Z-Mediated New Physics and Vector-Like Quark Models

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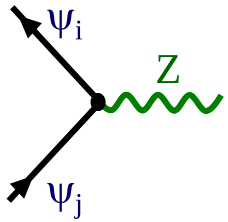
Overture

Z

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

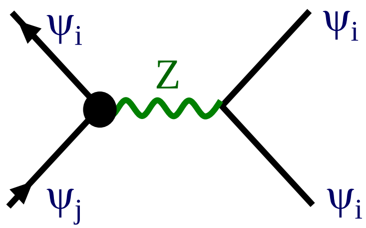
Z-Boson at Work (SM)



= 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

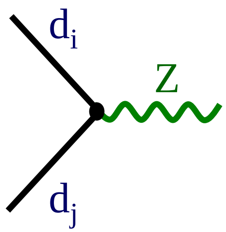
Govern most of rare K, $B_{s,d}$ decays

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

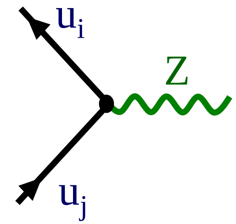
$B \to K(K^*)l^+l^-$, ε'/ε etc.

Z-Boson at Work (BSM)

FC couplings generated by some NP



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



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

Example:

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

$$L_{eff} = L_{SM} + \frac{1}{\Lambda^2}\sum_K C_K^{(6)} O_K^{(6)}$$ ← 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 17 min

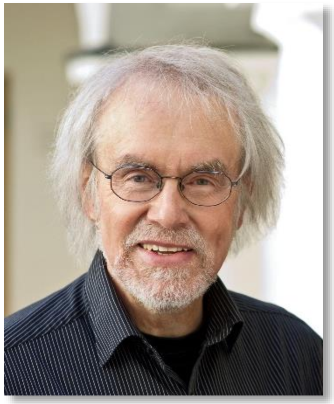
1. **What is the pattern of New Physics mediated by Z-boson?**

2. **How is it described by SMEFT?**

3. **What can models with Vector-like Quarks offer in this context?**

BBCJ Collaboration


Christoph Bobeth


AJB


Alejandro Celis


Martin Jung

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

Main Actors

SMEFT

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

(RH Scenario)

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

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

(LH Scenario)

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

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

Generated Z-Couplings:

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

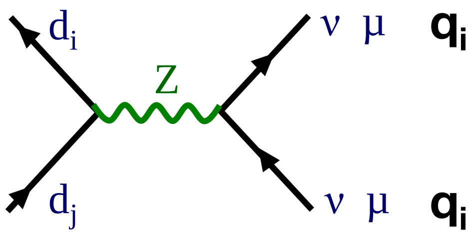
$$\left[\Delta^{d,u}_{L}(Z)\right]_{ij} = -\frac{g_Z}{2} v^2 \left[C^{(1)}_{Hq} \pm C^{(3)}_{Hq}\right]_{ij}$$

$\Lambda = \Lambda_{NP}$

$g_Z = \sqrt{g_1^2 + g_2^2}$

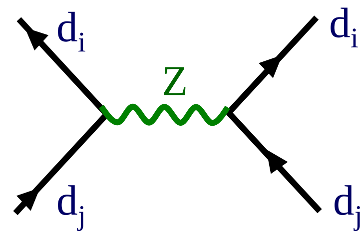
Simplified Z Scenarios

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)

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

ΔF=2 LR operators

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

$$0^{ij}_{LR,1} = \left[\bar{d}_i \gamma_\mu P_L d_j\right]\left[\bar{d}_i \gamma^\mu P_R d_j\right]$$

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

scale dependence

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

$$\lambda^{ij}_t = V^*_{ti} V_{tj}$$

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

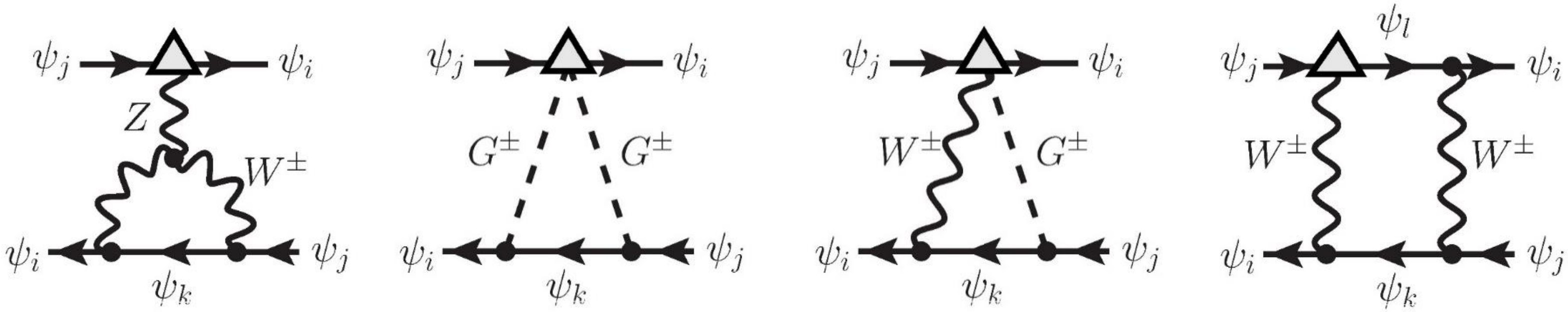
⇒ **Very strong constraint on rare decays!**

(in particular in K-system)

Lesson 2

(BBCJ)

μ_{EW} dependence cancelled by NLO Corrections



Corresponds to Z-penguin with $d^i\gamma^\mu P_L d^i$ 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 $\Delta F=2$ operators generated

But two couplings required to describe all effects.

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

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

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

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

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

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

(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

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

NA48 (CERN) (2001)
KTeV (Fermilab)

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

(RBC-UKQCD) (Lattice)

Use RBC-QCD:

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

(AJB, Gorbahn, Jamin, Jäger)

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

(Kitahara, Nierste, Tremper)

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

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

$$\left(\varepsilon'/\varepsilon\right) = \left(\varepsilon'/\varepsilon\right)_{SM} + \left(\varepsilon'/\varepsilon\right)_{NP}$$

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

$K^+ \to \pi^+ \nu\bar{\nu}$ 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 $|V_{ub}|, |V_{cb}|, \gamma$

SM:

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

Data

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

$K^+ \to \pi^+ \nu\bar{\nu}$ vs $K_L \to \mu^+\mu^-$

(BBCJ)

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

D´Ambrosio, Portoles (9610244)
Gérard, Smith, Trine (0508189)

⇒ $\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) \leq 2\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)_{SM}$

using

Dumm, Pich (9801298)
Isidori, Unterdorfer (0311084)

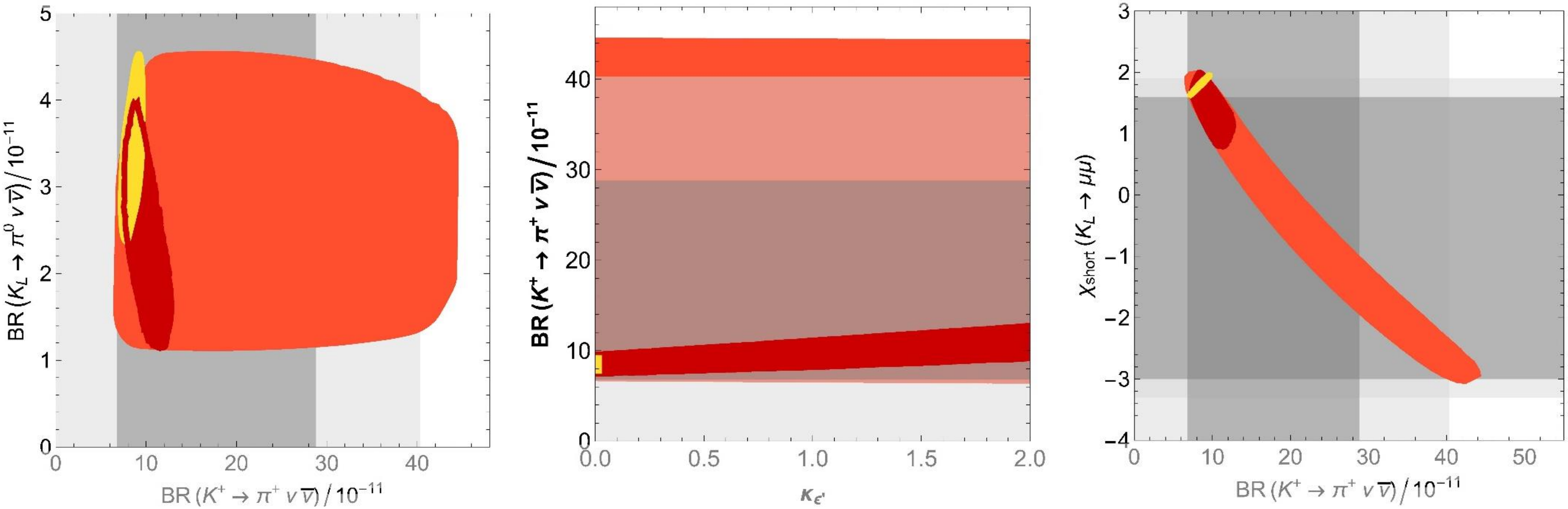
⇒ $\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) \leq \mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)_{SM}$

$K_L \to \mu^+\mu^-$ less relevant for RH scenarios because ε_K stronger (LR operators)

⇒ $\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) \leq 1.5\ \mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)_{SM}$

General RH Scenario

(BBCJ)



No ε_K

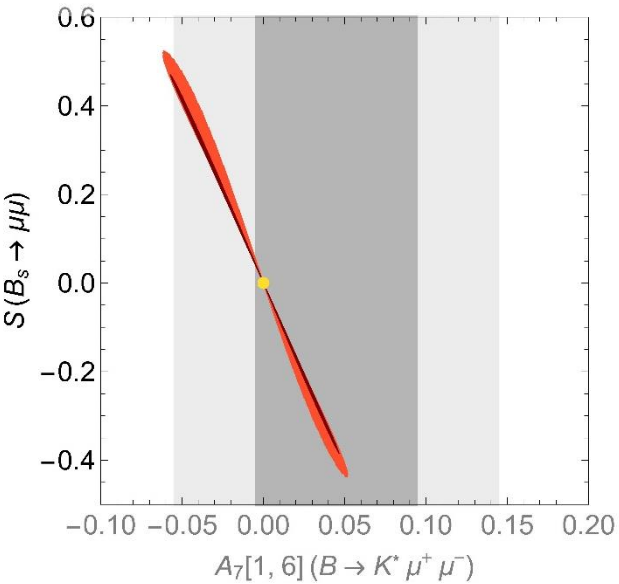
ε_K

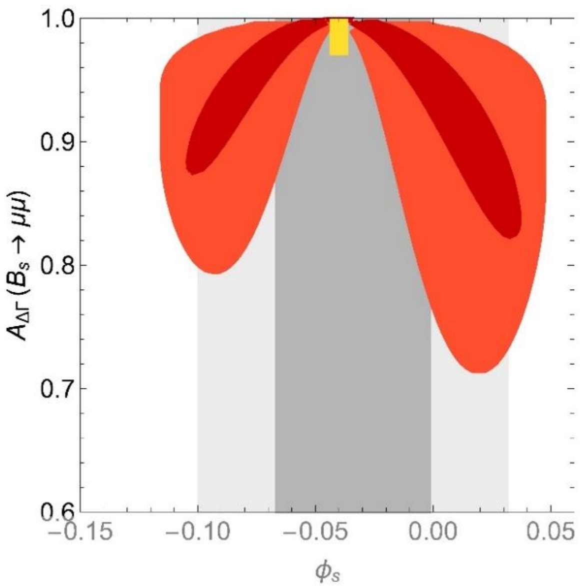
SM

ε'/ε anomaly solved

General RH Scenario

(BBCJ)





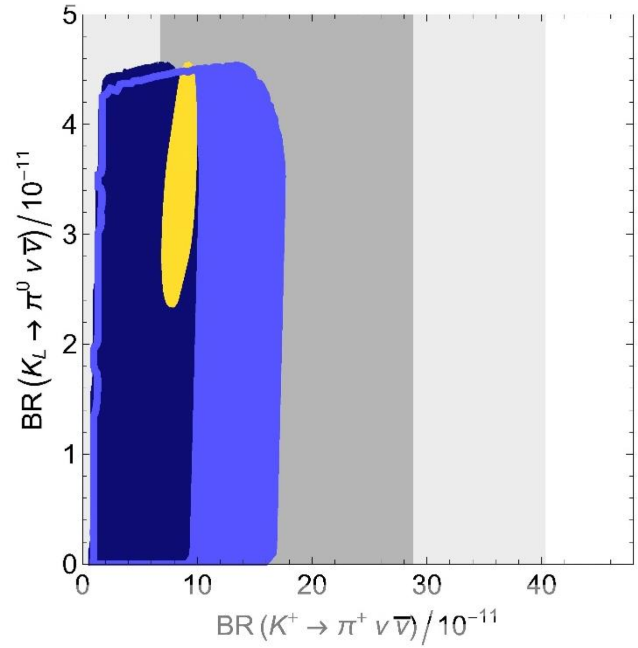
No ε_K

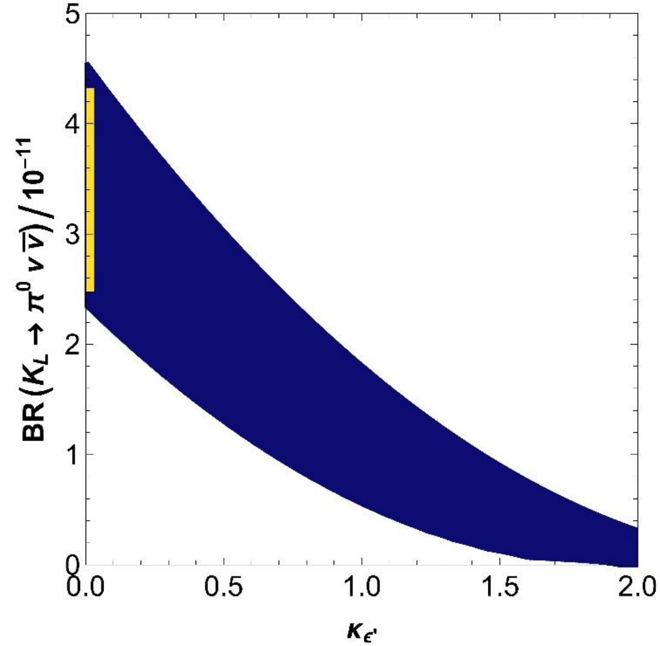
ε_K

SM

General LH Scenario

(BBCJ)





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

SM

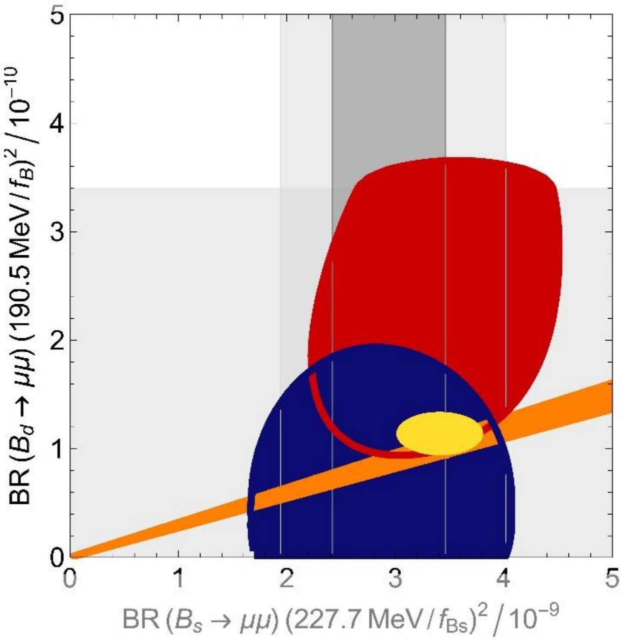
weak $K_L \to \mu^+\mu^-$

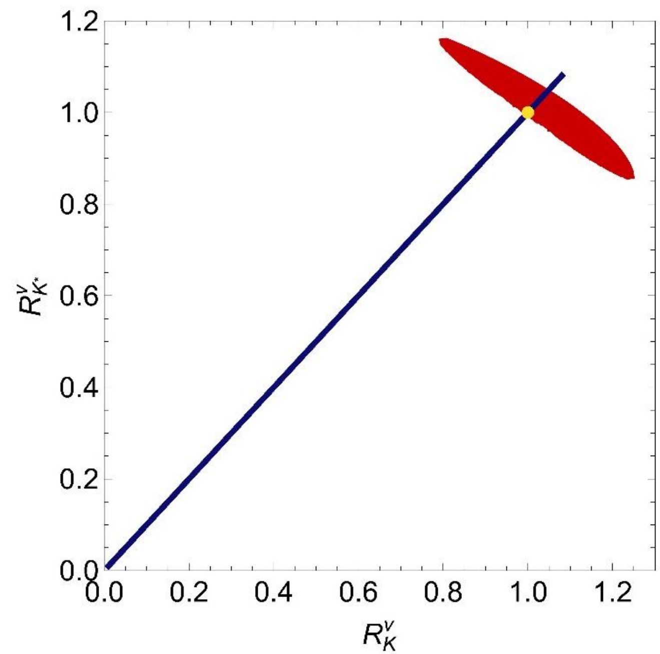
ε´/ε anomaly solved

LH vs. RH

LH

RH





SM

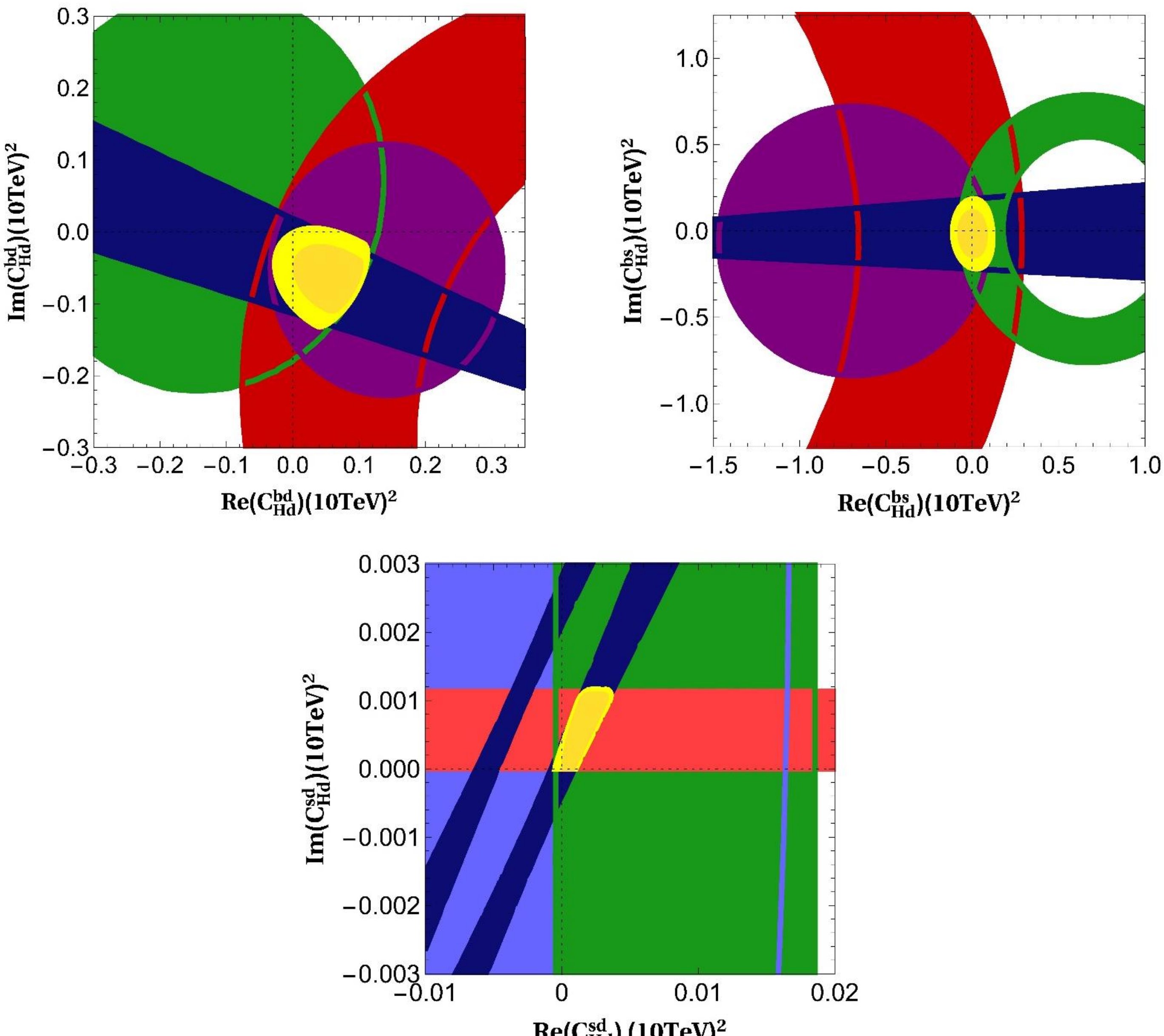
MFV

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

Final Messages on Z-Szenarios

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

Messages from Martin Jung



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

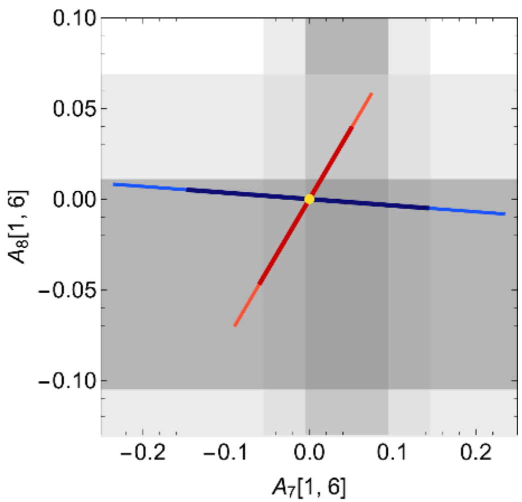
		B-Physics Anomalies	ε'/ε - Anomaly	
G_{SM}	(Z, box, RG)	No	★	3 LH, 2 RH
$G'_{SM}(S)$	(Z', box)	★	No	1 LH, 1 RH
$G'_{SM}(\Phi)$	(Z, Z', box)	★ (small)	★	3 LH, 1 RH

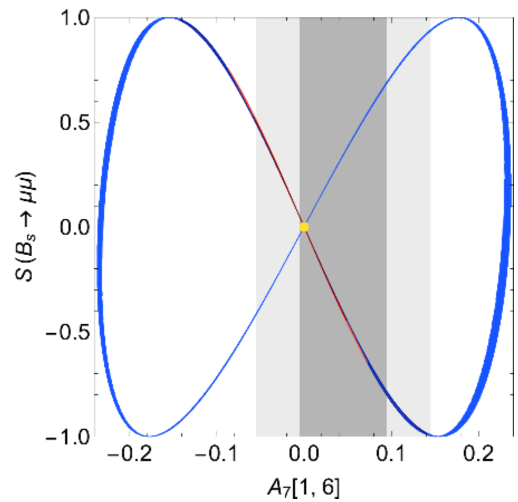
RG ≡ Yukawa effects   box ≡ boxes with VLQ + Scalars

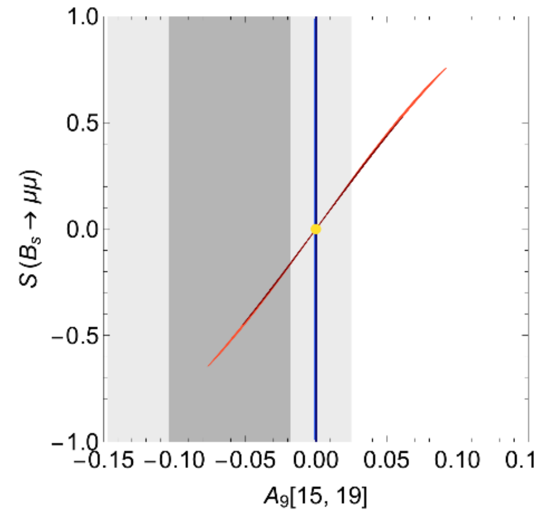
Vector-Like Quark Models

(G_{SM})

Large CP-Violating Effects







LH

RH

10 TeV

SM

LH

RH

1 TeV

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

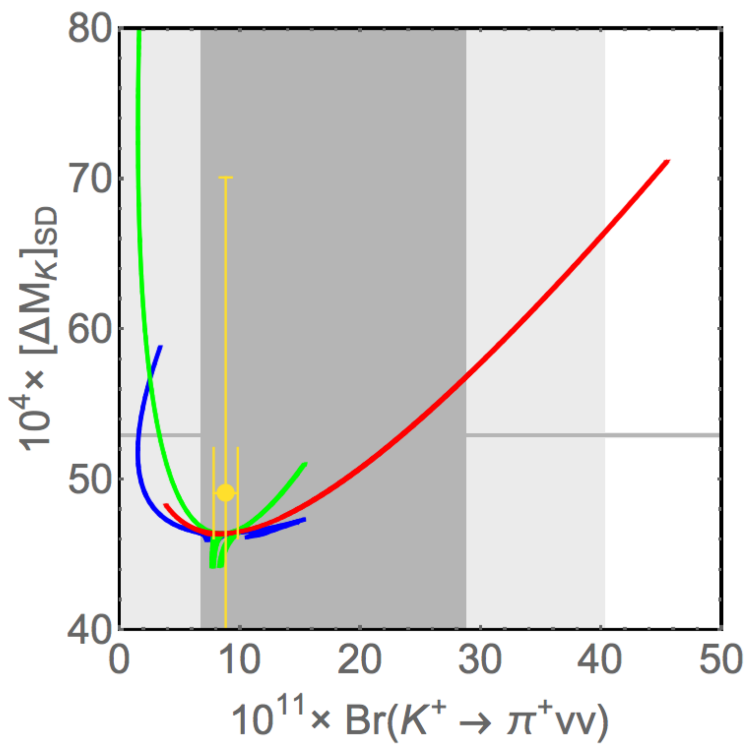
$B_s \to \mu^+\mu^-$

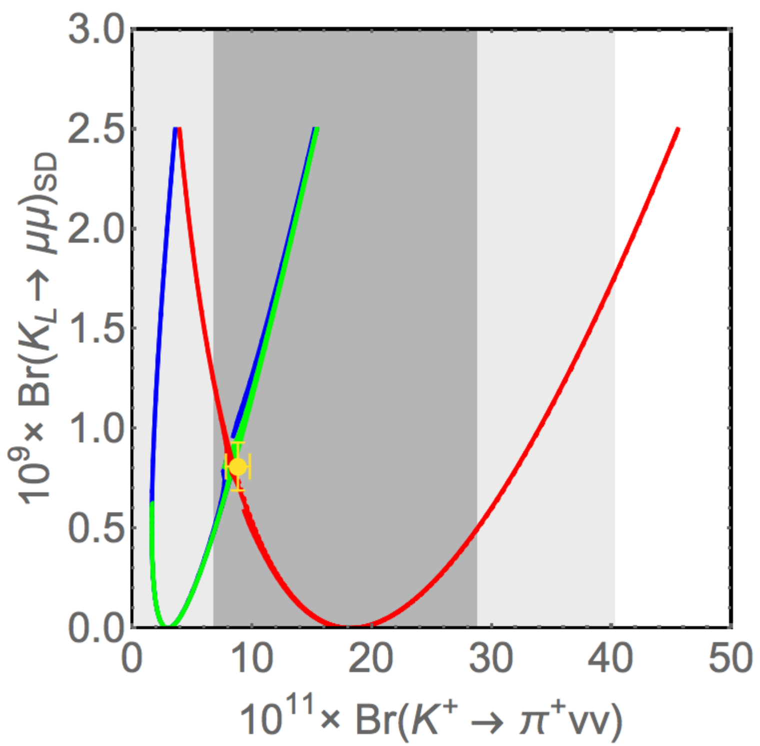
$$\frac{\sqrt{\Delta S_{NP}}}{\Delta Y_{NP}} = a\left[\frac{\Lambda_{NP}}{1\,\mathrm{TeV}}\right]$$

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

   Only Z

2. $G'_{SM}(S)$: Interesting effects only in $\Delta F=2$, $B \to K(K^*)\mu^+\mu^-$ (solve anomalies)
   Fail with ε'/ε, $K \to \pi\nu\bar{\nu}$, $B_{s,d} \to \mu^+\mu^-$

   Only Z´

3. $G'_{SM}(\Phi)$: Large effects in RH models in $K^+ \to \pi^+\nu\bar{\nu}$, $B_{s,d} \to \mu^+\mu^-$, ΔM_K
   smaller, but significant in LH.
   ε'/ε easily solved.
   $B \to K(K^*)\mu^+\mu^-$ anomalies only partly solved.

   Z, Z´

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

Main Messages

see ★

Exciting Times are just ahead of us !!!

Z still plays a role in searching for New Physics

Coming Years : Flavour Precision Era

LHC
Upgrade
E = 14 TeV
(CERN)

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

$K^+ \to \pi^+ \nu\bar{\nu}$ $(\sim 10^{-10})$ (CERN)

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

Lepton Flavour
Violation
$\mu \to e\gamma$
$\mu \to eee$
$\tau \to \mu\gamma,\ \tau \to 3\mu$

Electric
Dipole
Moments

Improved
Lattice
Gauge Theory
Calculations

Neutrinos

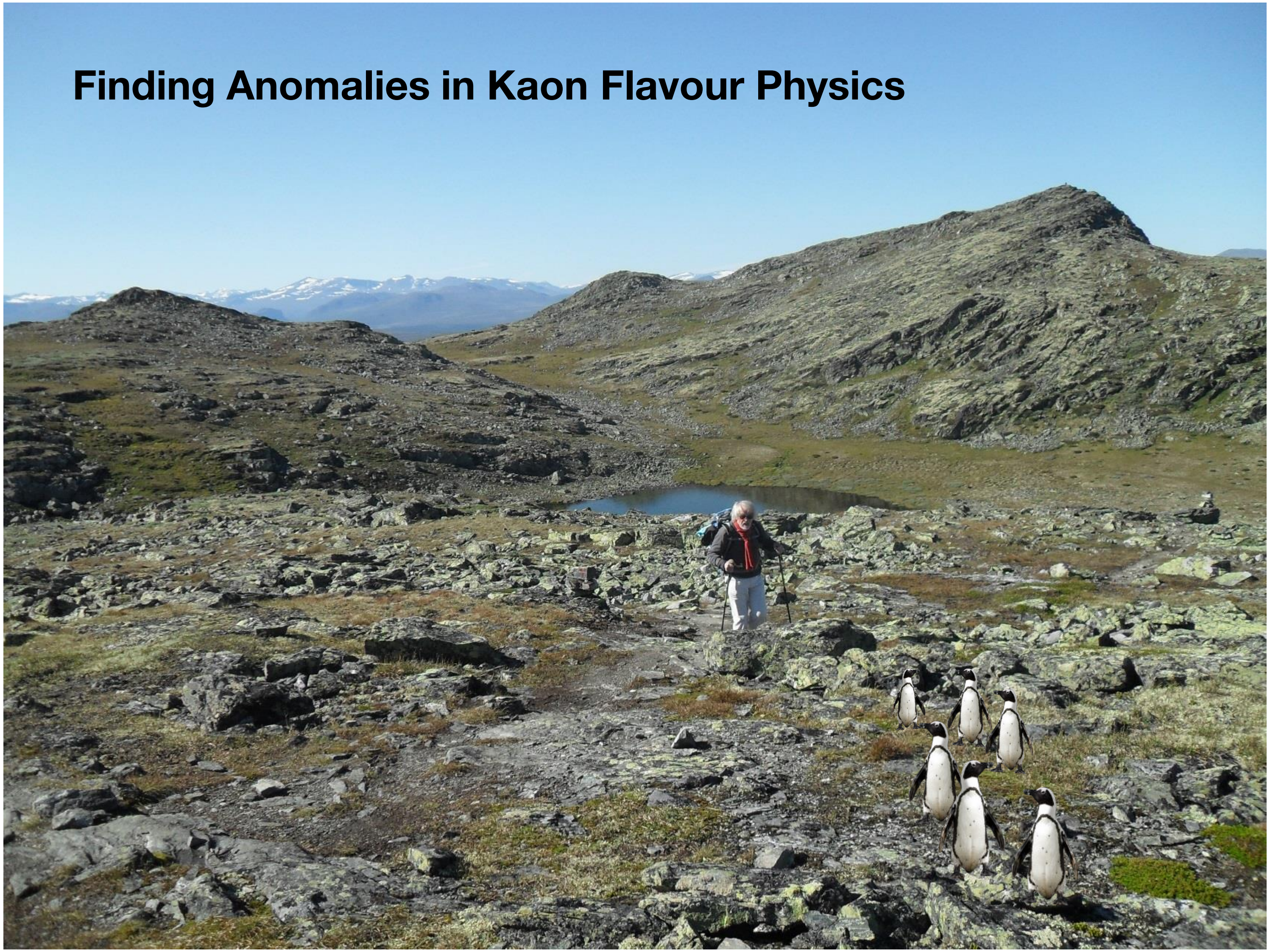
$(g\text{-}2)_\mu$

ε'/ε

2017-2025 : Expedition
Attouniverse → Zeptouniverse
10^{-18}m →10^{-21}m

The Return of Kaon Flavour Physics

Anomalies in Kaon Flavour Physics



Backup

CKM Uncertainties

AJB, Buttazzo, Girrbach-Noe, Knegjens 1503.02693

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

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

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

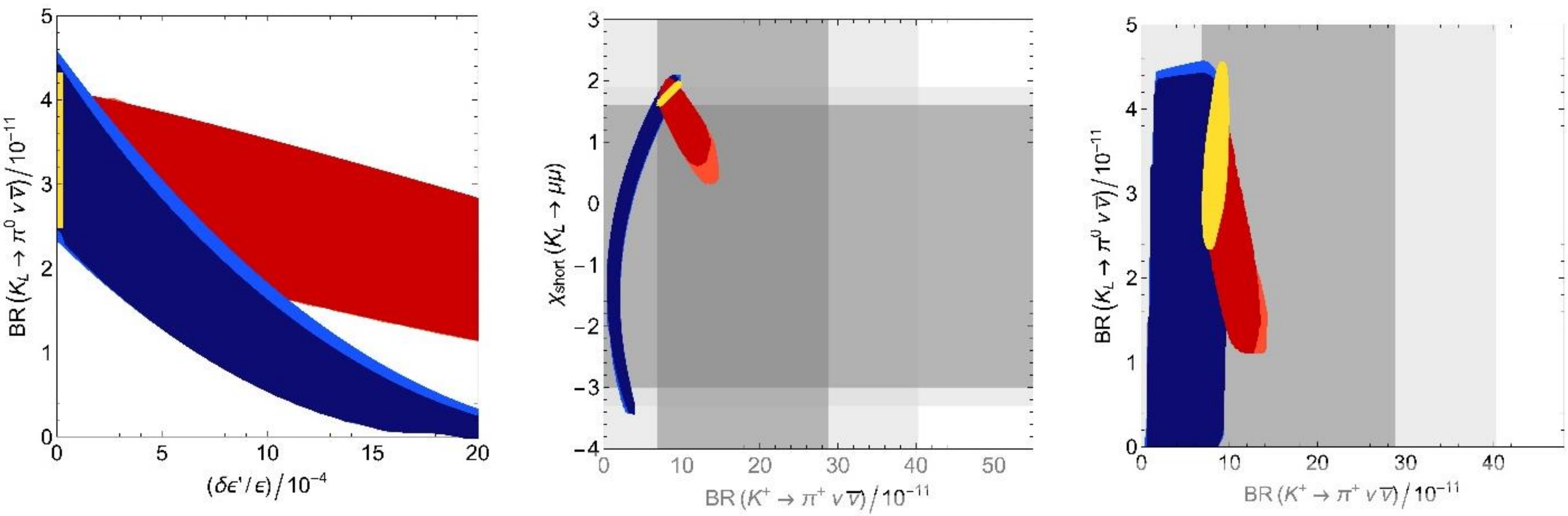
$$\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(8.39 \pm 1.11\right)\cdot 10^{-11}\left[\frac{|\varepsilon_K|}{2.23\cdot 10^{-3}}\right]^{1.07}\left[\frac{\gamma}{73.2^\circ}\right]^{-0.11}\left[\frac{V_{ub}}{3.88\cdot 10^{-3}}\right]^{-0.95}$$

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

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

Vector-Like Quark Models

(BBCJ)



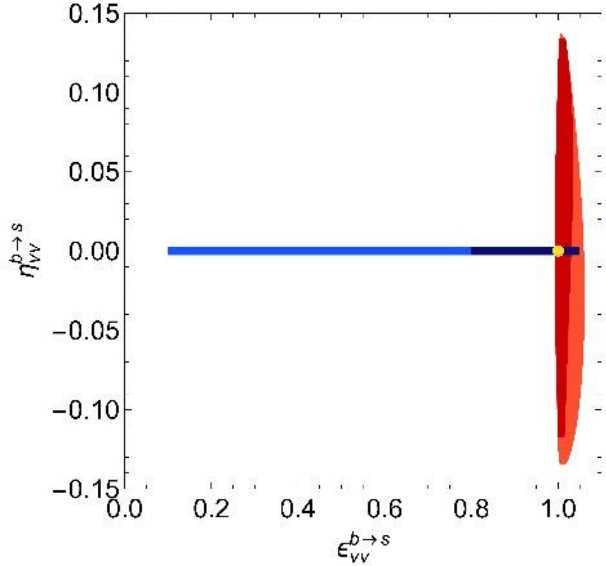
LH **SM** **LH**

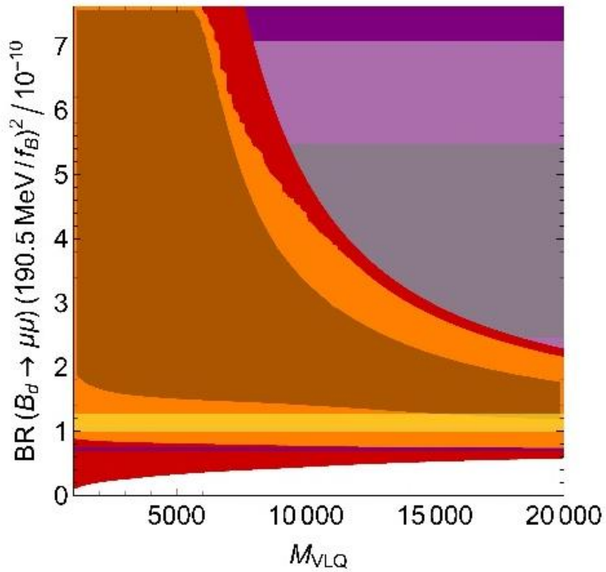
RH **RH**

10 TeV **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 ?

New Physics beyond the SM must exist !!!

**It is our duty to find it.
If not at the LHC then through high precision experiments.**

Quark Flavour Physics
Lepton Flavour Violation
EDMs + $(g-2)_{\mu,e}$

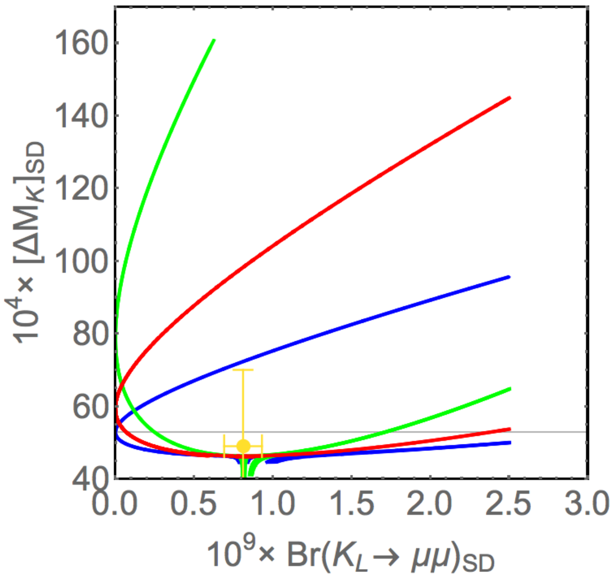
Most interesting effects in G_{SM} models:

General properties like in Z-models

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

- Large NP effects in ε'/ε, $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$
- Smaller but significant in $B_{s,d} \to \mu^+\mu^-$
- ε_K, $\Delta M_{s,d}$ tensions removed
- Combination of $\Delta F=2$ and $\Delta F=1$ observables allows to determine M_{VLQ} independently of Y_i

Patterns dependent on LH and RH currents


160
140
120
100
80
60
40
$10^4\times [\Delta M_K]_{SD}$
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$10^9\times Br(K_L\to \mu\mu)_{SD}$