Z-Mediated New Physics, Vector-Like Quark Models and Beyond

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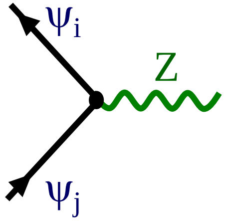
Overture

Z

After no signs of new particles at the LHC Z-boson is among SM particles particulary suited to be a messenger of New Physics at and beyond the LHC scales

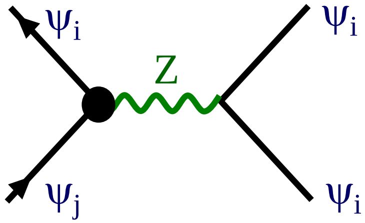
Z-Boson at Work (SM)



= 0

GIM

ψ_i = quarks, leptons



Z-Penguin enters leptonic, semi-leptonic, non-leptonic decays of mesons

gauge

$C(x_t, \xi)$
Inami-Lim (1981)

Gauge-independent functions:

Buchalla, AJB, Harlander (1990)

Box

$$X(x_t) = C(x_t) - 4B(x_t)$$

$$Y(x_t) = C(x_t) - B(x_t)$$

$$Z(x_t) = C(x_t) + \frac{1}{4} D(x_t)$$

Photon penguin

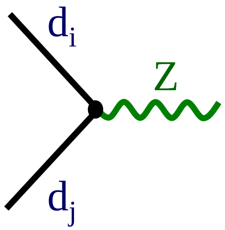
Govern most of rare K, $B_{s,d}$ decays

$B_{s,d} \to \mu^+\mu^-$, $K \to \pi\nu\bar{\nu}$,

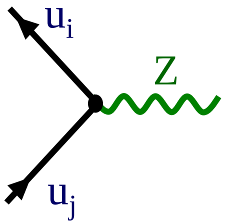
$B \to K\left(K^*\right)l^+l^-$, ε'/ε etc.

Z-Boson at Work (BSM)

FC couplings generated by some NP



$\left[\Delta_{L,R}^{d}(Z)\right]_{ij}$



$\left[\Delta_{L,R}^{u}(Z)\right]_{ij}$

<u>Example</u>:

Vector-like quarks mixing with SM quarks during electroweak symmetry breaking

(Nir; Aquila et al; Ishikawa, Ligeti, Wise)

Some recent phenomenological applications of General Z-scenario (simplified Z-models)

AJB, De Fazio, Girrbach (1211.1896)
AJB, Buttazzo, Knegjens (1507.08672)
AJB (1601.00005)

Gauge-Invariant Standard Model Effective Theory

Buchmüller, Wyler, 1990
Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010

Warsaw basis

$$L_{\text{eff}} = L_{SM} + \frac{1}{\Lambda^2} \sum_K C_K^{(6)} O_K^{(6)}$$

← Dimension 6 operators

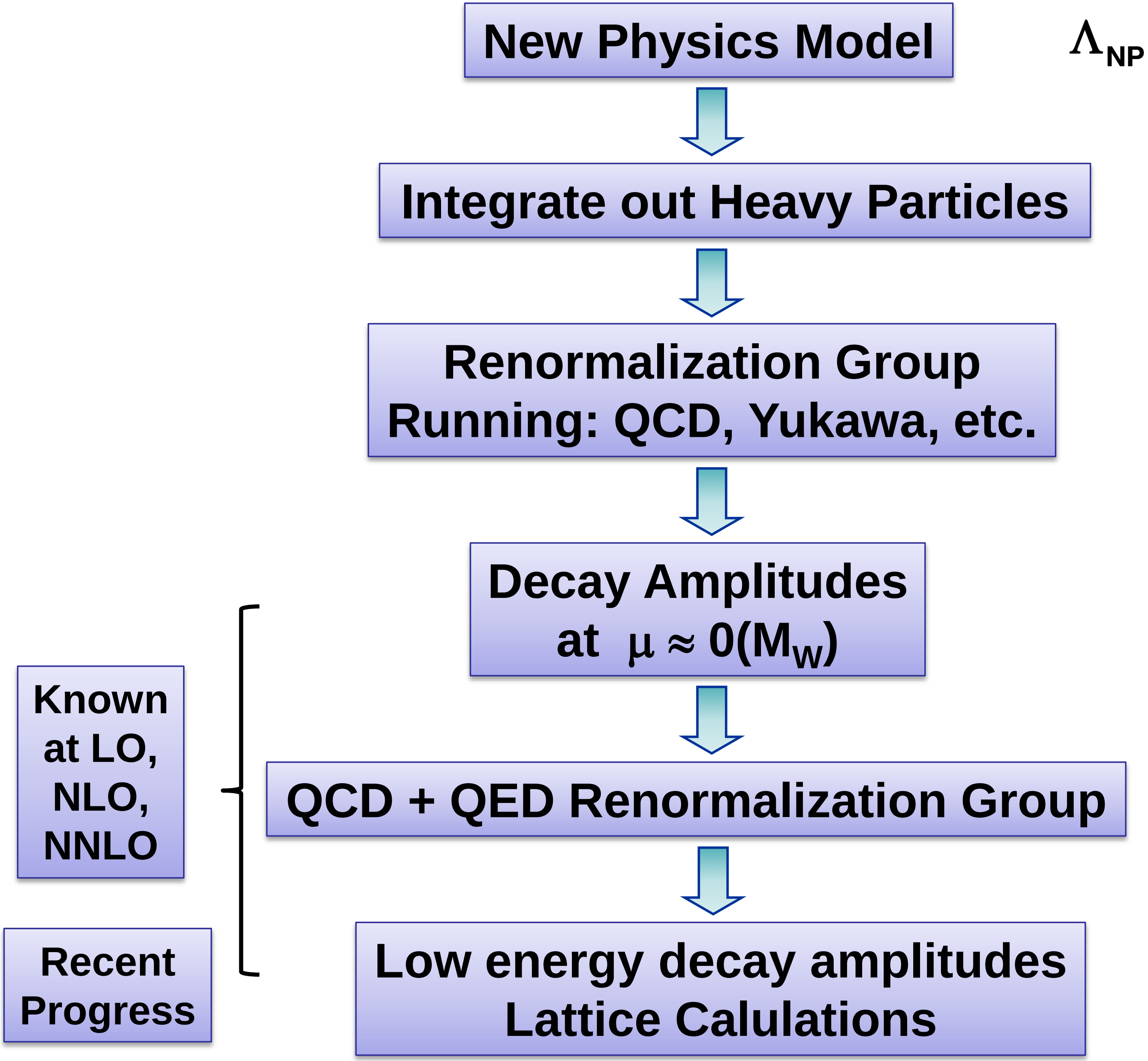
59 Operators when flavour indices omitted

2499 Operators with flavour indices Jenkins, Manohar, Trott

2499 x 2499 Anomalous dim matrix governs Renormalization Group evolution

from μ_{EW} to Λ = scale of new physics

But: **Useful results for analyses of specific models**



New Physics Model

Λ_{NP}

Integrate out Heavy Particles

Renormalization Group Running: QCD, Yukawa, etc.

Decay Amplitudes at $\mu \approx 0(M_W)$

QCD + QED Renormalization Group

Low energy decay amplitudes Lattice Calulations

Known at LO, NLO, NNLO

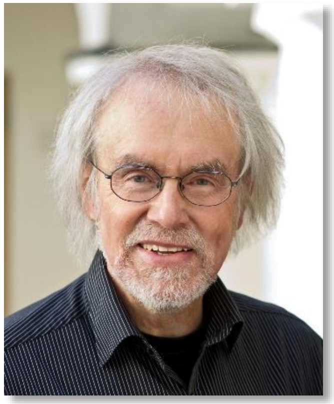
Recent Progress

Basic Questions for Next 24 min

1. **What is the pattern of New Physics mediated by Z-boson?**
2. **How is it described by SMEFT?**
3. **What can models with Vector-like Quarks offer in this context?**
4. **Z´ at work**

BBCJ Collaboration


Christoph Bobeth


AJB


Alejandro Celis


Martin Jung

1703.04753 (General Z Models) (40 pages)
1609.04783 (Vector-like Quark Models) (74 pages)

AJB 1601.00005 (Z´ models) (67 pages)

Main Actors

SMEFT

$$0_{Hd} = \left(H^{+} i\overleftrightarrow{D}_{\mu} H\right)\left[\bar{d}^{i}_{R}\gamma^{\mu} d^{j}_{R}\right]$$

(RH Scenario)

$$0^{(1)}_{Hq} = \left(H^{+} i\overleftrightarrow{D}_{\mu} H\right)\left[\bar{q}^{i}_{L}\gamma^{\mu} q^{j}_{L}\right]$$

$$0^{(3)}_{Hq} = \left(H^{+} i\overleftrightarrow{D}^{a}_{\mu} H\right)\left[\bar{q}^{i}_{L}\sigma^{a}\gamma^{\mu} q^{j}_{L}\right]$$

(LH Scenario)

$$\left[C_{Hd}\right]_{ij} \quad , \quad \left[C^{(1)}_{Hq}\right]_{ij} \quad , \quad \left[C^{(3)}_{Hq}\right]_{ij}$$

Complex Couplings

$$O\left(\frac{1}{\Lambda^{2}}\right)$$

Generated Z-Couplings:

$$\left[\Delta^{d}_{R}(Z)\right]_{ij} = -\frac{g_{Z}}{2} v^{2}\left[C_{Hd}\right]_{ij}$$

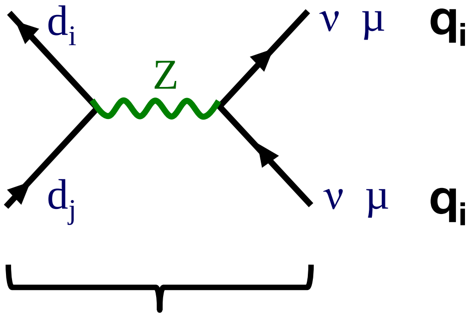
$$\left[\Delta^{d,u}_{L}(Z)\right]_{ij} = -\frac{g_{Z}}{2} v^{2}\left[C^{(1)}_{Hq} \pm C^{(3)}_{Hq}\right]_{ij}$$

$$\Lambda = \Lambda_{NP}$$

$$g_{Z} = \sqrt{g_{1}^{2} + g_{2}^{2}}$$

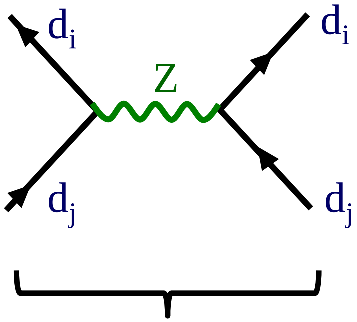
Simplified Z Scenarios

ΔF=1



Dim 6 Contributions
v^2/Λ^2

ΔF=2



Dim 8 Contributions
v^4/Λ^4

(only relevant for Λ < 3TeV)

What are the Dim 6 Contributions to ΔF=2 Processes in Z-Scenarios?

Use SMEFT to find out.

4 Lessons from SMEFT

(BBCJ)

Lesson 1

(RH Scenario)

$[C_{Hd}]_{ij} \neq 0$ **generates through RG evolution $\Lambda \to \mu_{EW}$ due to Yukawa couplings**

$\Delta F=2$ LR operators

which are further enhanced through QCD RG evolution and large hadronic matrix elements.

$$\lambda_t^{ij} = V_{ti}^* V_{tj}$$

$$x_t = \frac{m_t^2}{M_W^2}$$

$$O^{ij}_{LR,1} = \left[\bar{d}_i \gamma_\mu P_L d_j\right]\left[\bar{d}_i \gamma^\mu P_R d_j\right]$$

$$C^{ij}_{LR,1}(\mu_{EW}) \propto v^2 \lambda_t^{ij} \left[C_{Hd}\right]_{ij} x_t \ln\frac{\Lambda}{\mu_{EW}}$$

$$i, j = d, s, b$$

scale dependence

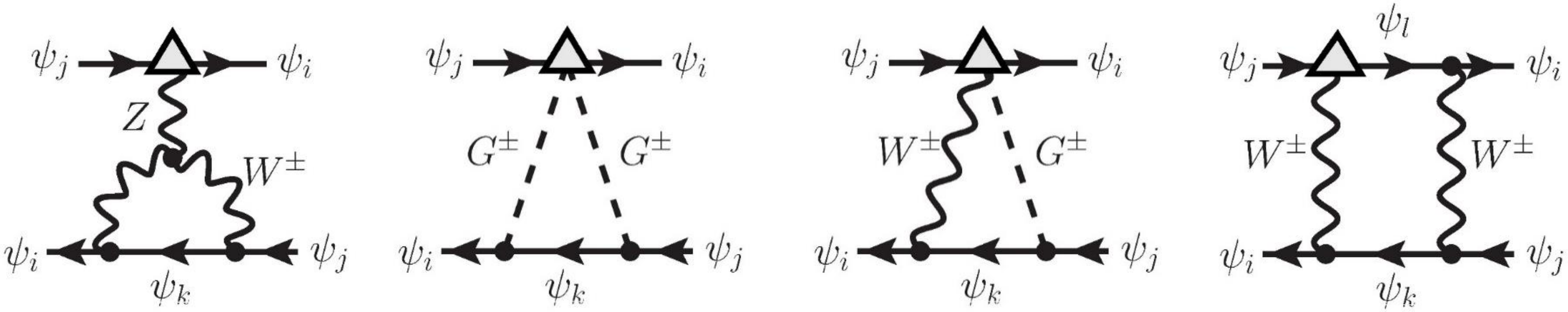
⇒ **Very strong constraint on rare decays!**

(in particular in K-system)

Lesson 2

(BBCJ)

μ_{EW} dependence cancelled by NLO Corrections



Corresponds to Z-penguin with $\bar{d}^i \gamma^\mu P_L d^i$ replaced by $\Delta_R^{ij}(Z)$

Cancel gauge dependence of the first diagram

New gauge-independent Function $H_1(x_t)$

Analog to $X(x_t)$, $Y(x_t)$, $Z(x_t)$ in SM (confirmed by Endo et al. V2)

(Endo, Kitahara, Mishima, Yamamoto (1612.08839))

Lesson 3

(BBCJ)

In LH scenario no new ΔF=2 operators generated

But two couplings required to describe all effects.

$$\left[\Delta_L^d(Z)\right]_{ij} \sim C_{Hq}^{(+)}$$

$$C_{Hq}^{(\pm)} = C_{Hq}^{(1)} \pm C_{Hq}^{(3)}$$

$$\left[\Delta_L^u(Z)\right]_{ij} \sim C_{Hq}^{(-)}$$

$i,j = d,s,b$

$$\left[\Delta C_{VLL}\left(\mu_{EW}\right)\right]^{ij} \propto \lambda_t^{ij} v^2 x_t \left[C_{Hq}^{(-)} \ln \underbrace{\frac{\Lambda}{\mu_{EW}} + F\left(C_{Hq}^{(\pm)}, x_t, \mu_{EW}\right)}\right]$$

$$O_{VLL}^{ij} = \left[\bar{d}_i \gamma_\mu P_L d_j\right]^2$$

(SM operator)

Connection between up and down through $SU(2)_L$ invariance

Cancellation of μ_{EW} dependence.

2 gauge independent Functions $H_1(x_t)$, $H_2(x_t)$

Lesson 4

(BBCJ)

in down sector

In rare decays (ΔF=1) only $C_{Hq}^{(+)}$ enters
but in ΔF=2 $C_{Hq}^{(+)}$ and $C_{Hq}^{(-)}$

$\left[\Delta_L^d(Z)\right]_{ij}$ insufficient

No model independent correlation
between ΔF=1 and ΔF=2 transitions

In contrast to simplified models

- Weak constraints on rare decays from ΔF=2
- Still correlations between various ΔF=1 transitions present
- In specific models also (ΔF=2) ↔ (ΔF=1)

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!

Yet also anomaly in CP-violation in K-physics (ε´/ε)

$\varepsilon' =$ **CP-violation in Decay** $(K_L \to \pi\pi)$

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

ε'/ε Anomaly

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

NA48 (CERN) (2001)
KTeV (Fermilab)

$$\left(\varepsilon'/\varepsilon\right)_{\text{SM}} = \left(1.4 \pm 6.9\right) \cdot 10^{-4}$$

(RBC-UKQCD) (Lattice)

Use RBC-QCD

$$\left(\varepsilon'/\varepsilon\right)_{\text{SM}} = \left(1.9 \pm 4.5\right) \cdot 10^{-4}$$

(AJB, Gorbahn, Jamin, Jäger)

$$\left(\varepsilon'/\varepsilon\right)_{\text{SM}} = \left(1.1 \pm 5.1\right) \cdot 10^{-4}$$

(Kitahara, Nierste, Tremper)

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

(AJB, Gérard)
(Dual QCD Approach, I/N)
(1507.06326)

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

ε´/ε Anomaly

Largest anomaly in Flavour Physics

$$\boxed{\left(\varepsilon'/\varepsilon\right)_{\text{exp}}=\left(16.6\pm2.3\right)\cdot10^{-4}}$$

NA48 (CERN) (2001)
KTeV (Fermilab)

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$$\boxed{\left(\varepsilon'/\varepsilon\right)=\left(\varepsilon'/\varepsilon\right)_{\text{SM}}+\left(\varepsilon'/\varepsilon\right)_{\text{NP}}}\quad\boxed{\left(\varepsilon'/\varepsilon\right)_{\text{NP}}=\kappa_{\varepsilon'}\cdot10^{-3}}$$

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

Waiting for NA62, KOPIO

SM:

$$\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = (8.4 \pm 1.0) \cdot 10^{-11}$$
$$\mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right) = (3.4 \pm 0.6) \cdot 10^{-11}$$

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

$K^+ \rightarrow \pi^+\nu\bar{\nu}$ vs $K_L \rightarrow \mu^+\mu^-$ (Z)

(BBCJ)

The fate of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ in LH scenarios depends on the sign of the interference between SD and LD part of the dispersive part of $K_L \rightarrow \mu^+\mu^-$

$\left\{\begin{array}{l}\text{D´Ambrosio, Portoles (9610244)}\\ \text{Gérard, Smith, Trine (0508189)}\end{array}\right\}$ ⇨ $\text{Br}\left(K^+ \rightarrow \pi^+\nu\bar{\nu}\right) \leq 2\text{Br}\left(K^+ \rightarrow \pi^+\nu\bar{\nu}\right)_{\text{SM}}$

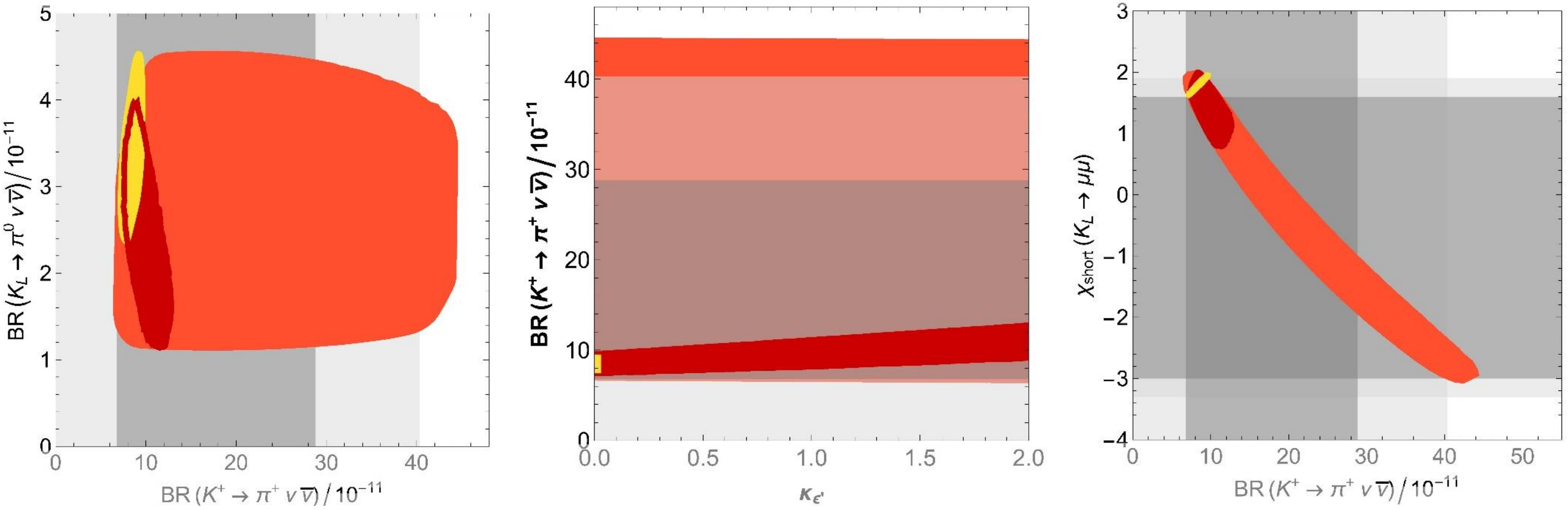
using

$\left\{\begin{array}{l}\text{Dumm, Pich (9801298)}\\ \text{Isidori, Unterdorfer (0311084)}\end{array}\right\}$ ⇨ $\text{Br}\left(K^+ \rightarrow \pi^+\nu\bar{\nu}\right) \leq \text{Br}\left(K^+ \rightarrow \pi^+\nu\bar{\nu}\right)_{\text{SM}}$

$K_L \rightarrow \mu^+\mu^-$ less relevant for RH scenarios because ε_K stronger (LR operators) ⇨ $\text{Br}\left(K^+ \rightarrow \pi^+\nu\bar{\nu}\right) \leq 1.5\,\text{Br}\left(K^+ \rightarrow \pi^+\nu\bar{\nu}\right)_{\text{SM}}$

General RH Scenario

(BBCJ)



🟥 **No ε_K**

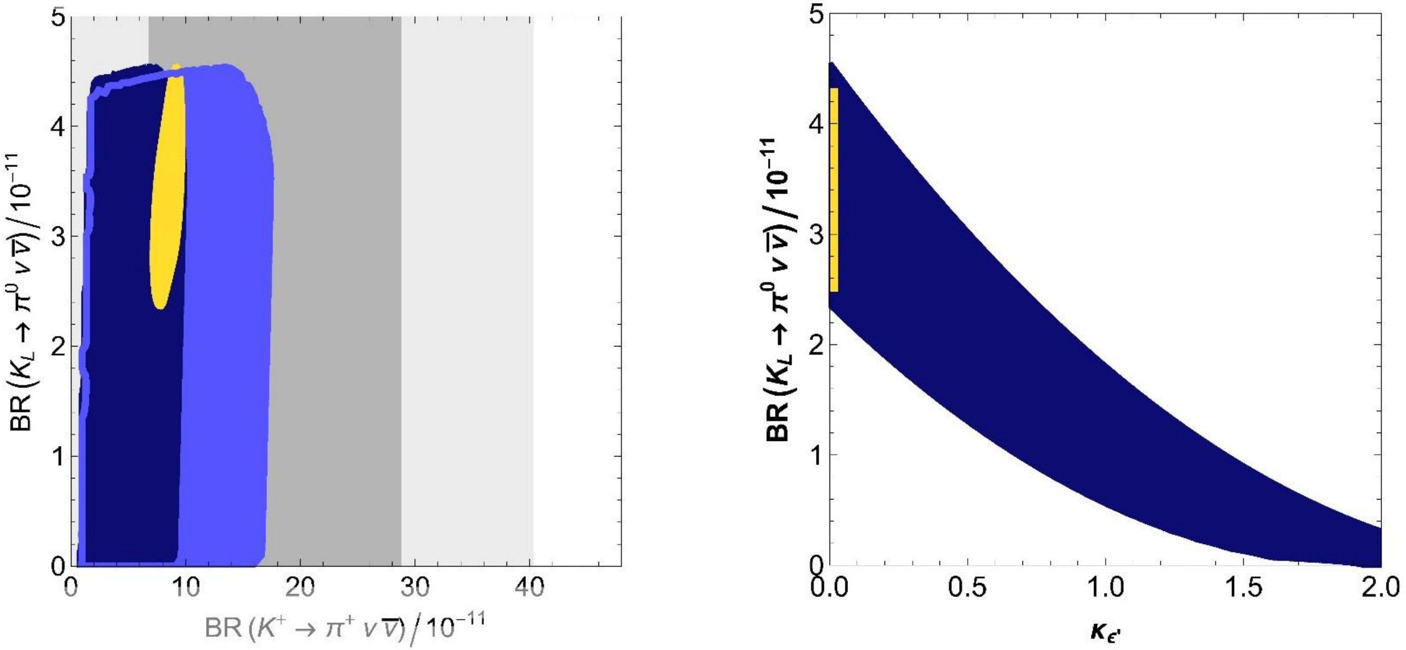
🟥 **ε_K**

🟨 **SM**

ε´/ε anomaly solved

General LH Scenario

(BBCJ)



🟦 **strong $K_L \to \mu^+\mu^-$**

🟦 **weak $K_L \to \mu^+\mu^-$**

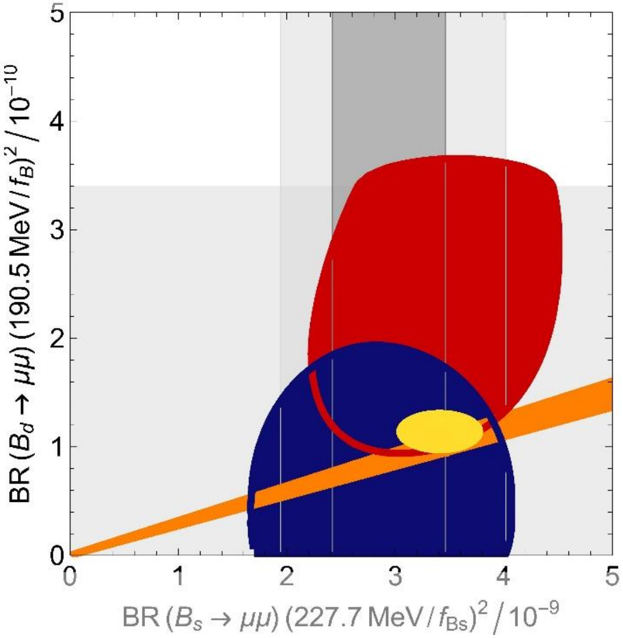
🟨 **SM**

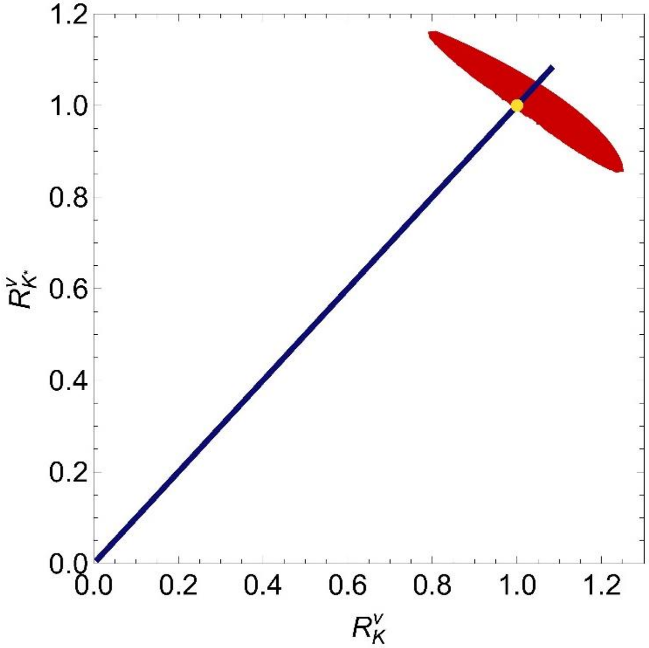
ε´/ε anomaly solved

LH vs. RH

🟦 **LH**

🟥 **RH**





🟨 **SM**

🟧 **MFV**

$\mathbf{B \to K(K^*)\nu\bar{\nu}}$

Final Messages on Z-Scenarios

1. ε'/ε -anomaly can easily be explained
2. $K_L \to \pi^0 \nu\bar{\nu}$ can only be suppressed unless both LH and RH couplings at work. AJB (1601.0005)
   Endo et al (1612.08839)
3. $K^+ \to \pi^+ \nu\bar{\nu}$ can be enhanced but only by a factor of 2
4. Interesting effects in $B_{s,d} \to \mu^+\mu^-$ (in particular in RH scenario)
5. Less interesting in $B \to K(K^*)\nu\bar{\nu}$
6. No explanation of $P_5', R_K, R_{K^*}, R(D), R(D^*)$ anomalies !

11 Vector-like Quark (VLQ) Models

Bobeth, AJB, Celis, Jung
1609.04783

(5)	$G_{SM} = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$	Ishikawa, Ligeti, Wise (1506.03484)
(2)	$G'_{SM}(S) = G_{SM} \otimes U(1)_{L_\mu - L_\tau}$	Altmannshofer et al. (1403.1269)
(4)	$G'_{SM}(\Phi) = G_{SM} \otimes U(1)_{L_\mu - L_\tau}$	BBCJ

		B-Physics Anomalies	ε'/ε - Anomaly	
G_{SM}	(Z, box, RG)	No	★	3 LH, 2 RH
$G'_{SM}(S)$	(Z', box)	★	No	1 LH, 1 RH
$G'_{SM}(\Phi)$	(Z, Z', box)	★	★	3 LH, 1 RH

RG ≡ Yukawa effects

box ≡ boxes with VLQ + Scalars

Combination of $\Delta F=2$ and $\Delta F=1$ processes can determine New Physics scale Λ_{NP}

(BBCJ)

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

$B_s\to\mu^+\mu^-$

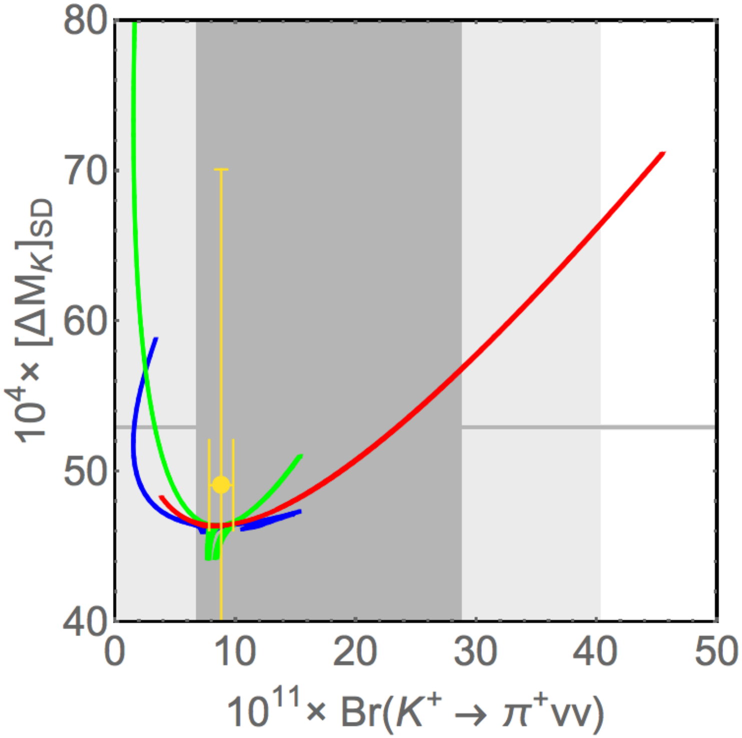
$$\frac{\sqrt{\Delta S_{NP}}}{\Delta Y_{NP}}=a\left[\frac{\Lambda_{NP}}{1\,\mathrm{TeV}}\right]$$

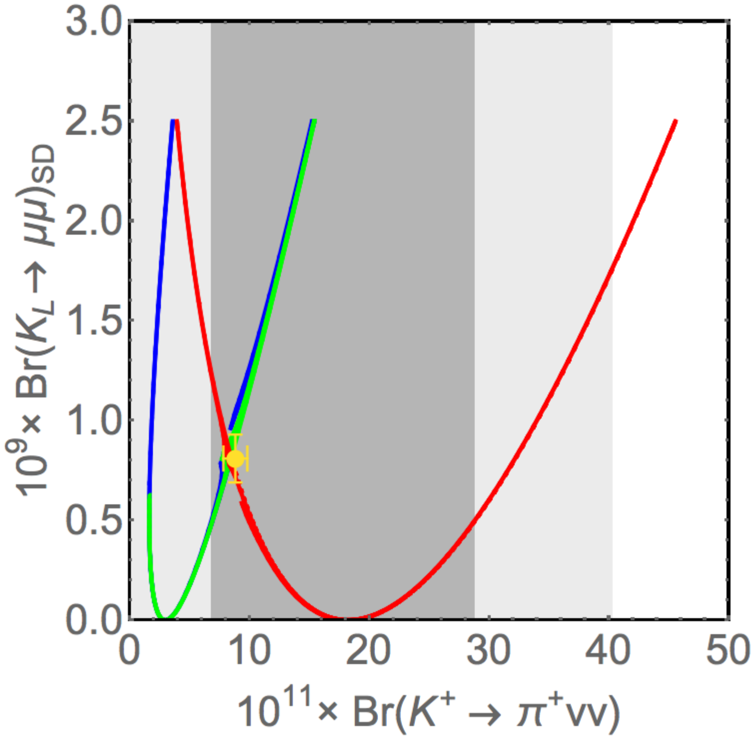
See also
AJB, De Fazio, Girrbach,
Carlucci, 1211.1237
(331 Models)

a: independent of CKM and Yukawa couplings
but dependent on quantum numbers of VLQs

$G'_{SM}(\Phi)$

ΔM_K strikes back ★





from Christoph Bobeth

Messages on VLQ Models

1. G_{SM} models:

Only Z

Similar to Z-models but more specific in LH-models

2. $G'_{SM}(S)$:

Only Z´

Interesting effects only in $\Delta F=2$,

$B \rightarrow K(K^*)\mu^+\mu^-$ (solve anomalies)

Fail with ε'/ε , $K \rightarrow \pi\nu\bar{\nu}$, $B_{s,d} \rightarrow \mu^+\mu^-$

3. $G'_{SM}(\Phi)$:

Z, Z´

Large effects in RH models in

$K^+ \rightarrow \pi^+\nu\bar{\nu}$, $B_{s,d} \rightarrow \mu^+\mu^-$, ΔM_K

smaller, but significant in LH.

ε'/ε easily solved.

$B \rightarrow K(K^*)\mu^+\mu^-$ anomalies only partly solved.

4. Large enhancement of $Br\left(B \rightarrow K(K^*)\nu\bar{\nu}\right)$ would require several VLQ representations at work.

General Z´ at Work

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

Here : ε'/ε, $K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$, ΔM_K

Q_6, Q_6' – QCD Penguin operators

Q_8, Q_8' – Electroweak Penguin operators

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 but can provide $\Delta(\varepsilon'/\varepsilon) > 0$ $$\left(\frac{\mathrm{Im}\,C_6}{\mathrm{Im}\,C_8} \right)^{NP} \approx 0(1)$$

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

Strategy (Z′)

AJB (1601.00005)

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

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

(Im)

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

$$0.1 \le \kappa_\varepsilon \le 0.4$$

(Im, Re)

ε_K more important than $K_L \to \mu^+\mu^-$ in Z′ models

Re and Im Parts: Z′ Couplings

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

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

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

Basic Structure of NP Contributions

AJB (1601.00005)

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

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

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

$$\text{Dominance of } Q_6\,(Q_6') \;\Rightarrow\; {\rm Im} \gg {\rm Re} \;\Rightarrow\; \{\Delta M_K^{\rm NP} < 0\}$$

(large)

$$\text{Dominance of } Q_8\,(Q_8') \;\Rightarrow\; {\rm Re} \gg {\rm Im} \;\Rightarrow\; \{\Delta M_K^{\rm NP} > 0\}$$

(small)

Distinction between these scenarios

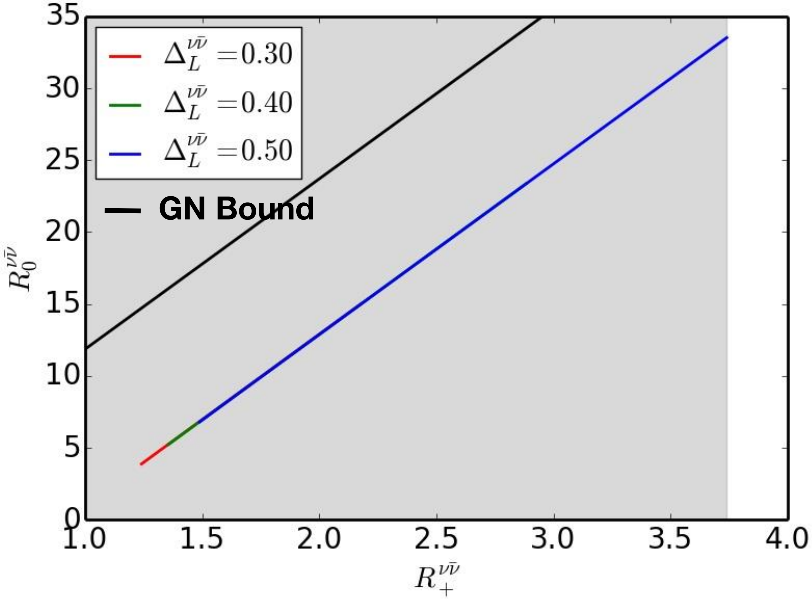
Main Message

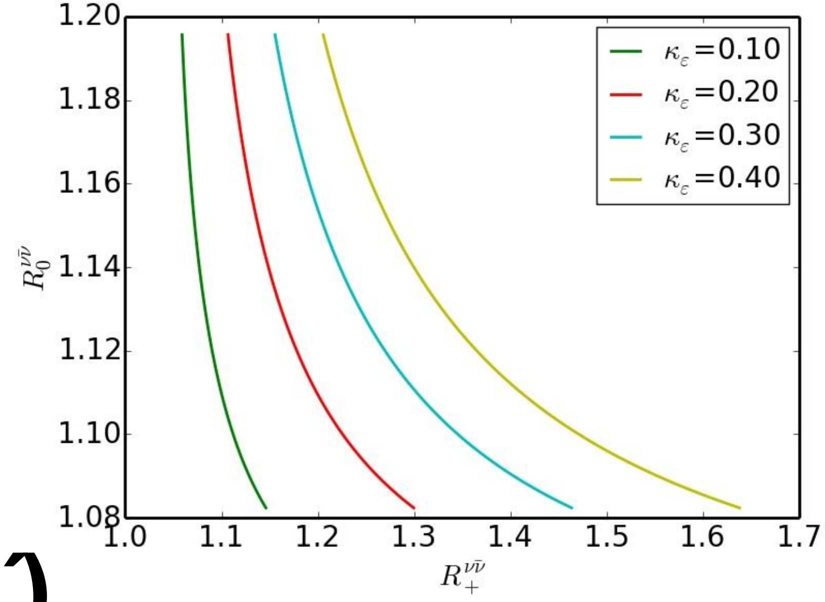
Correlation between ε'/ε and $K \rightarrow \pi\nu\bar{\nu}$ in Z´ scenarios depends on whether QCP Penguin (Q_6) or EWP (Q_8) dominates NP in $\boxed{\varepsilon'/\varepsilon}$

QCDP (Q_6)

$(0.5 < \kappa_{\varepsilon'} < 1.5)$

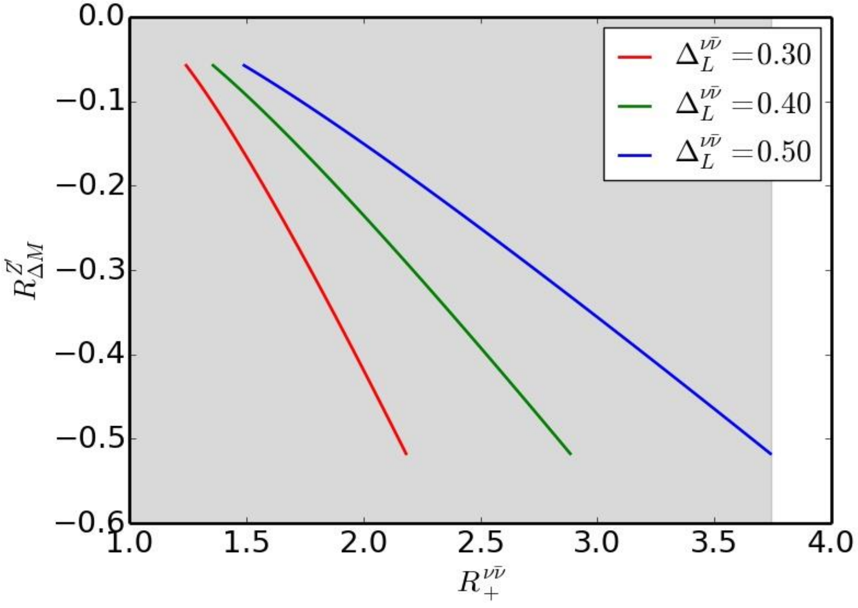
EWP (Q_8)





(Z′)

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

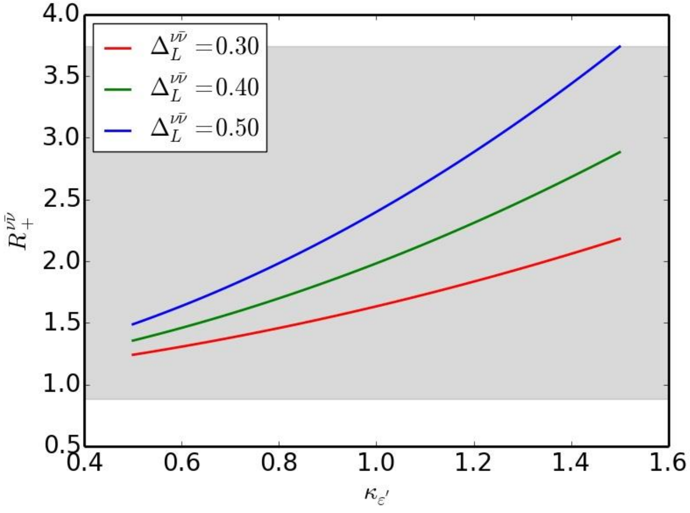


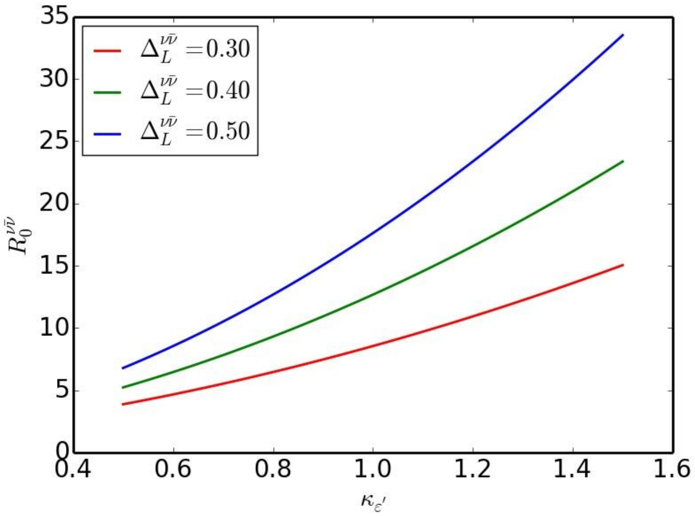
$$R_+^{\nu\bar{\nu}} = \frac{\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)}{\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)_{SM}}$$

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

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

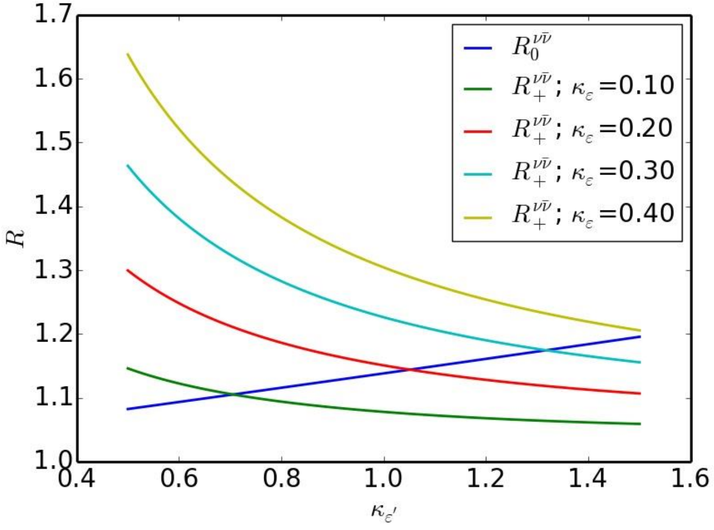
QCD Penguin (Q_6)





Electroweak Penguin (Q_8)

(Z´)



What about ΔI = 1/2 Rule?

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

Since 1955

Gell-Mann
Pais

1986, 2014

Large N including
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 $\mathrm{Re}A_2$

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

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

Main Messages

see ★

Exciting Times are just ahead of us !!!

Coming Years : Flavour Precision Era

LHC Upgrade
E = 14 TeV
(CERN)

Precision
$B_{d,s}$ – Meson Decays
LHCb, CMS
KEK (Japan)

★

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ (~ 10^{-10}) (CERN)

$K_L \rightarrow \pi^0 \nu\tilde{\nu}$ (~ $3 \cdot 10^{-11}$) J-PARC (Japan)

Lepton Flavour Violation

$\mu \rightarrow e\gamma$

$\mu \rightarrow eee$

$\tau \rightarrow \mu\gamma,\ \tau \rightarrow 3\mu$

Electric Dipole Moments

Improved Lattice Gauge Theory Calculations

Neutrinos

★

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

★

ε'/ε

$\Delta I = ½$ Rule, ΔM_K

2017-2025 : Expedition Attouniverse → Zeptouniverse

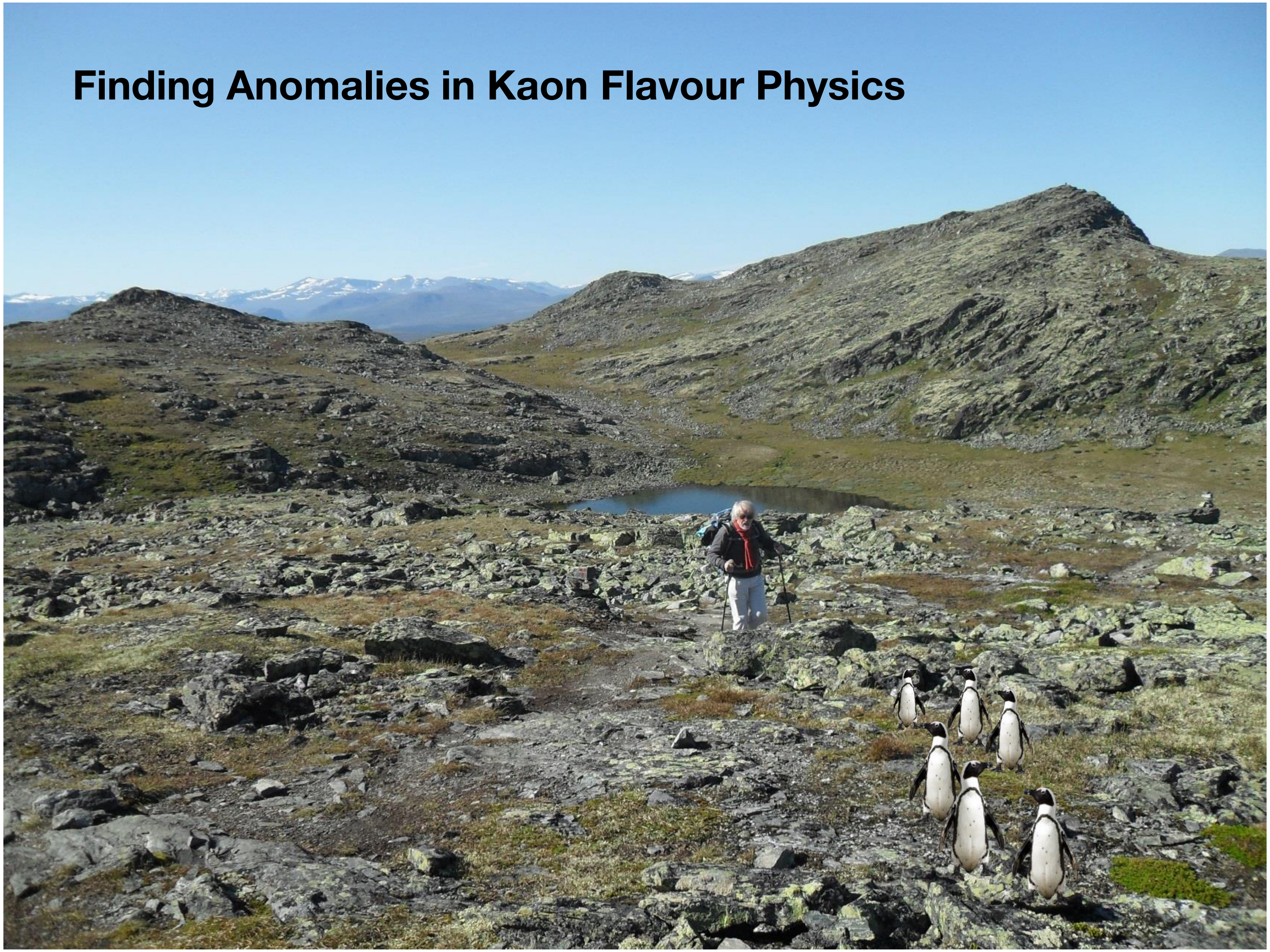
10^{-18}m → 10^{-21}m

The Return of Kaon Flavour Physics

Looking for Anomalies in Kaon Flavour Physics

Photo: Gurli Buras

Anomalies in Kaon Flavour Physics



Finding Anomalies in Kaon Flavour Physics

Photo: Gurli Buras

Backup

CKM Uncertainties

AJB, Buttazzo,
Girrbach-Noe,
Knegjens
1503.02693

$$\mathrm{Br}\left(K^+\to\pi^+\nu\bar{\nu}\right)=\left(8.39\pm0.30\right)\cdot10^{-11}\left[\frac{\left|V_{cb}\right|}{0.0407}\right]^{2.8}\left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

$$\mathrm{Br}\left(K_L\to\pi^0\nu\bar{\nu}\right)=\left(3.36\pm0.05\right)\cdot10^{-11}\left[\frac{\left|V_{ub}\right|}{3.88\cdot10^{-3}}\right]^{2}\left[\frac{\left|V_{cb}\right|}{0.0407}\right]^{2}\left[\frac{\sin\gamma}{\sin(73.2)}\right]^{2}$$

$$\mathrm{Br}\left(K^+\to\pi^+\nu\bar{\nu}\right)=\left(8.39\pm0.58\right)\cdot10^{-11}\left[\frac{\gamma}{73.2^\circ}\right]^{0.81}\left[\frac{\overline{\mathrm{Br}}\left(B_s\to\mu^+\mu^-\right)}{3.4\cdot10^{-9}}\right]^{1.42}\left[\frac{227.7}{F_{B_s}}\right]^{2.84}$$

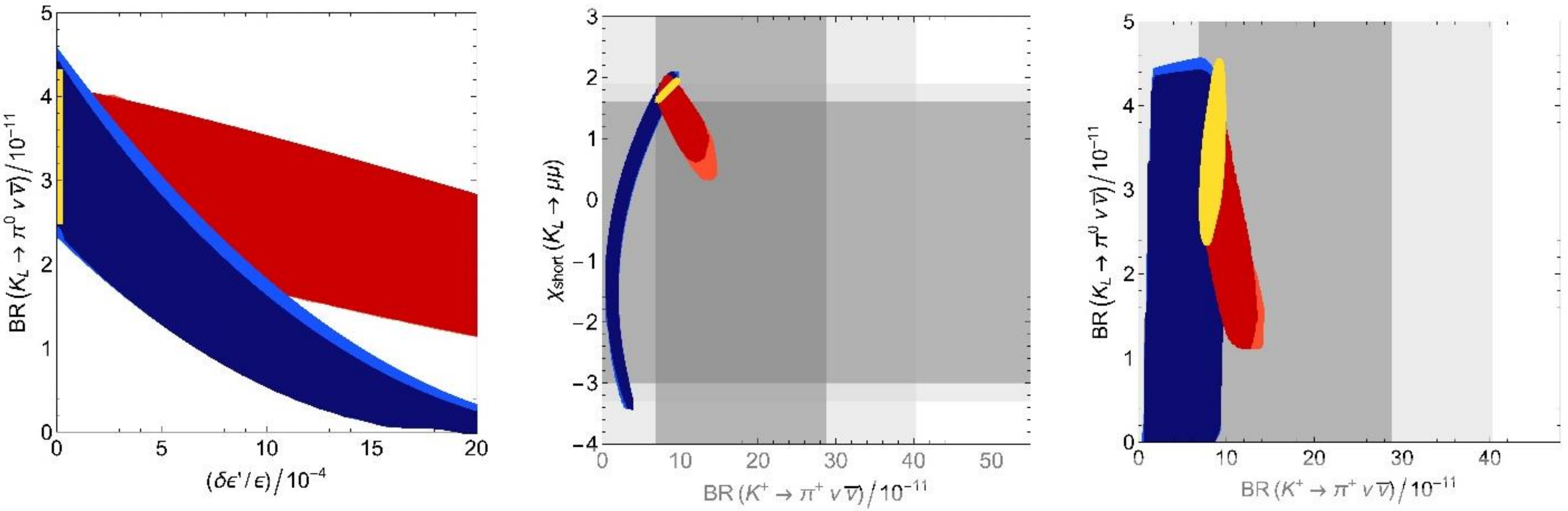
$$\mathrm{Br}\left(K^+\to\pi^+\nu\bar{\nu}\right)=\left(8.39\pm1.11\right)\cdot10^{-11}\left[\frac{\left|\varepsilon_K\right|}{2.23\cdot10^{-3}}\right]^{1.07}\left[\frac{\gamma}{73.2^\circ}\right]^{-0.11}\left[\frac{V_{ub}}{3.88\cdot10^{-3}}\right]^{-0.95}$$

$$\mathrm{Br}\left(K^+\to\pi^+\nu\bar{\nu}\right)=\left(8.4\pm1.0\right)\cdot10^{-11}$$

$$\mathrm{Br}\left(K_L\to\pi^0\nu\bar{\nu}\right)=\left(3.4\pm0.6\right)\cdot10^{-11}$$

Vector-Like Quark Models

(BBCJ)



🟦 **LH**

🟥 **RH**

10 TeV

🟨 **SM**

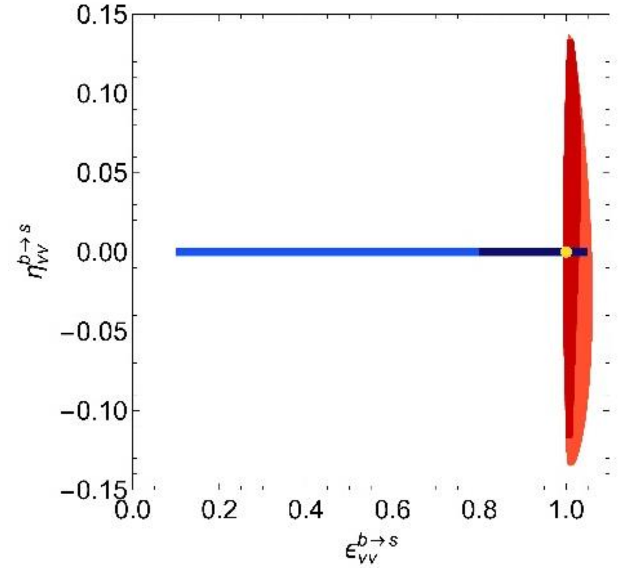
🟦 **LH**

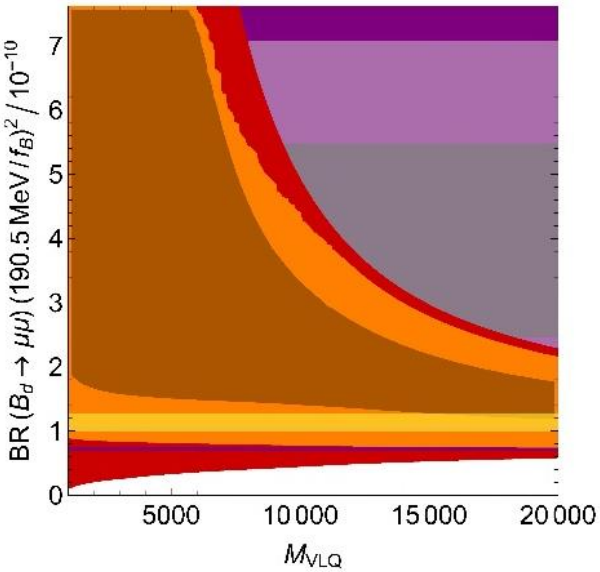
🟦 **RH**

1 TeV

Vector-Like Quark Models

(BBCJ)





Basic Questions in Flavour Physics

New Flavour violating CPV phases?

Flavour Conserving CPV phases?

Non-MFV Interactions?

Right-Handed Charged Currents?

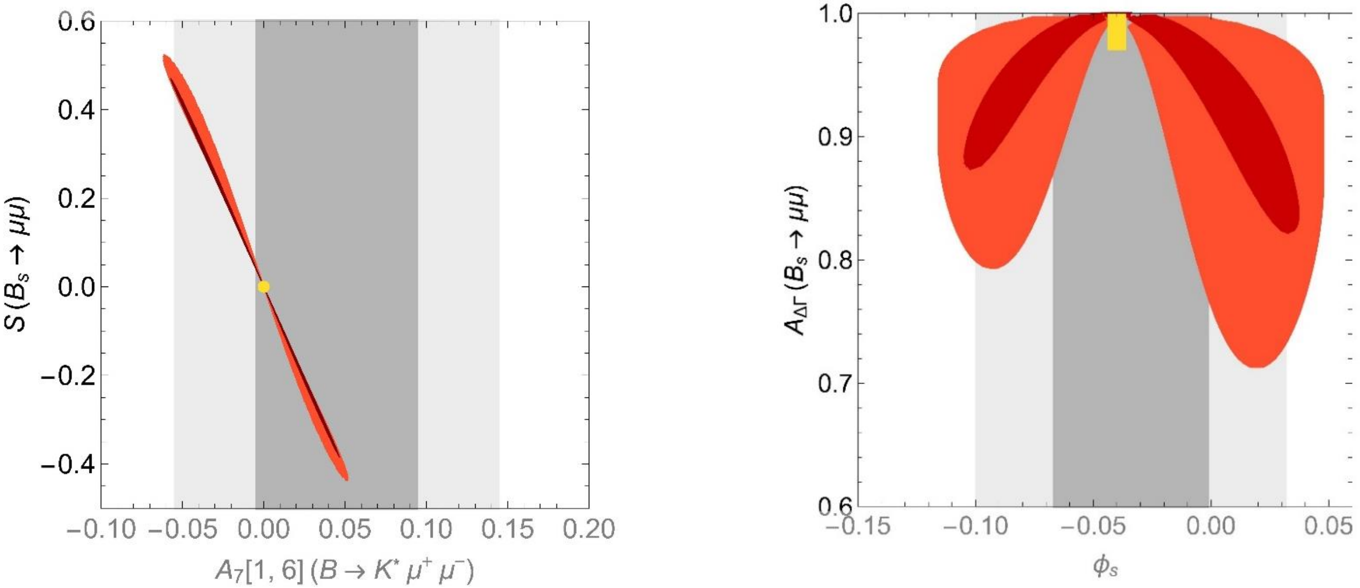
Scalars H^0, $H^\pm$ and related FCNC´s?

New Fermions? New Gauge Bosons?

★ How to explain dynamically 22 free Parameters in the Flavour Sector ?

General RH Scenario

(BBCJ)



🟥 No ε_K

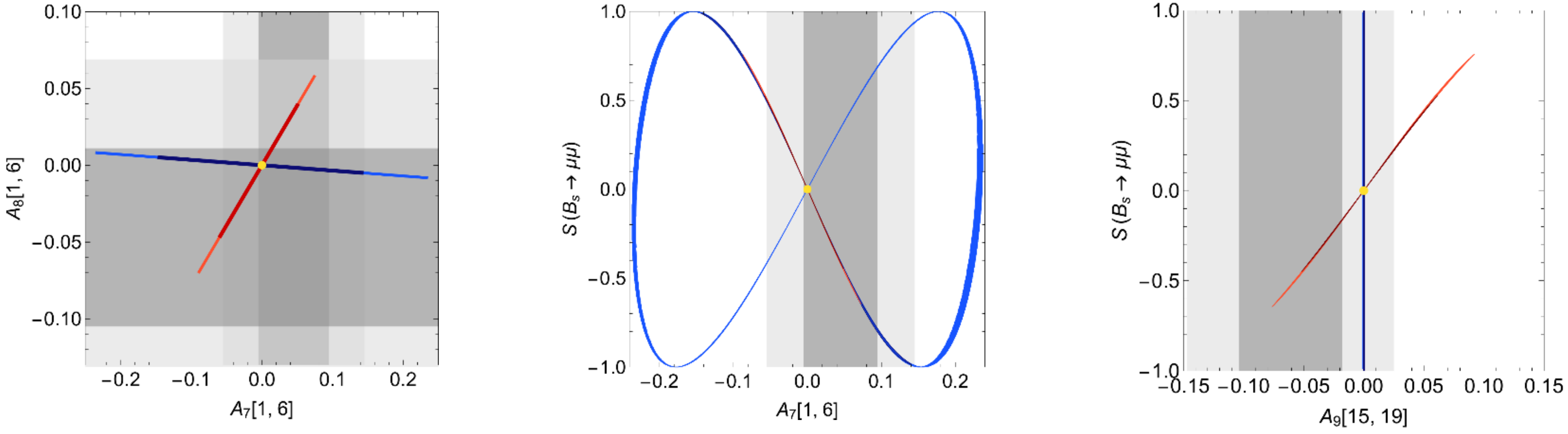
🟥 ε_K

🟨 SM

Vector-Like Quark Models

(G_{SM})

Large CP-Violating Effects



🟦 **LH**

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1 TeV