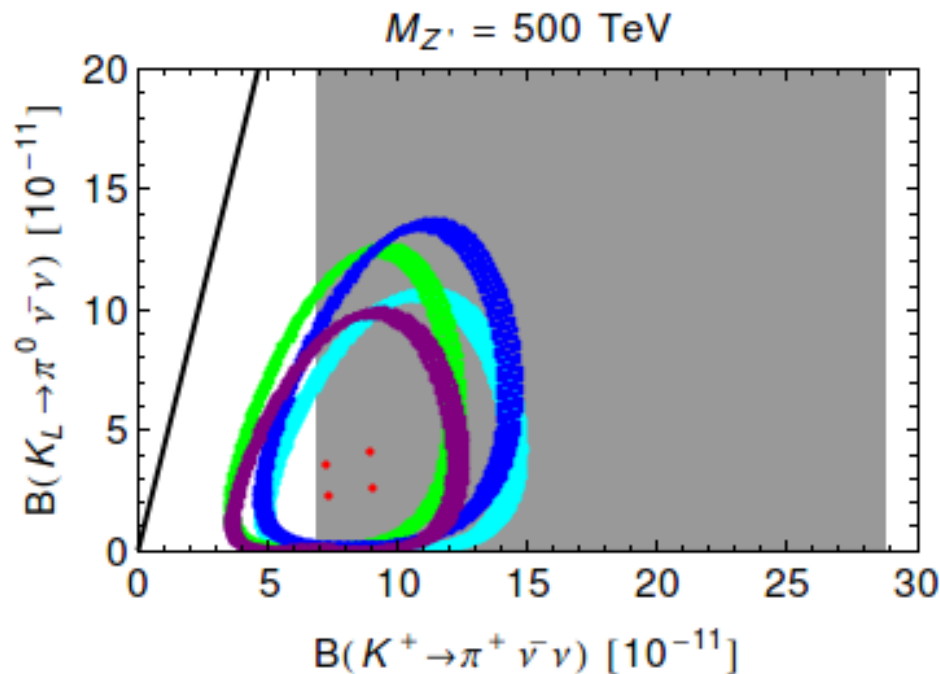
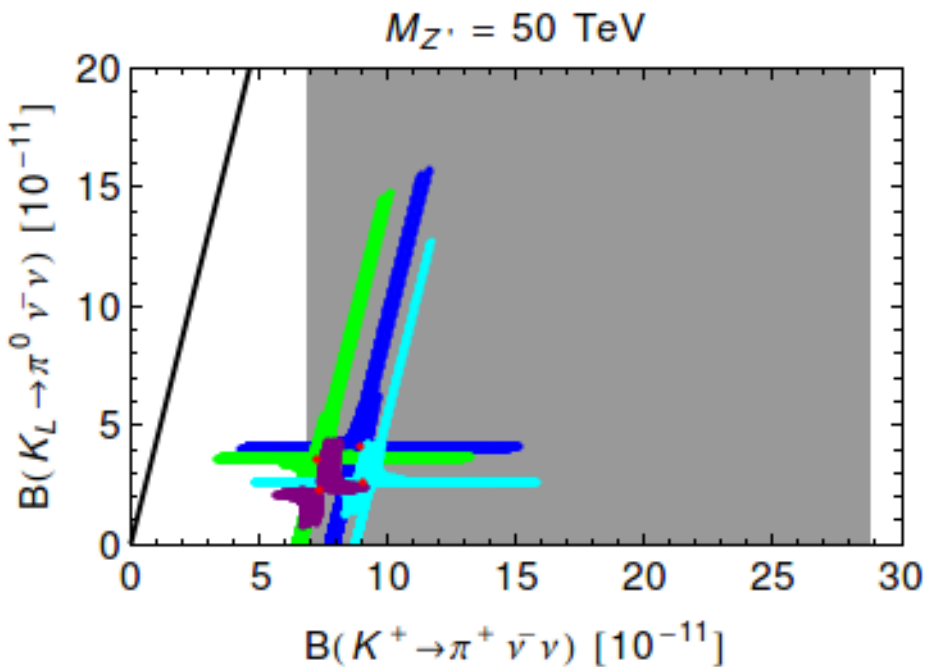
:

$K \rightarrow \pi \nu \bar{\nu}$: $\Lambda_{\text{NP}}^{\text{max}} \approx 2000 \text{ TeV}$
 B_d : $\Lambda_{\text{NP}}^{\text{max}} \approx 160 \text{ TeV}$
 B_s : $\Lambda_{\text{NP}}^{\text{max}} \approx 160 \text{ TeV}$

Yes we can !!

Heavy Z' at Work

AJB, Buttazzo, Girschbach-Noe, Knecht, 1407.0728



ε_K constraint

General discussion:
Blanke 0904.2528

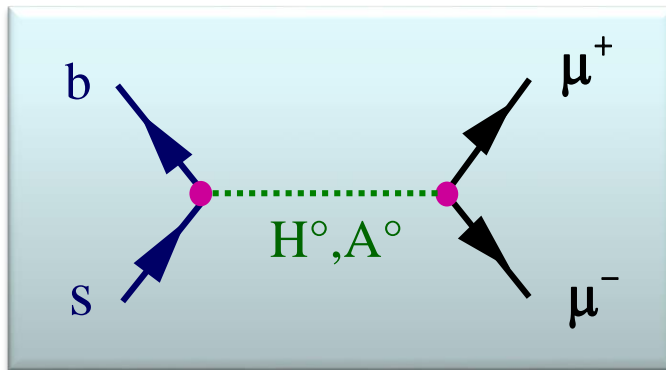
No ε_K constraint

Can we reach Zeptouniverse through S and P

AJB, Buttazzo, Girrbach-Noe, Kneijens, 1407.0728

Yes :

$$\mathbf{B}_{s,d} \rightarrow \mu^+ \mu^-$$



S : ≈ 350 TeV

P : ≈ 700 TeV

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

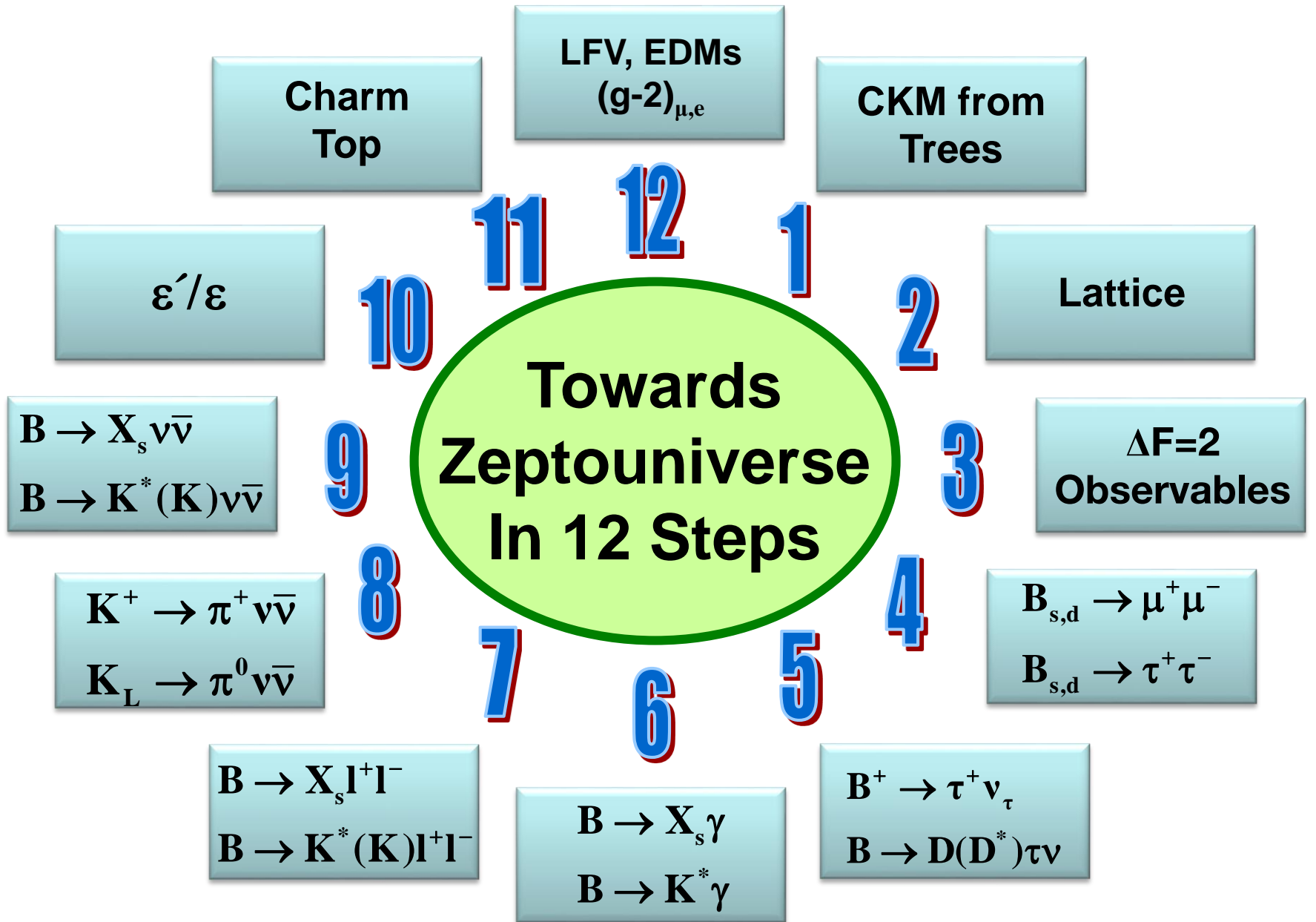
Similar to $K \rightarrow \pi \nu \bar{\nu}$ (**Z**):
No tuning necessary to reach Zeptouniverse

$$S=H^0$$

$$P=A^0$$

Open Questions to be answered hopefully in this Decade

- 1.** What is $\text{Br}(\text{K}^+ \rightarrow \pi^+ \nu \bar{\nu})$ from NA62?
- 2.** What is $\text{Br}(\text{K}_L \rightarrow \pi^0 \nu \bar{\nu})$ from KOTO?
- 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 $(\Delta M_K)^{\text{SM}}$? (Lattice)
- 6.** Does NP contribute to $\text{Re}A_0$ 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 !

Anomalies in Kaon Flavour Physics



Backup

RBC-UK QCD

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

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

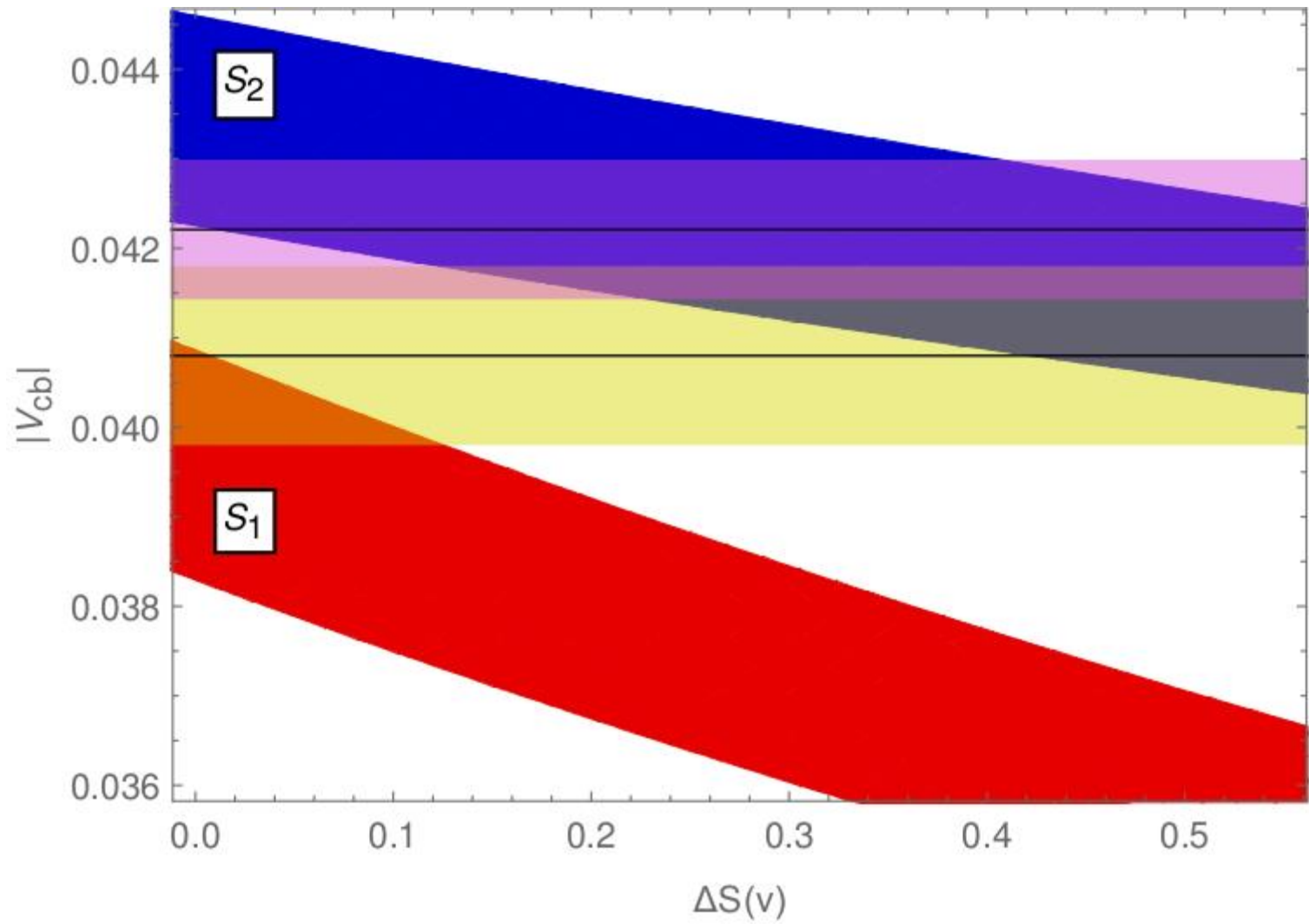
$$(\varepsilon'/\varepsilon)_{\text{exp}} = (16.6 \pm 2.3) \cdot 10^{-4}$$

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

Large N

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

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



Large N Approach

AJB, Gérard (2015)

vs

Lattice

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

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

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

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

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

$$\text{Re } A_2$$

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

Exp
22.4



$\Delta I = 1/2$ Rule

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

(will go down with new results)

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

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

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

$$\text{Re } A_2$$

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

RBC-UKQCD

Large N Approach

AJB, Gérard (2015)

vs

Lattice

$$\hat{B}_K = 0.73 \pm 0.02$$
$$(\hat{B}_K \leq 0.75)$$

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

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

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

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

Exp
22.4

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

(will go down with new results)

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

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

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

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

RBC-UKQCD

$\Delta I = 1/2$ Rule

Motivations for New Analysis

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

2. Stress CKM uncertainties in $\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$, $\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu})$

3. Point out correlation between

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$, $B_s \rightarrow \mu^+ \mu^-$ and γ
(NA62) (LHCb+CMS) (LHCb)

Basically
no CKM
uncertainties

4. Update correlation between

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

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

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, Kneijens: 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 Kneijens (Moriond) 1505.04928

Different Patterns of Flavour Violation

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

Q₈ EWP

AJB (1601.00005)

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

} No specific correlation

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

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

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

Unless Loop effects important

Q₈ EWP

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

AJB (1601.00005)

New Features

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

Possibility of simultaneous enhancements of

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

Example 1

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

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

$$K_L \uparrow \quad K^+ \downarrow \quad \text{with } \kappa_{\varepsilon'} \uparrow$$

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

NP Effects
 in ΔM_K
 small

Example 2

$$\text{Im} \Delta_{L,R} \gg \text{Re} \Delta_{L,R}$$

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

(no dependence on κ_{ε})

Correlation between K_L and K^+

On the branch parallel to Grossmann-Nir Bound

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

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

Since 1955

Gell-Mann
Pais

1986, 2014

Large N including
I/N corrections

Quark Evolution $1 \text{ GeV} \leq \mu \leq M_W$
Meson Evolution $0 \leq \mu \leq 1 \text{ GeV}$

Correct value
of $\text{Re}A_2$

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

Dominance
of current-
current
operators

Correct value
of $\text{Re}A_2$

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

RBC-QCD
(2013, 2015)

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

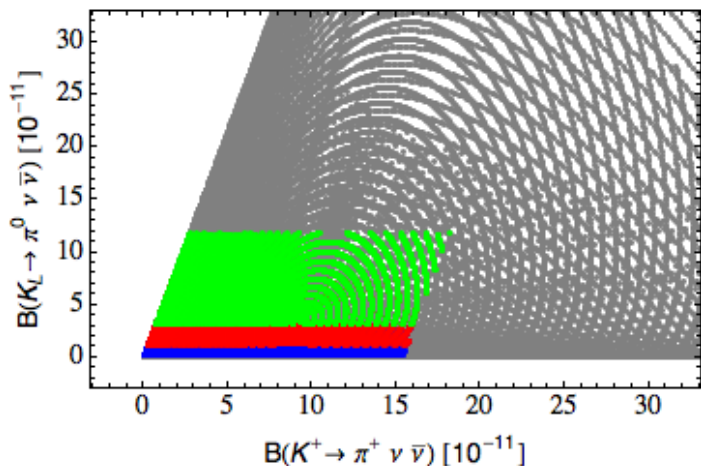
AJB
De Fazio
Girrbach-Noe
1404.3824

Z with FCNCs at Work

AJB, de Fazio,
Girrbach-Noe
1404.3824

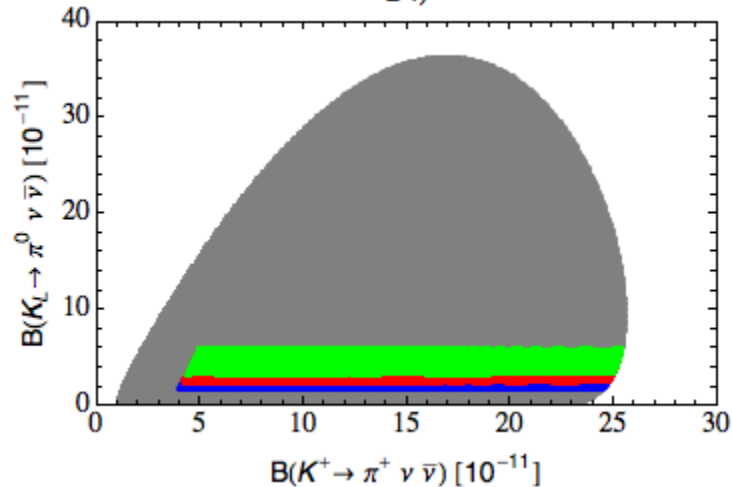
LHS

B f)



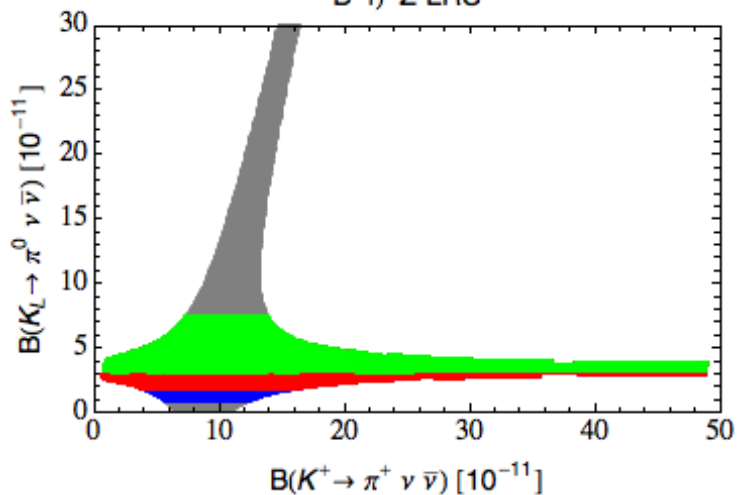
RHS

B f)






LRS

B f) Z LRS



 $\epsilon_K, \Delta M_K$ constraint

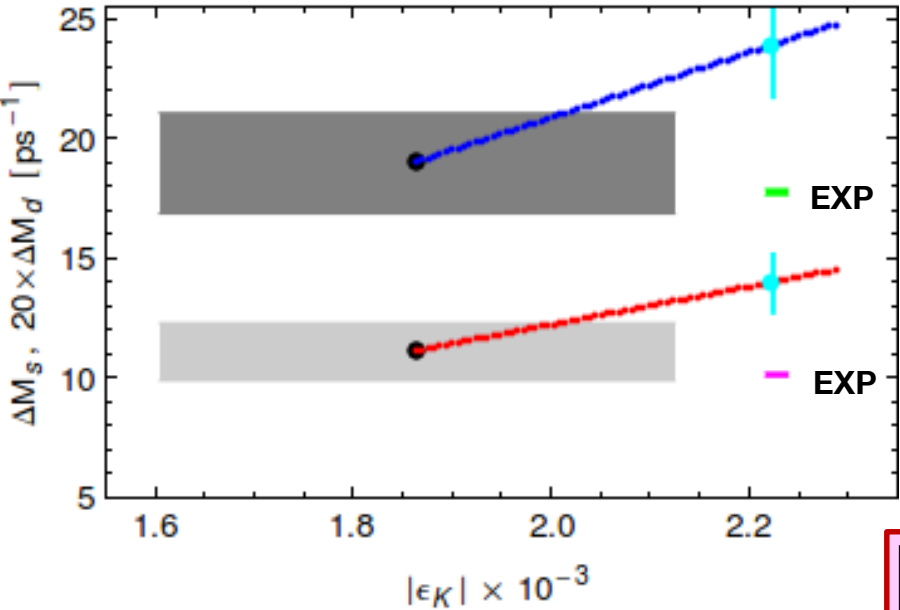
ϵ'/ϵ
+
 $K_L \rightarrow \mu^+ \mu^-$

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

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

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

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



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

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

$$|V_{cb}|$$

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

AJB + Girrbach 1306.3755
 Similar tension in
 Gauged Flavour Models:
 AJB, Merlo, Stamou (2011)

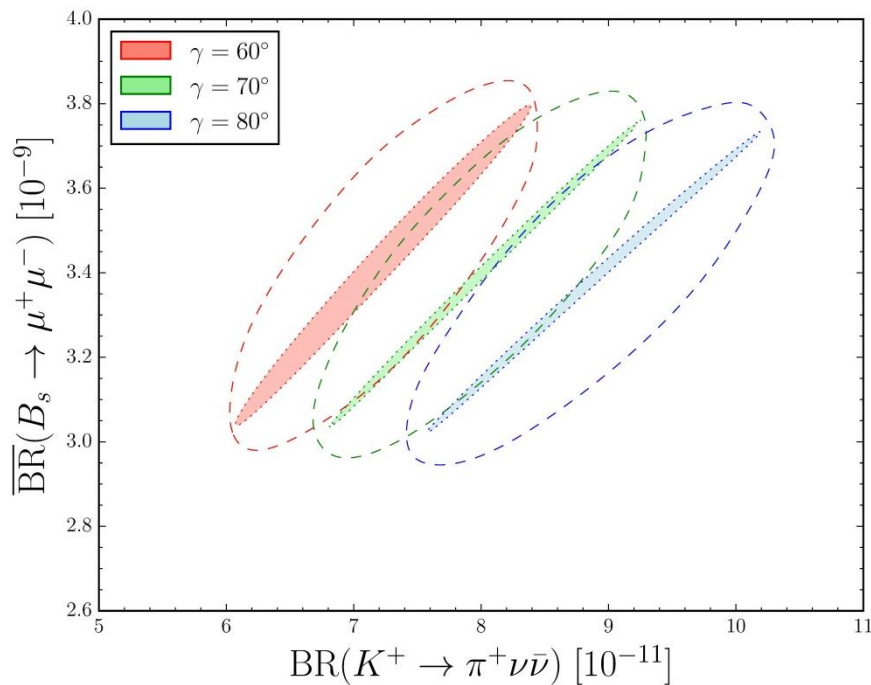
*) Can still work within MFV
 ($\Delta\epsilon_K > 0$ in MFV) Blanke + AJB
 (2006)

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

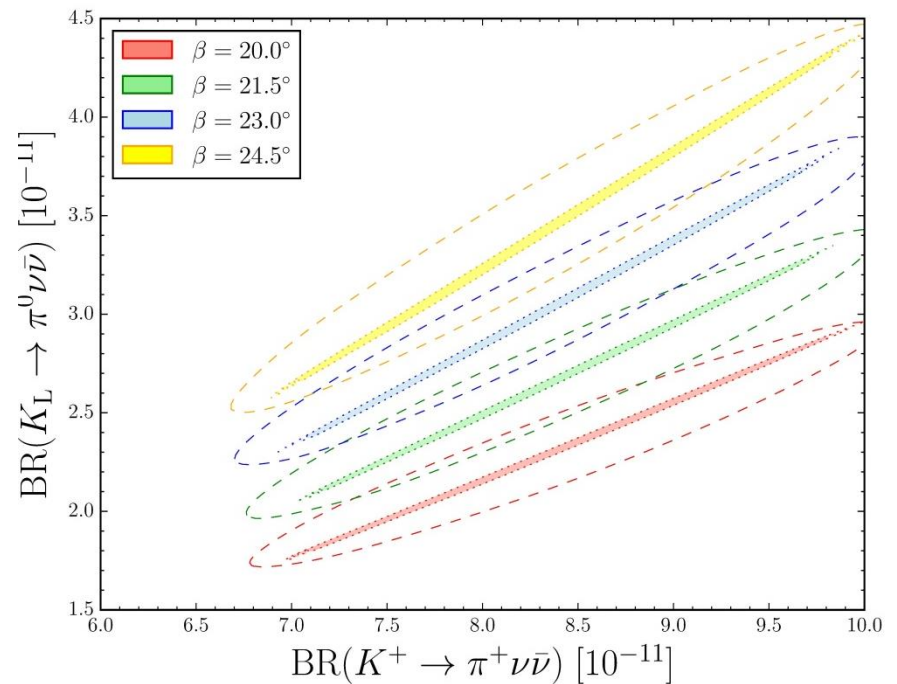
$$B_s \rightarrow \mu^+ \mu^-, K^+ \rightarrow \pi^+ \nu \bar{\nu}, \gamma$$

BBGK (2015)



$$K^+ \rightarrow \pi^+ \nu \bar{\nu}, K_L \rightarrow \pi^0 \nu \bar{\nu}, \beta$$

Buchalla, AJB (94)



General Properties

- 1.** $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ **CP-conserving**
- 2.** $K_L \rightarrow \pi^0 \nu \bar{\nu}$ **CP-violating**
- 3.** **Both sensitive to New Physics (NP)**
 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ bounded by $K_L \rightarrow \mu^+ \mu^-$
 $K_L \rightarrow \pi^0 \nu \bar{\nu}$ bounded by ε'/ε
- 4.** **The correlation between $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L \rightarrow \pi^0 \nu \bar{\nu}$ 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)

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

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

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

$$|V_{ub}| = (3.63 \pm 0.12) \cdot 10^{-3}$$

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

$$|V_{ub}| = (3.55 \pm 0.16) \cdot 10^{-3}$$

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

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

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

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

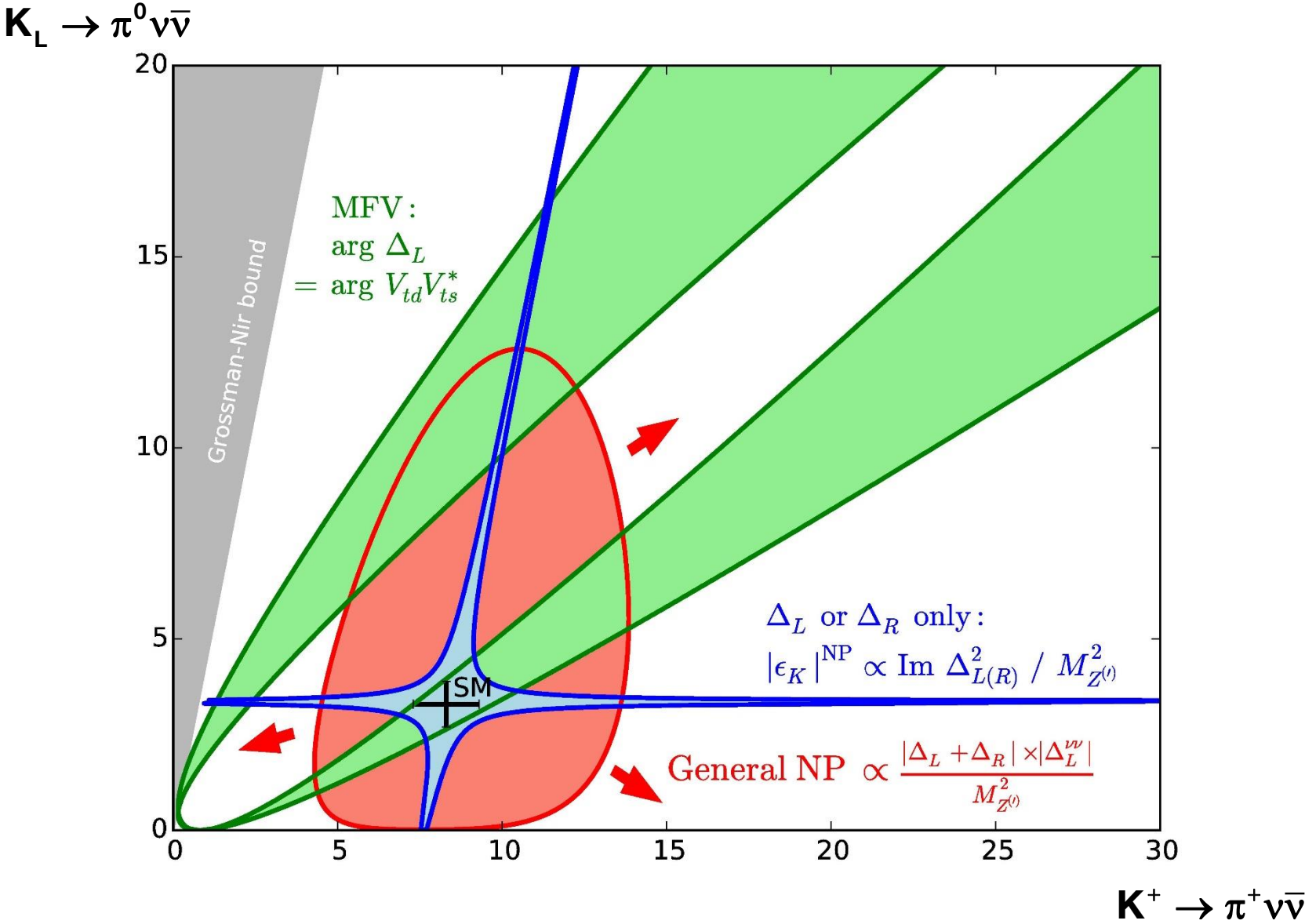
For $\text{Im}(V_{ts} V_{td}^*) = 1.4 \cdot 10^{-4}$

Below data but positive

Yet still large
uncertainties

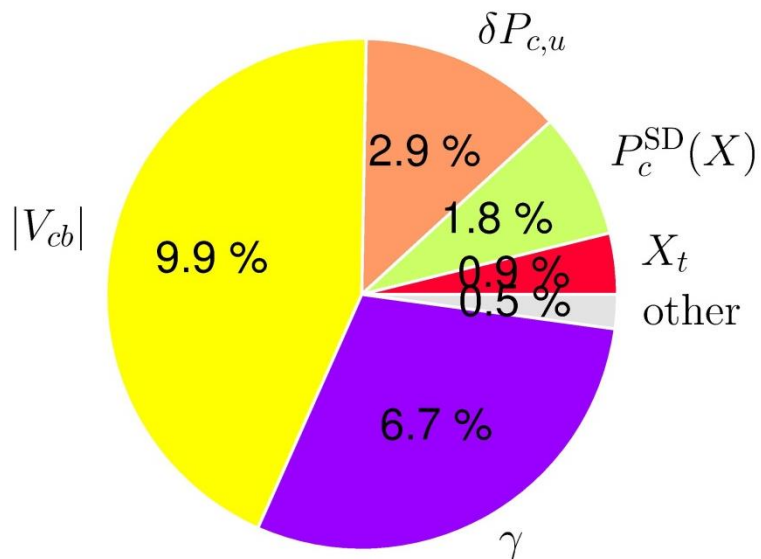
$\mathbf{K}_L \rightarrow \pi^0 \nu \bar{\nu}$ versus $\mathbf{K}^+ \rightarrow \pi^+ \nu \bar{\nu}$

AJB, Buttazzo, Kneegjens, 1507.08672

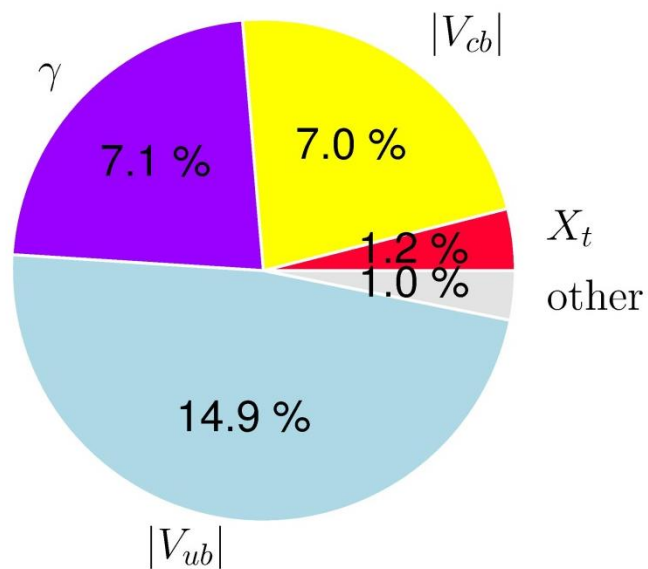


Error Budgets

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



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



Update: 1503.02693

$$P_c = 0.404 \pm 0.024$$

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

Z' outside the reach of the LHC

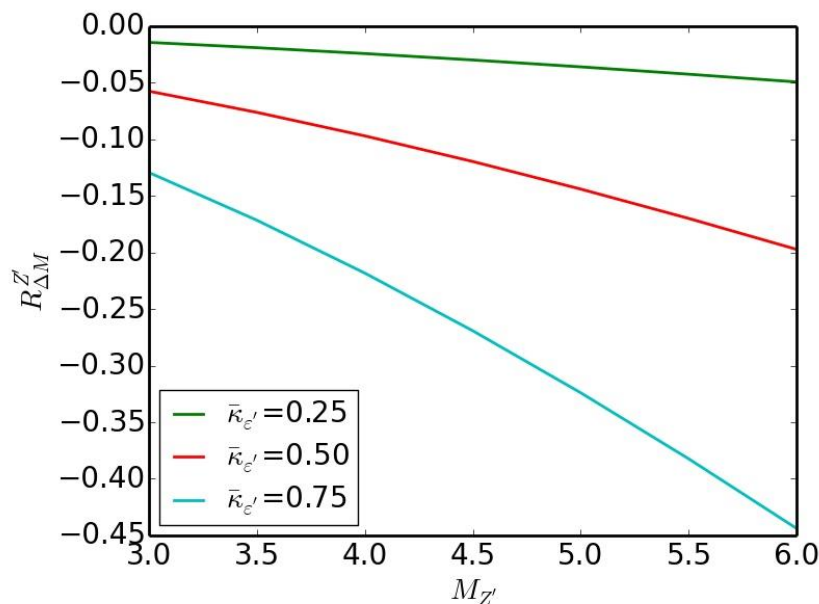
QCD Penguin

For fixed $\bar{\kappa}_{\varepsilon'}$: $\text{Br}(\text{K}_L \rightarrow \pi^0 \nu \bar{\nu})$, $\text{Br}(\text{K}^+ \rightarrow \pi^+ \nu \bar{\nu})$

But constraint
from ΔM_K

Independent of $M_{Z'}$

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



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

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

Using Tree Level Determination of CKM

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

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

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

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



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

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

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

$$\begin{array}{l} \overline{\text{Br}}(B_s \rightarrow \mu^+ \mu^-) = (3.4 \pm 0.3) \cdot 10^{-9} \\ \overline{\text{Br}}(B_s \rightarrow \mu^+ \mu^-)_{\text{exp}} = (2.8 \pm 0.7) \cdot 10^{-9} \end{array}$$

$$\begin{array}{l} \text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \cdot 10^{-11} \\ \text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (3.4 \pm 0.6) \cdot 10^{-11} \end{array}$$



AJB, Buttazzo,
Girrbach-Noe,
Knegjens
1503.02693