Waiting for New Physics

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IAS TUM Institute for Advanced Study

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erc

A Journey to the Very Short Distance Scales:

1676 - 2046

Microuniverse	10^{-6}m	Bacteriology Microbiology
Nanouniverse	10^{-9}m	Nanoscience
Femtouniverse	10^{-15}m	Nuclear Physics Low Energy Elementary Particle Physics
Attouniverse	10^{-18}m	High Energy Particle Physics (present)
High Energy Proton-Proton Collisions at the LHC	$5\cdot10^{-20}$m	Frontiers of Elementary Particle Physics in 2010´s
High Precision Measurements of Rare Processes (Europe, Japan, USA)	10^{-21}m	Zeptouniverse

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 + $(g-2)_{\mu,e}$

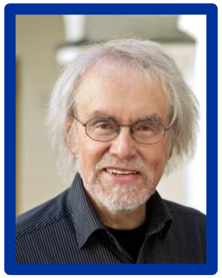
2015-2025 : Expedition

Attouniverse $\rightarrow$ Zeptouniverse

10^{-18}m $\rightarrow 10^{-21}$m

Advanced ERC Grant at the TUM Institute for Advanced Study
Zeptouniverse Base Camp

Present ERC Flavour Team


AJB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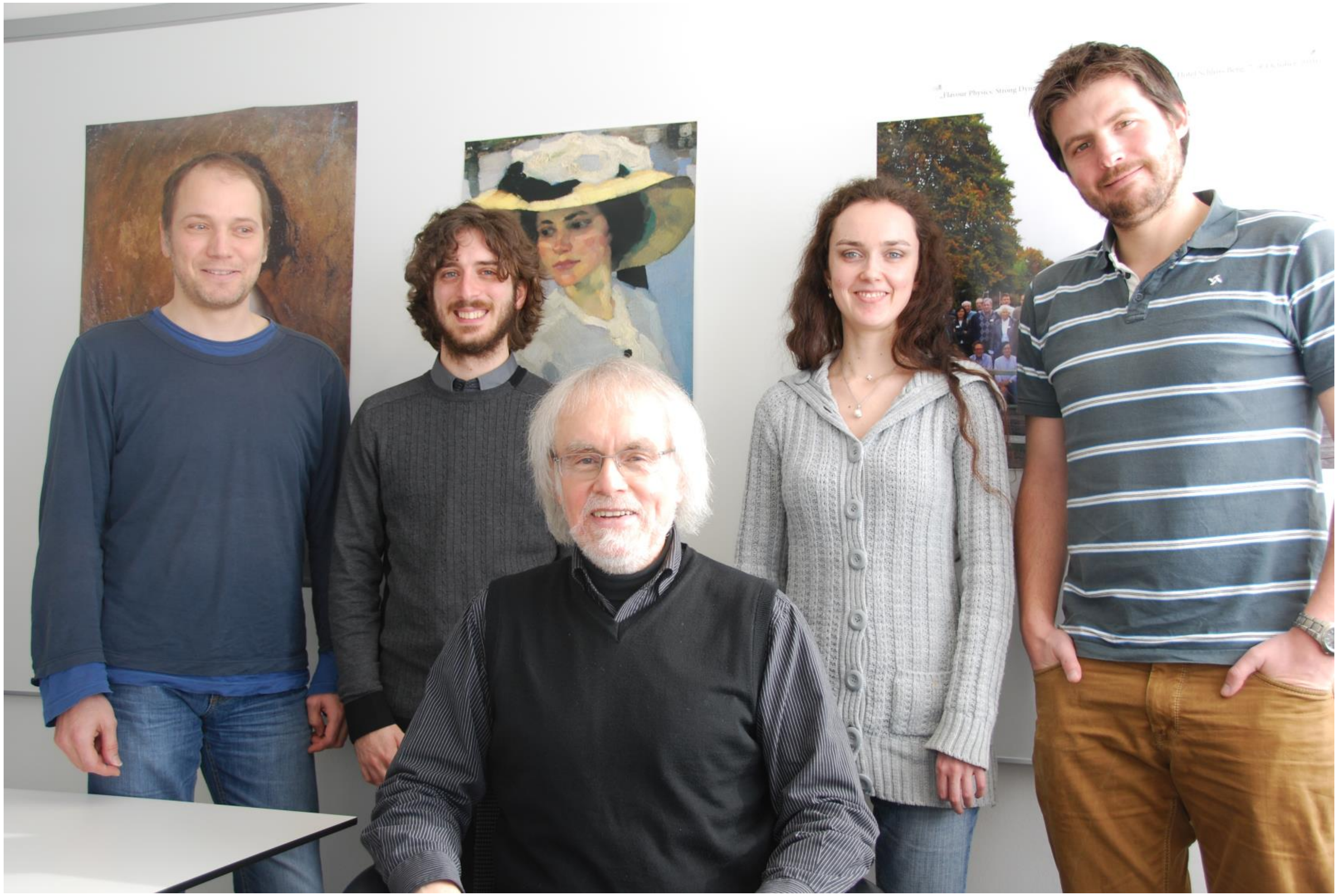
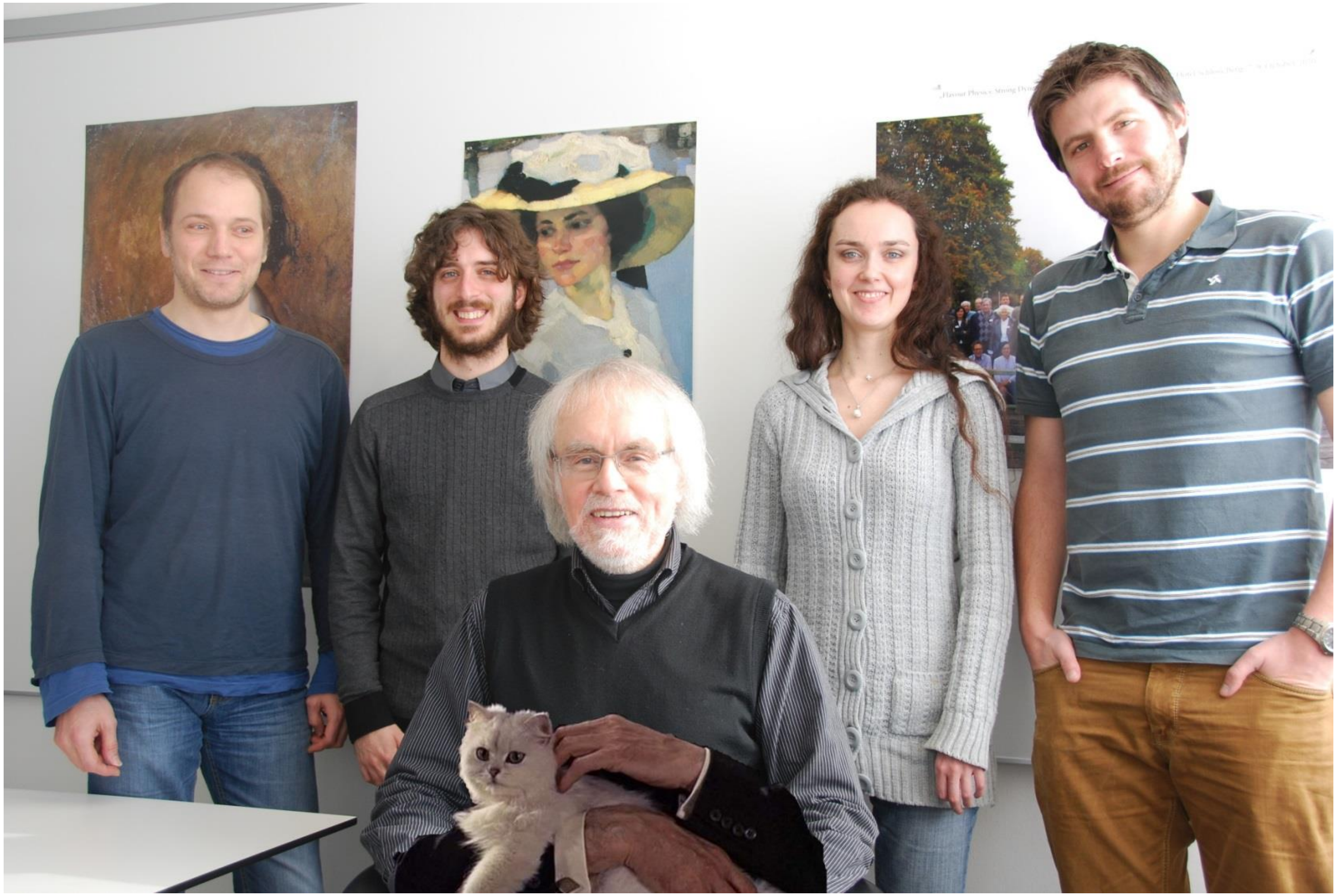
IAS Local Team



IAS Local Team



Study of Flavour Violation in NP Models

1. CMFV, MFV
2. $2HDM_{\overline{MFV}}$
3. LHT
4. 331
5. SUSY Flavour
6. SO(10)-GUT, $SSU(5)_{RN}$
7. $U(2)^3$
8. Z´
9. RHMFV
10. L-R Models
11. RS_c
12. Gauged Flavour Models

1012.1447
1204.5065

1306.3755

Towards Zeptouniverse In 12 Steps

1. CKM from Trees
2. Lattice
3. $\Delta F=2$ Observables
4. $B_{s,d} \to \mu^+\mu^-$
   $B_{s,d} \to \tau^+\tau^-$
5. $B^+ \to \tau^+\nu_\tau$
   $B \to D(D^*)\tau\nu$
6. $B \to X_s\gamma$
   $B \to K^*\gamma$
7. $B \to X_s l^+l^-$
   $B \to K^*(K) l^+l^-$
8. $K^+ \to \pi^+\nu\bar{\nu}$
   $K_L \to \pi^0\nu\bar{\nu}$
9. $B \to X_s\nu\bar{\nu}$
   $B \to K^*(K)\nu\bar{\nu}$
10. ε'/ε
11. Charm
    Top
12. LFV, EDMs
    $(g-2)_{\mu,e}$

Topics for Next 23 min

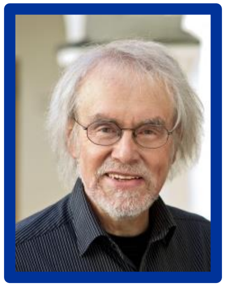
1. News on $B \to K^*(K)\nu\bar{\nu}$

2. News on $K^+ \to \pi^+\nu\bar{\nu},\ K_L \to \pi^0\nu\bar{\nu},\ \varepsilon'/\varepsilon$

1.

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

1409.4557


AJB


J.Girrbach-Noe


Christoph Niehoff


D.Straub

The Power of $B \to K^*(K)\nu\bar{\nu}$

1. Theoretically cleaner than $b \to s\mu^+\mu^-$ transitions (factorization exact, only formfactor uncertainties)
2. Sensitive to right-handed currents

Motivation for New *) Analysis

3. Improvement on formfactors (Lattice, LCSR) Bharucha Straub Zwicky
4. NLO Electroweak Corrections (Brod, Gorbahn, Stamou, 1009.0947)
5. New Data on $B \to K^*(K)l^+l^-$ put stronger constraints.

*) Altmannshofer, AJB, Straub, Wick (0902.0160)

Basic Structure

$$H_{eff}^{SM} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* C_L^{SM} O_L + h.c$$

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(C_L O_L + C_R O_R \right) + h.c$$

$$O_L \alpha \left(\bar{s} \gamma_\mu P_L b \right) \left(\bar{\nu} \gamma^\mu P_L \nu \right) \qquad O_R \alpha \left(\bar{s} \gamma_\mu P_R b \right) \left(\bar{\nu} \gamma^\mu P_L \nu \right)$$

$$\varepsilon = \frac{\sqrt{|C_L|^2 + |C_R|^2}}{|C_L^{SM}|} \qquad \eta = \frac{-\mathrm{Re}\left(C_L C_R^* \right)}{|C_L|^2 + |C_R|^2} \neq 0$$

only for
RH currents

$$R_K \neq R_{K^*}$$

$$R_K \equiv \frac{Br\left(B \to K \nu \bar{\nu}\right)}{Br^{SM}\left(B \to K \nu \bar{\nu}\right)} = \left(1 - 2\eta\right) \varepsilon^2$$

$$R_{K^*} \equiv \frac{Br\left(B \to K^* \nu \bar{\nu}\right)}{Br^{SM}\left(B \to K^* \nu \bar{\nu}\right)} = \left(1 + 1.34\eta\right) \varepsilon^2$$

⇒

Predictions for

$F_L(K^*)$ (Longitudinal polarization fraction)

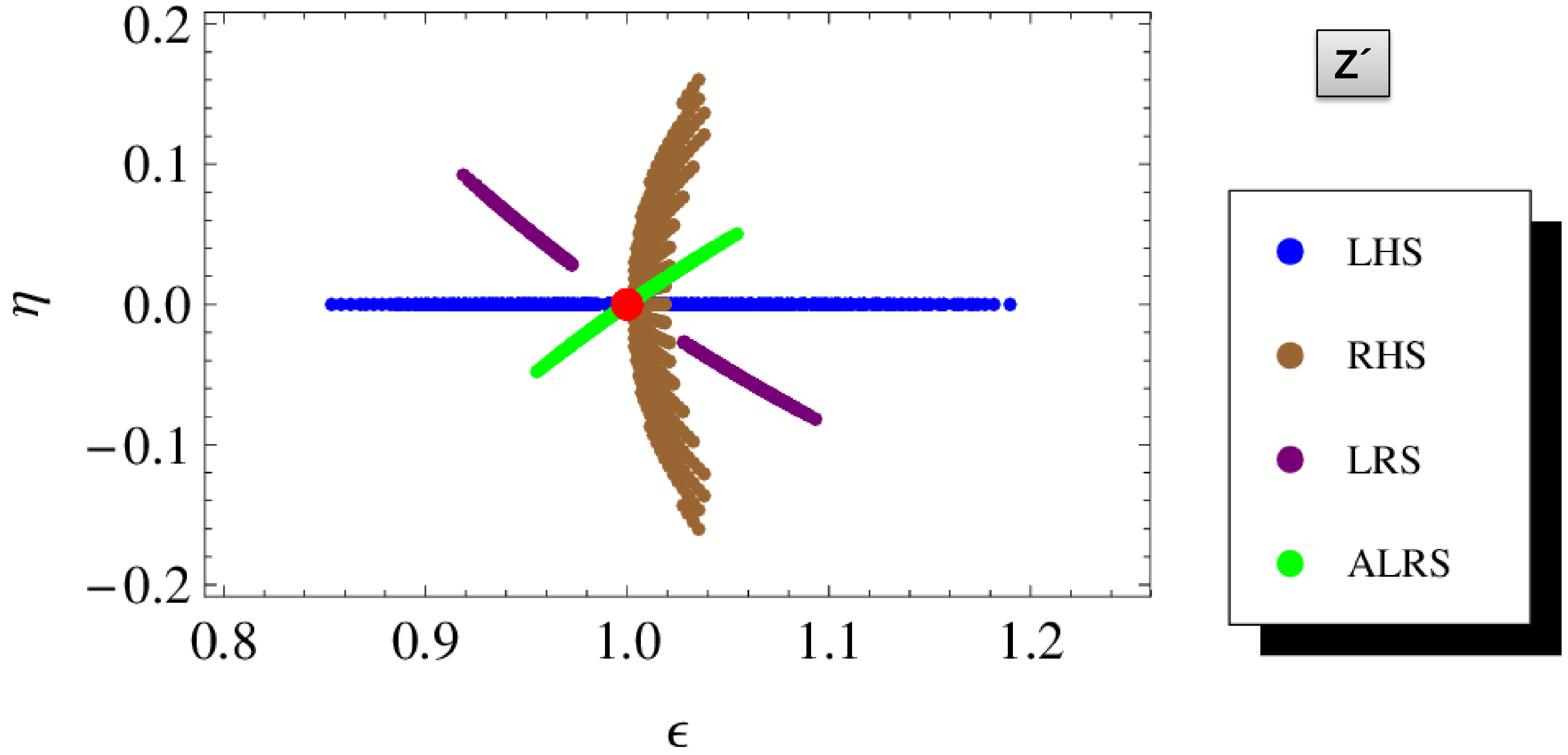
$Br\left(B \to X_s \nu \bar{\nu}\right)$

(ε, η) : Parameters for $b \to s\nu\bar{\nu}$ Transitions

$B \to K^* \nu\bar{\nu}$ $B \to K\nu\bar{\nu}$ $B \to X_s \nu\bar{\nu}$

1211.1896
AJB, de Fazio, Girrbach-Noe

Z´



Powerful tests of right-handed currents

Altmannshofer, AJB, Straub, Wick
0902.0160

Updated SM Prediction

Exp

$$Br\left(B^+ \to K^+ \nu\bar{\nu}\right)_{SM} = \left(3.98 \pm 0.43 \pm 0.19\right)\cdot 10^{-6} \qquad < 1.7\cdot 10^{-5}\,(\text{BaBar})$$

$$Br\left(B^0 \to K^{*0}\, \nu\bar{\nu}\right)_{SM} = \left(9.19 \pm 0.86 \pm 0.50\right)\cdot 10^{-6} \qquad < 5.5\cdot 10^{-5}\,(\text{Belle})$$

(formfactor) (CKM)*

Larger by 40% than previos estimates

<u>Better:</u>

$$Br\left(B^+ \to K^+ \nu\bar{\nu}\right) = \left[\frac{|V_{cb}|}{0.0409}\right]^2 \left(3.98 \pm 0.43\right)\cdot 10^{-6}$$

$$F_L = 0.47 \pm 0.03$$

$$Br\left(B^0 \to K^{*0}\, \nu\bar{\nu}\right) = \left|\frac{|V_{cb}|}{0.0409}\right|^2 \left(9.19 \pm 0.86\right)\cdot 10^{-6}$$

* $|V_{cb}| = 0.0409\ (10)$

Correlation with $b \to s l^+ l^-$

Neutrinos and charged leptons related by $SU(2)_L$ symmetry.

$$O_9^{(')} = \left(\bar{s}\gamma_\mu P_{L(R)} b\right)\left(\bar{l}\gamma^\mu l\right) \qquad O_{10}^{(')} = \left(\bar{s}\gamma_\mu P_{L(R)} b\right)\left(\bar{l}\gamma^\mu \gamma_5 l\right)$$

SM-EFT = OPE with dim = 6 invariant under SM gauge symmetry.

(1008.4884)
Grzadkowski et al.

Examples:

Z´

$$C_L^{NP} = \frac{C_9^{NP} - C_{10}^{NP}}{2} \qquad C_R = \frac{C_9' - C_{10}'}{2}$$

Z

$$C_L^{NP} = C_{10}^{NP} \qquad C_R = C_{10}'$$

Z, Z´ with Z-Z´ mixing

$$C_L^{NP} = \frac{C_9^{NP} - C_{10}^{NP}}{2} + 3\frac{\tilde{C}_Z}{2} \qquad C_R = \frac{C_9' - C_{10}'}{2} + 3\frac{\tilde{C}_Z'}{2}$$

$\tilde{C}_Z, \tilde{C}_Z'$ model dependent (Z-Z'mixing) (Example 331)

AJB + Fulvia + Jennifer (1311.6729)

Anomalies in $B \to K(K^*)\mu^+\mu^-$, $B_s \to \mu^+\mu^-$

Matias et al
Altmannshofer+Straub,
Jäger et al
Bobeth et al
Hiller+Schmaltz
Hurth et al

Reproduced with $C_9^{NP} \simeq -C_{10}^{NP} < 0$

$b \to s\nu\bar{\nu}$: $C_L = C_L^{SM} + C_L^{NP}$ $\quad C_L^{SM} < 0$

BGNS (1409.4557)

Z' : $C_L^{NP} = \frac{C_9^{NP} - C_{10}^{NP}}{2} \approx C_9^{NP}$ $\rightarrow$ enhancement of $B \to K(K^*)\nu\bar{\nu}$

Z : $C_L^{NP} = C_{10}^{NP} \approx -C_9^{NP}$ $\rightarrow$ suppression of $B \to K(K^*)\nu\bar{\nu}$

If $C_9^{NP} < 0 \qquad C_{10}^{NP} = 0$ $\Rightarrow$ enhancement by Z'
no effect from Z

See also leptoquark models: Hiller + Schmaltz, Fajfer et al.
Nardecchia et al.

3 Correlated Anomalies

(LHCb)

Matias et al
Altmannshofer+Straub,
Jäger et al
Bobeth et al
Hiller+Schmaltz
Hurth et al
Fajfer et al
Crivellin et al
Nardecchia et al

$$R_{K\mu\mu} = \frac{\mathrm{Br}\left(B^+ \to K^+\mu^+\mu^-\right)^{[15,22]}}{\mathrm{Br}\left(B^+ \to K^+\mu^+\mu^-\right)^{[15,22]}_{SM}} < 1$$

$$R_{K^*\mu\mu} = \frac{\mathrm{Br}\left(B^0 \to K^{*0}\mu^+\mu^-\right)^{[15,19]}}{\mathrm{Br}\left(B^0 \to K^{*0}\mu^+\mu^-\right)^{[15,19]}_{SM}} < 1$$

$$R_{\mu\mu} = \frac{\mathrm{Br}\left(B_s \to \mu^+\mu^-\right)}{\mathrm{Br}\left(B_s \to \mu^+\mu^-\right)_{SM}} < 1$$

Can be reproduced partly by Z but fully by Z´ with left-handed quark FCNC couplings.

$$C_9^{NP} \approx -C_{10}^{NP}$$

(V) (A) $\mu^+\mu^-$

$R_{K^*(K)} \equiv R_{K^*(K)\nu\bar{\nu}}$
can distinguish between
Z and Z´ solution

$$R_{K^*(K)}(Z') > 1$$
$$R_{K^*(K)}(Z) < 1$$

Z´ wins over Z

Z´ can reproduce all LHCb anomalies
including $\mathrm{Br}\left(B^+ \to K^+\mu^+\mu^-\right) < \mathrm{Br}\left(B^+ \to K^+e^+e^-\right)$

Z : $\left\{g_V^{\mu\mu}(Z)\,\mathrm{small}\right\} \;\to\; C_9^{NP}\,\mathrm{small}$

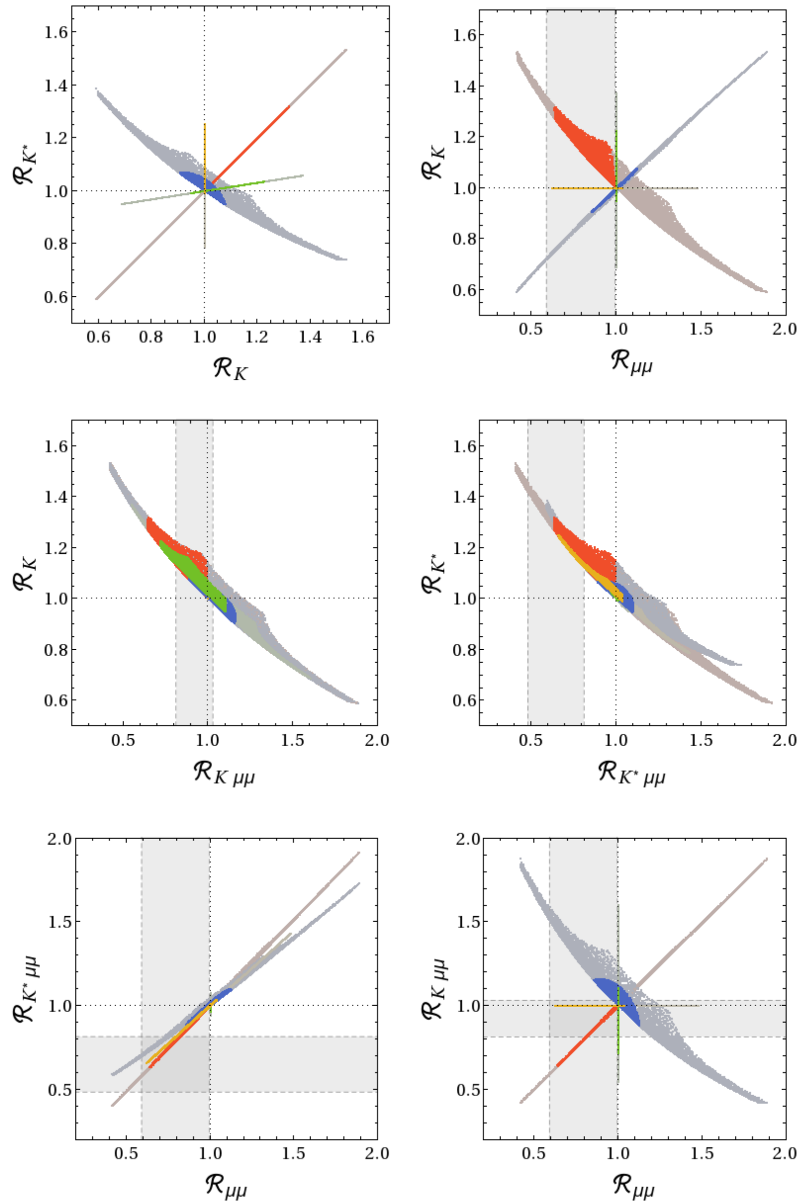
$$\mathrm{Br}\left(B^+ \to K^+\mu^+\mu^-\right) \simeq \mathrm{Br}\left(B^+ \to K^+e^+e^-\right)$$

$B \to K(K^*)\nu\bar{\nu}$, $B \to \mu^+\mu^-$, $B \to K(K^*)l^+l^-$

AJB
Girrbach-Noe
Niehoff
Straub

1409.4557

Z´



LHS

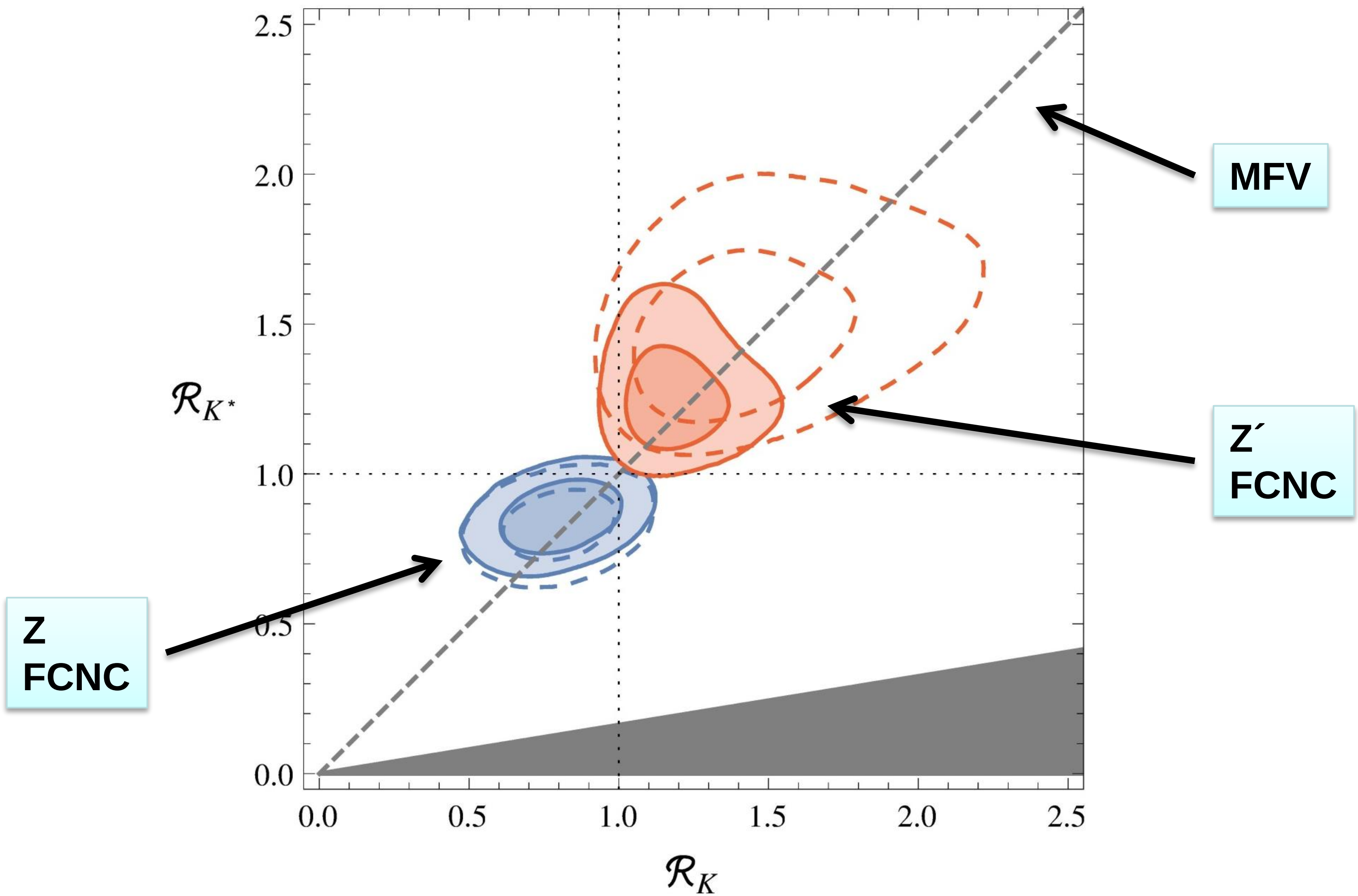
RHS

LRS

ALRS

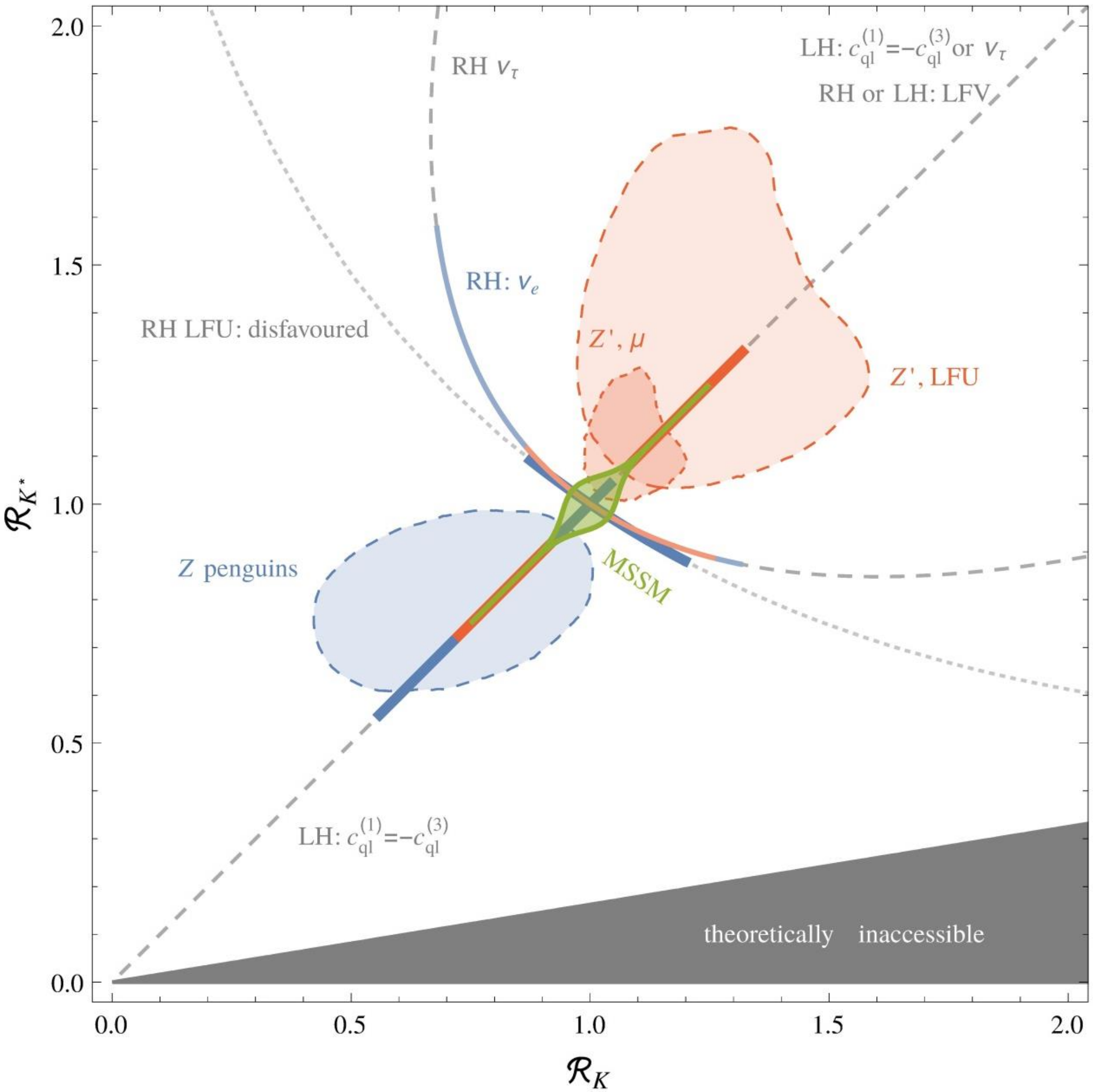
$B \to K(K^*)\nu\bar{\nu}$

BGNS 1409.4557



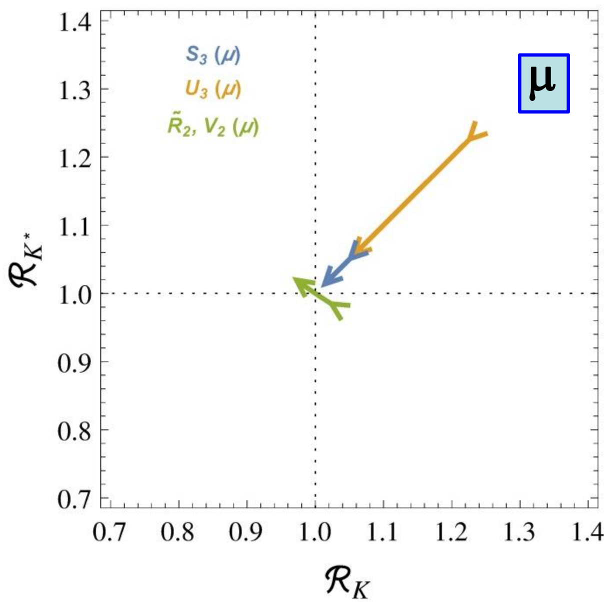
$B \to K(K^*)\nu\bar{\nu}$

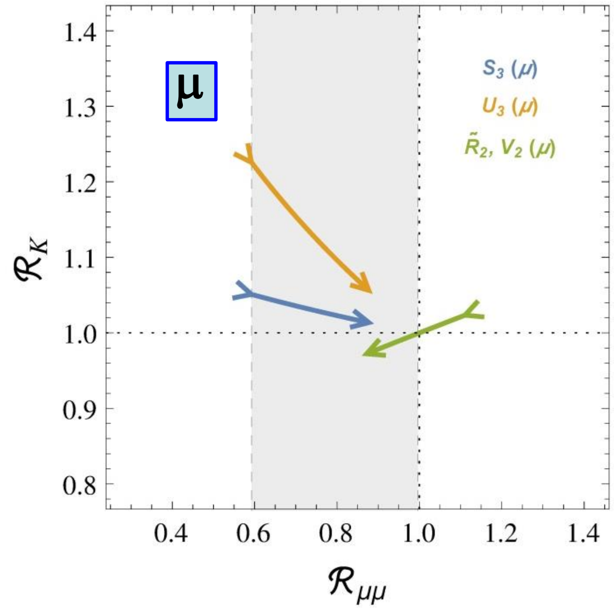
BGNS 1409.4557



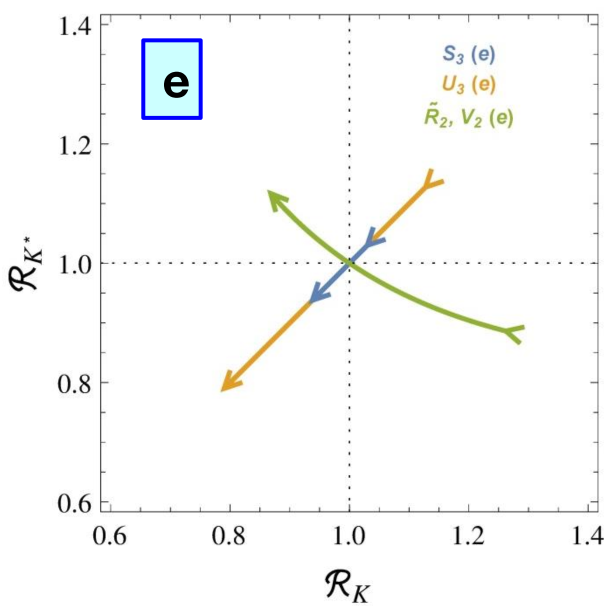
Leptoquarks at Work

BGNS, 1409.4557





Large effects for τ and S_1



	$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$			Spin
S_3	$\bar{3}$	3	1/3	0
$\bar{R}_2$	3	2	1/6	0
U_3	3	3	2/3	1
V_2	$\bar{3}$	2	5/6	1
S_1	$\bar{3}$	1	1/3	0

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

$R_K \neq R_{K^*}$ will be problematic for :

MFV, Z′ with LH couplings, certain PC scenarios
MSSM, $SU(2)_L$ singlet or triplets LQ, 331

NP
at most
$\pm$ 30%

$R_K \neq R_{K^*}$ can distinguish between Z and Z′ explanation of $b \to s l^+ l^-$ anomalies

$b \to s\mu^+\mu^-$ Data ⇒ max $\pm$ 60% NP for LFU
$\pm$ 20% if NP only in muons and ν_μ

In the presence of LF non-universality NP in $b \to s\nu\bar{\nu}$ could be LARGE ! Examples: NP only in (τ, ν_τ) Leptoquarks

Main message:

Finding small NP effects in $b \to s\mu^+\mu^-$ would not imply necessarily small NP effects in $b \to s\nu\bar{\nu}$

Intermezzo

Status of $B_{s,d} \to \mu^+\mu^-$

The first NLO QCD Calculation of $B_{s,d} \to \mu^+\mu^-$

Buchalla + AJB (Nucl. Phys. B400 (1993) 225)

- Reduction of μ_t dependence in $m_t(\mu_t)$
- Finding missing factor of two in branching ratios.

Values of $Br(B_s \to \mu^+\mu^-)_{SM} \sim 3-4\cdot 10^{-9}$

$Br(B_d \to \mu^+\mu^-)_{SM} \sim 1\cdot 10^{-10}$

were with us for last 15 years

Theoretical Improvements over years : Buchalla, AJB; Misiak, Urban (~1998)

September 2013

Recently: full NLO Electroweak, NNLO QCD

Bobeth, Gorbahn, Hermann, Misiak, Stamou, Steinhauser

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

$$Br(B_d \to \mu^+\mu^-)_{SM} = (1.06 \pm 0.09)\cdot 10^{-10}$$

Data (LHCb+CMS)

$$(2.8 \pm 0.7)\cdot 10^{-9}$$

$$\left(3.6^{+1.6}_{-1.4}\right)\cdot 10^{-10}$$

Warning: $|V_{cb}|$ ($|V_{ts}|$) Dependence

BGHMSS use $|V_{cb}|_{incl} \approx 42 \cdot 10^{-3}$ ⇒ $\overline{Br}(B_s \to \mu\bar{\mu})_{SM} = (3.65 \pm 0.23) \cdot 10^{-9}$

$(2.8 \pm 0.7) \cdot 10^{-9}$

(LHCb+CMS)

But for $|V_{cb}|_{excl} \simeq 39 \cdot 10^{-3}$ ⇒ $\overline{Br}(B_s \to \mu\bar{\mu})_{SM} \approx (3.1 \pm 0.2) \cdot 10^{-9}$

Different Route

(AJB 2003)
(Knegjens 2014)

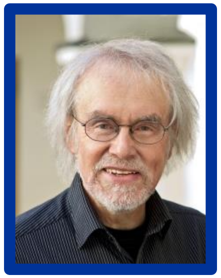
$$\overline{Br}(B_s \to \mu\bar{\mu})_{SM} = (3.5 \pm 0.2) \cdot 10^{-9} \left[\frac{(\Delta M_s)^{SM}}{(\Delta M_s)^{Data}}\right]\left[\frac{1.33}{\hat{B}_s}\right]$$

(No V_{cb}, F_{B_s} dependence)

↑ Lattice

2.

News on $K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^o \nu\bar{\nu}$, ε'/ε



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 $|V_{ub}|$, $|V_{cb}|$, γ

Data

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

General Properties

1. $K^+ \to \pi^+ \nu\bar{\nu}$ CP-conserving

2. $K_L \to \pi^o \nu\bar{\nu}$ CP-violating

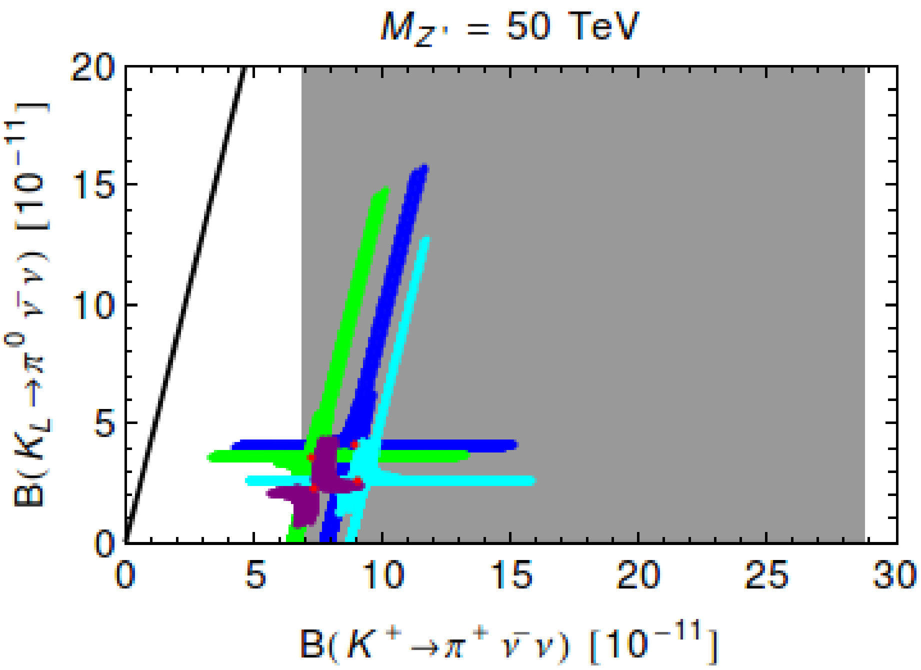
3. Both sensitive to New Physics (NP)
   $K^+ \to \pi^+ \nu\bar{\nu}$ bounded by $K_L \to \mu^+\mu^-$
   $K_L \to \pi^0 \nu\bar{\nu}$ bounded by ε'/ε

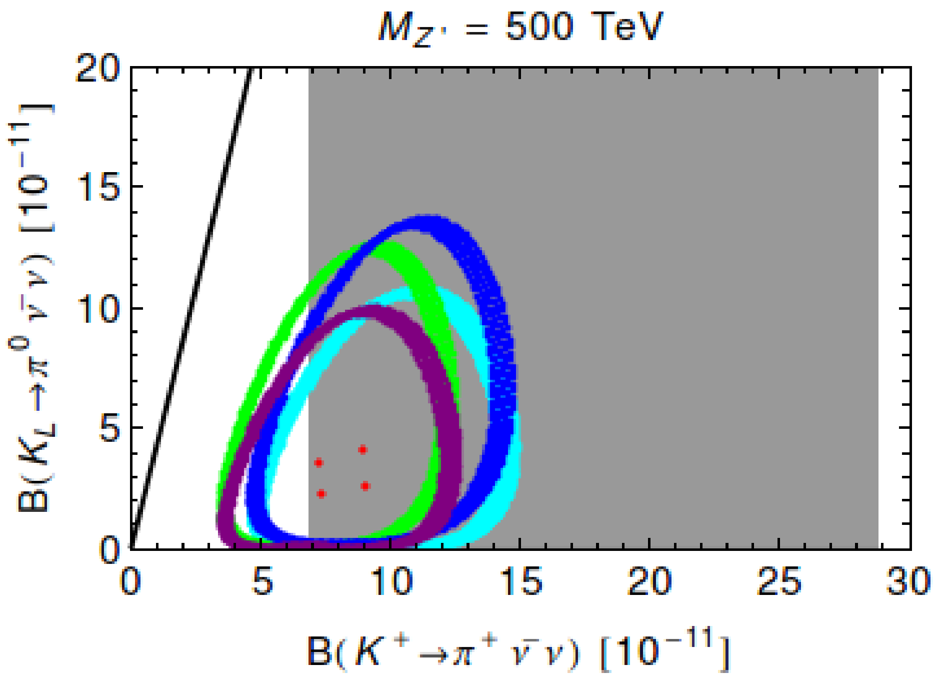
4. The correlation between $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ depends on the ε_K constraint (Blanke 0904.2528)

5. Can probe scales far above LHC.

Heavy Z´ at Work

AJB, Buttazzo, Girrbach-Noe, Knegjens, 1407.0728





ε_K constraint

General discussion:
Blanke 0904.2528

No ε_K constraint

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

Strategy A: Use Tree Level Determination of CKM

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

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

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

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

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

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

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

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

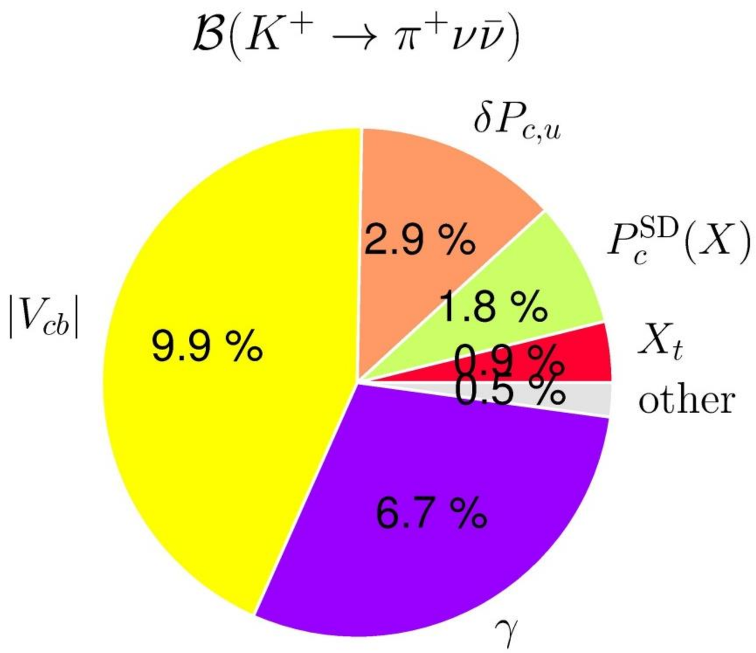
CKM Uncertainties

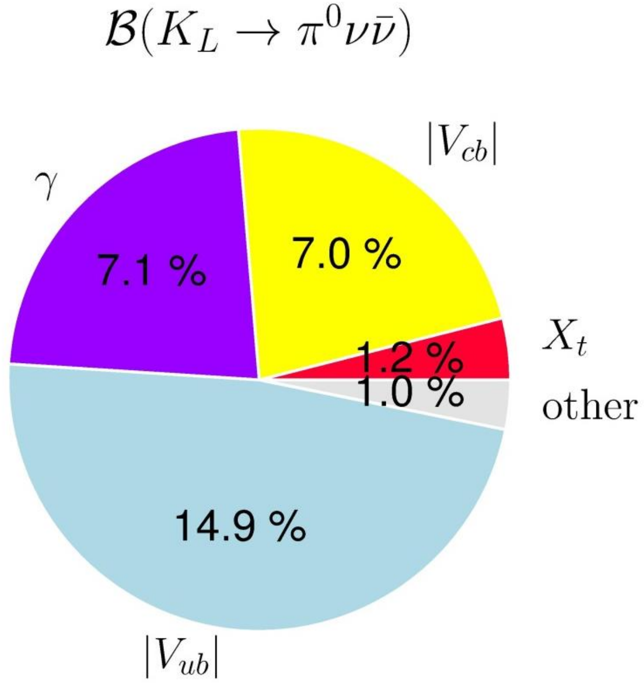
$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(8.39 \pm 0.30\right) \cdot 10^{-11} \left[\frac{|V_{cb}|}{0.0407}\right]^{2.8} \left[\frac{\gamma}{73.2^\circ}\right]^{0.71}$$

$$Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) = \left(3.36 \pm 0.09\right) \cdot 10^{-11} \left[\frac{|V_{ub}|}{3.88 \cdot 10^{-3}}\right]^{2} \left[\frac{|V_{cb}|}{0.0407}\right]^{2} \left[\frac{\sin\gamma}{\sin(73.2)}\right]^{2}$$

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(65.3 \pm 3.1\right) \left[\overline{Br}\left(B_s \to \mu^+\mu^-\right)\right]^{1.4} \left[\frac{\gamma}{70^\circ}\right]^{0.71} \left[\frac{227\ \text{MeV}}{F_{B_s}}\right]^{2.8}$$

Error Budgets





Update: 1503.02693

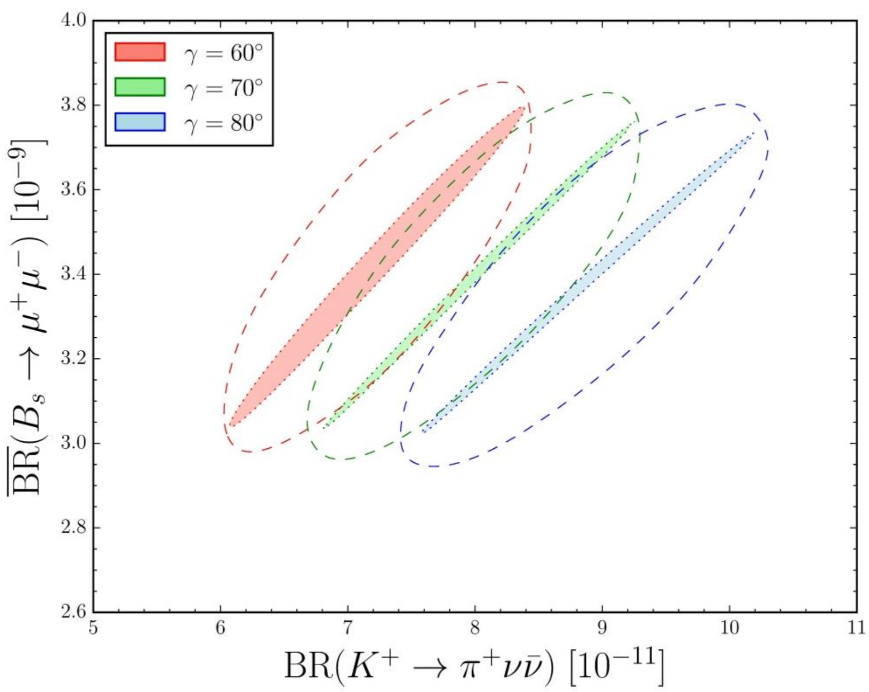
$P_c = 0.404 \pm 0.024$

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

Correlations

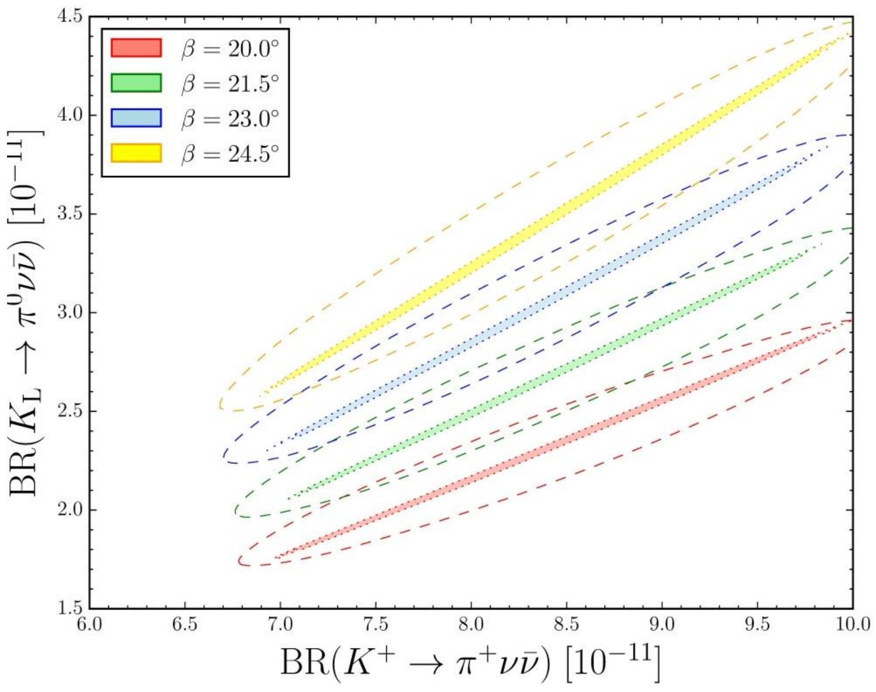
$B_s \to \mu^+\mu^-$, $K^+ \to \pi^+\nu\bar{\nu}$, γ

BBGK (2015)



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

Buchalla, AJB (94)



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

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

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

$$\gamma = (69.5 \pm 5.0)^\circ$$

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

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

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

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

New Analysis of ε'/ε in the SM

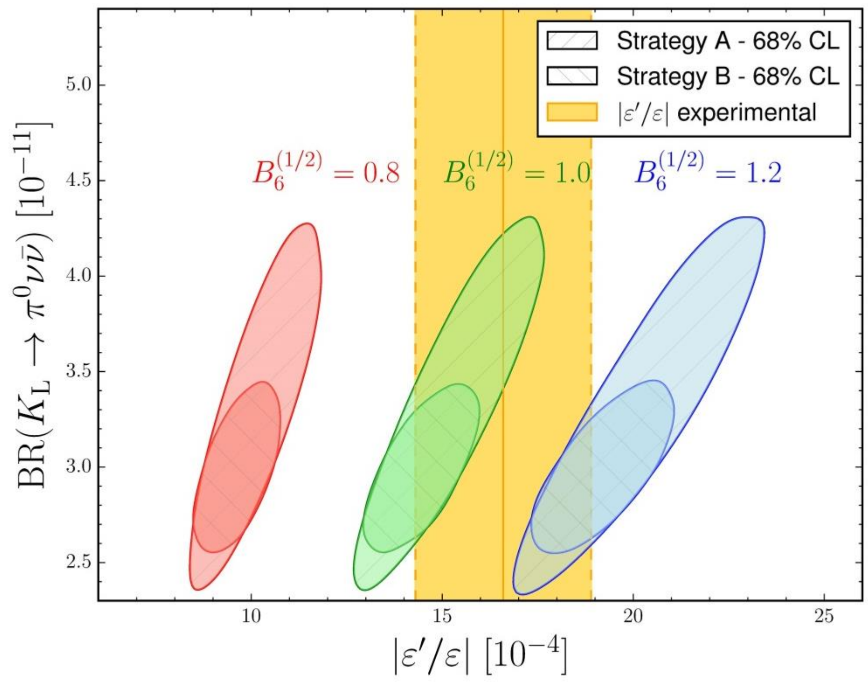
BBGK

QCD Penguins: $B_6^{(1/2)} = 1.0 \pm 0.2$ — Large N

EW Penguins: $B_8^{(2/3)} = 0.76 \pm 0.05$ — RBC-UKQCD

$$\mathrm{Re}\,(\varepsilon'/\varepsilon) = (16.5 \pm 2.6) \cdot 10^{-4}$$

NA48, KTeV



$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ and $K_L \rightarrow \pi^0 \nu\bar{\nu}$ beyond SM

Review Mod. Phys.: AJB, Schwab, Uhlig (2008) (0405132)
AJB, Buttazzo, Knegjens: hep-ph-1504.xxxx

MFV, $U(2)^3$: 20-30% effects, strong correlation between K^+ and K_L

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 to appear soon

see Rob Knegjens (Moriond)

Finale: Vivace !

Main Message

Rare K, B_s, B_d Decays will play crucial role in identifying New Physics hopefully present on the route

Attouniverse → Zeptouniverse

Coming Years : Flavour Precision Era

LHC
Upgrade
E = 14 TeV
(CERN)

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

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

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

Lepton Flavour
Violation
$\mu \to e\gamma$
$\mu \to eee$

Electric
Dipole
Moments

Improved
Lattice
Gauge Theory
Calculations

Neutrinos

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

Exciting Times are just ahead of us !!!

Superstars and Stars of Quark Flavour Physics

Superstars

ε_K, ΔM_s, ΔM_d, $S_{\psi K_S}$	(TH)
$B_s \to \mu^+\mu^-$, $B_d \to \mu^+\mu^-$, $S_{\psi\varphi}(\varphi_s)$	(LHCb, CMS, ATLAS)
$B \to K\nu\bar{\nu}$, $B \to K^*\nu\bar{\nu}$, $B \to X_s\nu\bar{\nu}$	(Belle II)
$K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$	(NA62, J-Parc)

Stars

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

$B \to D^*\tau\nu_\tau$ $\quad B \to D\tau\nu_\tau$

Old Superstar

ε'/ε will strike back provided B_6 (QCD Penguins) will be precisely known.

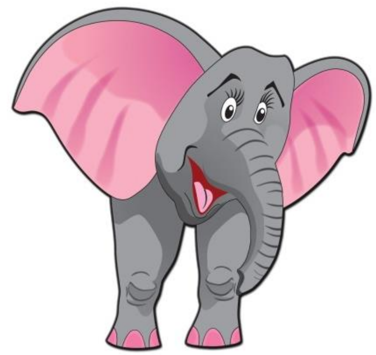
B_8 (EW Penguins) $\approx 0.76 \pm 0.05$ (UK-QCD)

A Zeptouniverse Vision

Seen only in

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

$B_{d,s} \rightarrow \mu^+\mu^-$

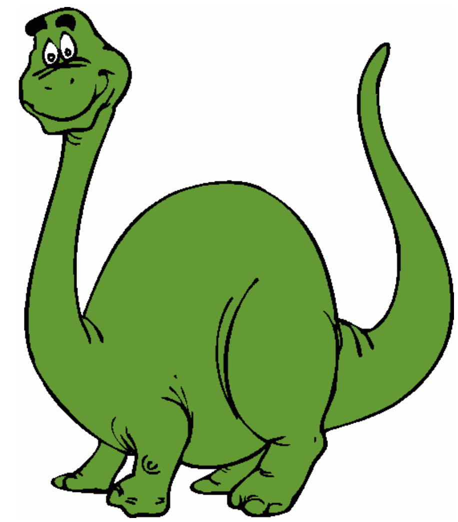


Seen in

Rare B_d

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

$B_{d,s} \rightarrow \mu^+\mu^-$



Seen in

Rare B_s

Rare B_d

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

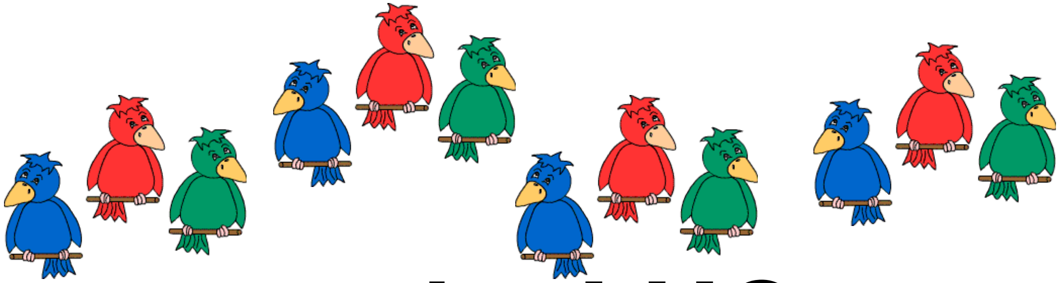
$B_{d,s} \rightarrow \mu^+\mu^-$

Final Message

Great hopes to see many oases on the way Attouniverse → Zeptouniverse

Final Message

Great hopes to
see many oases
on the way
Attouniverse → Zeptouniverse
and



at the LHC

Backup

Warning: $|V_{cb}|$ ($|V_{ts}|$) Dependence

BGHMSS use $|V_{cb}|_{\rm incl} \approx 42\cdot 10^{-3}$

$$\bar{B}r(B_s \to \mu\bar{\mu})_{SM} = (3.65 \pm 0.23)\cdot 10^{-9}$$

$$(2.9 \pm 0.7)\cdot 10^{-9}$$

(LHCb+CMS)

But for $|V_{cb}|_{\rm excl} \simeq 39\cdot 10^{-3}$

$$\bar{B}r(B_s \to \mu\bar{\mu})_{SM} \approx (3.1 \pm 0.2)\cdot 10^{-9}$$

Different Route

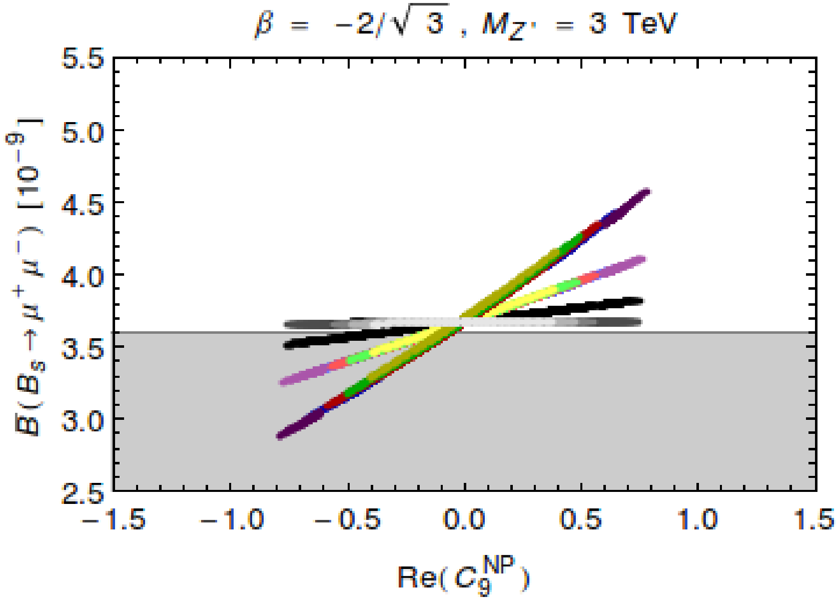
(AJB 2003)
(Knegjens 2014)

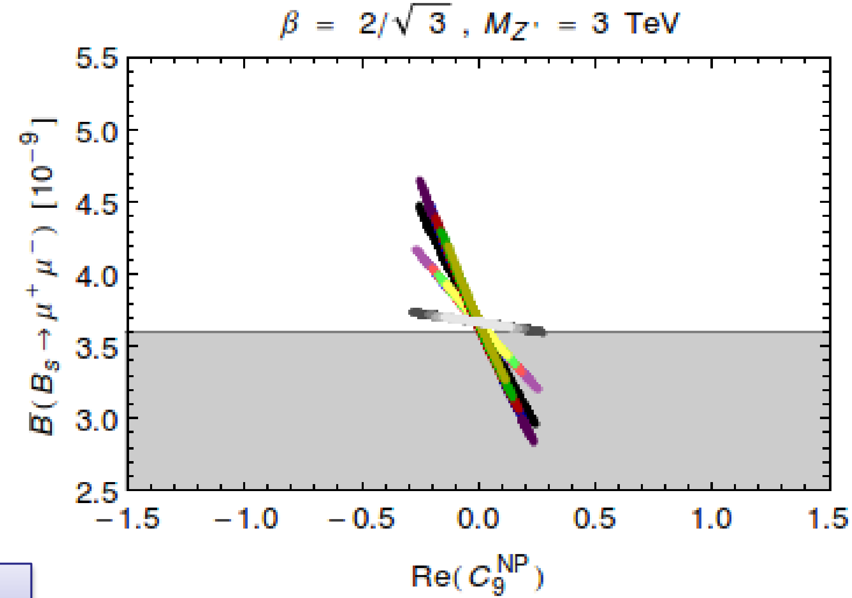
$$\bar{B}r(B_s \to \mu\bar{\mu})_{SM} = (3.5 \pm 0.2)\cdot 10^{-9}\left[\frac{(\Delta M_s)^{SM}}{(\Delta M_s)^{Data}}\right]\left[\frac{1.33}{\hat{B}_s}\right]$$

(No V_{cb}, F_{B_s} dependence)

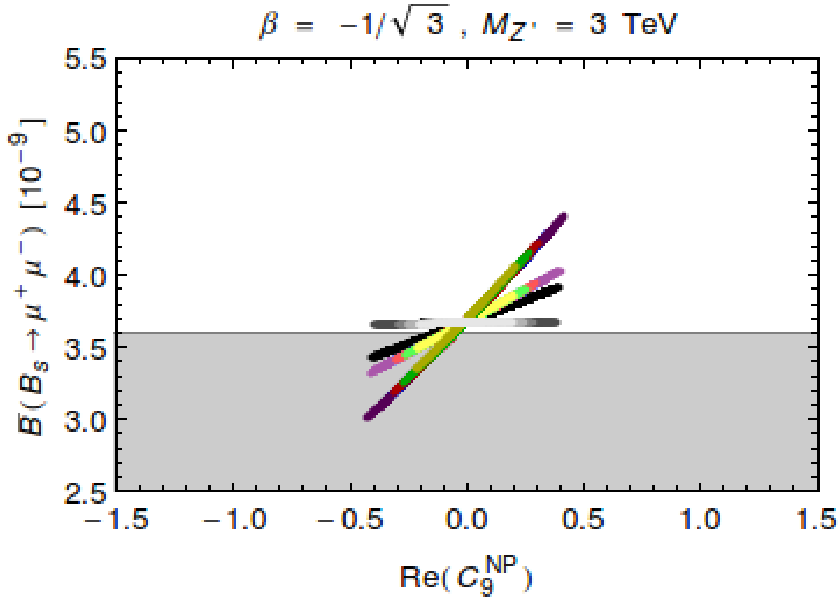
Lattice

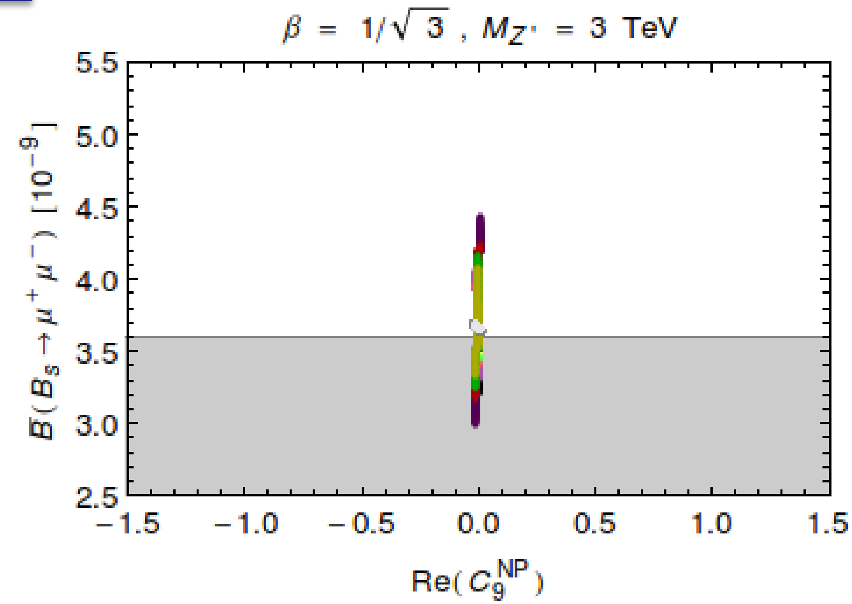
Correlations in 331 Models 1405.3850





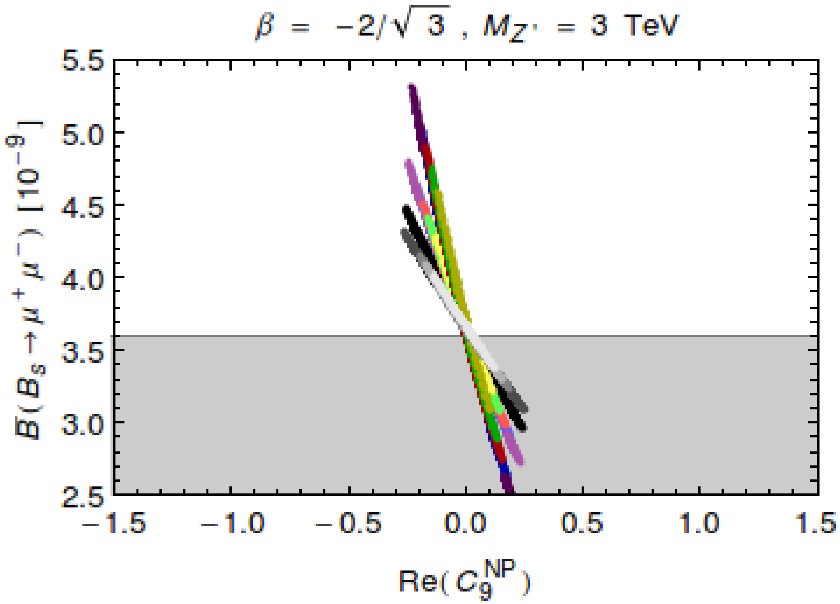
F_1

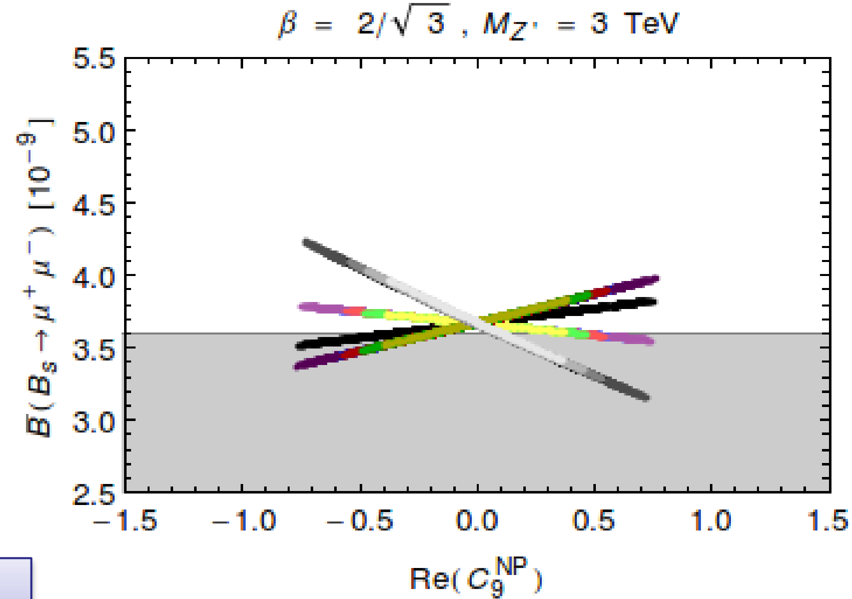




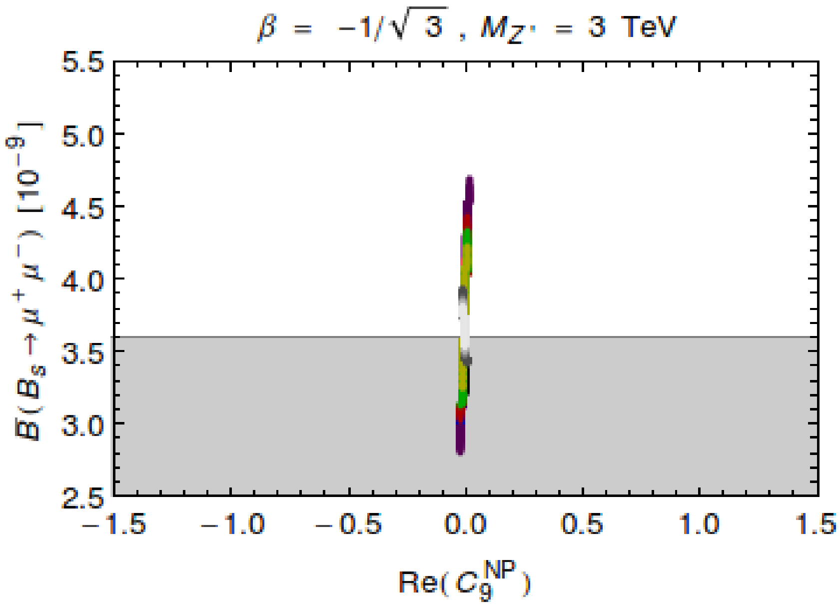
Correlations in 331 Models

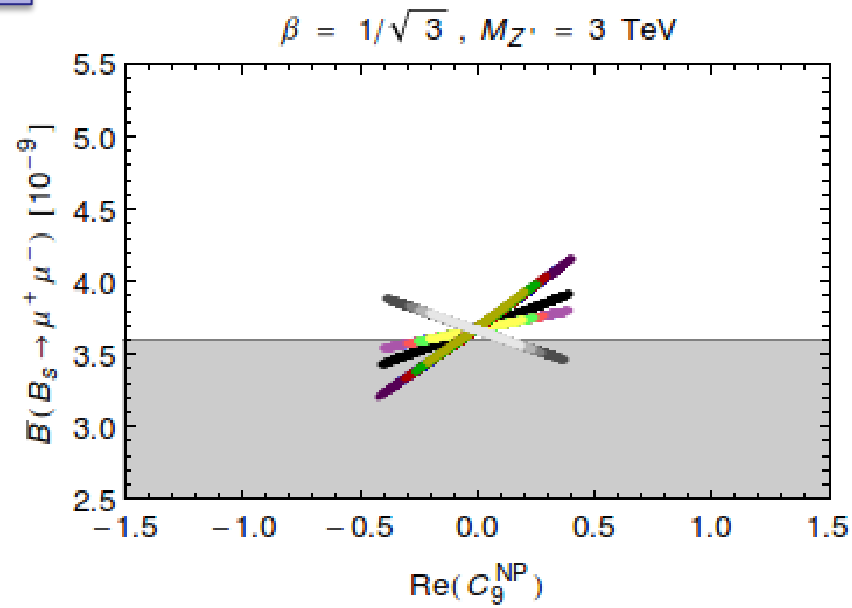
1405.3850





F_2





Effective Theory Approach ($\Delta F=2$)

$$H_{eff}(\Delta F=2) = \underbrace{H_{eff}^{SM}(\Delta F=2)}_{\text{Must be precisely known to identify NP}} + H_{eff}^{NP}(\Delta F=2)$$

$$H_{eff}^{NP}(\Delta F=2) = \sum_{ij} \frac{c_{ij}}{\Lambda_{NP}^2} \underbrace{Q_{ij}(\Delta F=2)}_{\text{4-quark operators}}$$

Utfitters
Isidori, Nir, Perez

For $c_{ij} = 0(1)$ sensitivity to physics $\Lambda_{NP} > 1000$ TeV (LR operators) $(\varepsilon_K, \Delta M_K)$

But with the help of $\Delta F=2$ only it is not possible to learn with ET about the nature of the dynamics at Λ_{NP}

We need **$\Delta F=1$ transitions : Rare K, $B_{s,d}$, D decays** ★

Effective Theory Approach ($\Delta F=1$)

$$H_{eff}(\Delta F=1) = H_{eff}^{SM}(\Delta F=1) + H_{eff}^{NP}(\Delta F=1)$$

$$H_{eff}^{NP}(\Delta F=1) = \sum_{ij} \frac{d_{ij}}{\Lambda_{NP}^2} Q_{ij}(\Delta F=1)$$

Limitations of ET :

a) ET does not provide concrete relations between the c_{ij} ($\Delta F=2$) and d_{ij}($\Delta F=1$) present in concrete models.

Impossible to incorporate

Impact of $\Delta F=2$ transitions on rare K, $B_{s,d}$ decays

b) ET does not provide relations between different coefficients in concrete models:

Example

331 Models

Beyond ET :

In models with Z´ and Z FCNCs their contribution can interfere constructively and destructively implying very different results

AJB
De Fazio
Girrbach-Noe
1405.3850

R measurement

SM expectations: (S.Fajfer, J.Kamenik, I.Nisandzic, PRD **85**, 094025 (2012))

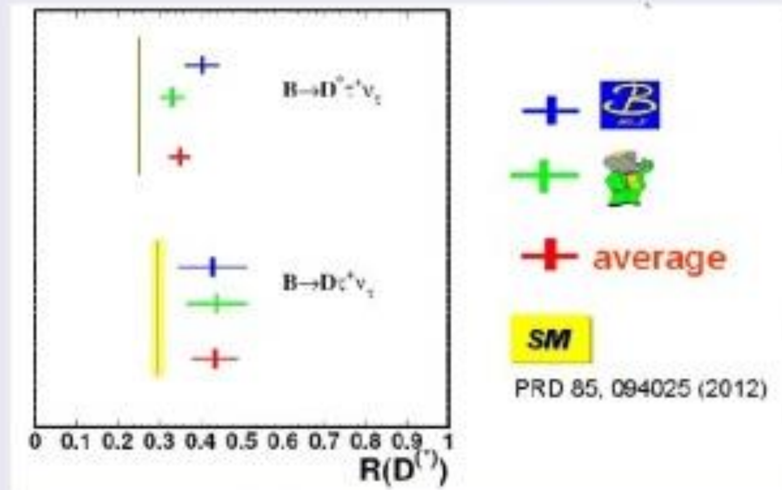
$R(D) = 0.297 \pm 0.017,\ R(D^*) = 0.252 \pm 0.003$

BABAR SM deviations

- $R(\overline{D}^*)$ 2.7σ
- $R(\overline{D})$ 2.0σ
- $R(\overline{D}^{(*)})$ 3.4σ

Belle average SM deviations

- $R(\overline{D}^*)$ 3.0σ
- $R(\overline{D})$ 1.4σ
- $R(\overline{D}^{(*)})$ 3.3σ



private average of Belle results

Belle and *BABAR* average deviation from **SM**

- $R(\overline{D}^*)$ 3.8σ
- $R(\overline{D})$ 2.4σ
- $R(\overline{D}^{(*)})$ 4.8σ

Observed deviations between observable and SM expectations for $R_{D(*)}$ are not only due to improvement of experimental results but also reduction theoretical uncertainties.

LQCD expectations . A. Bailey, *et al.*, Phys. Rev. Lett. **109**, 071802, (2012), arXiv:1206.4992 [hep-ph].

$R(D) = 0.316 \pm 0.012 \pm 0.007$

Simple Tests in the Coming Years

- Sign of $S_{\psi\varphi}$
- $$\frac{Br(B_d \to \mu^+\mu^-)}{Br(B_s \to \mu^+\mu^-)} = \frac{\tau(B_d)}{\tau(B_s)} \frac{m_{B_d}}{m_{B_s}} \frac{F^2_{B_d}}{F^2_{B_s}} \left|\frac{V_{td}}{V_{ts}}\right|^2$$
- $$\frac{Br(B_s \to \mu^+\mu^-)}{Br(B_d \to \mu^+\mu^-)} = \frac{\hat{B}_d}{\hat{B}_s} \frac{\tau(B_s)}{\tau(B_d)} \frac{\Delta M_s}{\Delta M_d}$$
- $Br(K^+ \to \pi^+\nu\bar{\nu});\ Br(K_L \to \pi^0\nu\bar{\nu})$
- **Lepton Flavour Violation**

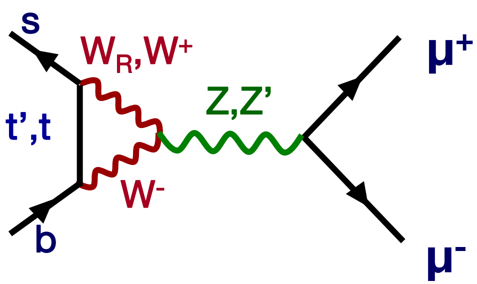
  $\mu \to e\gamma,\ \mu \to 3e,\ \tau \to 3\mu$

  $\tau \to e\gamma,\ \tau \to 3e$

  $\tau \to \mu\gamma$
- ε'/ε provided QCD Penguin hadronic matrix under control

Standard Candles of Flavour Physics

$B_s \to \mu^+\mu^-$ Beyond the Standard Model



+

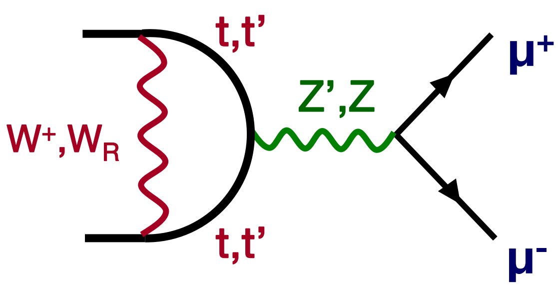
Other Z-Penguins and Boxes

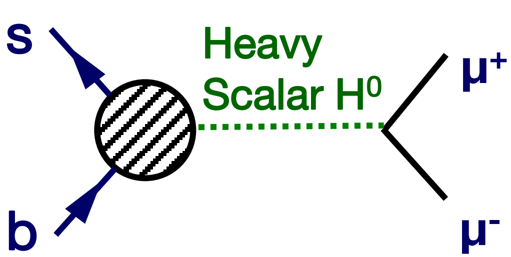
SM: (3.2 ± 0.2) · 10^{-9}

Model Independent Limit (95% C.L.)

$$Br(B_s \to \mu^+\mu^-) < 5.6 \cdot 10^{-9}$$

Altmannshofer, Paradisi, Straub 1111.1257





$$\frac{(\tan\beta)^6}{M_H^4}$$

in SUSY

$$Br(B_s \to \mu^+\mu^-) < 11 \cdot 10^{-9}$$

In the case of

$$Br(B_s \to \mu^+\mu^-) > 6 \cdot 10^{-9}$$

distinction between Z,Z' and H^0 possible

Minimal Effective Model with Right-Handed Currents

AJB, Gemmler, Isidori (1007.1993)

- Explains the difference $|V_{ub}|_{excl} \neq |V_{ub}|_{incl}$
- Softens $B^+ \to \tau^+ \nu_\tau$ problem (large V_{ub})

But with large $S_{\psi\varphi}$ predicted: (2010)

Large $Br(B_s \to \mu^+\mu^-)$, SM-like $Br(B_d \to \mu^+\mu^-)$, too large $S_{\psi K_s}$

Impact of small $S_{\psi\varphi}$ from LHCb (2012) (Relief !!)

SM-like $Br(B_s \to \mu^+\mu^-)$, $Br(B_d \to \mu^+\mu^-)$, $S_{\psi K_s}$ ok

can be large

LHT after LHCb Data

Our 2006 Predictions (Blanke et al.) :

$Br\left(B_{s,d} \to \mu^+\mu^-\right)$ within 40% from SM

$\left|S_{\psi\varphi}\right| \lesssim 0.25$

$\left\{S_{\psi\varphi} > 0.20\right\} \Rightarrow \left\{\begin{array}{l}\text{No New Physics Effects} \\ \text{in } K^+ \to \pi^+\nu\bar{\nu}, K_L \to \pi^0\nu\bar{\nu}\end{array}\right\}$

Concerning B-Physics : LHCb Data = Relief for LHT model *)

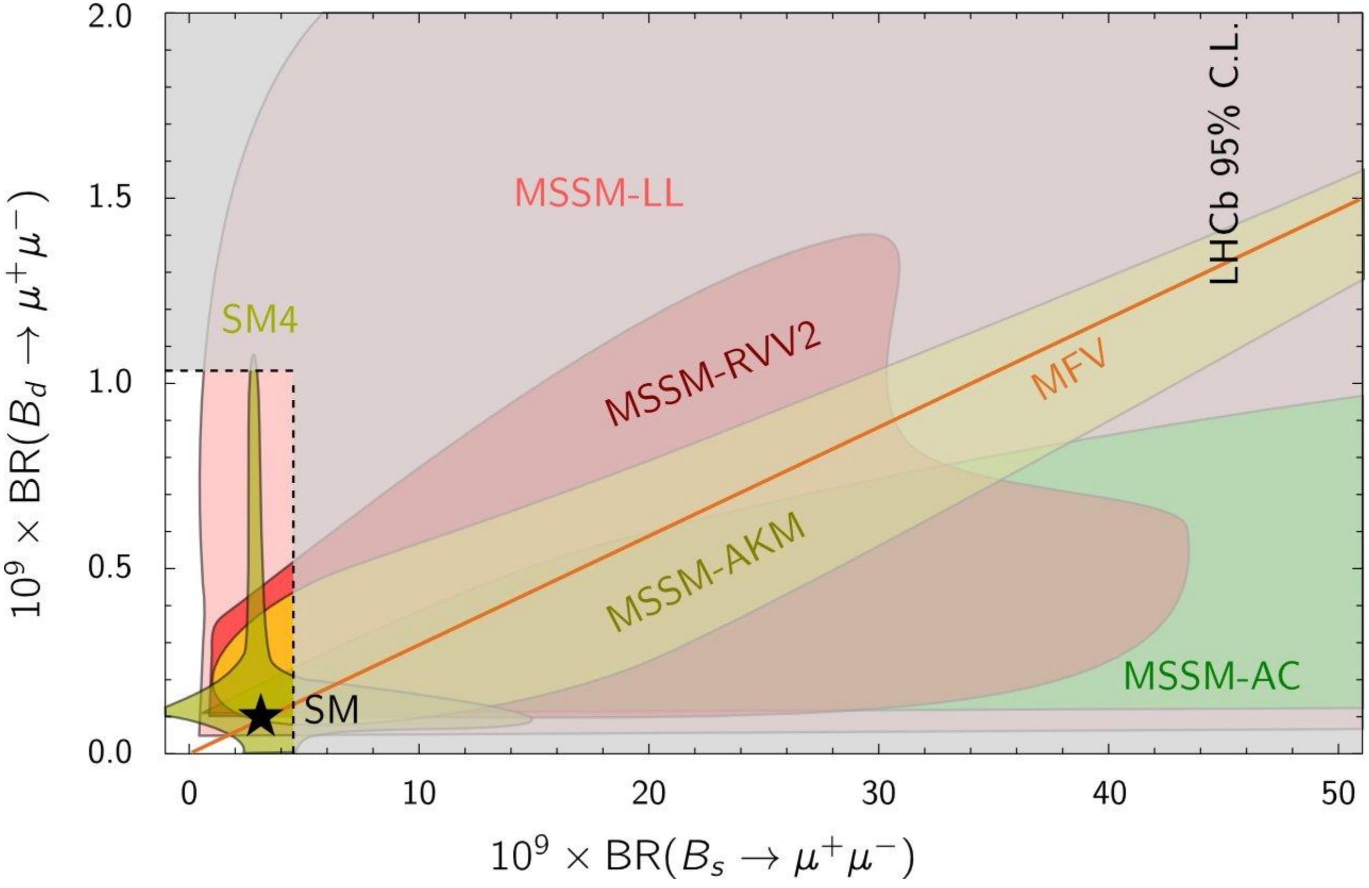
Concerning K-Physics : LHCb opened the road to large NP effects in rare K-decays within LHT model *)

*) The same impact of LHCb on Rare B and K decays within RS_c model

Effects in $B_{s,d} \to \mu^+\mu^-$ even smaller

Supersymmetric Models Facing LHCb Data

ABGPS
Straub 1012.3893



Models with new left-handed currents favoured

Can $|V_{ub}|_{excl} \neq |V_{ub}|_{incl}$ be explained through right-handed currents?

Crivellin; Chen + Nam; Feger, Mannel et al.; AJB, Gemmler, Isidori

RHMFV

Works better with small $S_{\psi\varphi}$

$|V_{ub}|_{excl} = 3.12\ (26) \cdot 10^{-3}$

$|V_{ub}|_{inc} = 4.27\ (38) \cdot 10^{-3}$

$\varepsilon \approx \frac{\upsilon_L}{\upsilon_R}$

$$|V_{ub}|_{excl} = |V_{ub}^L + a\varepsilon^2 V_{ub}^R|$$

$$|V_{ub}|_{inc} \approx |V_{ub}^L|$$

Generally: in principle yes

But a very detailed analysis of $SU(2)_L \otimes SU(2)_R \otimes U(I)_{B-L}$ with $g_L \neq g_R$; $V_L \neq V_R$ (mixing) including FCNC constraints + EWP constraints shows that in this concrete model the effect of RH currents too small !!

Blanke
AJB
Gemmler
Heidsieck
(1111.5014)

Comparison of Simplest Models

	$\Delta\lvert\varepsilon_K\rvert$	ΔM_d	ΔM_s	$\Delta S_{\psi K_s}$	$\Delta S_{\psi\varphi}$	Favoured $\lvert V_{ub}\rvert$
CMFV	+	+	+	0	0	exclusive
$2HDM_{\overline{MFV}}$	0	±	±	-	+	inclusive
$U(2)^3$	+	±	±	- 0 +	+ 0 -	inclusive exclusive

$$\left(\frac{\Delta M_s}{\Delta M_d}\right)_{CMFV} = \left(\frac{\Delta M_s}{\Delta M_d}\right)_{MU(2)^3} = \left(\frac{\Delta M_s}{\Delta M_d}\right)_{SM}$$

(the same relation for $B_{s,d} \to \mu^+\mu^-$)

$$S_{\psi K_s} = \sin\left(2\beta + 2\varphi_{new}\right)$$

$$S_{\psi\varphi} = \sin\left(2\lvert\beta_s\rvert - 2\varphi_{new}\right)$$

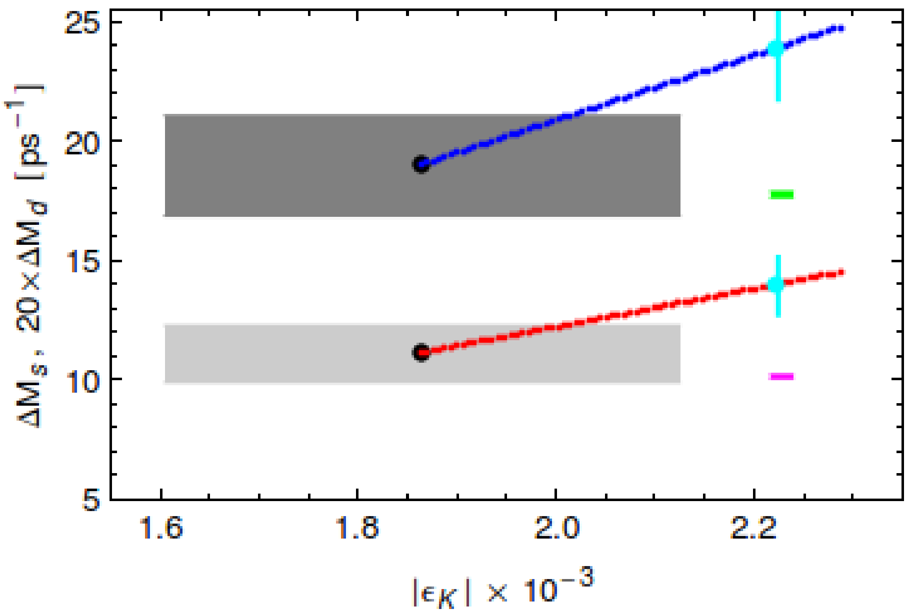
$$\beta = F\left(\lvert V_{ub}\rvert, \gamma\right)$$

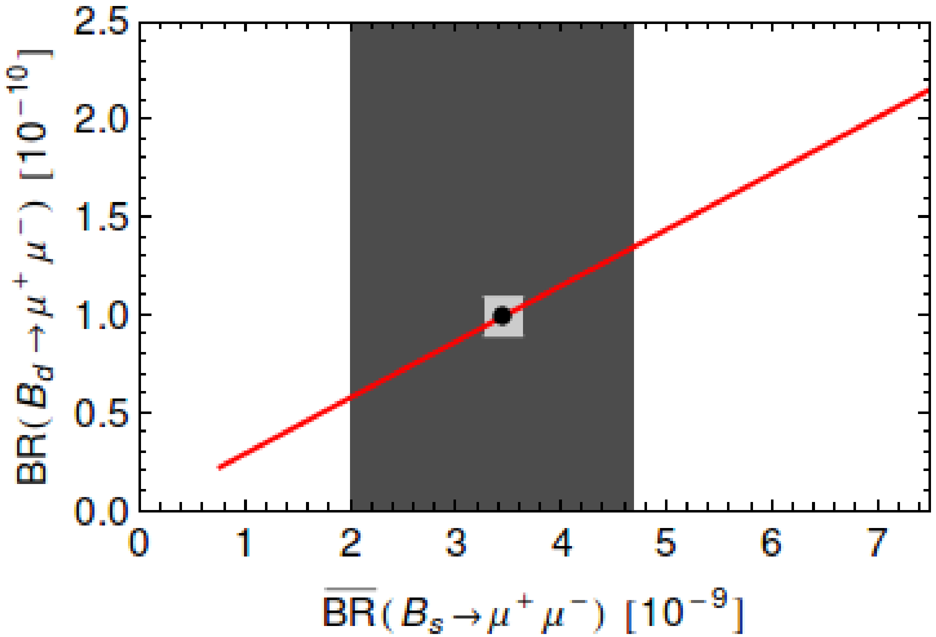
(weak)

Constrained Minimal Flavour Violation

AJB + J. Girrbach (2012)

0007085
0310208
0604057





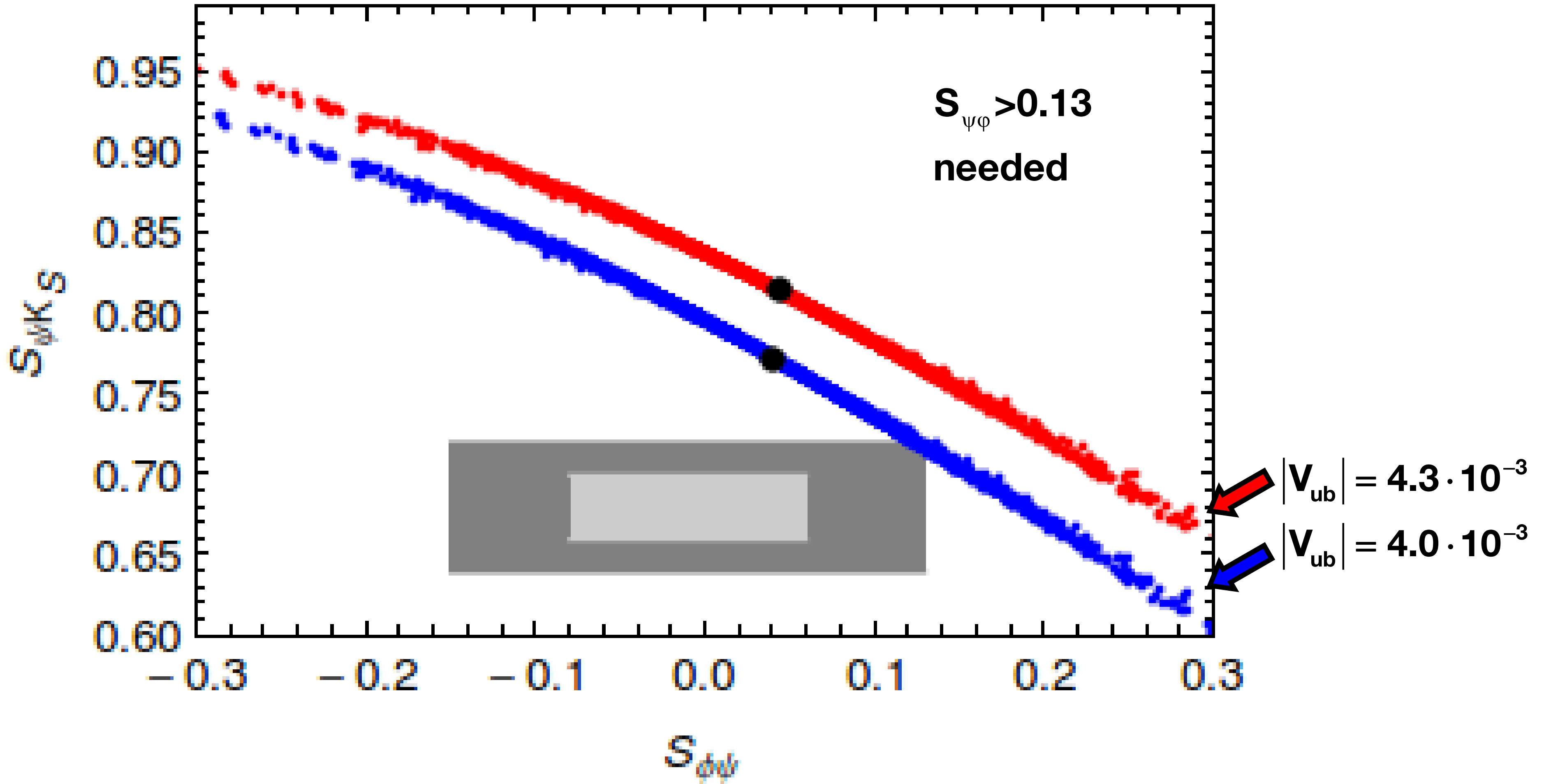
Tension within CMFV EXP

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

$$\overline{Br}(B_s\to\mu^+\mu^-) = \left(3.2\,{}^{+1.5}_{-1.2}\right)\cdot 10^{-9}$$

$2HDM_{\overline{MFV}}$ Facing LHCb Data

AJB, Girrbach, Nagai (2013)

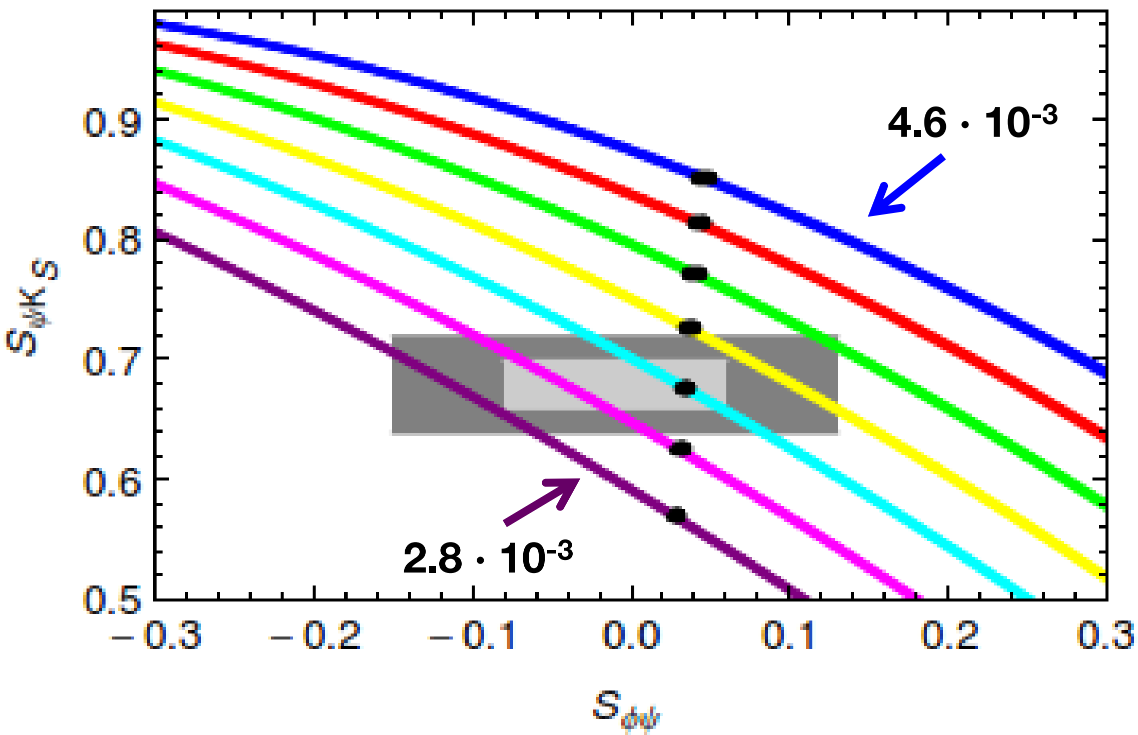


AJB, Carlucci, Gori, Isidori; 1005.5310
AJB, Isidori, Paradisi; 1007.5291

AJB
Girrbach
(1206.3878)

$S_{\psi K_s} - S_{\psi\varphi} - |V_{ub}|$ Correlation in $U(2)^3$

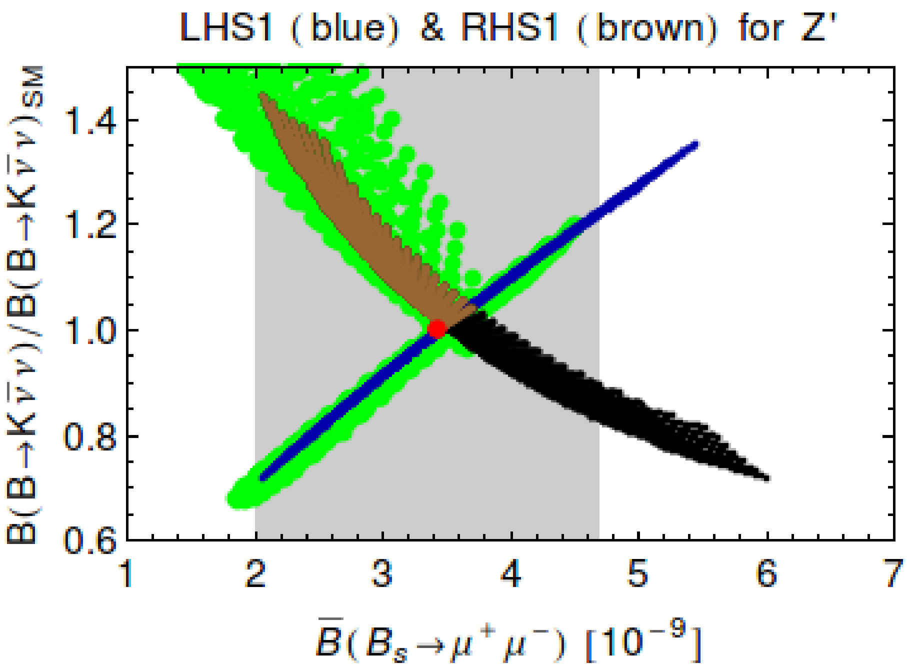
Important test of $U(2)^3$ Models

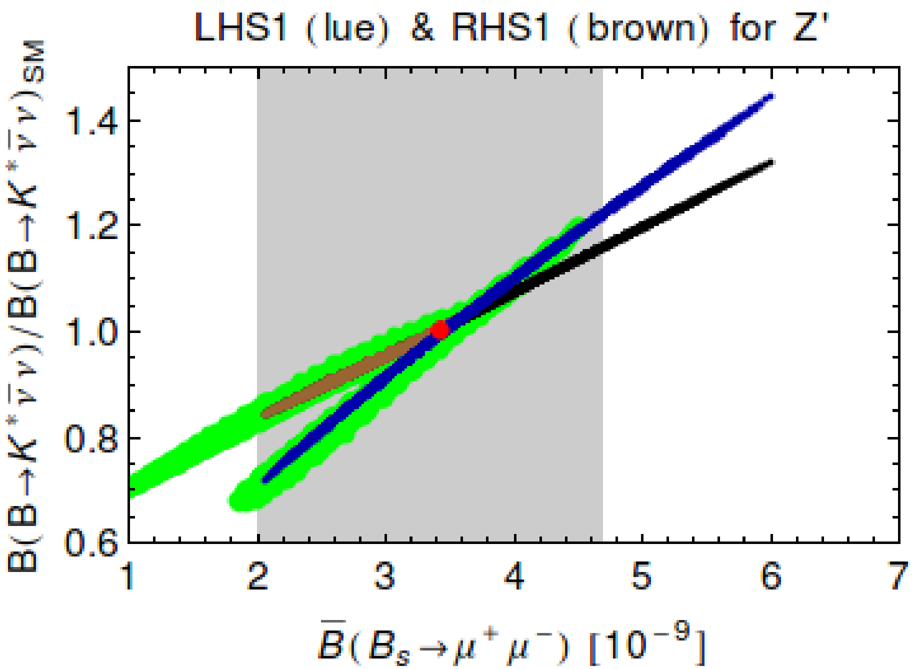


$\gamma = 68°$

In the $U(2)^3$ Symmetric World we could determine $|V_{ub}|$ without significant hadronic uncertainties (QCD penguins)

Distinguishing Left-Handed Currents from Right-Handed Currents





AJB, De Fazio, Girrbach 1211.1896

Altmannshofer et al. 0902.0160

■ : **forbidden by $b \to sll$**

■ : **allowed by $b \to sll$**

Z'-Couplings

	$\bar{\Delta}_L^{sb}(Z')$	$\bar{\Delta}_A^{\mu\bar{\mu}}(Z')$	$\bar{\Delta}_V^{\mu\bar{\mu}}(Z')$	$\bar{\Delta}_L^{db}(Z')$
	complex	real	real	complex
$\Delta M_s,\ S_{\psi\varphi}$	✖			
$B_d \to K^* \mu^+\mu^-$	✖	✖	✖	
$B_s \to \mu^+\mu^-$	✖	✖		
$B_d \to \mu^+\mu^-$		✖		✖
$\Delta M_d,\ S_{\psi\varphi}$				✖

$$\bar{\Delta}_i = \frac{\Delta_i}{M_{Z'}}$$

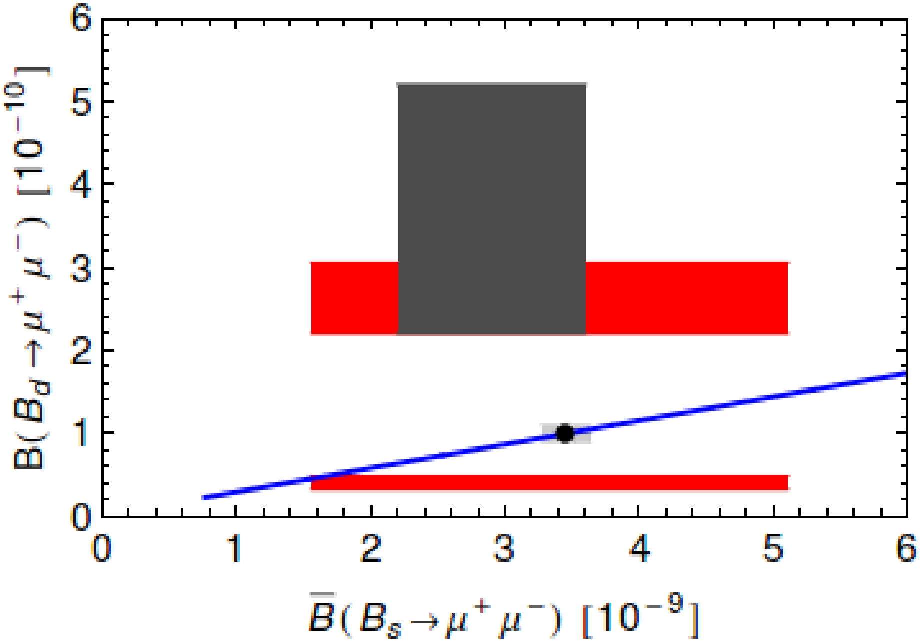
reduced coupling ($\bar{\Delta}_i$); coupling (Δ_i)

Z-Couplings $\Delta_{A,V}^{\mu\mu}$ fixed

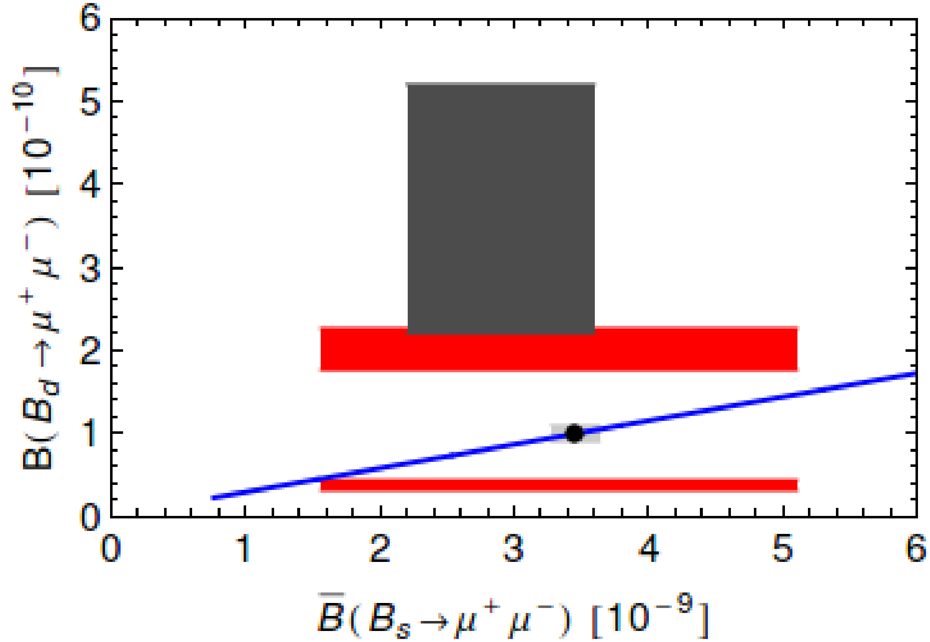
$$SU(2)_L:\quad \Delta_L^{\nu\nu}(Z') = \frac{\Delta_V^{\mu\bar{\mu}}(Z') - \Delta_A^{\mu\bar{\mu}}(Z')}{2} \Rightarrow b \to s\nu\bar{\nu}$$

Violation of CMFV (Z′)

High V_{ub}



Low V_{ub}

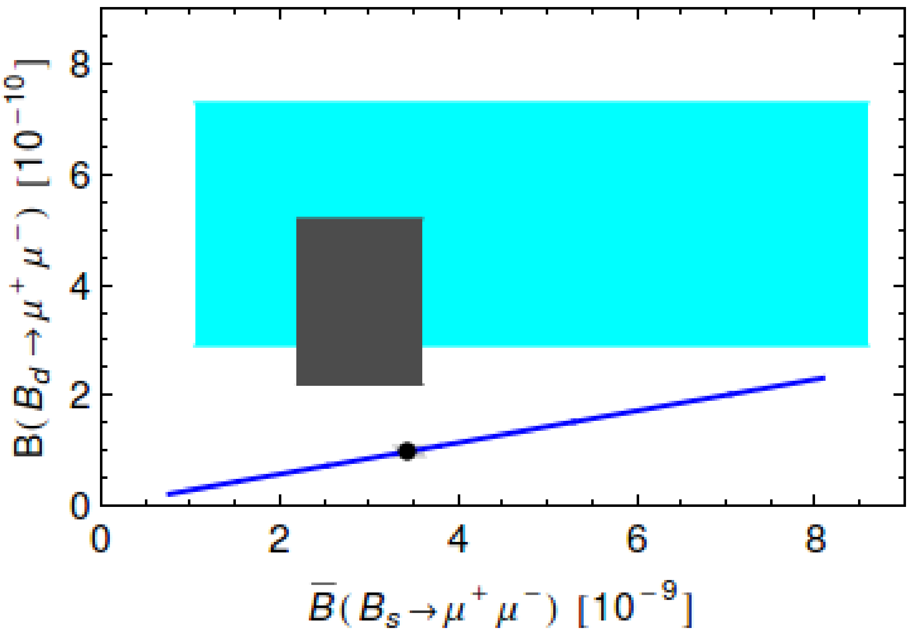


CMS + LHCb

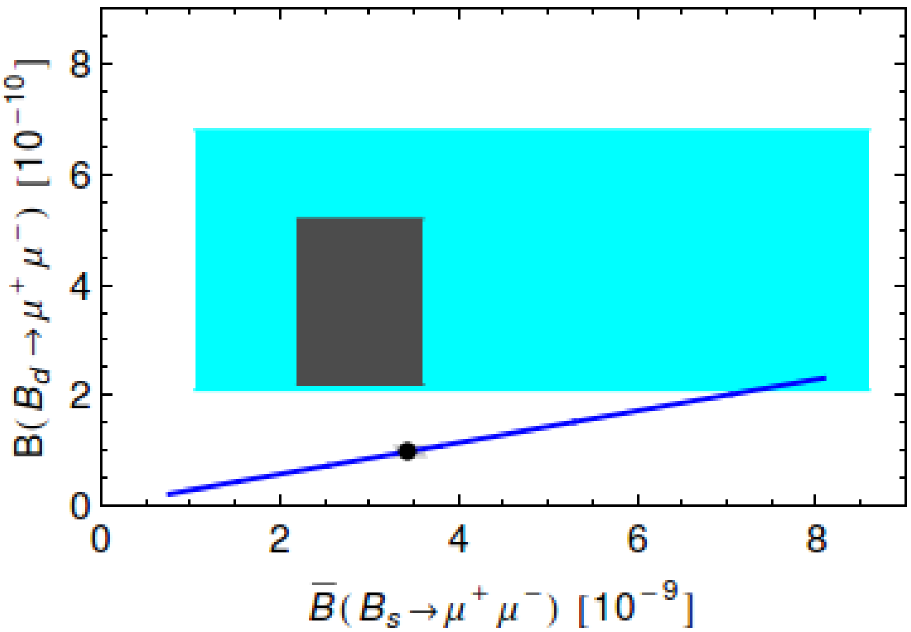
SM

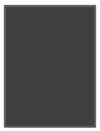
Violation of CMFV (Z)

High V_{ub}



Low V_{ub}





CMS + LHCb

● **SM**

Anomalies in $B_d \to K^* \mu^+ \mu^-$

(24 angular observables. Good agreement with SM but three deviations)

LHCb	**SM** (Altmannshofer + Straub)	
$\langle F_L \rangle_{[1.6]} = 0.66 \pm 0.07$	0.77 ± 0.04	
$\langle S_5 \rangle_{[1.6]} = 0.10 \pm 0.10$	-0.14 ± 0.02	
$\langle S_4 \rangle_{[14,16]} = -0.07 \pm 0.11$	0.29 ± 0.07	(Not understood in any model)

Extensive Analyses:

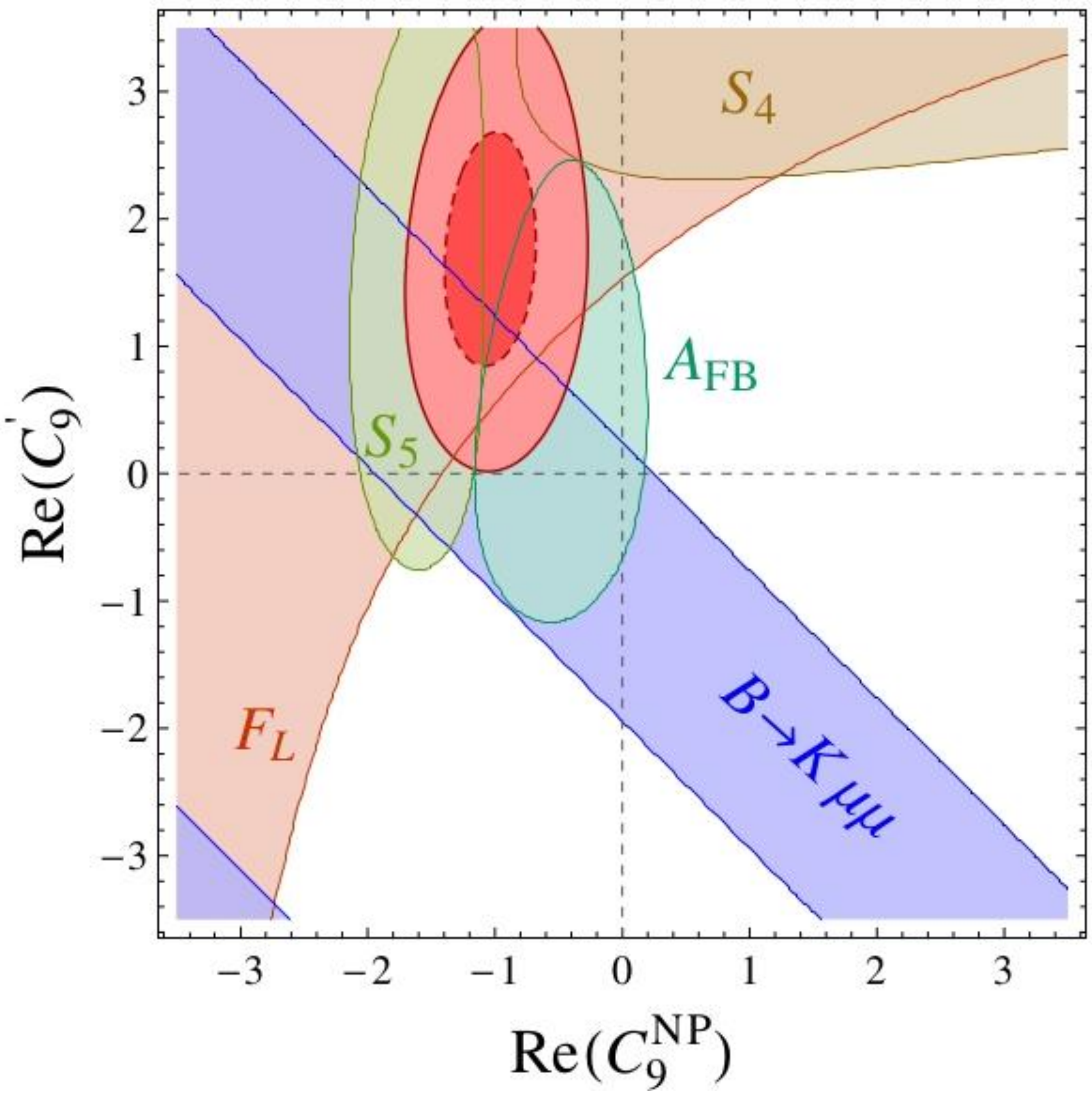
Descotes-Genon, Matias, Virto (1307.5683)
Altmannshofer + Straub (1308.1501)

DMV
AS
$$C_{7\gamma}^{NP} < 0, \quad C_9^{NP} < 0$$

or

AS
$$C_9^{NP} < 0, \quad C_9^{'} \approx -C_9^{NP}$$

right-handed



Altmannshofer Straub (1308.1501)

Left-handed Z´ and Z FCNC Couplings Facing $B_d \to K^* \mu^+\mu^-$ Anomalies

(AJB + Girrbach, 1309.2466)

Z fails because of small vector coupling to muons when $\Delta M_{s,d}$ constraints taken into account.

Z´ Suggested by Descotes-Genon, Matias, Virto (1307.5683)

Softens $\langle F_L \rangle$, $\langle S_5 \rangle$ anomalies

provided $C_9^{NP} \approx -1.5$ in a correlated manner

See also Altmannshofer Straub (1308.1501)

Note: In Z´ models $C_{7\gamma}^{NP} = 0$ (1211.1896)

→ Optimal solutions to $\langle F_L \rangle$, $\langle S_5 \rangle$ (1309.2466)

$C_9^{NP} \neq 0, \quad C_9' = 0$ (LHS)

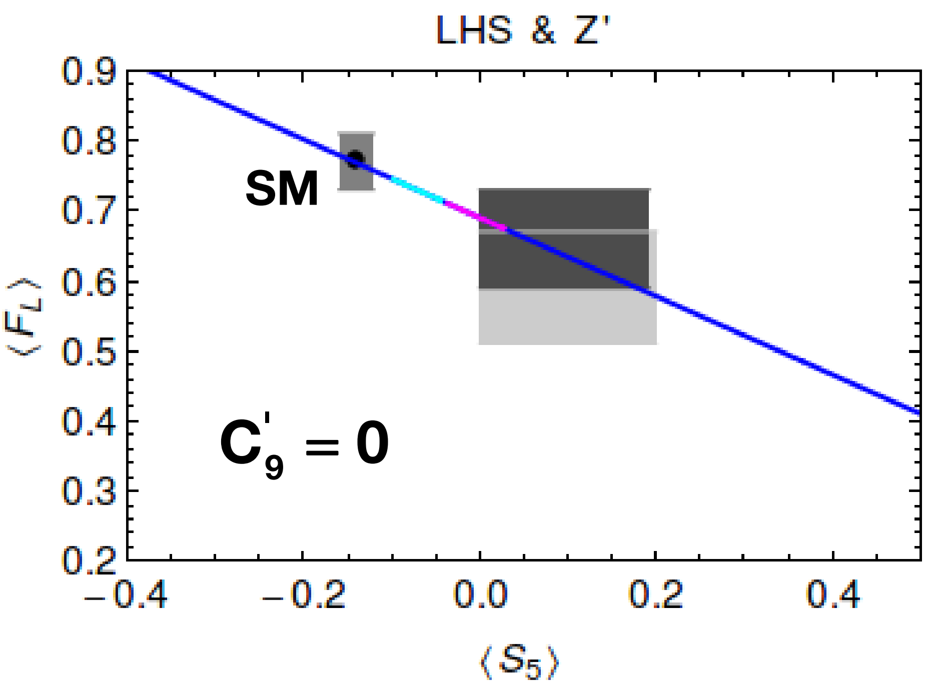
$C_9^{NP} \neq 0, \quad C_9' \approx -C_9^{NP}$ (ALRS)

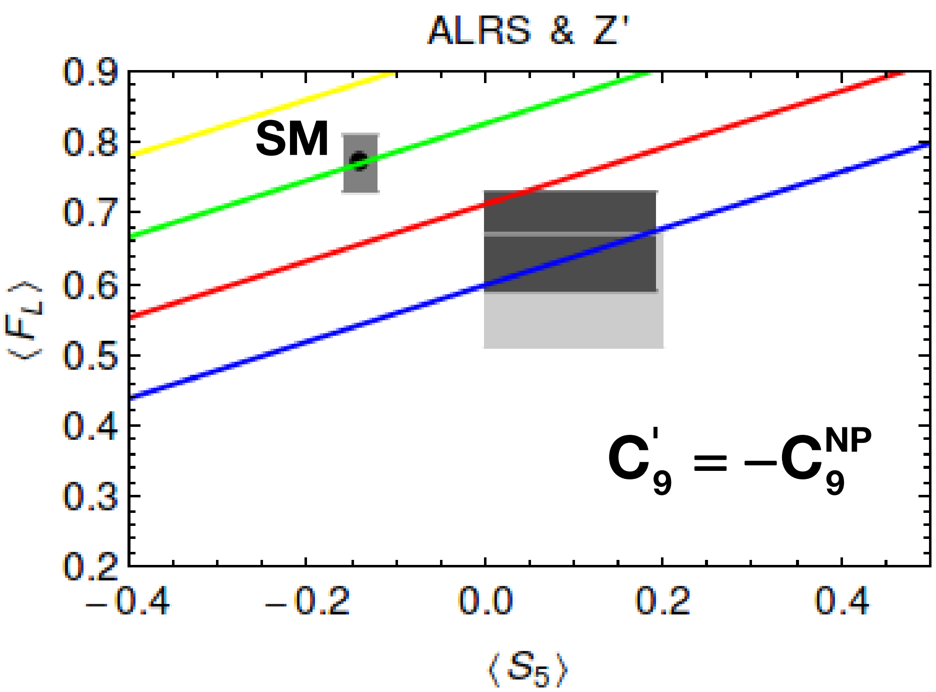
Fails for $\langle S_4 \rangle$ must be SM-like

New Correlations

(General Z′)

(AJB + Girrbach, 1309.2466)





(cyan) $C_9^{NP} = -(0.8 \pm 0.3)$

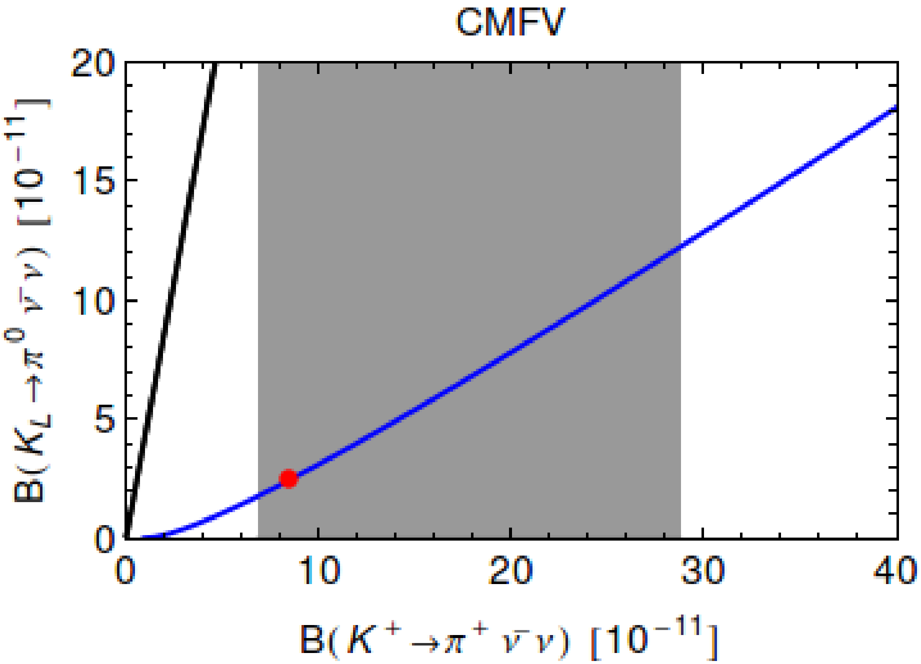
(magenta) $C_9^{NP} = -(1.6 \pm 0.3)$

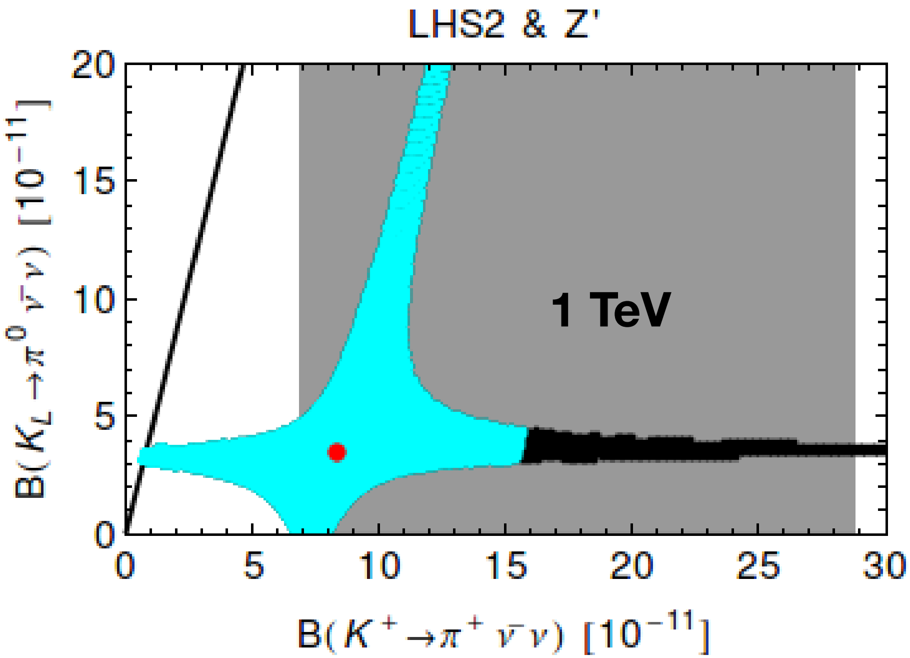
(red) $C_9^{NP} = -1.0$

(blue) $C_9^{NP} = -2.0$

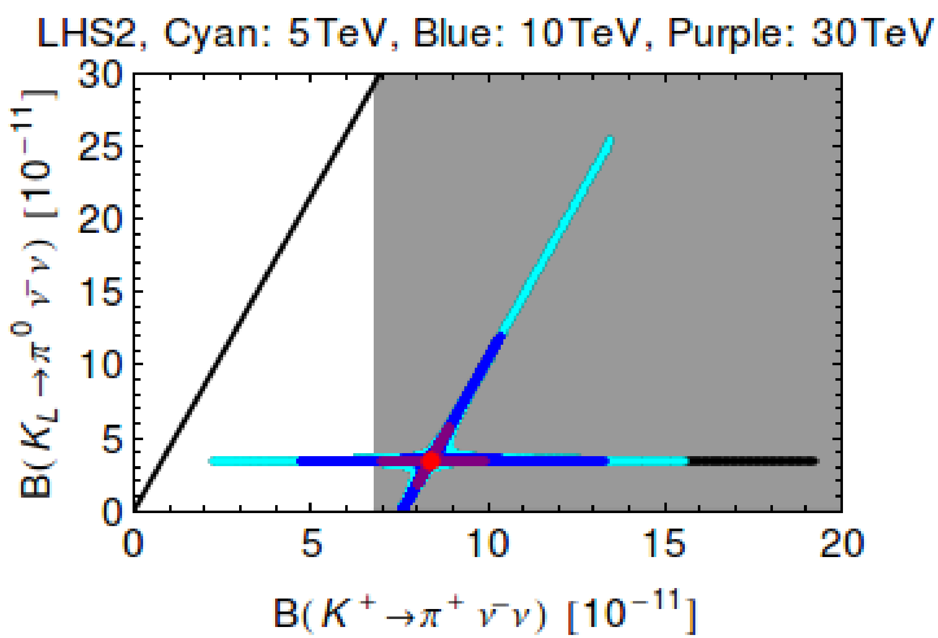
(green) $C_9^{NP} = 0$

1211.1896

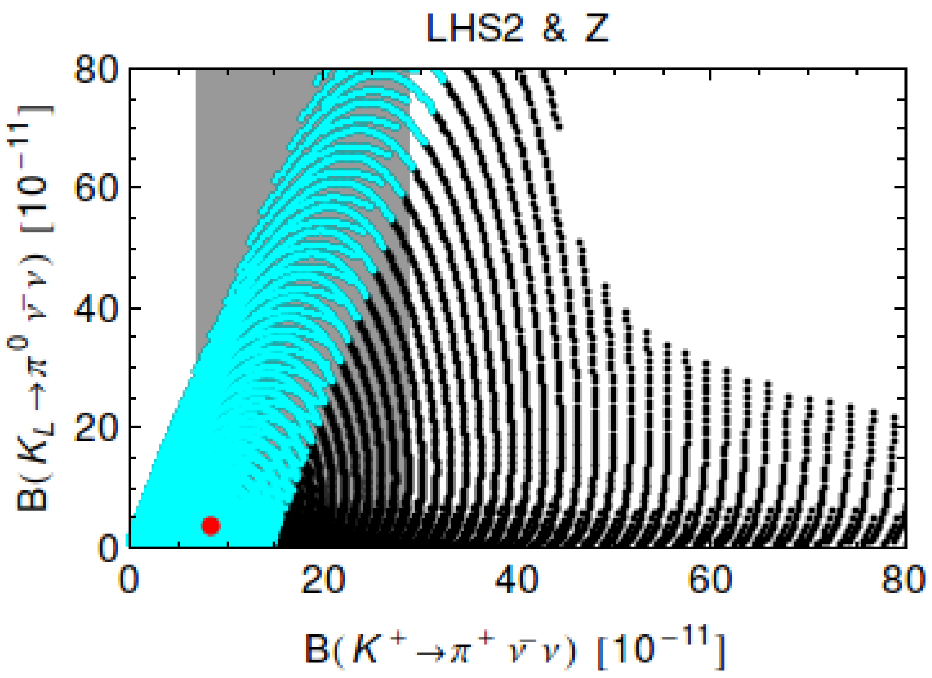


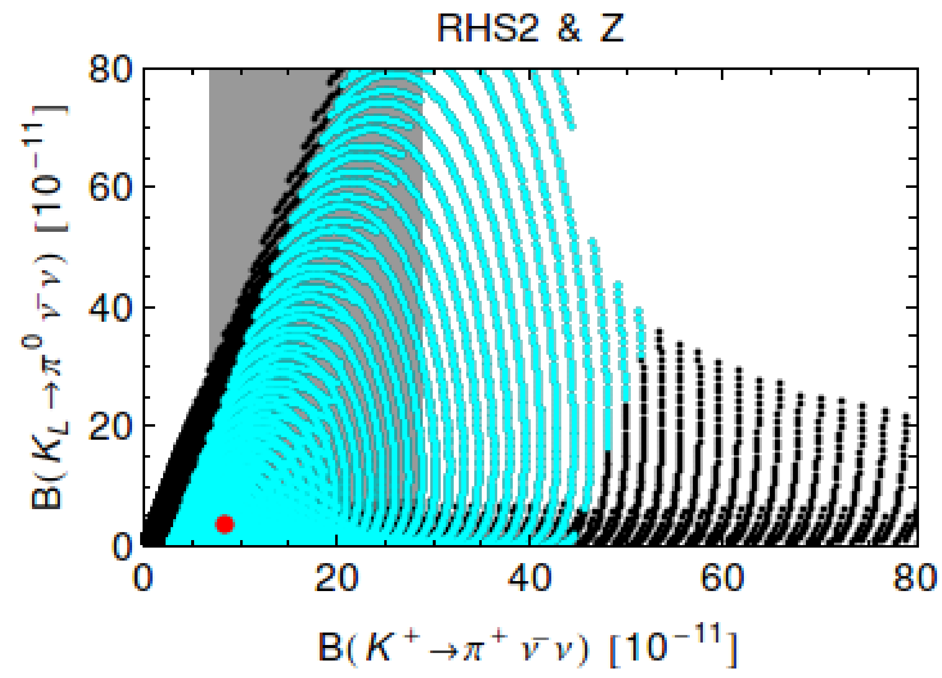


Sensitivity to $M_{Z'}$ beyond the LHC



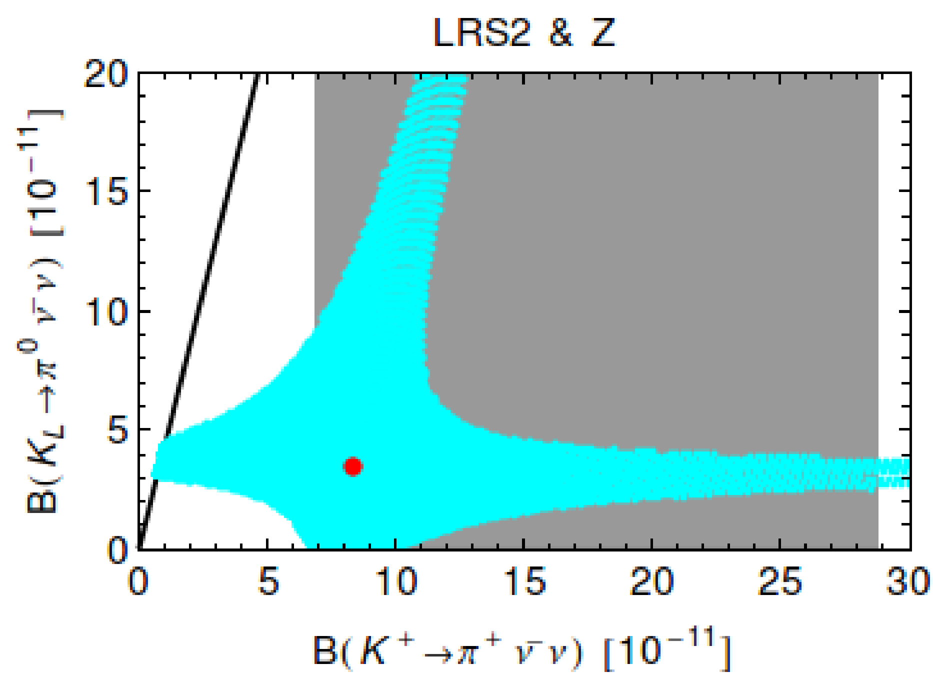
■ : **forbidden by $K_L \to \mu^+\mu^-$**



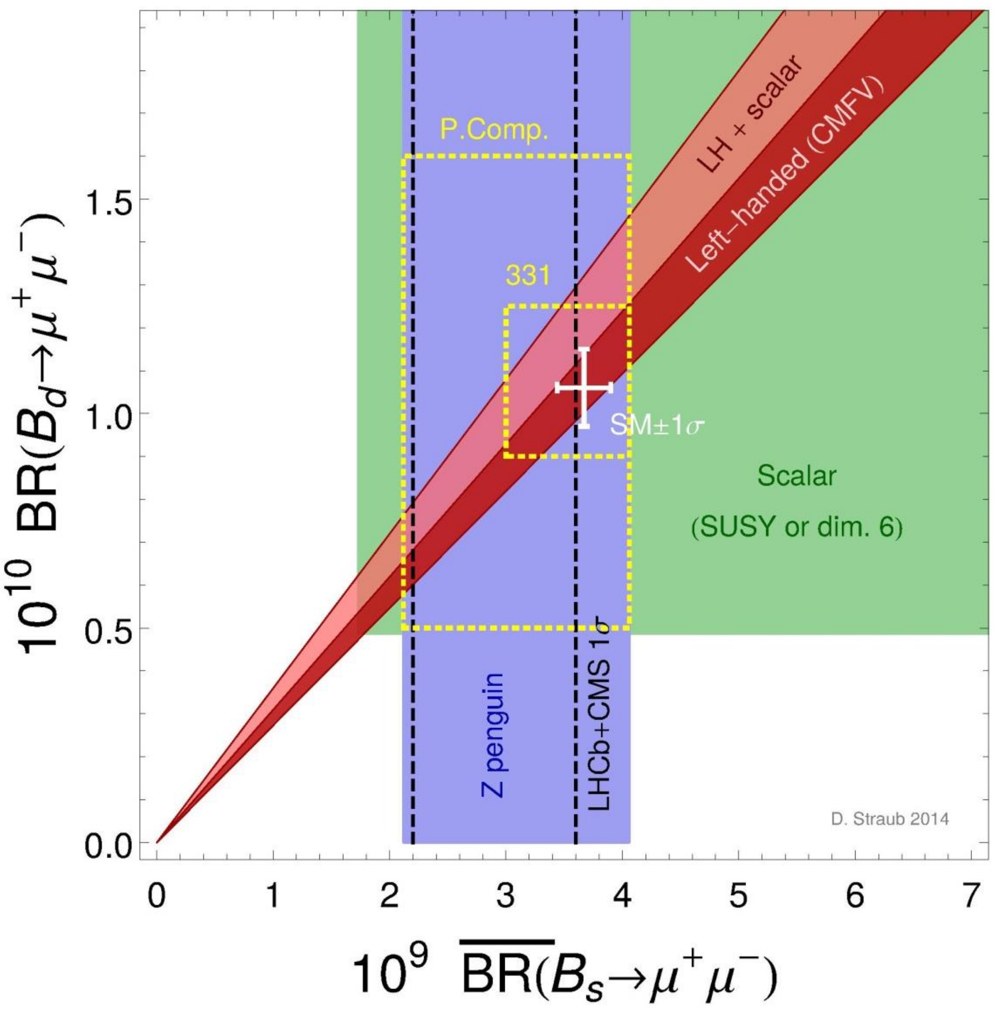


: **forbidden by $K_L \to \mu^+\mu^-$**

LHS, RHS
LRHS



Straub´s Plot 2014



Two Versions of Effective Theories

Wilson Coefficients → Local operators

1.

$$L_{eff} = L_{SM} + \sum_i \frac{c_i}{\Lambda_i^2} Q_i$$

which results from integrating out heavy fields (c_i, Λ_i depend on parameters of a given theory)

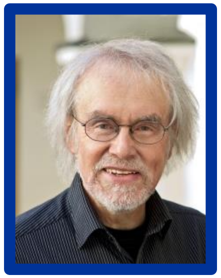
Very powerful framework in flavour physics, RG, etc.

2.

ET ≡ The coefficients c_i, Λ_i are free parameters. Completion unknown. Very limited framework in flavour physics except for cases when flavour symmetries and their breakdown are assumed: MFV $(U(3))^3$, $U(2)^3$,…

1.

Can we reach Zeptouniverse 10^{-21}m (~ 200 TeV) by means of Quark Flavour Physics?



AJB

D.Buttazzo

J.Girrbach-Noe

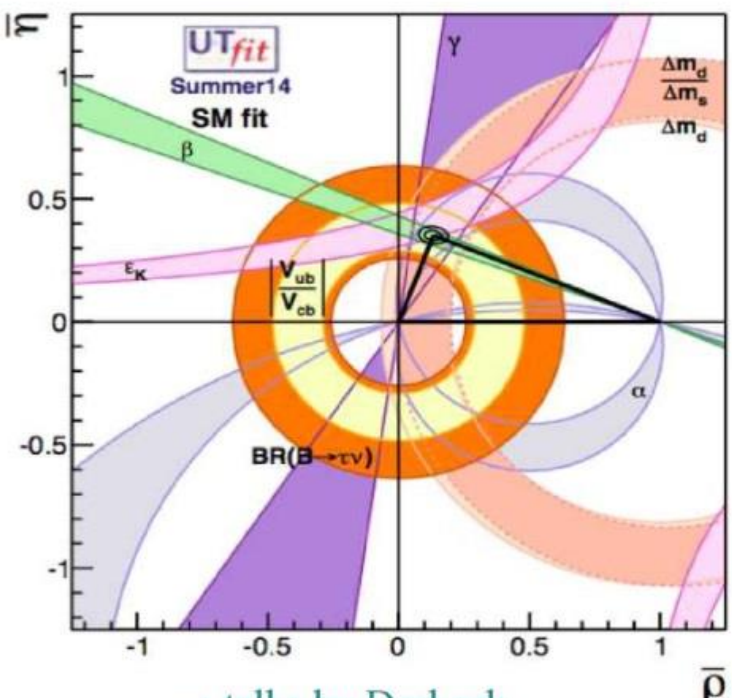
R.Knegjens

See also Charles et al. (1309.2293)

- *Are there other sources of flavor symmetry breaking (beside the SM Yukawa couplings)?*

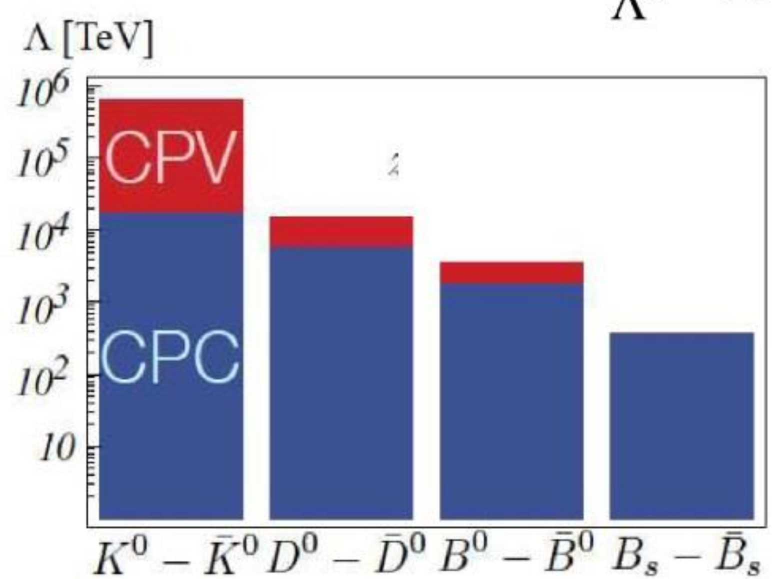
- *What determines the observed pattern of quark & lepton mass matrices?*

That's the question addressed by precision measurements (& searches) of flavor-changing processes of quarks & charged-leptons → So far everything seems to fit well with the SM→ Strong limits on NP



→ talks by Derkach

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda^2} O_{\Delta F=2}$$



Kamenik '13, G.I. '13, ...
[*wide literature*]

The sensitivity of $\Delta F=2$ processes to scales $\Lambda_{NP} > 1000$ TeV is impressive !!!

Yet Three points to be made in this talk

1 New Physics at these scales cannot be measured in K, B_s, B_d, D rare decays (NP effects negligible)

↓

2 We cannot learn much about the nature of this physics through $\Delta F=2$ processes and Effective Theory approach except when flavour symmetries $U(3)^3$ (MFV), $U(2)^3$ are involved.

3 We need badly rare decays to learn about physics beyond the LHC.

? What are the maximal scales at which NP can be seen in rare K, B_s, B_d, D decays?

L and R Quark Couplings in Tree Level FCNCs

ΔF=2 — Cannot distinguish between L and R (square)

$$\varepsilon_K,\ \Delta M_{s,d} \sim a g_L^2 + a g_R^2 + c\, g_L g_R$$

|c| >> |a|
Hadronic matrix elements + RG

K: $c \sim 150\, a$ $B_{s,d}$: $c \sim 7\, a$

ΔF=1 — Can distinguish between L and R

L → R

A Decays governed by V-quark couplings (γ_μ) : $K^+ \to \pi^+ \nu\bar{\nu},\ K_L \to \pi^0 \nu\bar{\nu},\ B \to K \nu\bar{\nu}$ — No sign flip in NP contribution

B Decays governed by A-quark couplings ($\gamma_\mu \gamma_5$) : $K_L \to \mu^+\mu^-,\ B_{s,d} \to \mu^+\mu^-,\ B \to K^* \nu\bar{\nu}$ — Sign flip in NP contribution

L → R ⇒ Correlations A ↔ B change to Anticorrelations A ↔ B

DNA - Charts

1306.3755

AJB + Girrbach

- SM-like

- suppression relative to SM

- enhancement relative to SM

correlation

anti-correlation

DNA - Charts

1306.3755

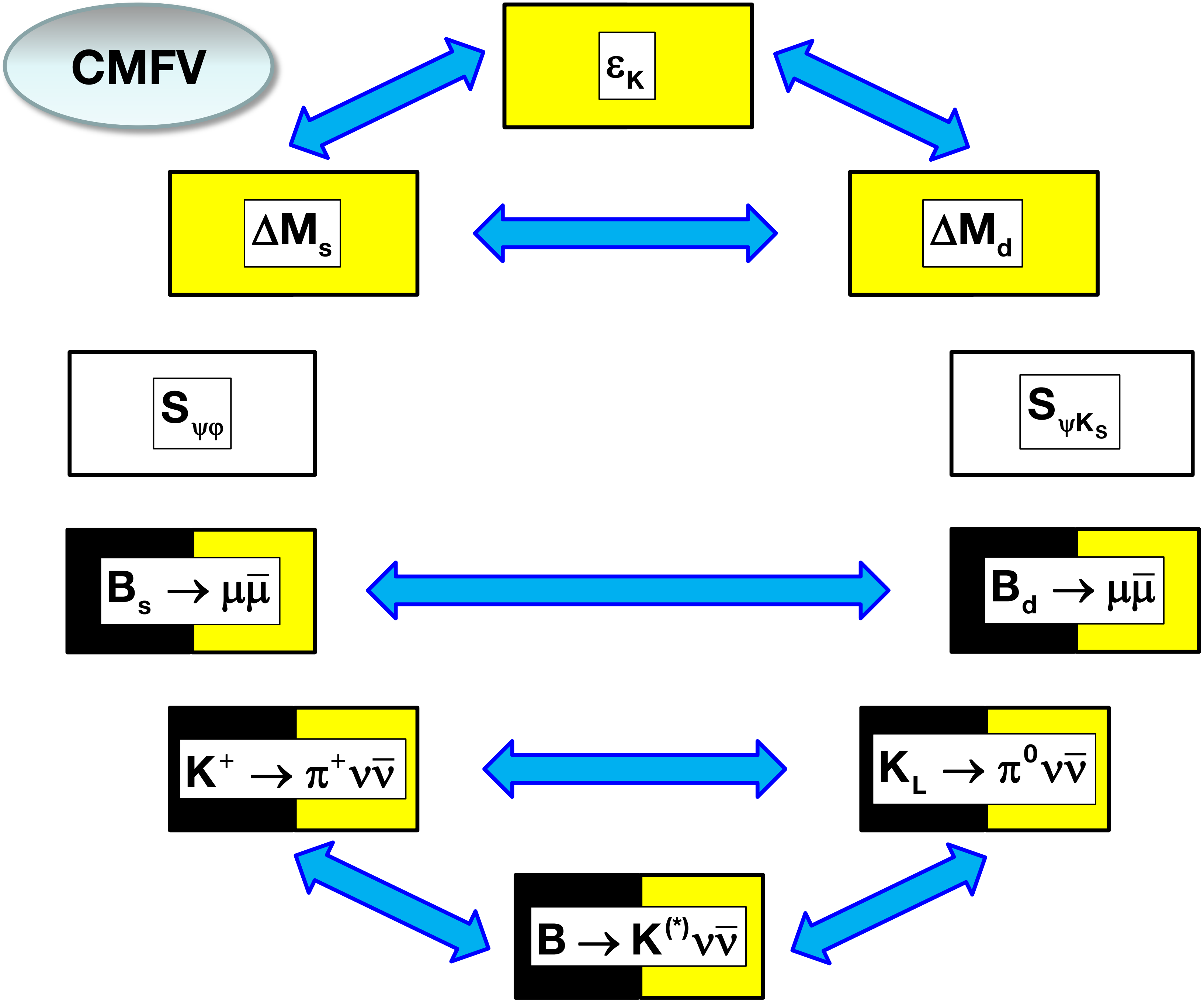
AJB + Girrbach

- SM-like
- suppression relative to SM
- enhancement relative to SM

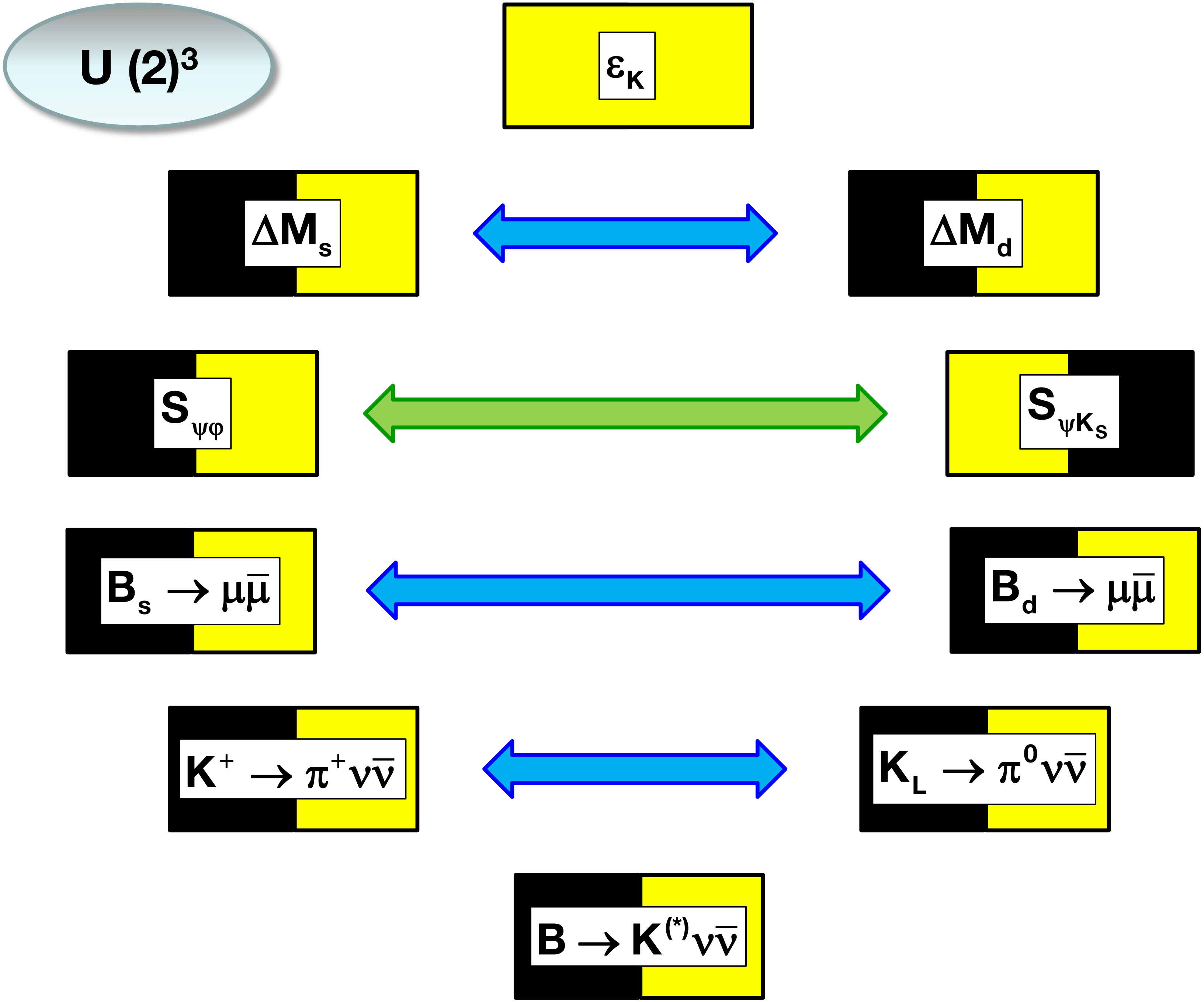
correlation

anti-correlation

Searching for New Physics on the Way to Zeptouniverse



CMFV
ε_K
ΔM_s
ΔM_d
$S_{\psi\varphi}$
$S_{\psi K_S}$
$B_s \to \mu\bar{\mu}$
$B_d \to \mu\bar{\mu}$
$K^+ \to \pi^+\nu\bar{\nu}$
$K_L \to \pi^0\nu\bar{\nu}$
$B \to K^{(*)}\nu\bar{\nu}$



$U(2)^3$
ε_K
ΔM_s
ΔM_d
$S_{\psi\varphi}$
$S_{\psi K_S}$
$B_s \to \mu\bar{\mu}$
$B_d \to \mu\bar{\mu}$
$K^+ \to \pi^+\nu\bar{\nu}$
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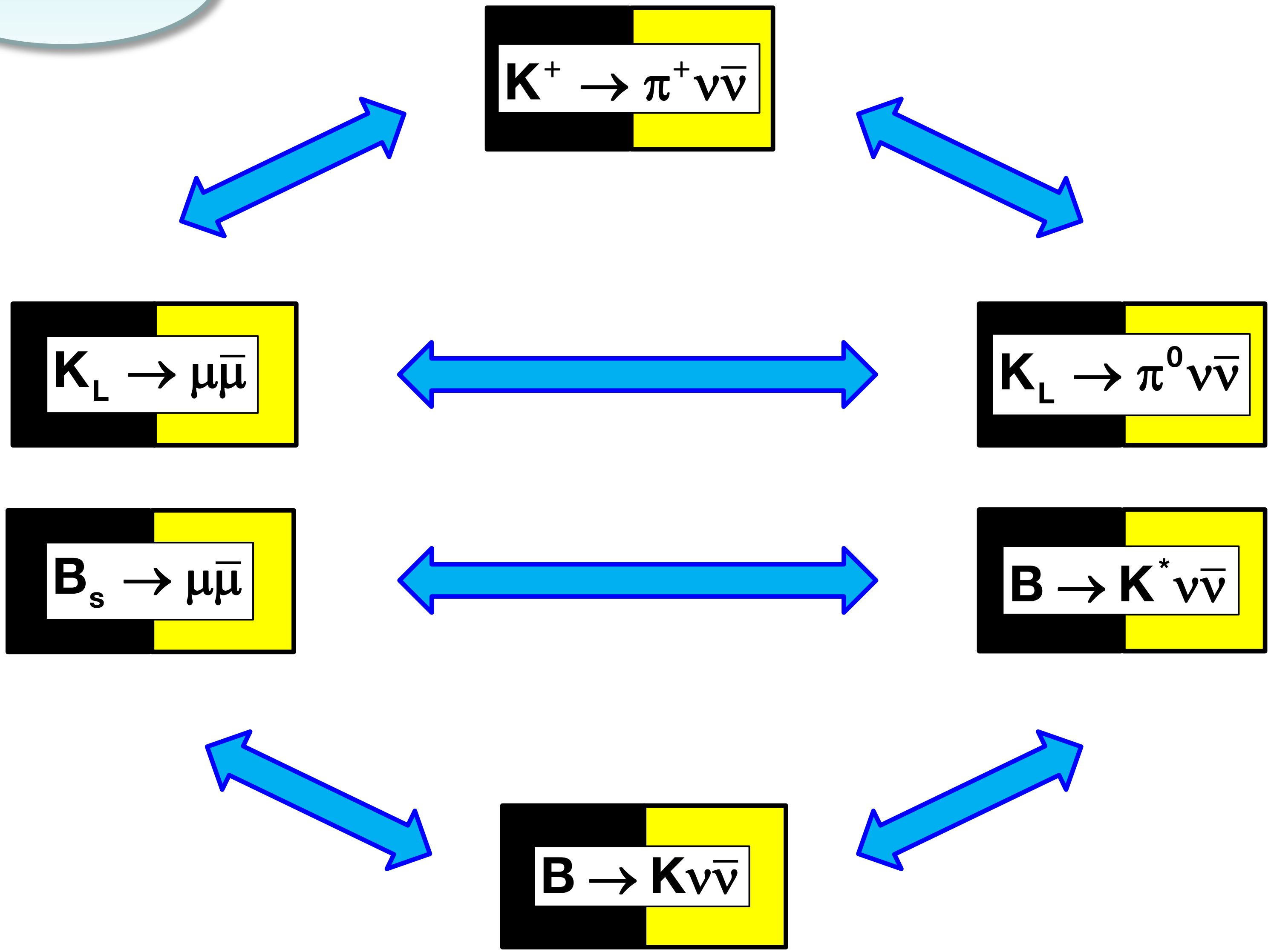
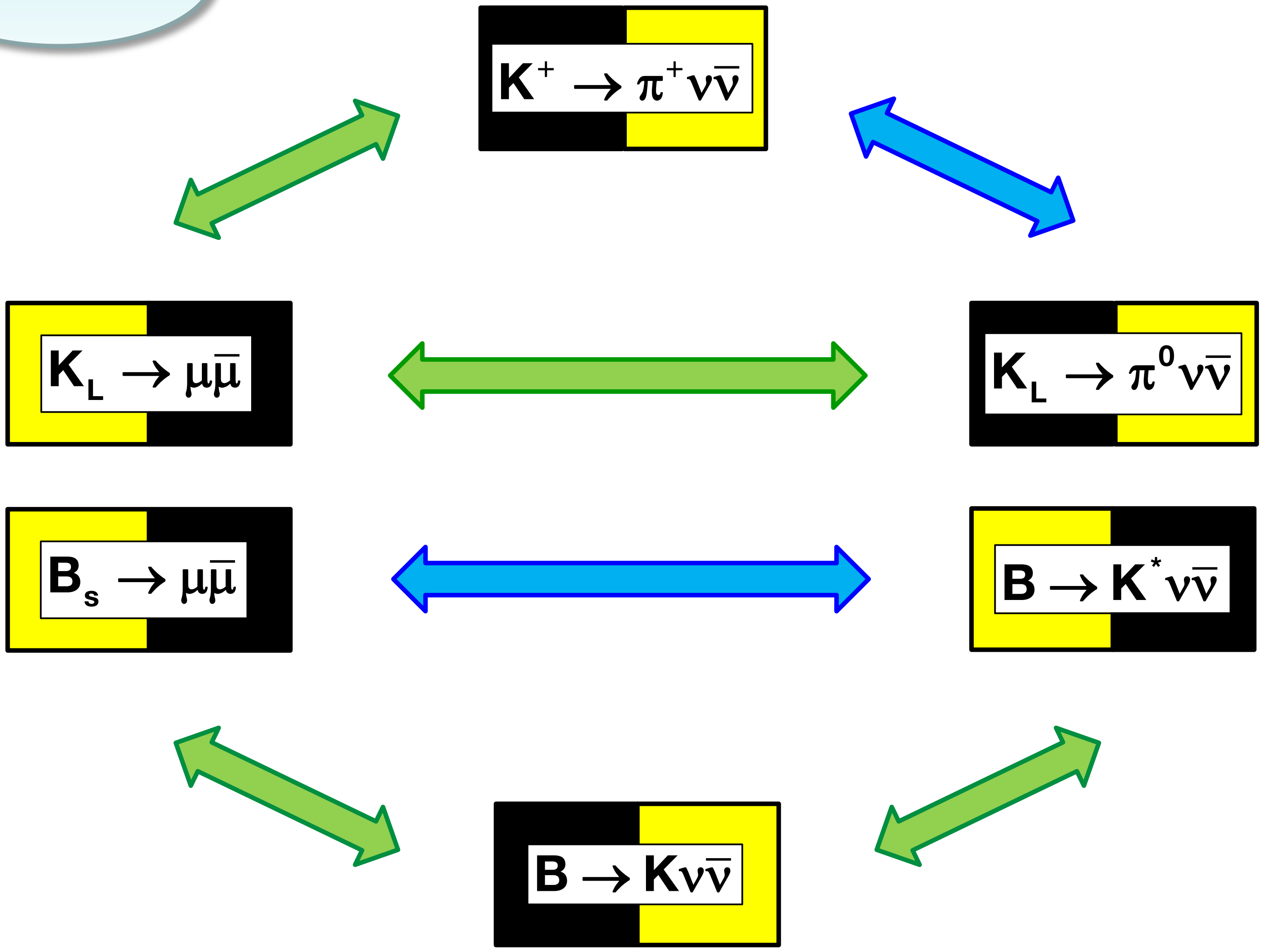
Z′/Z LHS



$K^+ \to \pi^+ \nu\bar{\nu}$
$K_L \to \mu\bar{\mu}$
$K_L \to \pi^0 \nu\bar{\nu}$
$B_s \to \mu\bar{\mu}$
$B \to K^* \nu\bar{\nu}$
$B \to K \nu\bar{\nu}$

Z′/Z RHS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Can we reach Zeptouniverse through Quark Flavour Physics ?

AJB, Buttazzo, Girrbach-Noe, Knegjens, 1407.0728

Due to limits of theory and experiment the answer depends on whether Zeptouniverse is “populated“ by

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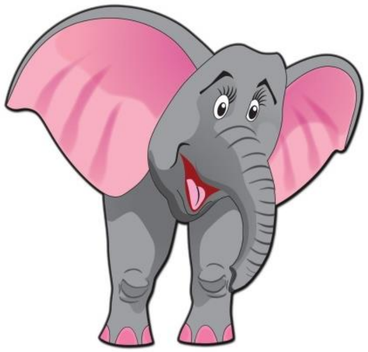

In QFT :

Large couplings

(still consistent with perturbativity)

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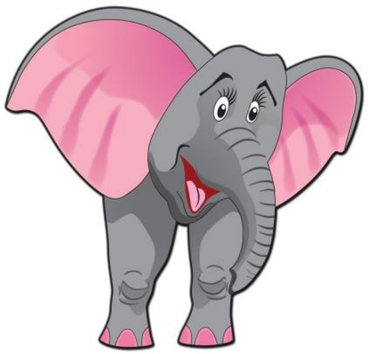

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Moderate couplings

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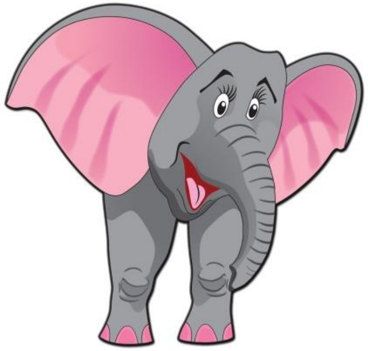
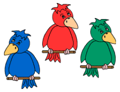




In QFT :

Large couplings

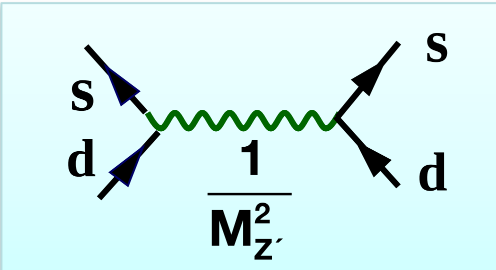
(still consistent with perturbativity)

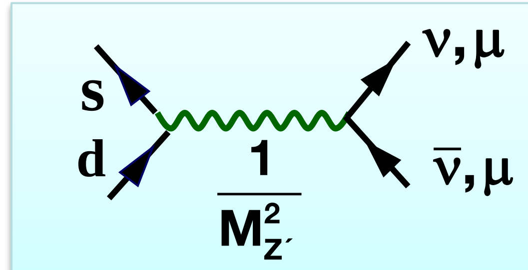
Moderate couplings

Small couplings

Answer within Z´-Models

(Stringent correlations between $\Delta F=2$ and $\Delta F=1$)





Similar for B_s, B_d, D,…

For fixed lepton couplings, after $\Delta F=2$ constraints, NP effects in rare decays decrease as $1/M_{Z'}$

Strategy:

Assume largest g_{ij} and $g_{\nu\nu}$, $g_{\mu\mu}$ couplings subject to $\Delta F=2$ constraints on g_{sd}, g_{sb}, g_{db}

$g_{ij} \approx 3$ still allowed by perturbativity but often not by $\Delta F=2$ constraints.

NP effects should still be sufficiently large to be able to see correlations.

Main Messages from this Study

(Maximal Resolution of Short Distance Scales)

1

If only g_L or g_R flavour changing Z´ couplings to quarks present and $\Delta F=2$ constraints taken into account:

$K \to \pi\nu\bar{\nu}$	~ 200 TeV	B_d physics:	~ 15 TeV	Maximal scales that can be explored
		B_s physics:	~ 15 TeV	

2

If $g_L = \pm g_R$ the scales are lower:
LR operator in $\Delta F=2$ enhanced through RG + chiral enhancement in ΔM_K, ε_K

→ Smaller couplings

→ Lower scales at which NP dynamics can be tested

3

In order to probe scales above 50 TeV even with B_s, B_d physics we need either left-handed or right-handed elefants:

$g_L \neq g_R$ $\quad$ $g_R \neq 0$ $\quad$ $g_L \neq 0$

but $g_L \gg g_R$ or $g_R \gg g_L$

Allows us to obtain significant NP effects in rare K, $B_{s,d}$ decays while satisfying $\Delta F=2$ constraints

Important: Cannot be distinguished through $\Delta F=2$ observables

(Help from LR operators with some tuning)

But: Can be distinguished through correlations in rare K and B decays

(See DNA Charts)

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

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

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

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

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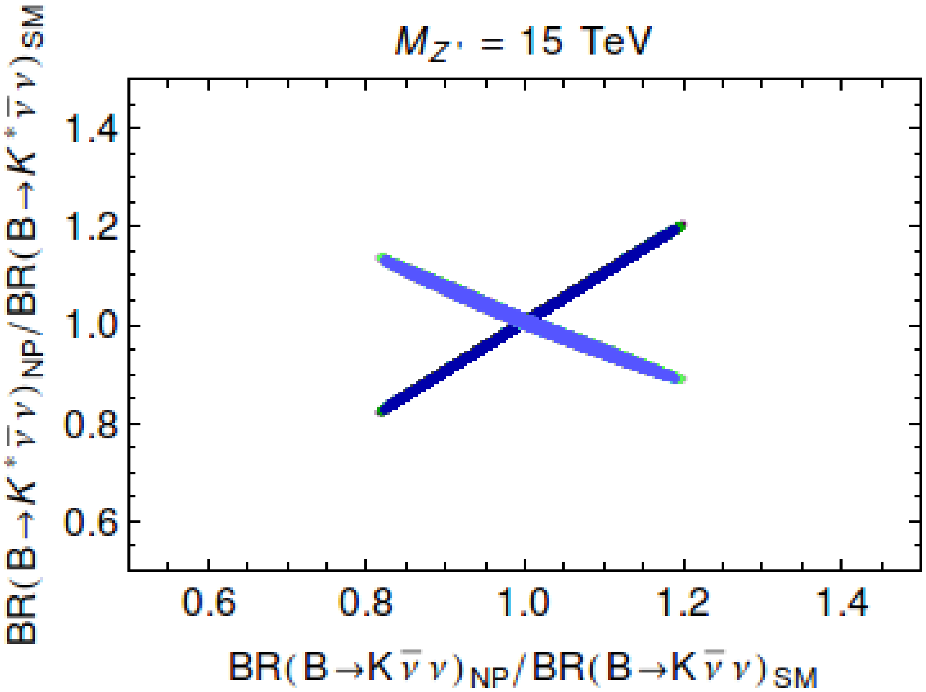
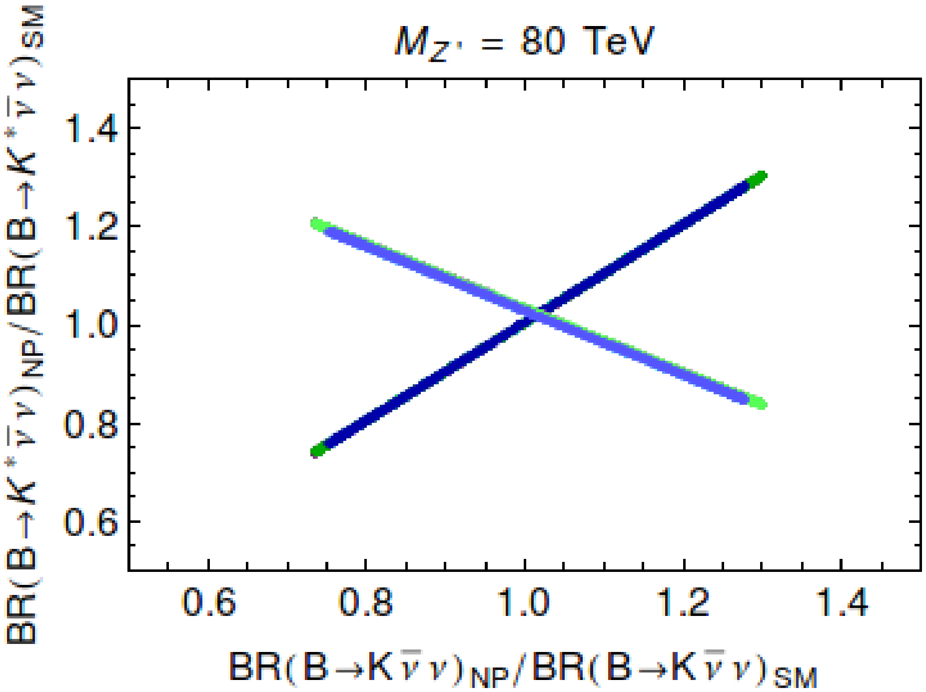
B_s : $\Lambda_{NP}^{max} \simeq 160$ TeV

Yes we can !!

Heavy Z´ at Work

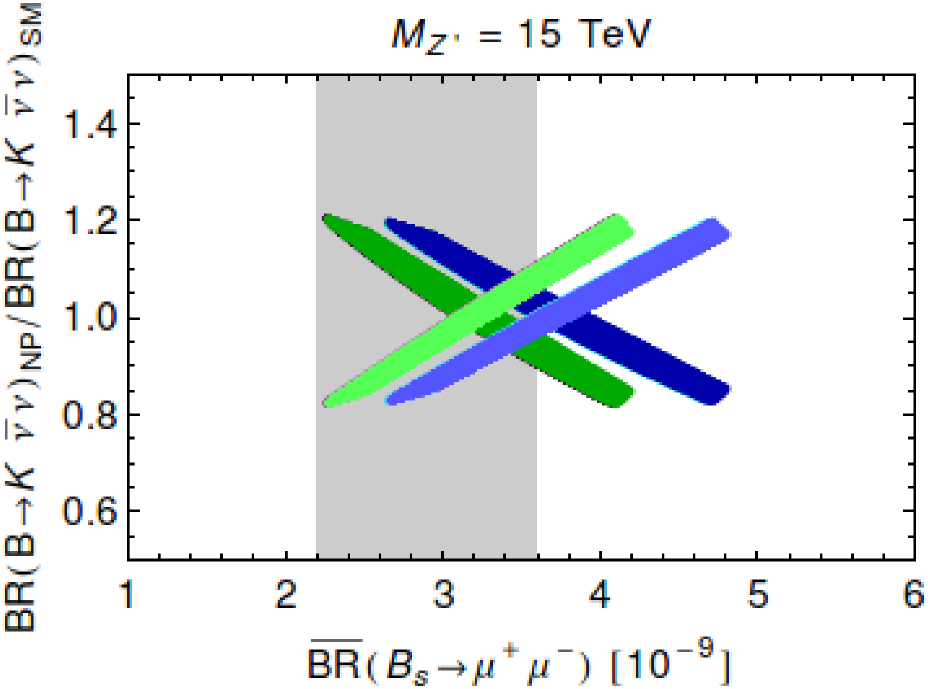


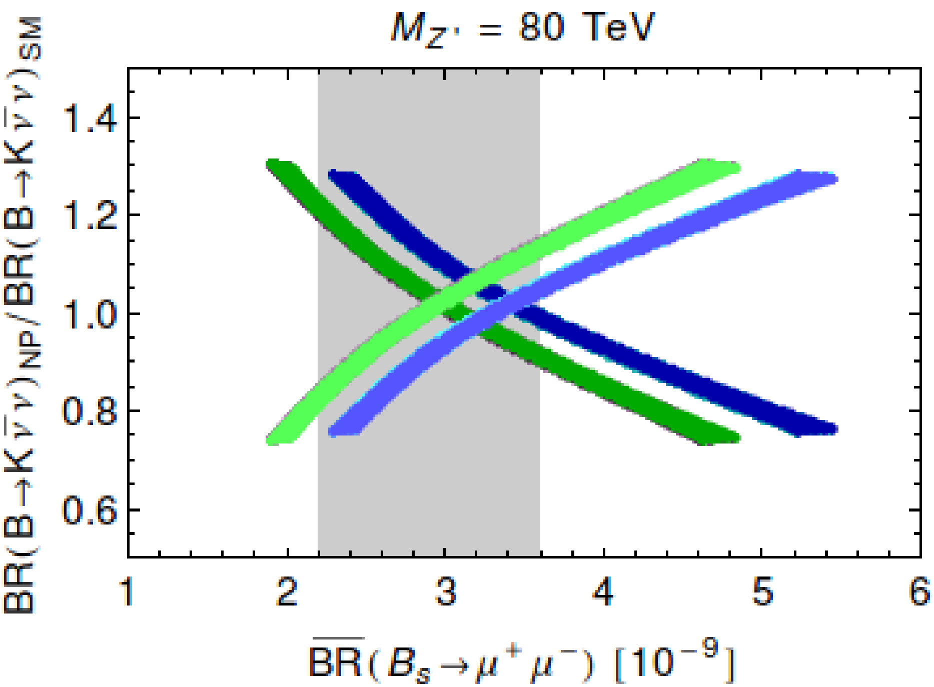


ΔF=2 constraint

No ΔF=2 constraint

Heavy Z´ at Work





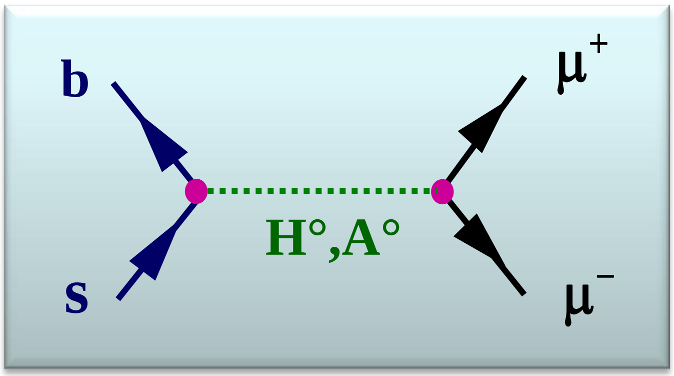
ΔF=2 constraint

No ΔF=2 constraint

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°**