Flavour Expedition to the Zeptouniverse

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ERC Workshop
Mainz, November 2014

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

In our search for a more fundamental theory we need to improve our understanding of Flavour

Present Status

November 2014

1. $$\frac{Br(B_d \to \mu^+\mu^-)}{Br(B_s \to \mu^+\mu^-)} \approx (4.3 \pm 1.8)\left[\frac{Br(B_d \to \mu^+\mu^-)}{Br(B_s \to \mu^+\mu^-)}\right]_{\substack{SM\\CMFV}}$$
   (LHCb, CMS)

2. Anomalies in angular observables in $B_d \to K^* \mu^+\mu^-$ (LHCb)

   ?

3. $B \to D^* \tau\nu,\ B \to D\tau\nu$ (2-3 σ) (BaBar)
   (4 σ) (+ Belle)

4. Breakdown of Lepton-Universality in $B^+ \to K^+ l^+ l^-$

5. Some Tensions in UT-fits (present already since 2008)

2015-2025 : Expedition
Attouniverse $\to$ Zeptouniverse
10^{-18}m $\to 10^{-21}$m

Quark Flavour Physics =

2015-2025 : Expedition
Attouniverse → Zeptouniverse
10^{-18}m →10^{-21}m

Quark Flavour Physics =

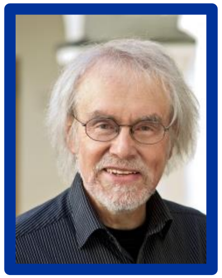
Searching for New Physics on the Way to Zeptouniverse

Searching for New Physics on the Way to Zeptouniverse

21st Century

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

Present ERC Flavour Team



AJB

J.Girrbach-Noe

G.Isidori

S.Pokorski

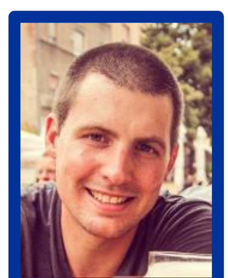
F. De Fazio

D.Buttazzo

G.Buchalla

A.Ibarra

C.Bobeth



R.Knegjens

M.Ratz

O.Cata

Basic Questions for Next 28min

1. Can Quark Flavour Physics give us insight into the dynamics at very SD scales if no direct clear signal of NP will be seen at the LHC? No new particles below 6 TeV.

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

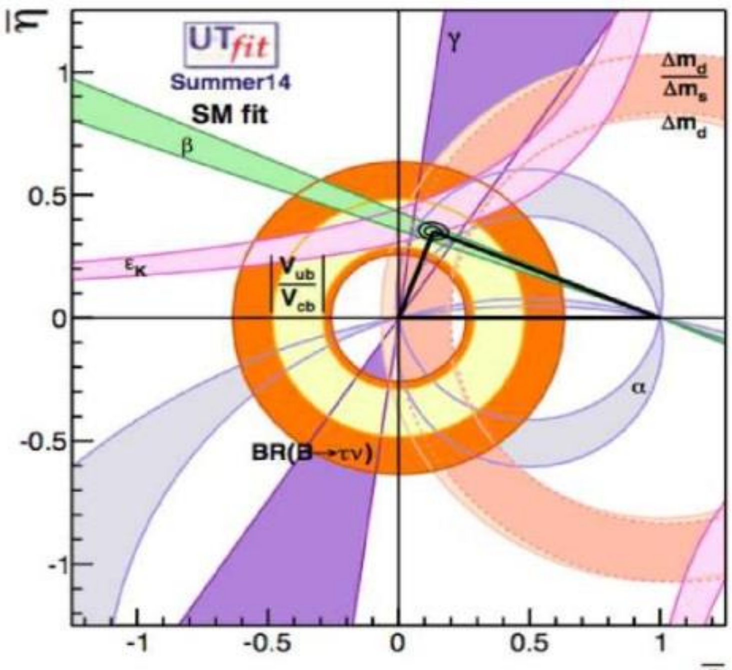
3. Which Processes could give us the best resolution of SD scales?

See also Charles et al. (1309.2293)

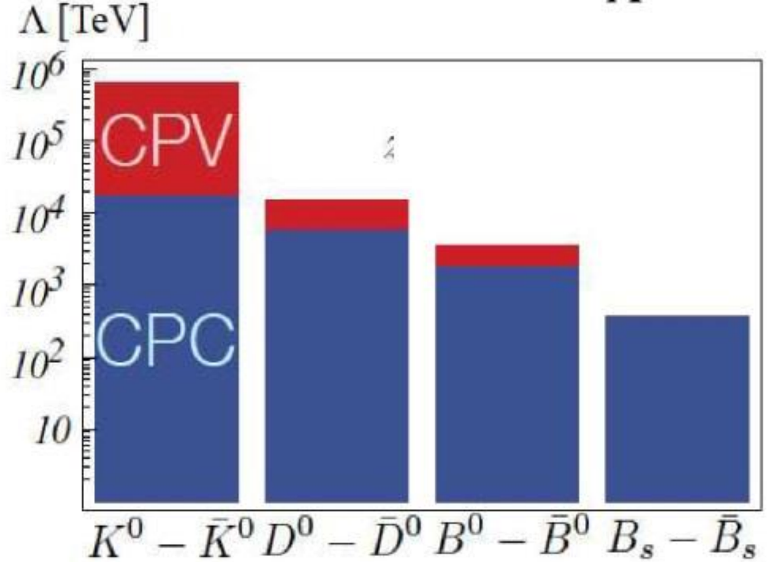
- *Are there other sources of flavor symmetry breaking (beside the SM Yukawa couplings)?*
- *What determines the observed pattern of quark & lepton mass matrices?*

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

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



→ talks by Derkach



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?

Three Basic Requirements

1 **Precise CKM parameters from tree level decays (negligible NP contributions)**

Main Targets : $|V_{ub}|,\ |V_{cb}|,\ \gamma$

2 **Precise Lattice QCD Calculations**

Main Targets : $F_{B_s}, F_{B_d}, \hat{B}_{B_d}, \hat{B}_{B_s}, B_8^{(2/3)}, B_6^{(1/2)}$ $+$ formfactors $(B \to K^*, K)$

Significant progress in the last years (dynamical fermions) but higher precision needed in order to see small NP effects.

Determination of $|V_{ub}|$ and $|V_{cb}|$ Crucial for Identification of New Physics

AJB + Girrbach-Noe, 1306.3755 ⇦ (Dependently on $|V_{ub}|$ and $|V_{cb}|$ different NP is required to fit the data)

Crivellin + Pokorski; 1407.1320
(NP explanation in the difference between exclusive and inclusive determinations currently ruled out)

Scenarios

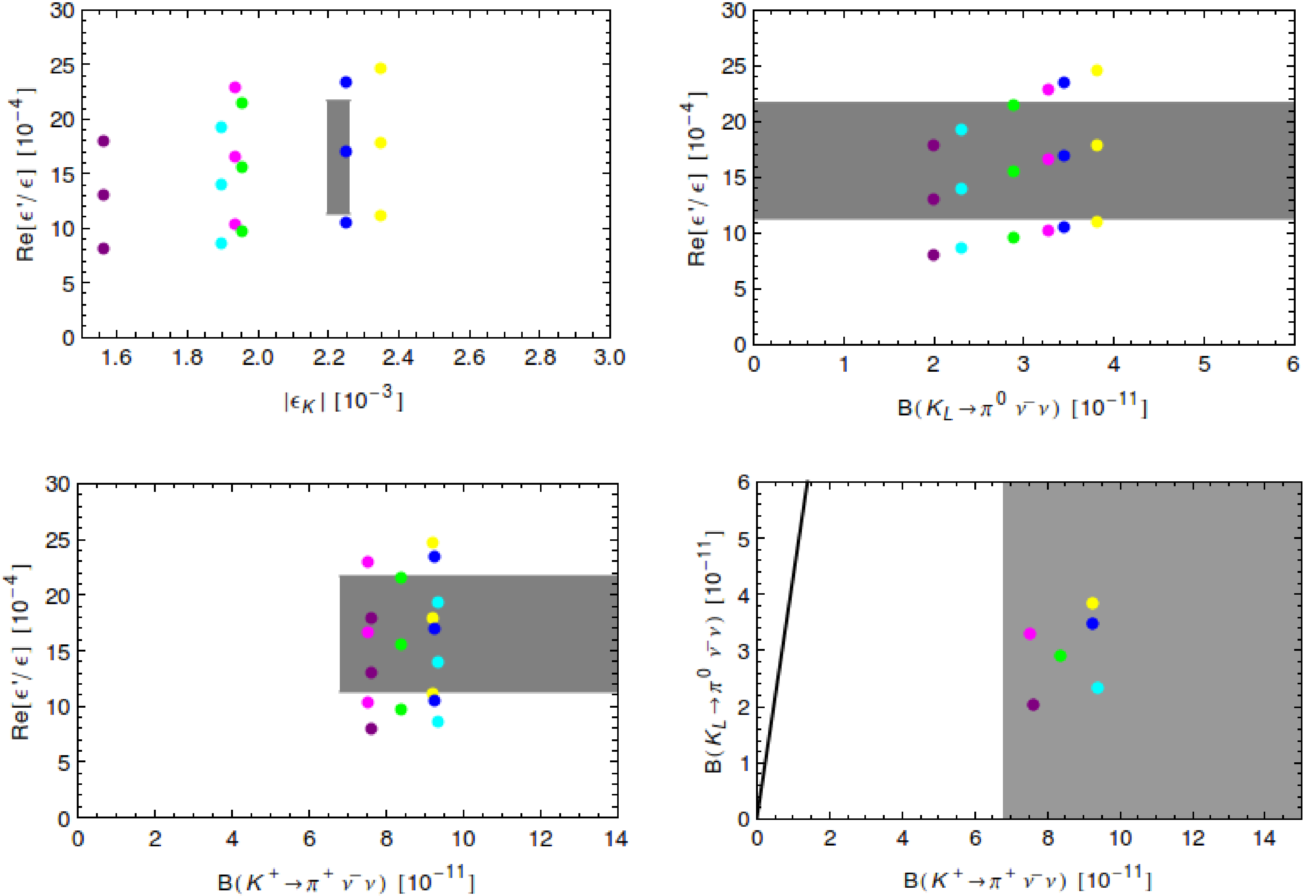
$\vert V_{ub}\vert \cdot 10^{-3}$	$\vert V_{cb}\vert \cdot 10^{-3}$
3.2	39.0
3.2	42.0
4.1	39.0
4.1	42.0
3.7	40.5
3.9	42.0

Data

$$10^3 |V_{ub}|_{exc} \approx 3.4 \pm 0.3$$
$$10^3 |V_{ub}|_{inc} \approx 4.3 \pm 0.3$$
$$10^3 |V_{cb}|_{exc} \approx 39 \pm 1.0$$
$$10^3 |V_{cb}|_{inc} \approx 42 \pm 1.0$$

AJB, De Fazio, Girrbach-Noe, 1404.3824

SM Predictions for different $|V_{ub}|$, $|V_{cb}|$



3

NLO + NNLO QCD Corrections and NLO Electroweak Corrections to Wilson Coefficients

1988 - 2014

Task completed !!

26 Years !

AJB: 1102.5650 (Update, Sept. 2014)

Most recent

NLO Electroweak to $B_{s,d} \to \mu^+\mu^-$

NNLO QCD to $B_{s,d} \to \mu^+\mu^-$

Bobeth, Gorbahn, Stamou

Hermann, Misiak, Steinhauser

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

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

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

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

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

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

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

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 (↑ $\hat{B}_s$)

In Order to identify New Physics through Flavour Physics

We need

1. **Many precision measurements of many observables and precise theory.**

2. **Study Patterns on Flavour Violation in various New Physics models (correlations between many flavour observables).**

…and

3. Correlations between low energy flavour observables and Collider Physics (LHC, Tevatron)

Here top-down approach more powerful in flavour physics

Study of Flavour Violation in NP Models more powerful

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 New SM 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. $B^+ \to \tau^+\nu_\tau$
6. $B \to X_s\gamma$
   $B \to K^*\gamma$
7. $B \to X_s l^+l^-$
   $B \to K^*(K) l^+l^-$
8. $K \to \pi\nu\bar{\nu}$
9. $B \to X_s\nu\bar{\nu}$
   $B \to K^*(K)\nu\bar{\nu}$
10. ε'/ε
11. Charm
    Top
12. LFV, EDMs
    $(g-2)_{\mu,e}$

Superstars and Stars of Quark Flavour Physics

Superstars

ε_K, ΔM_s, ΔM_d, $S_{\psi K_S}$	(TH)
$B_s \to \mu^+\mu^-$, $B_d \to \mu^+\mu^-$, $S_{\psi\varphi}\left(\varphi_s\right)$	(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) $\approx$ 0.65 ± 0.05 (UK-QCD)

The Power of Correlations between Flavour Observables (Correlation Primer)

Crucial Tool for exploring Attouniverse → Zeptouniverse

Important Messages

1. Correlations between decays of a given meson test the Dirac structure of couplings.

2. Correlations between decays of different mesons test the flavour structure of couplings (flavour symmetries).

Stressed by Monika Blanke (CKM 2014)

Two Simplest General Frameworks

MFV (CMFV) $U(3)^3$

(symmetry between 3 generations)

Stringent Correlations between K, B_s, B_d

No new sources of flavour and CP violation

$$S_{\psi K_s} = \sin 2\beta \quad , \quad S_{\psi\varphi} = S_{\psi\varphi}^{SM} = \text{small}$$

No Right-handed currents

$U(2)^3$ Flavour Symmetry

(symmetry between two light generations)

Stringent Correlations between B_s and B_d

Correlations $K \leftrightarrow B_{s,d}$ absent

New sources of CP violation in B_s, B_d but

$S_{\psi K_s} \leftrightarrow S_{\psi\varphi}$ anticorrelated

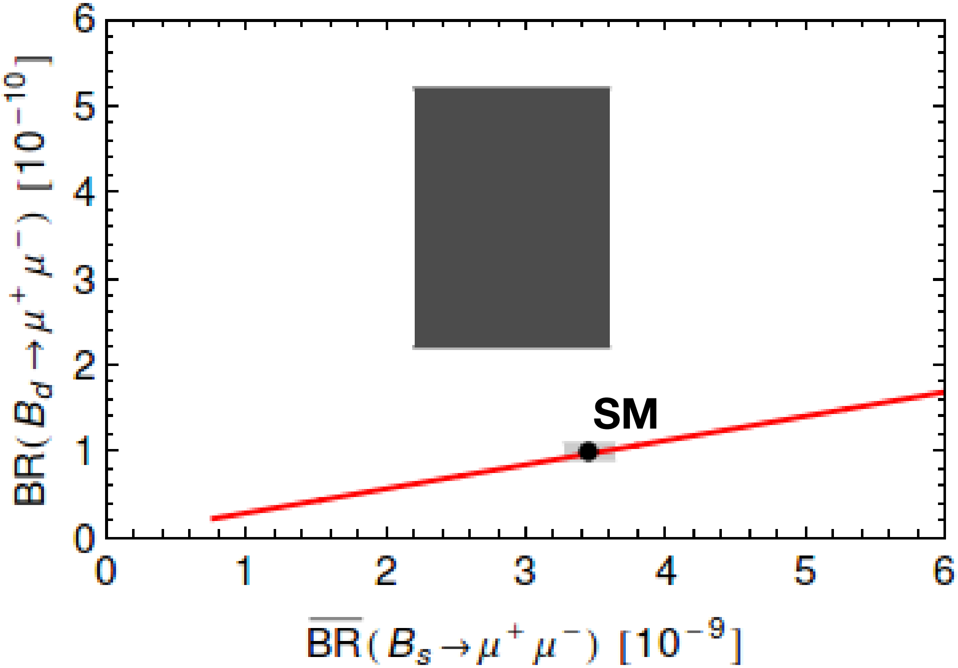
Right-handed currents strongly suppressed

Constrained Minimal Flavour Violation

$[U(3)]^3$ flavour symmetry

Valid also in $U(2)^3$

AJB
Hurth, Isidori, Kamenik, Mescia



Golden Relation

$$\frac{Br(B_s \to \mu^+\mu^-)}{Br(B_d \to \mu^+\mu^-)} = \frac{\hat{B}_d}{\hat{B}_s}\frac{\tau(B_s)}{\tau(B_d)}\frac{\Delta M_s}{\Delta M_d}$$

AJB 2003

$$\hat{B}_d / \hat{B}_s \simeq 0.99 \pm 0.02 \quad \text{(tmQCD)}$$

No CKM
No weak decay constants

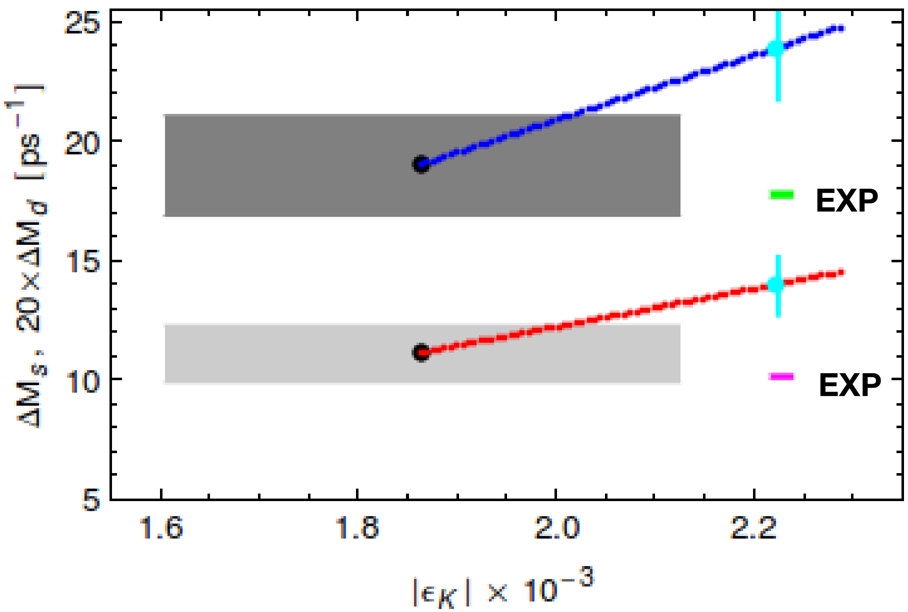
$$\overline{Br}(B_s \to \mu^+\mu^-) = (2.8 \pm 0.7) \cdot 10^{-9}$$

$$Br(B_d \to \mu^+\mu^-) = \left(3.6^{+1.6}_{-1.4}\right) \cdot 10^{-10}$$

(LHCb + CMS)

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

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



AJB + Girrbach 1306.3755

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

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

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

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

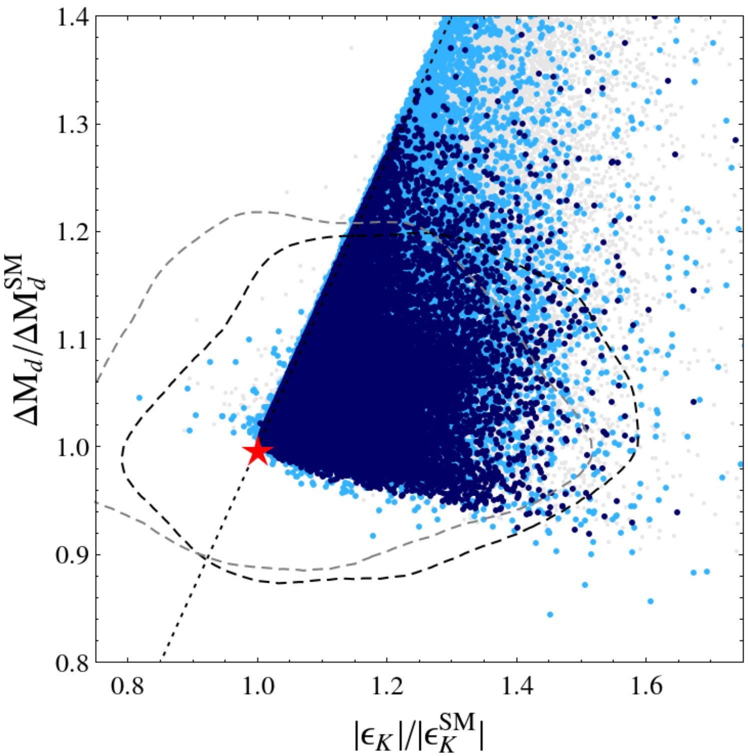
Lunghi + Soni (2008)
AJB + Guadagnoli (2008)

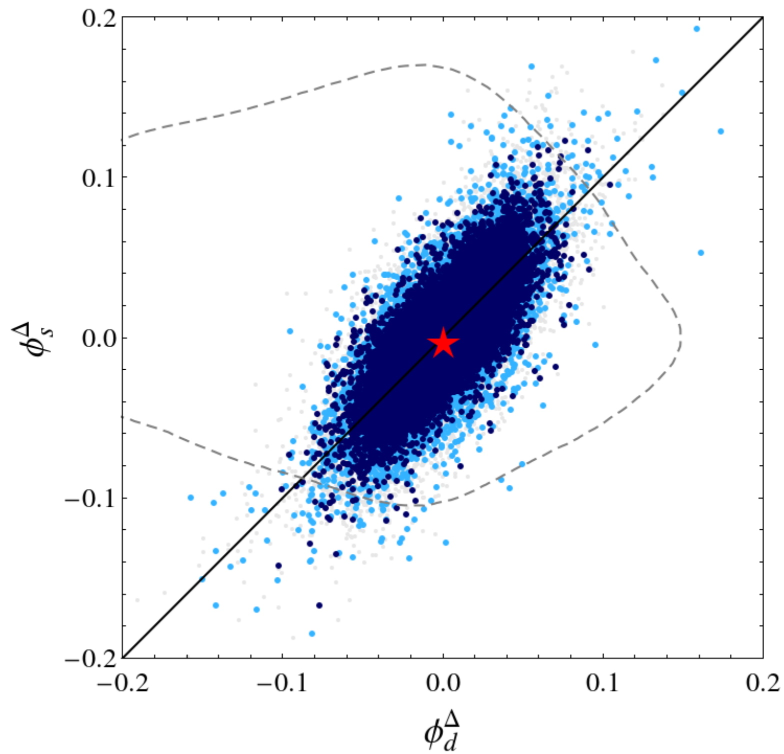
*) Can still work within MFV
($\Delta\varepsilon_K > 0$ in MFV) Blanke + AJB (2006)

Both tensions can only be clarified through improved $|V_{ub}|$, $|V_{cb}|$ + Lattice Input and improved measurement of $S_{\psi K_s}$

ΔF=2 Observables in Split-Family or "Natural" SUSY with U(2)³ Flavour Symmetry

Barbieri, Buttazzo, Sala, Straub (2014)





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

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

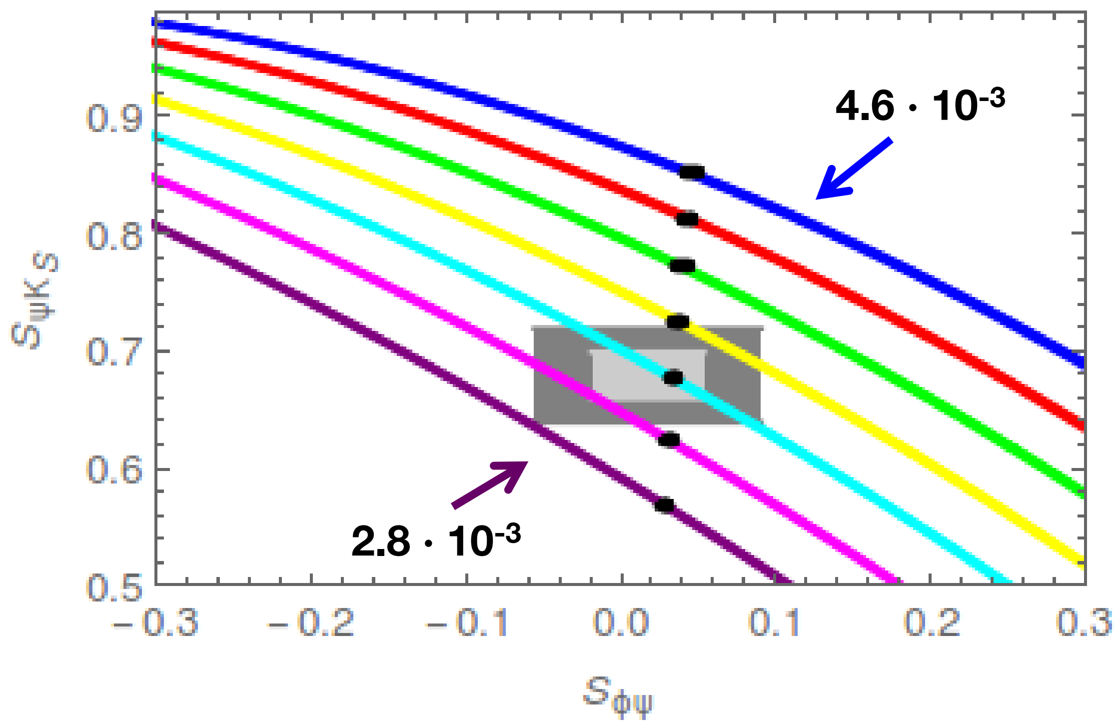
Tensions removed

$$S_{\psi K_s} = \sin(2\beta + \varphi_d^\Delta)$$
$$S_{\psi\varphi} = \sin(2|\beta_s| - \varphi_s^\Delta)$$
$$\varphi_d^\Delta = \varphi_s^\Delta$$

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



Assuming absence of RH currents

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

L and R Quark Couplings in Tree Level FCNCs

$\Delta F=2$ — 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: $c \sim 150\ a$ $B_{s,d}$: $c \sim 7\ a$

$\Delta F=1$ — Can distinguish between L and R

A Decays governed by V-quark couplings (γ_μ) : $K^+ \to \pi^+ \nu\bar{\nu},\ K_L \to \pi^0 \nu\bar{\nu},\ B \to K \nu\bar{\nu}$

$L \to R$: No sign flip in NP contribution

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

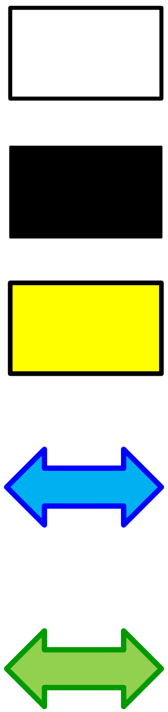
Sign flip in NP contribution

$L \to R$ ⇒ Correlations $A \leftrightarrow B$ change to Anticorrelations $A \leftrightarrow B$

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

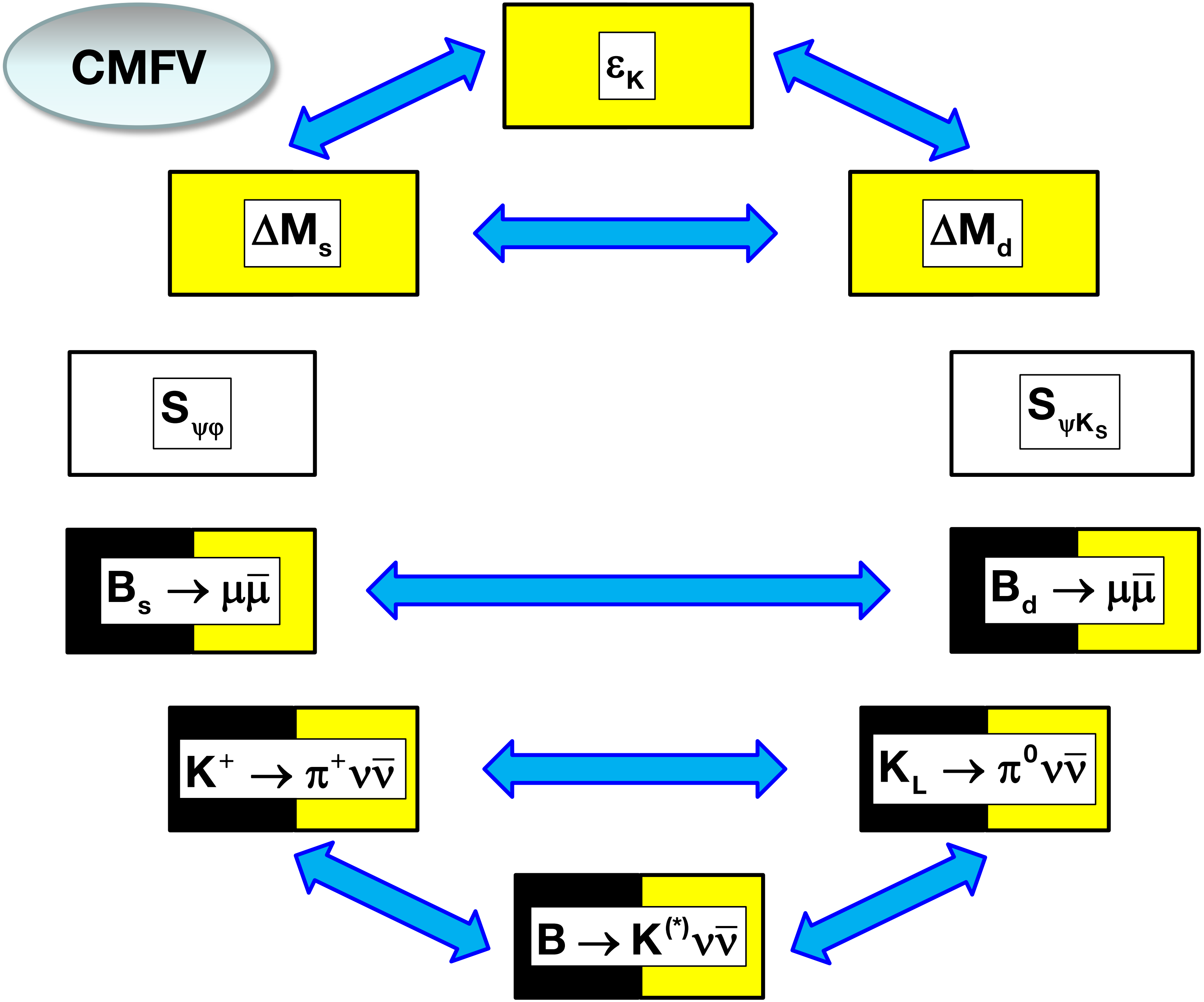
- suppression relative to SM

- enhancement relative to SM

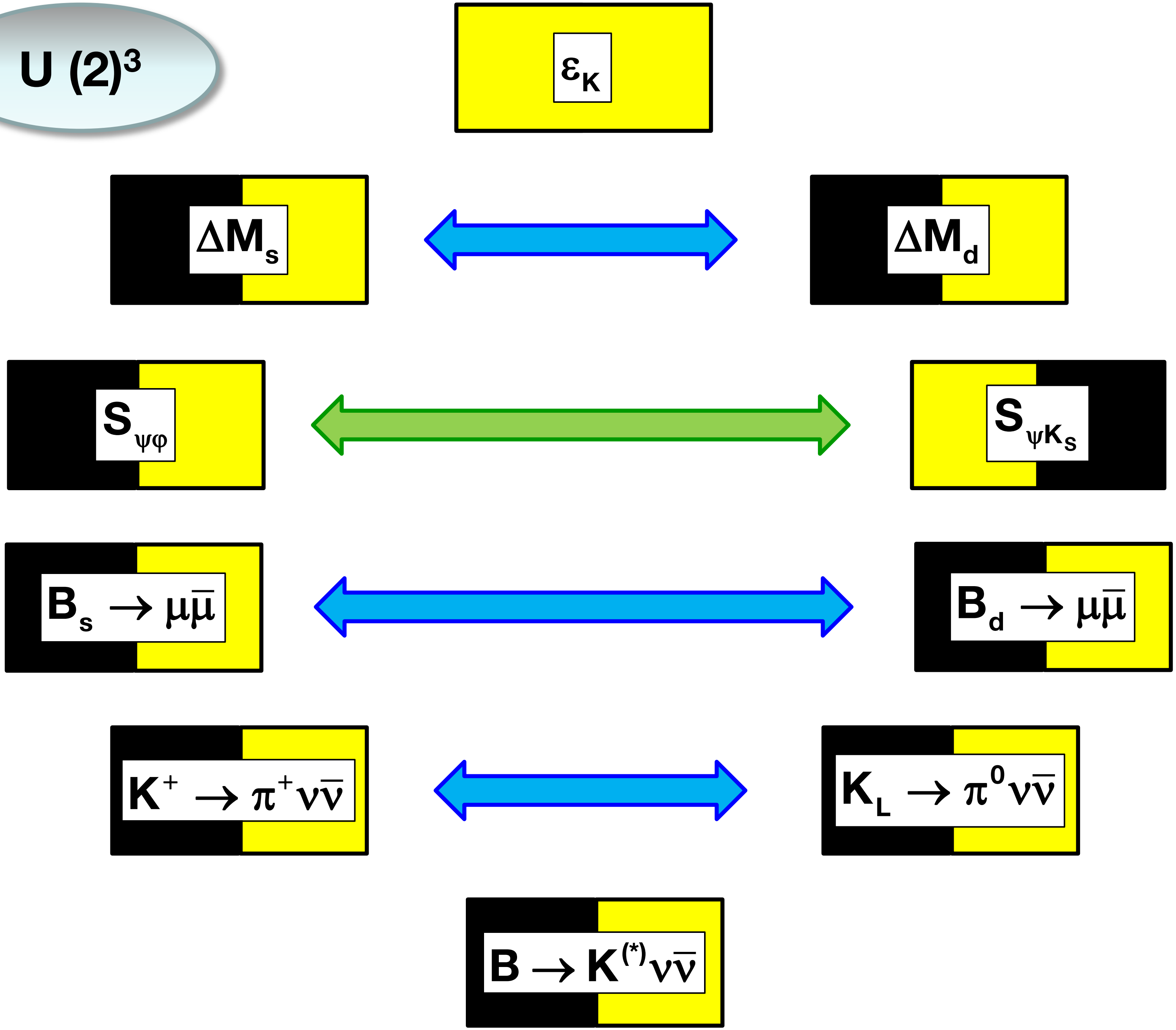
correlation

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
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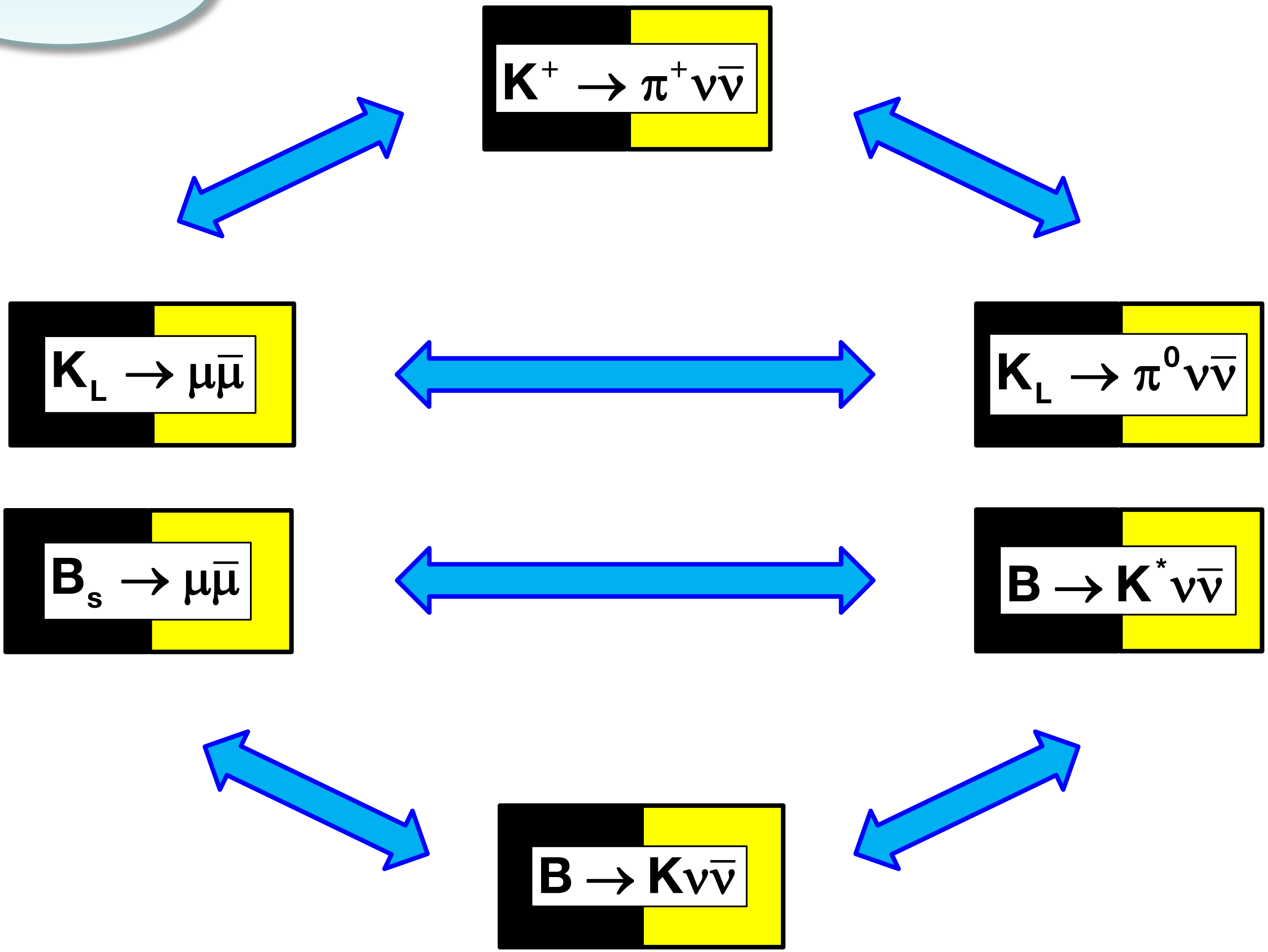
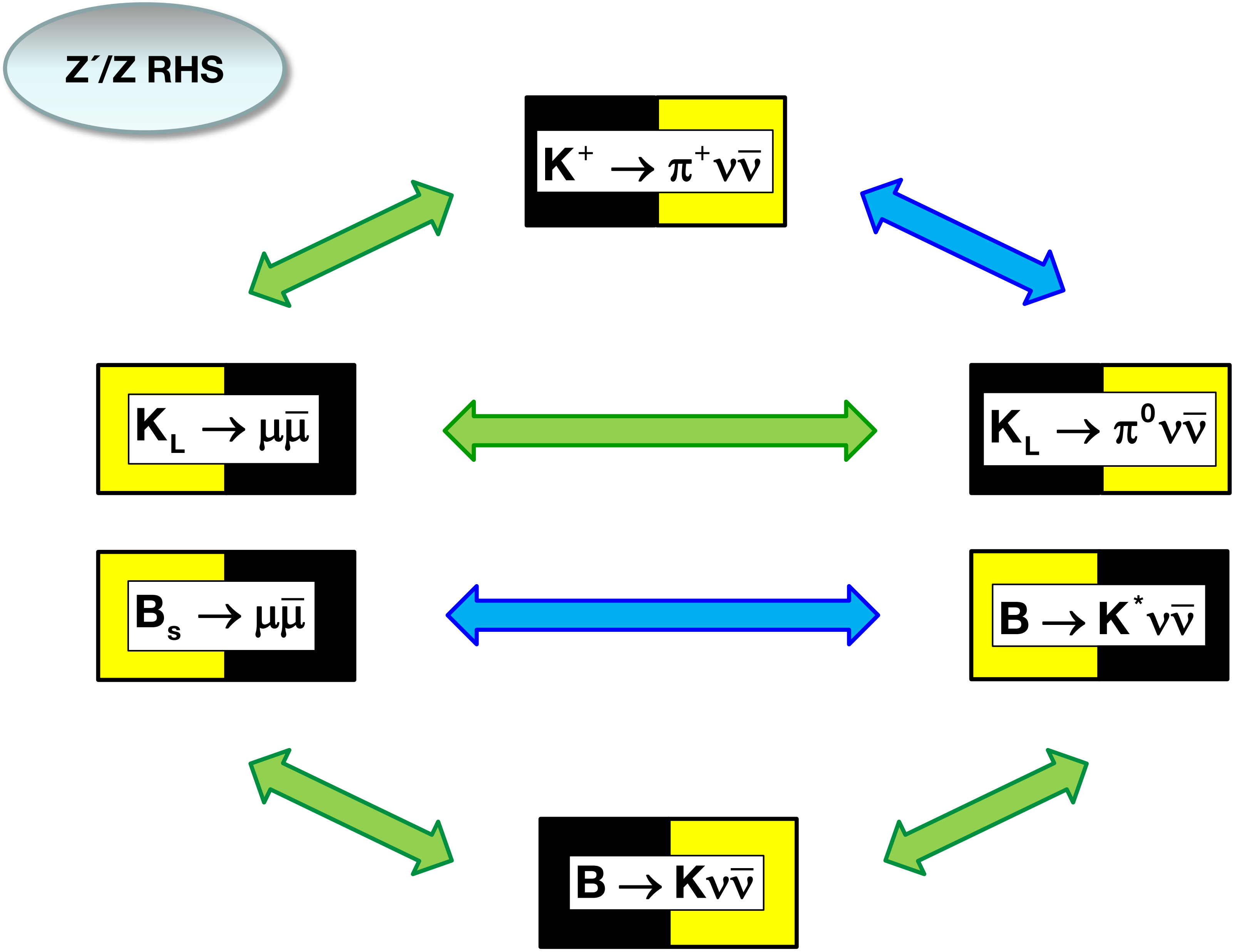
Z′/Z LHS



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


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

3 Correlated Anomalies

(LHCb)

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

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

$$R_{K^*\mu\mu} = \frac{Br\left(B^0 \to K^{*0}\mu^+\mu^-\right)^{[15,22]}}{Br\left(B^0 \to K^{*0}\mu^+\mu^-\right)^{[15,22]}_{SM}} < 1$$

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

Can be reproduced by Z or Z´ with left-handed FCNC couplings.

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

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

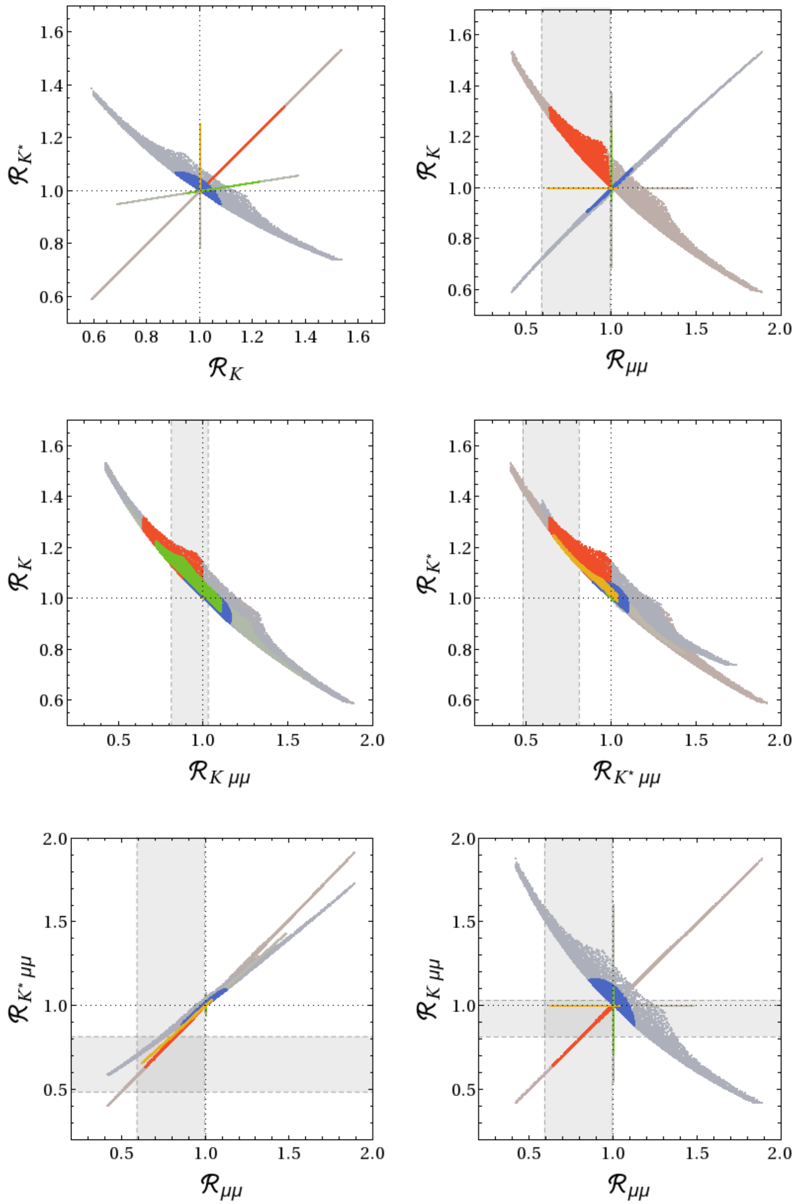
$R_{K^*(K)} \equiv R_{K^*(K)\nu\bar{\nu}}$
can distinguish between
Z and Z´ solution

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

AJB
Girrbach-Noe
Niehoff
Straub

1409.4557

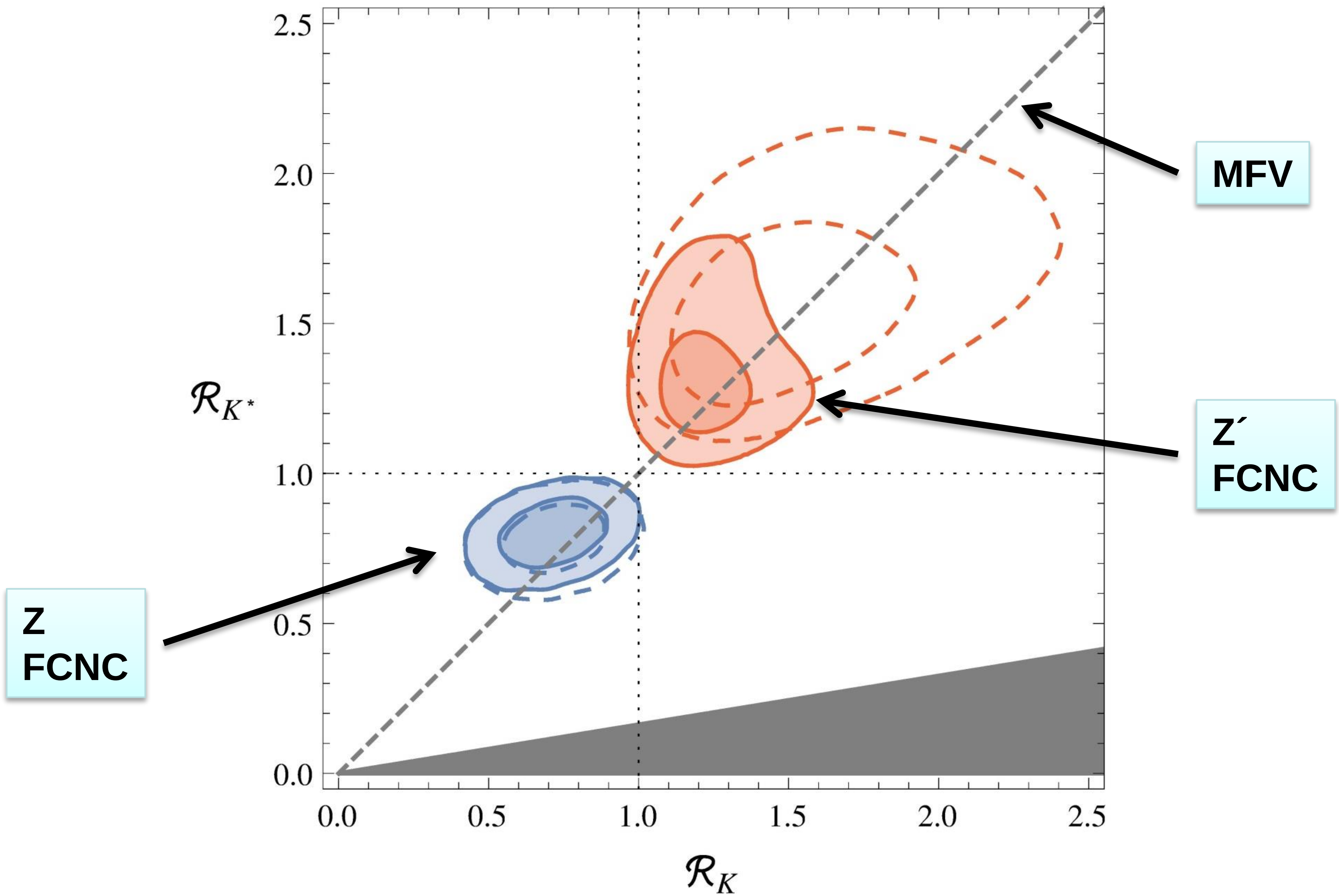
Z´



- **LHS**
- **RHS**
- **LRS**
- **ALRS**

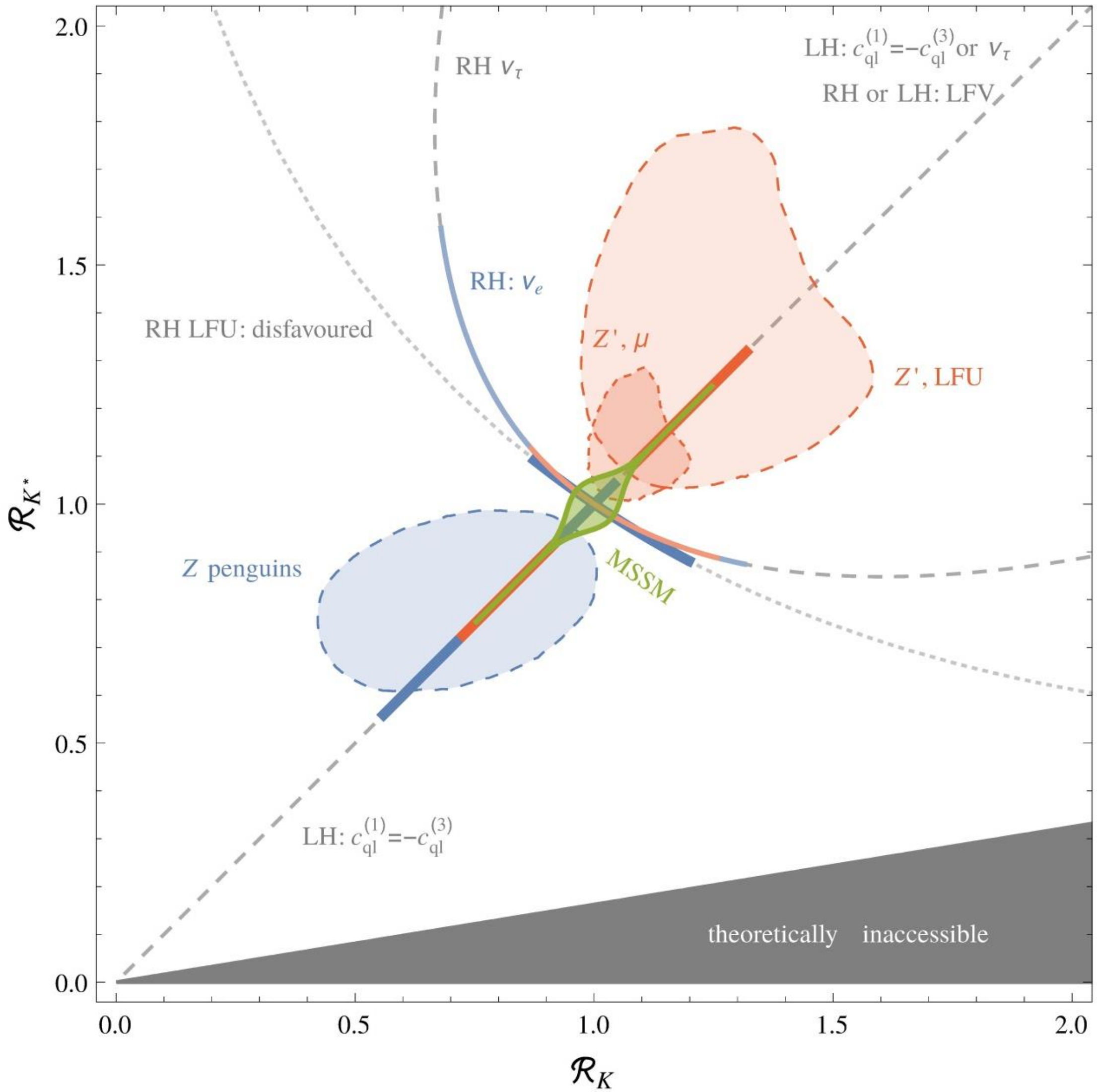
$B \to K(K^*)\nu\bar{\nu}$

BGNS 1409.4557



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

BGNS 1409.4557



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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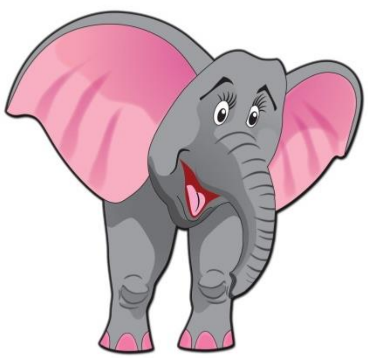

In QFT :

Large couplings

(still consistent with perturbativity)

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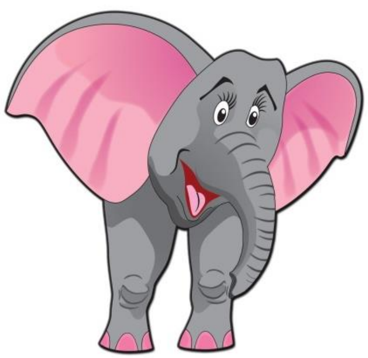

In QFT :

Large couplings

(still consistent with perturbativity)

Moderate couplings

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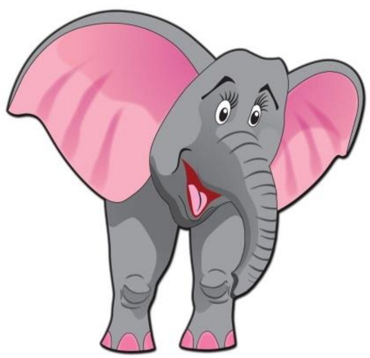
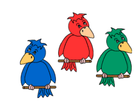
AJB, Buttazzo, Girrbach-Noe, Knegjens, 1407.0728

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





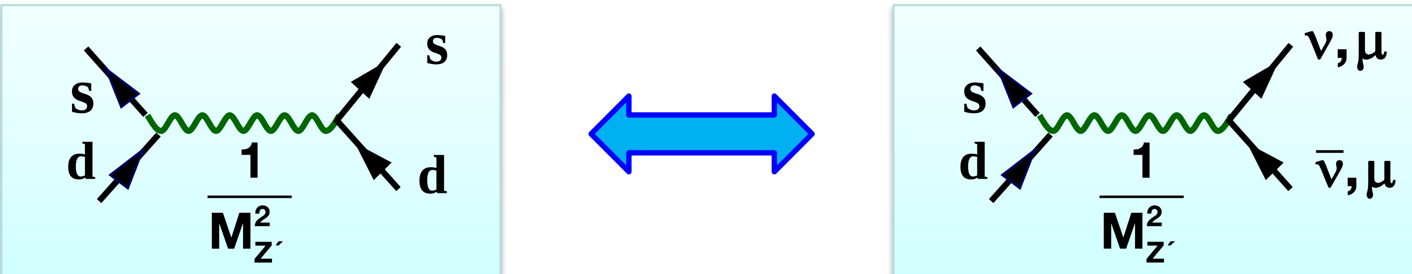
In QFT :

Large couplings	Moderate couplings	Small couplings

(still consistent with perturbativity)

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

B_s physics: ~ 15 TeV

Maximal scales that can be explored

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:

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

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 $g_L^{ij} << g_R^{ij}$ or $g_L^{ij} >> g_R^{ij}$:

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

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

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

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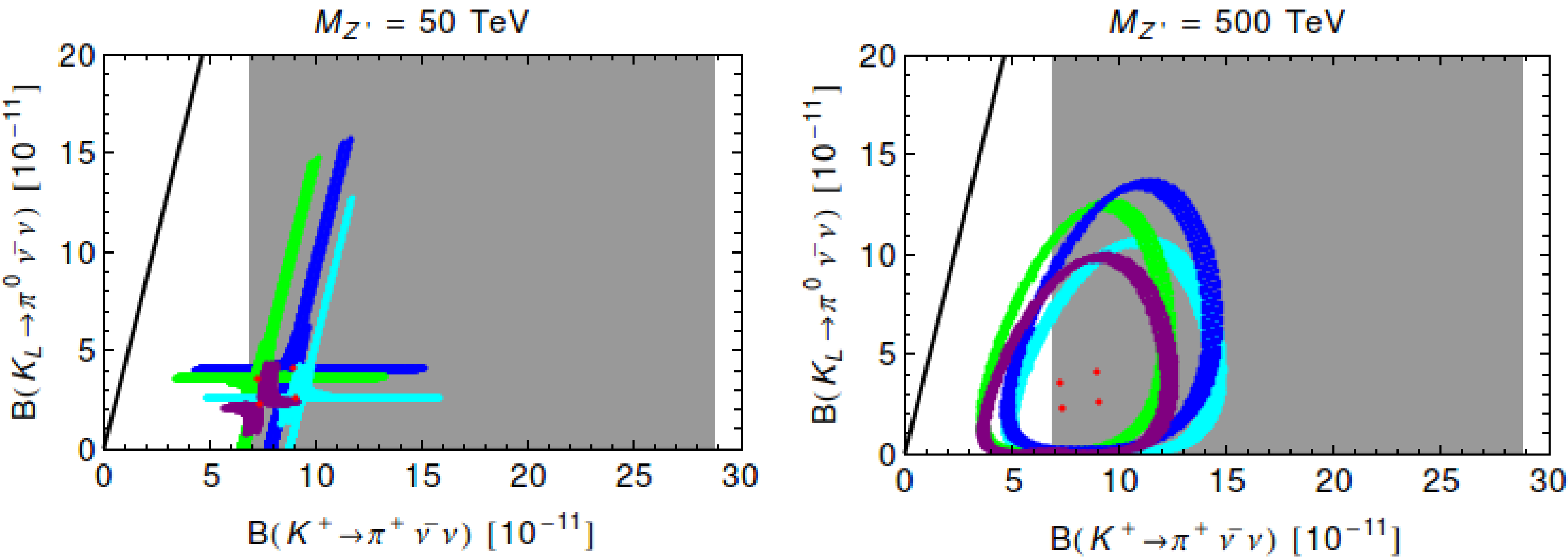
B_d : $\Lambda_{NP}^{max} \simeq 160$ TeV

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

Yes we can !!

Heavy Z´ at Work

AJB, Buttazzo, Girrbach-Noe, Knegjens, 1407.0728

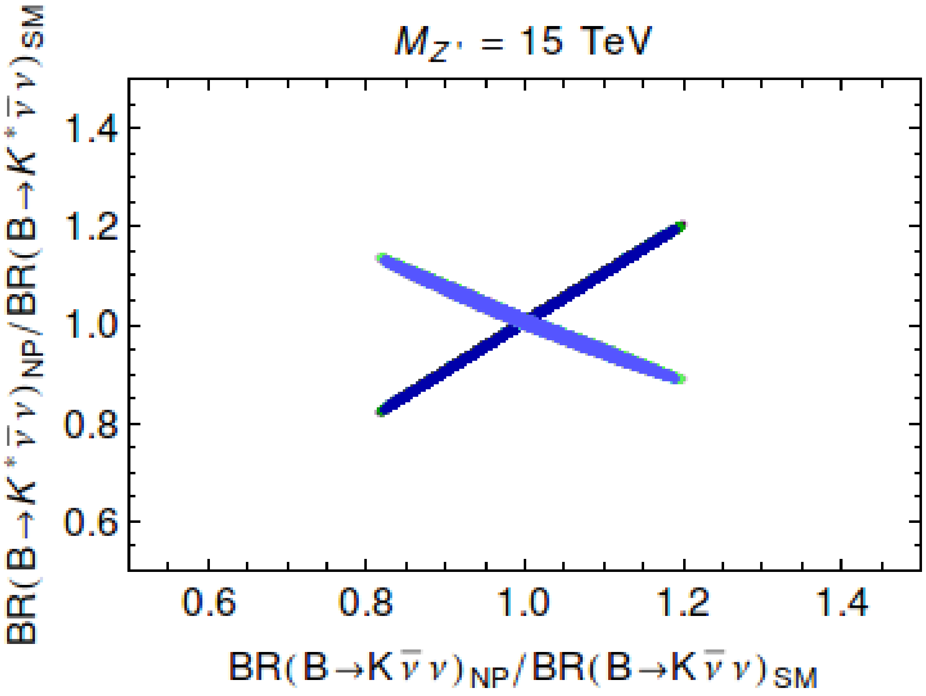


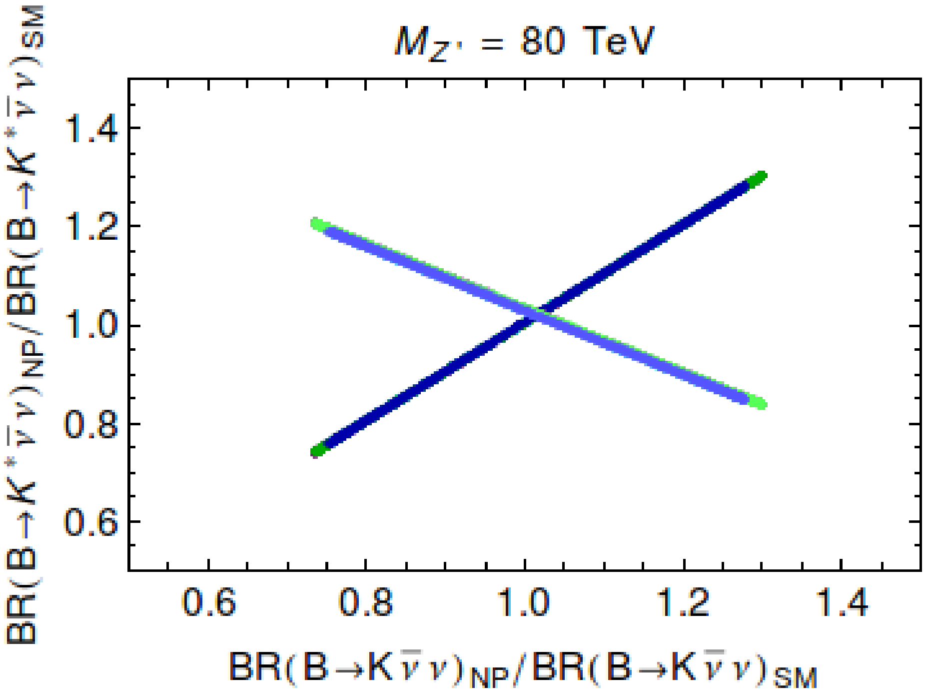
ε_K constraint

General discussion:
Blanke 0904.2528

No ε_K constraint

Heavy Z´ at Work

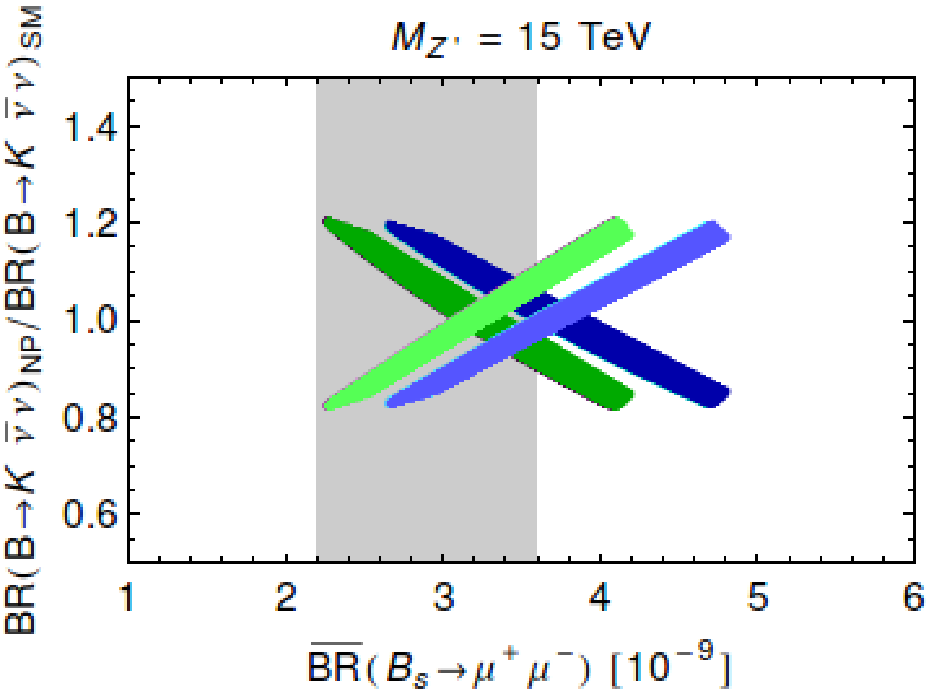


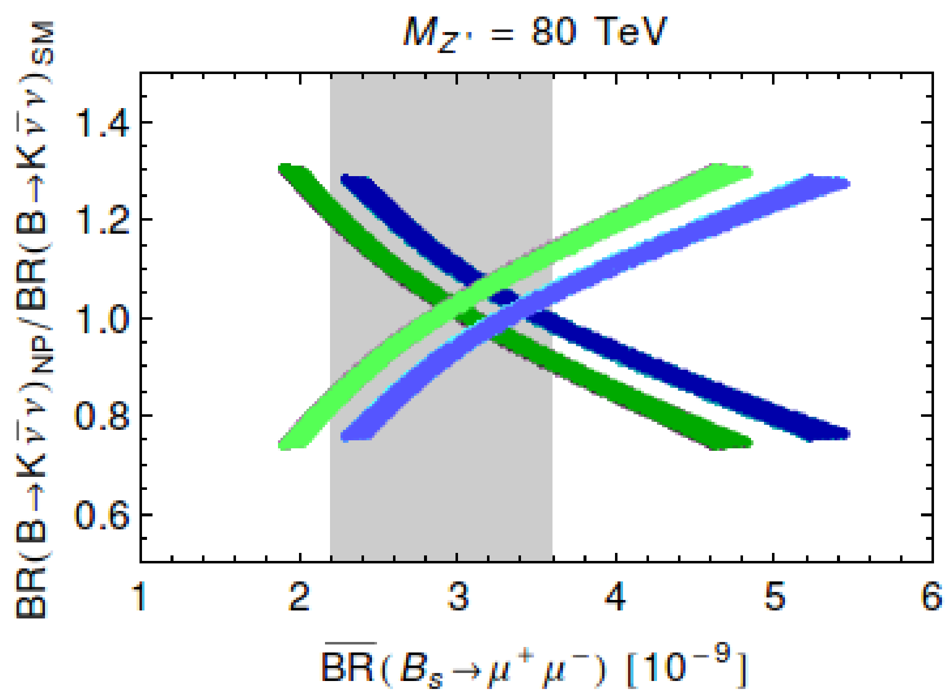


ΔF=2 constraint

No ΔF=2 constraint

Heavy Z´ at Work





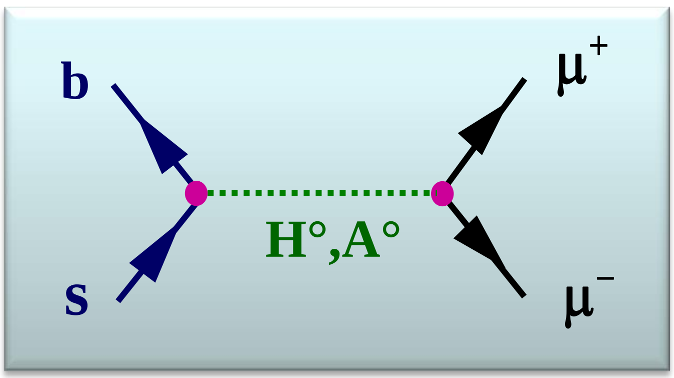
ΔF=2 constraint

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°

Finale: Vivace !

Finale: Vivace !

We are approaching the Happy End !!

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)

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

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

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

Electric
Dipole
Moments

Improved
Lattice
Gauge Theory
Calculations

Neutrinos

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

Exciting Times are just ahead of us !!!

Towards Zeptouniverse In 12 Steps

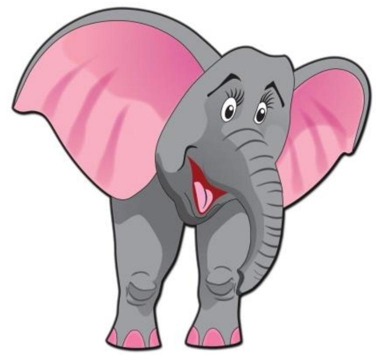
1. CKM from Trees
2. Lattice
3. $\Delta F=2$ Observables
4. $B_{s,d} \to \mu^+\mu^-$, $B_{s,d} \to \tau^+\tau^-$
5. $B^+ \to \tau^+\nu_\tau$
6. $B \to X_s\gamma$, $B \to K^*\gamma$
7. $B \to X_s l^+l^-$, $B \to K^*(K) l^+l^-$
8. $K \to \pi\nu\bar{\nu}$
9. $B \to X_s\nu\bar{\nu}$, $B \to K^*(K)\nu\bar{\nu}$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

A Zeptouniverse Vision

Seen only in

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

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

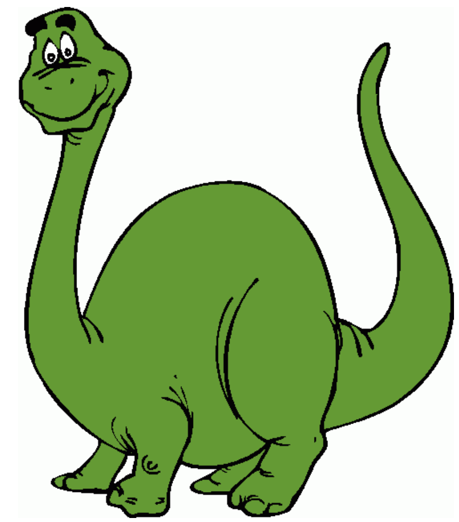


Seen in

Rare B_d

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

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



Seen in

Rare B_s

Rare B_d

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

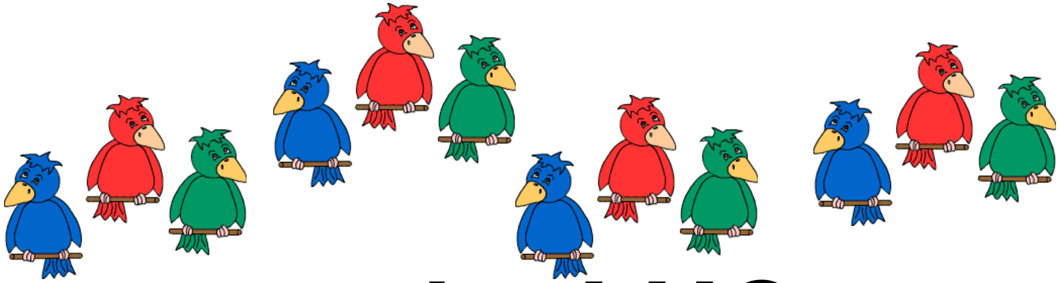
$B_{d,s} \to \mu^+\mu^-$

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

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

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

(LHCb+CMS)

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

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

Different Route

(AJB 2003)
(Knegjens 2014)

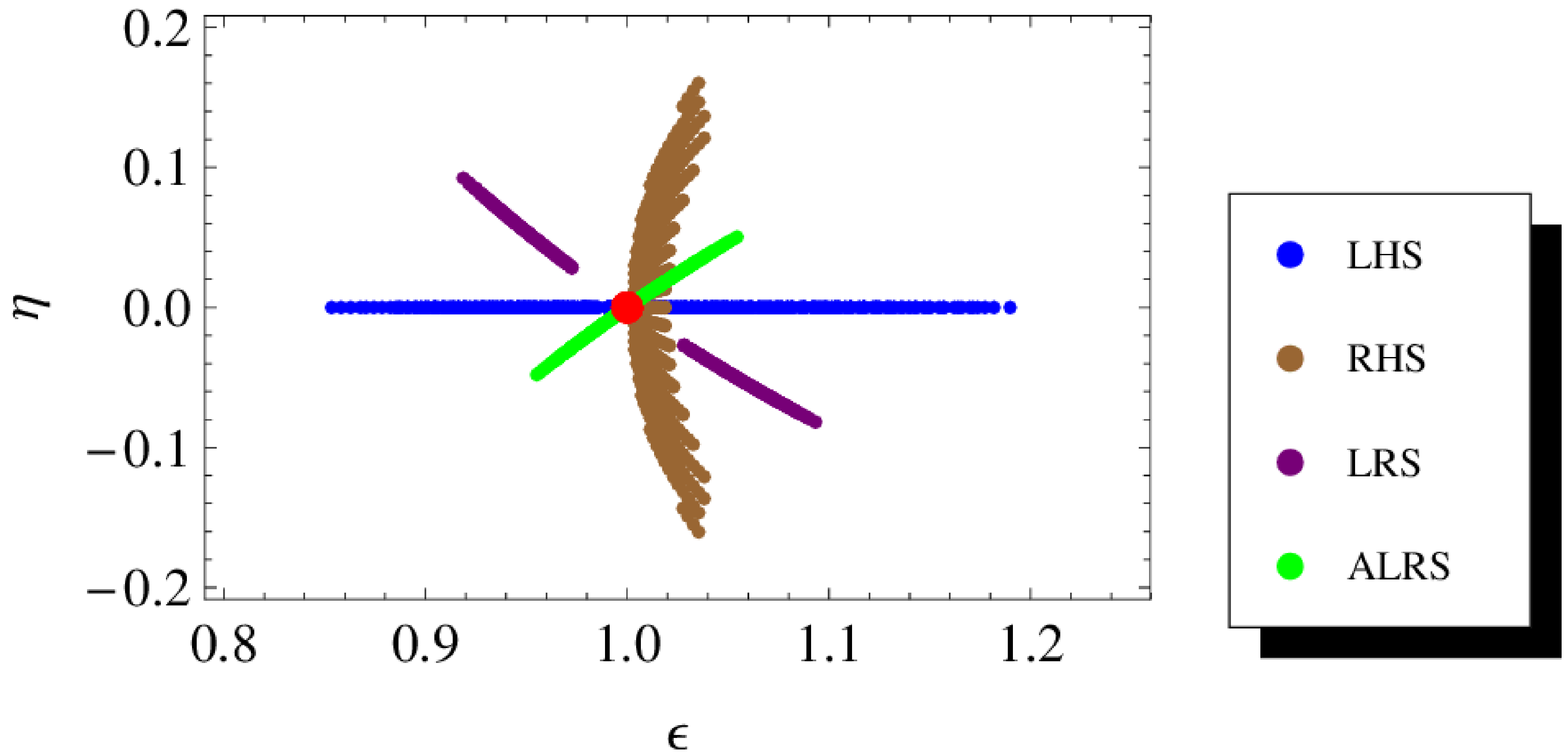
$$\bar{Br}(B_s \to \mu\bar{\mu})_{SM} = (3.5 \pm 0.2)\cdot 10^{-9}\left[\frac{(\Delta M_s)^{SM}}{(\Delta M_s)^{Data}}\right]\left[\frac{1.33}{\hat{B}_s}\right]$$

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

Lattice

(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**

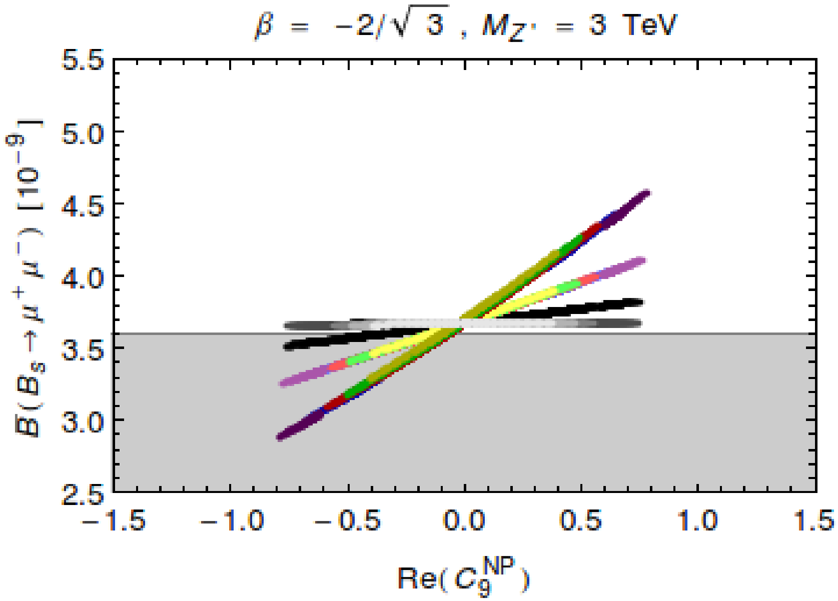


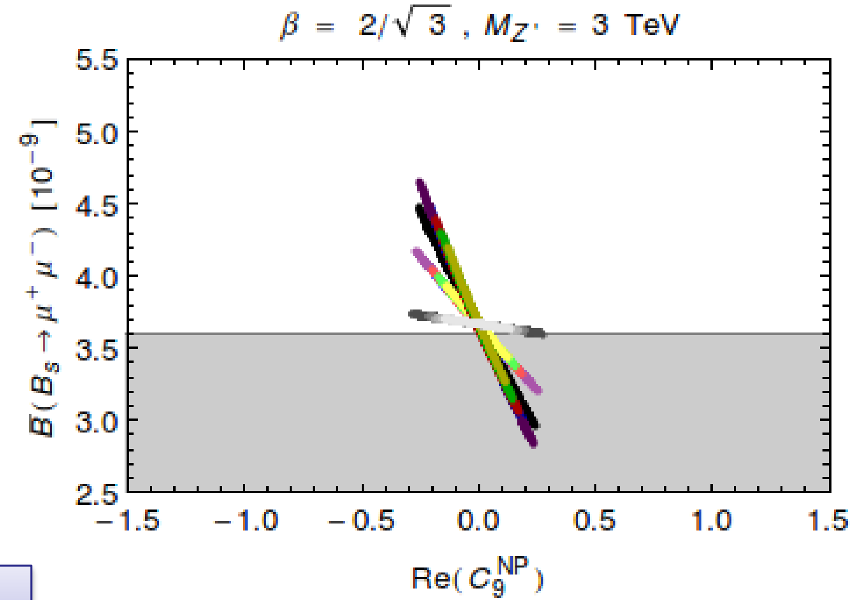
Powerful tests of right-handed currents

Altmannshofer, AJB, Straub, Wick 0902.0160

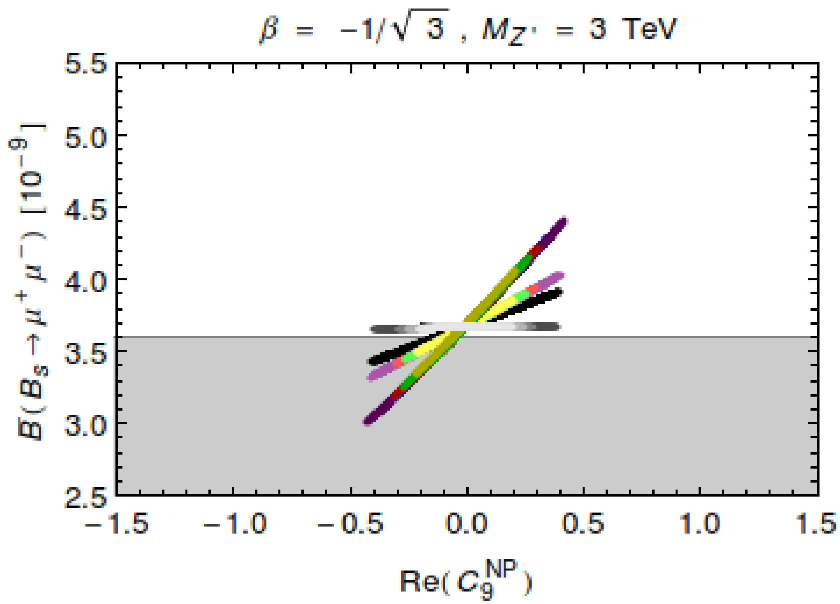
Correlations in 331 Models

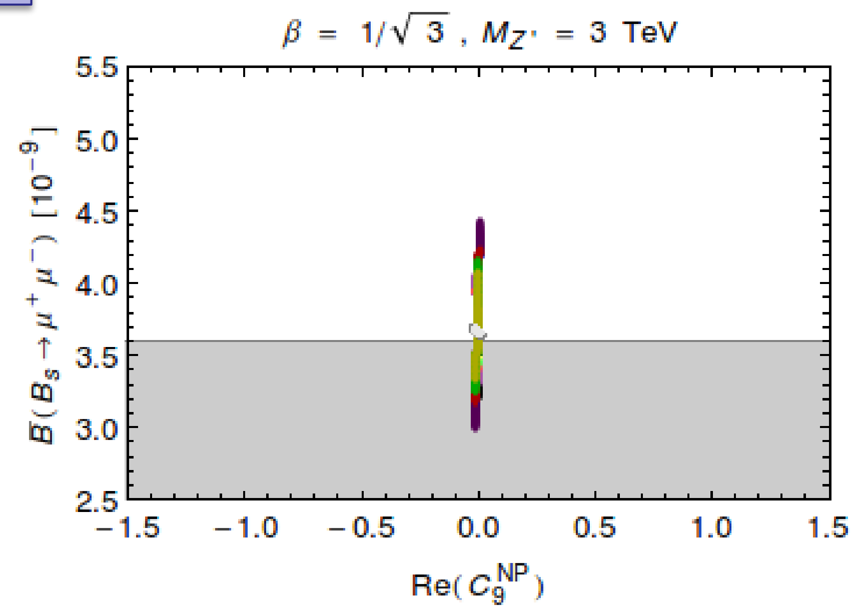
1405.3850



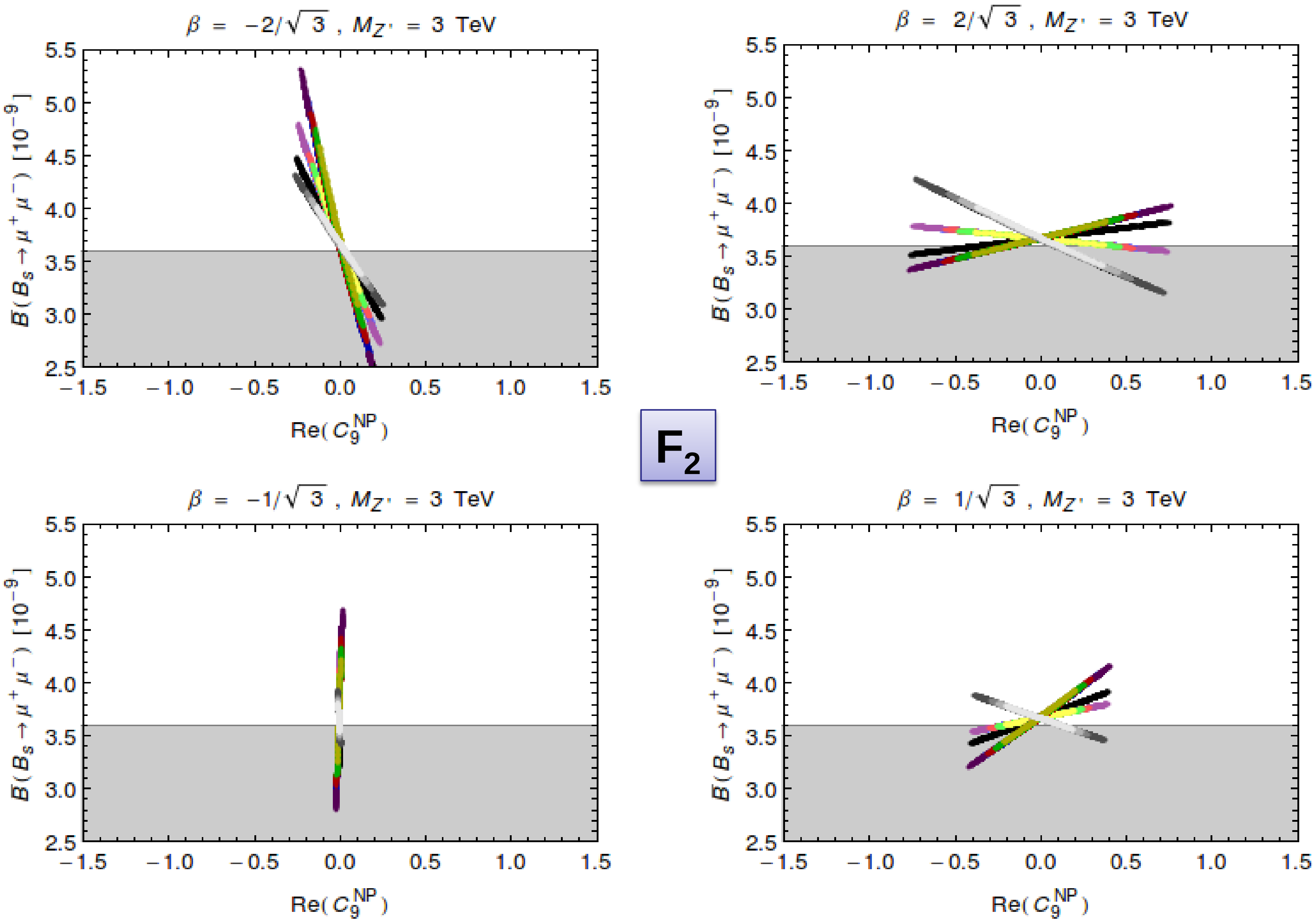


F_1





Correlations in 331 Models 1405.3850



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))

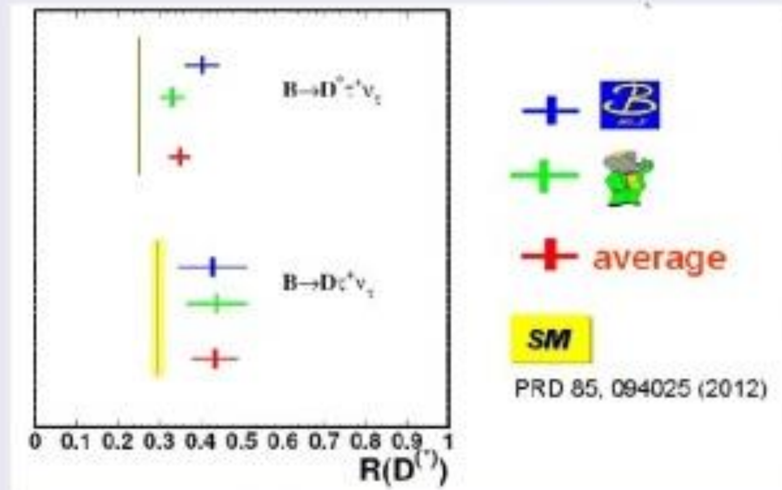
$R(D) = 0.297 \pm 0.017,\ R(D^*) = 0.252 \pm 0.003$

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].

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

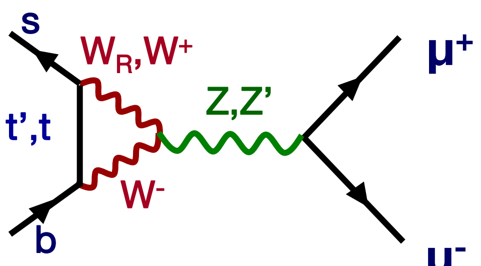
Simple Tests in the Coming Years

- 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



+

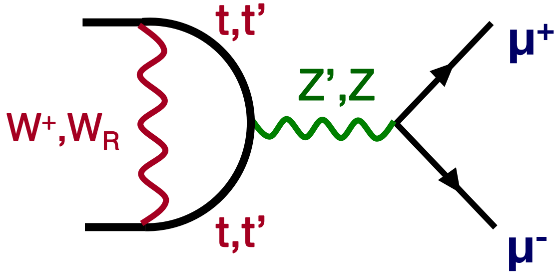
Other Z-Penguins and Boxes

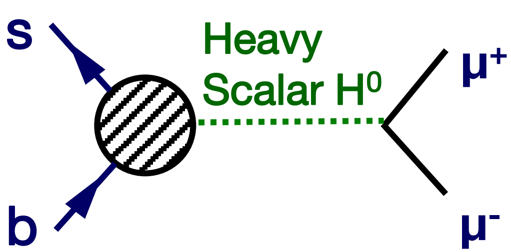
SM: (3.2 ± 0.2) · 10^{-9}

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

$K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ (Z°-penguins)

(TH cleanest FCNC decays in Quark Sector)

Extensive TH efforts over 20 years :

Buchalla, AJB; Misiak, Urban (NLO QCD)
AJB, Gorbahn, Haisch, Nierste (NNLO QCD)
Brod, Gorbahn, Stamou (QED, EW two loop)
Isidori, Mescia, Smith (several LD analyses)
Buchalla, Isidori (LD in $K_L \to \pi^0 \nu\bar{\nu}$)

$$\frac{Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)}{Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)} = 3.2 \pm 0.2$$

SM :

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(8.4 \pm 0.7\right) \cdot 10^{-11}$$

$$Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) = \left(2.6 \pm 0.4\right) \cdot 10^{-11}$$

Exp :

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(17\,{}^{+11}_{-10}\right) \cdot 10^{-11}$$

(E787, E949 Brookhaven)

$$Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) \le 6.8 \cdot 10^{-8}$$

(E391a, KEK)

Future :

NA62
ORCA (FNAL)

J-PARC KOTO

Both very sensitive to New Physics

CP-conserving
TH uncertainty 2-3%

CP-Violation in Decay
TH uncertainty 1-2%

LHT after LHCb Data

Our 2006 Predictions
(Blanke et al.) :

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

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

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

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

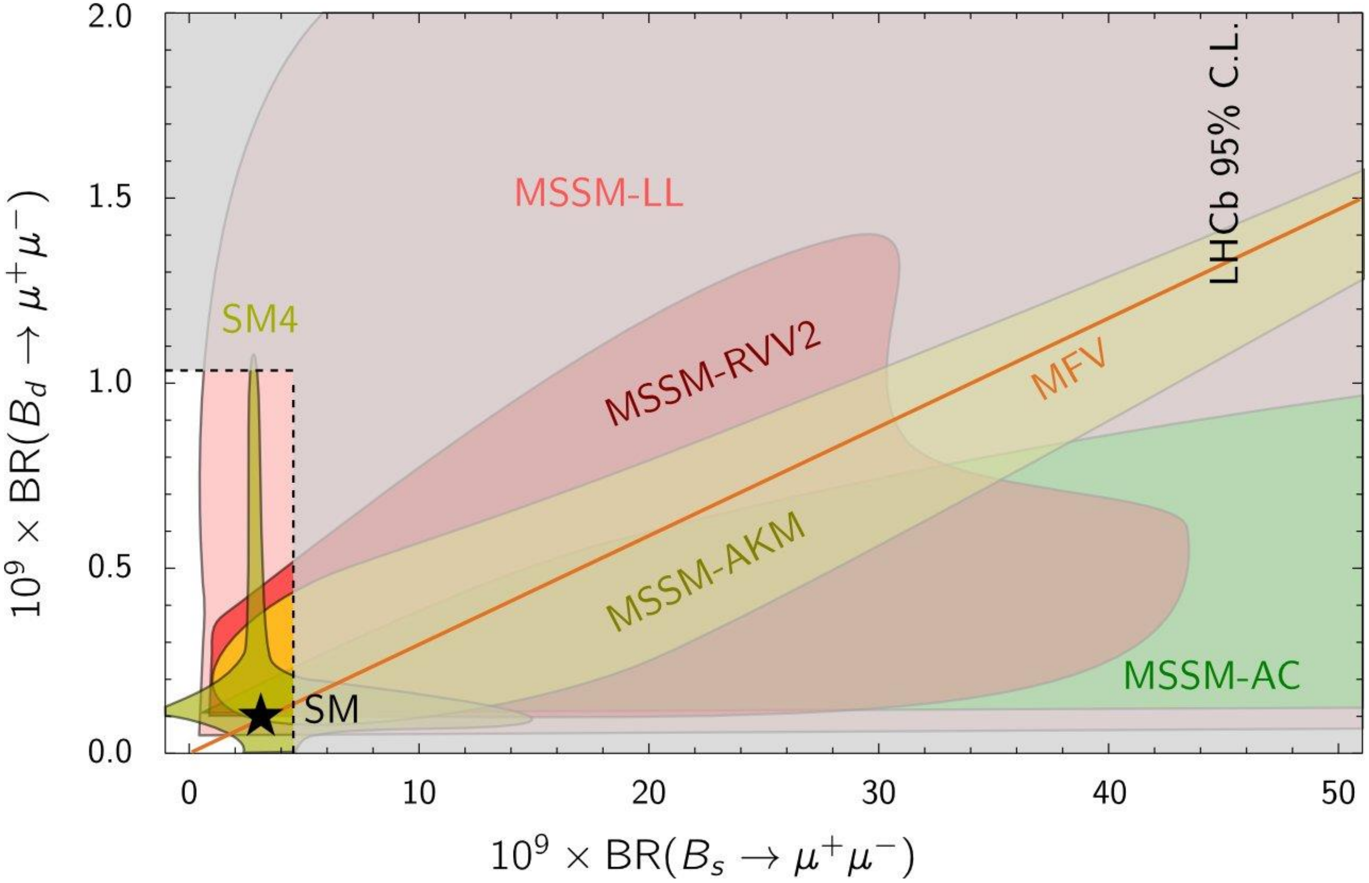
Concerning K-Physics : LHCb opened the road to large NP effects in rare K-decays within LHT model *)

*) 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 $SU(2)_L \otimes SU(2)_R \otimes U(I)_{B\text{-}L}$ 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 $B_{s,d} \to \mu^+\mu^-$)

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

$$S_{\psi\varphi} = \sin(2|\beta_s| - 2\varphi_{new})$$

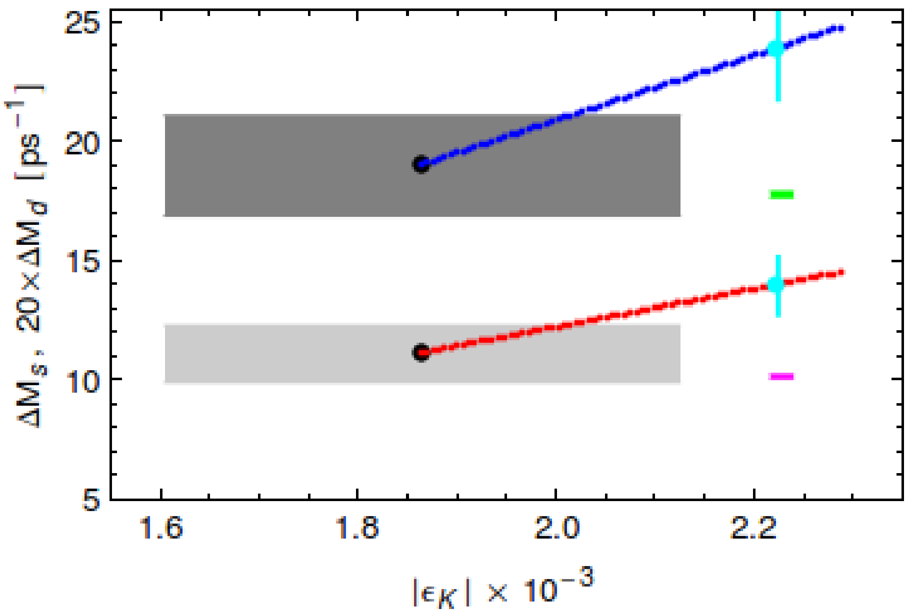
$$\beta = F(|V_{ub}|, \gamma)$$

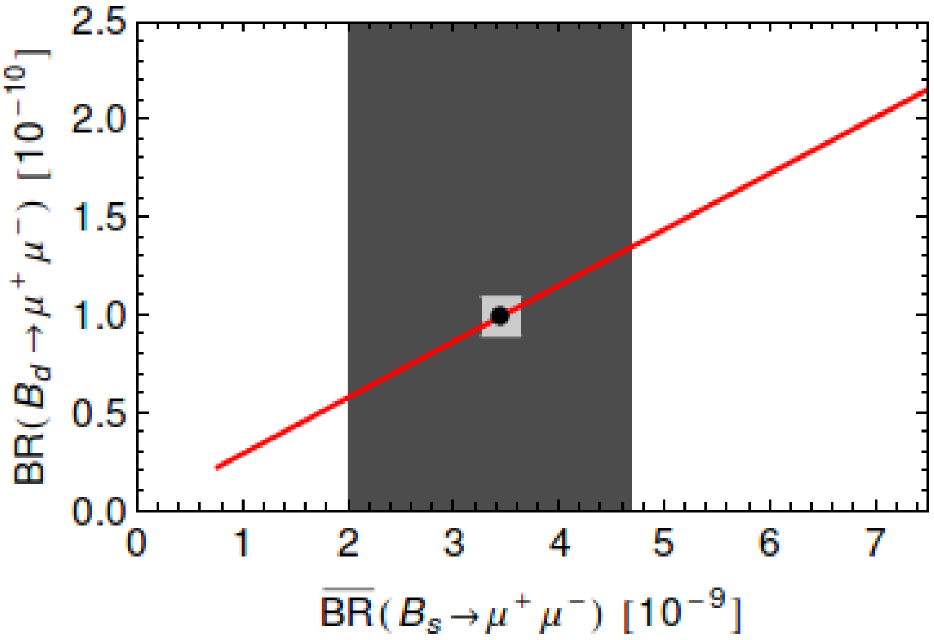
(weak)

Constrained Minimal Flavour Violation

AJB + J. Girrbach (2012)

0007085
0310208
0604057





Tension within CMFV

EXP

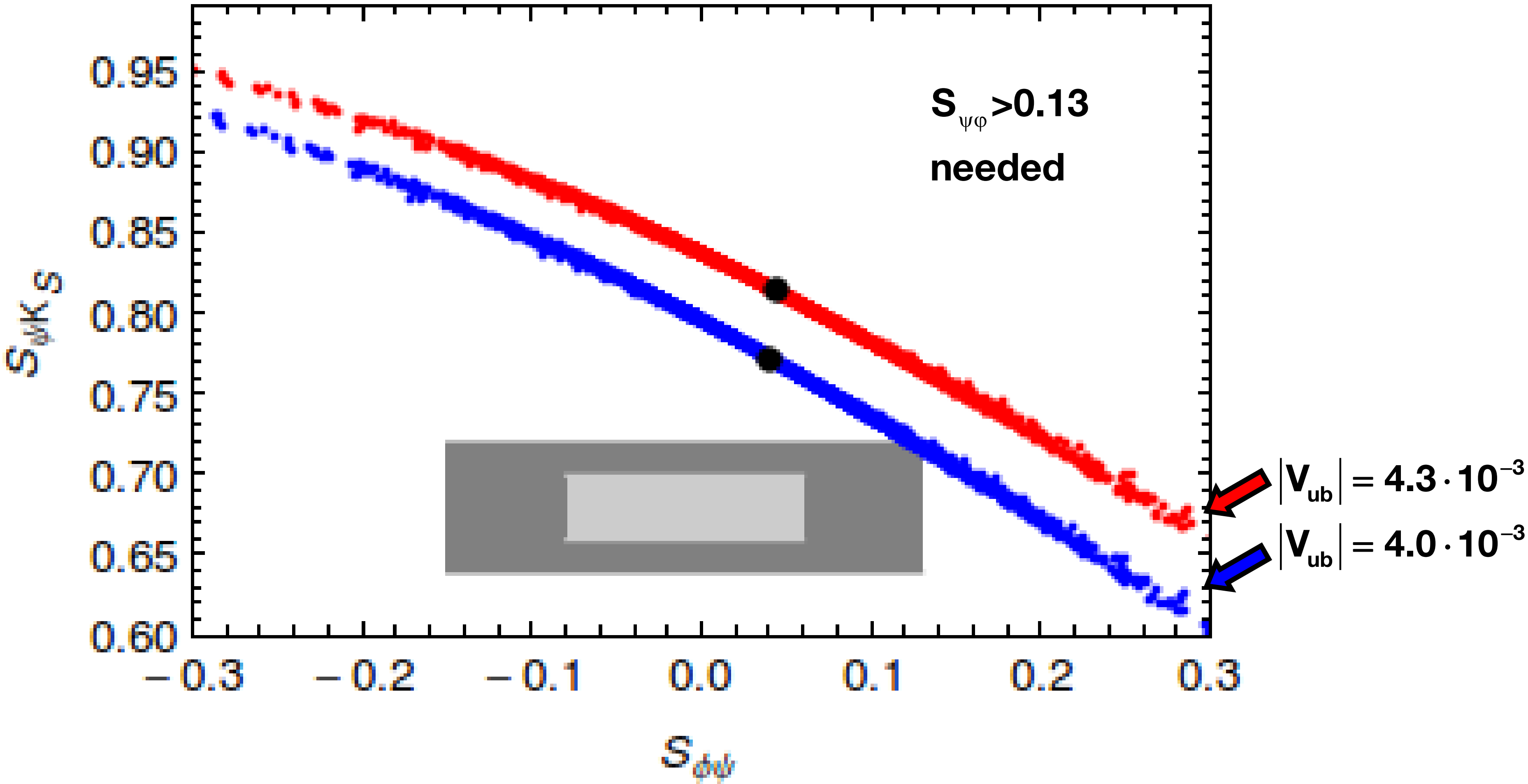
Similar tension in Gauged Flavour Models: AJB, Merlo, Stamou (2011)

EXP

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

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

AJB, Girrbach, Nagai (2013)

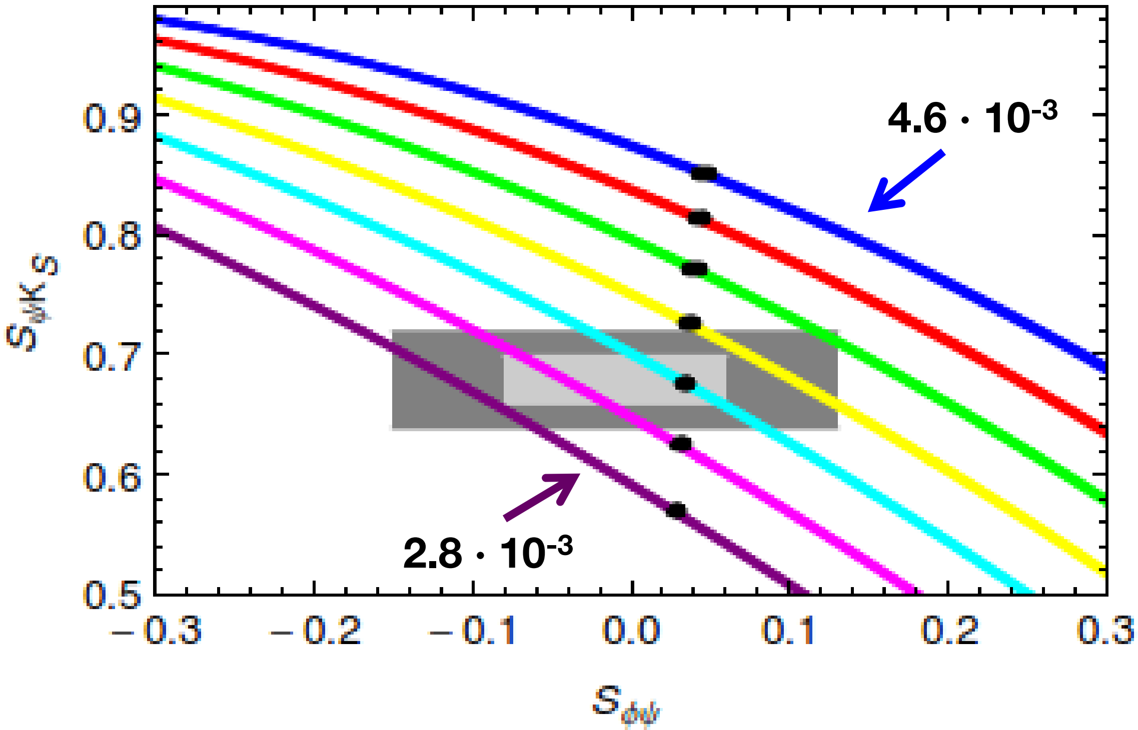


AJB, Carlucci, Gori, Isidori; 1005.5310
AJB, Isidori, Paradisi; 1007.5291

AJB
Girrbach
(1206.3878)

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

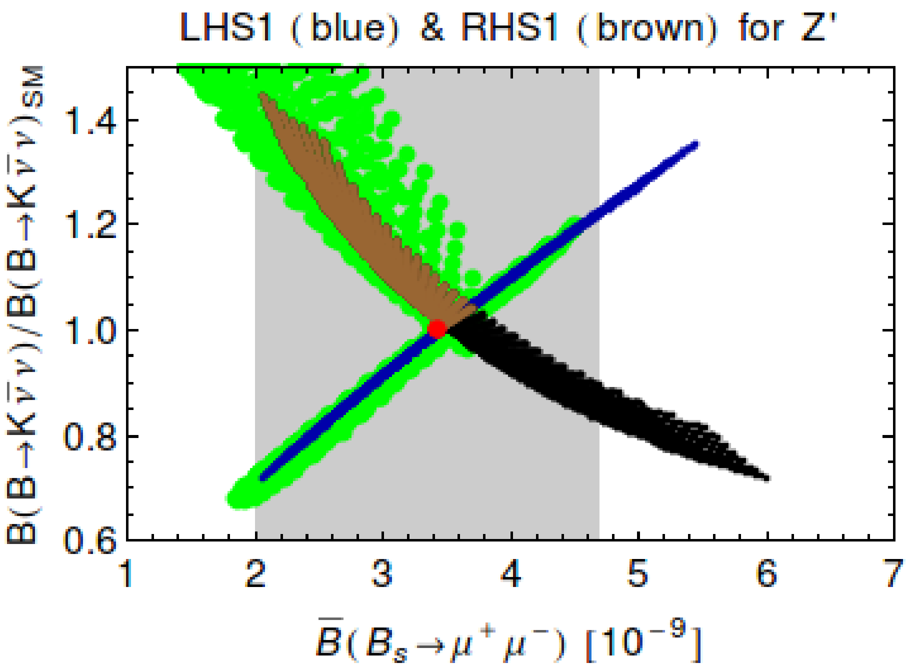
Important test of $U(2)^3$ Models

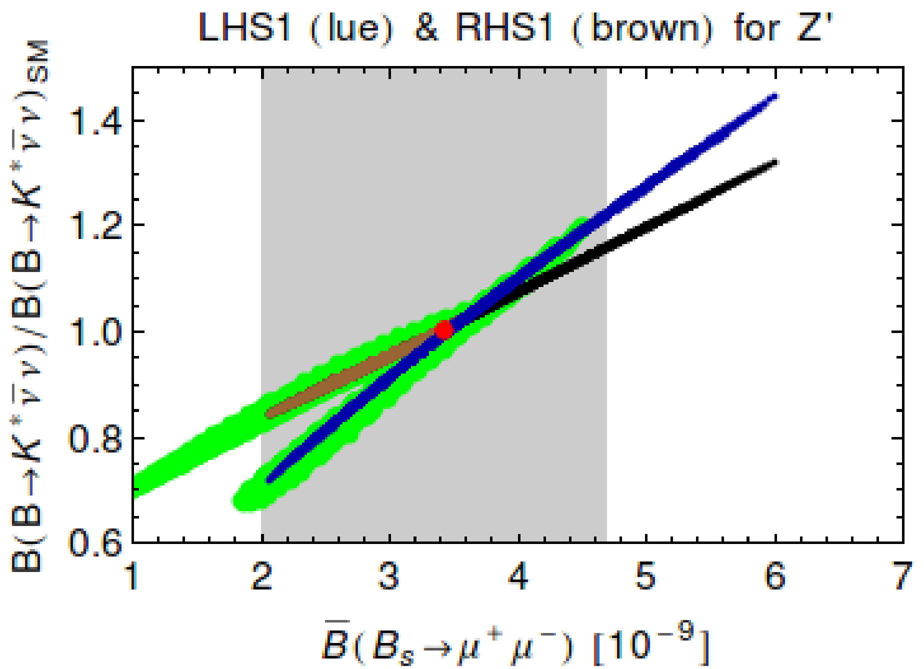


$\gamma = 68°$

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
$\Delta M_s,\ S_{\psi\phi}$	✖			
$B_d \to K^* \mu^+\mu^-$	✖	✖	✖	
$B_s \to \mu^+\mu^-$	✖	✖		
$B_d \to \mu^+\mu^-$		✖		✖
$\Delta M_d,\ S_{\psi\phi}$				✖

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

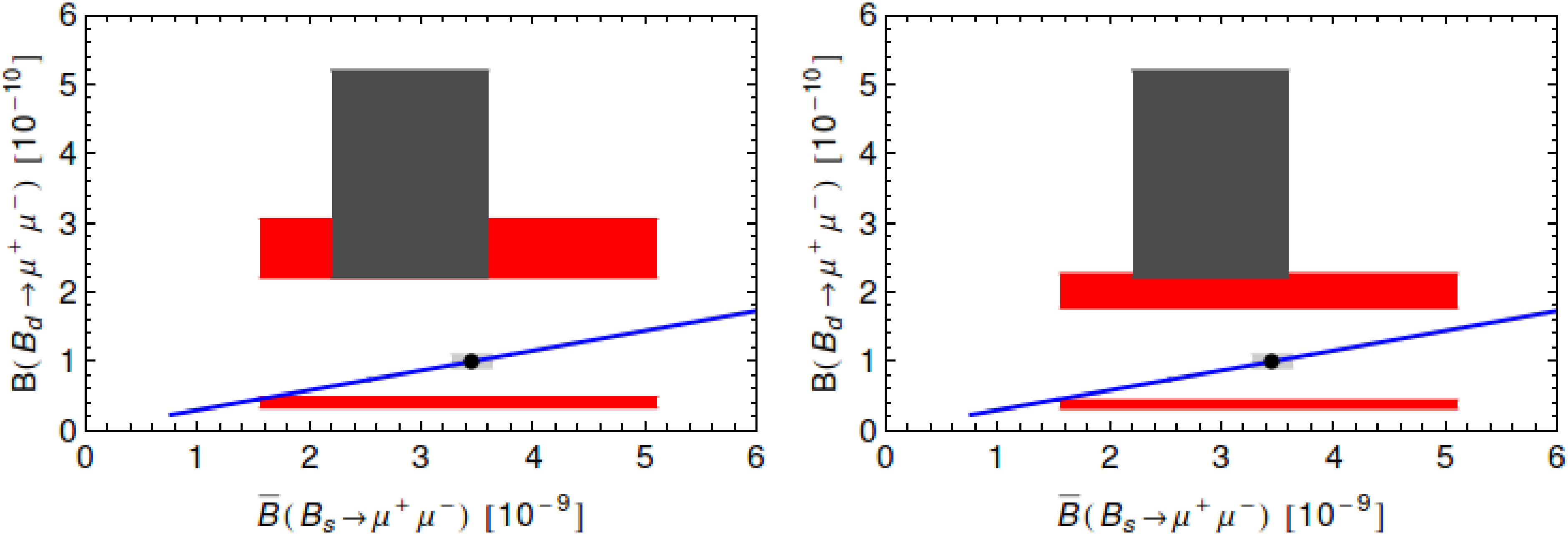
reduced coupling ($\bar{\Delta}_i$); coupling (Δ_i)

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}**

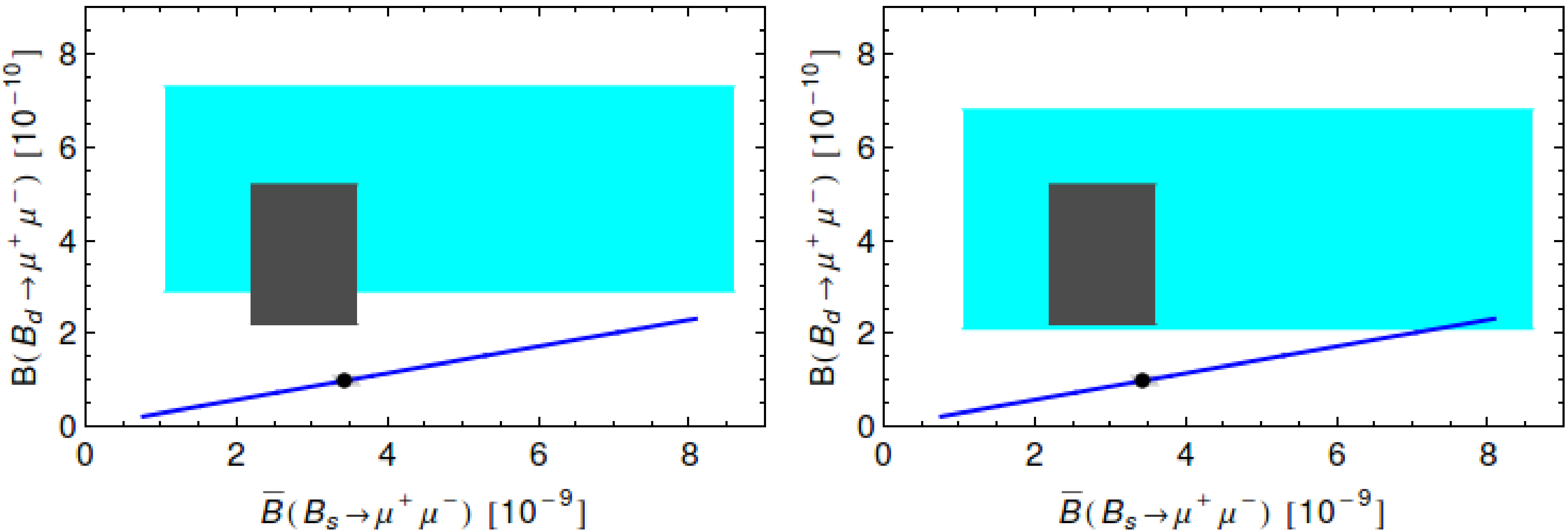


CMS + LHCb

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

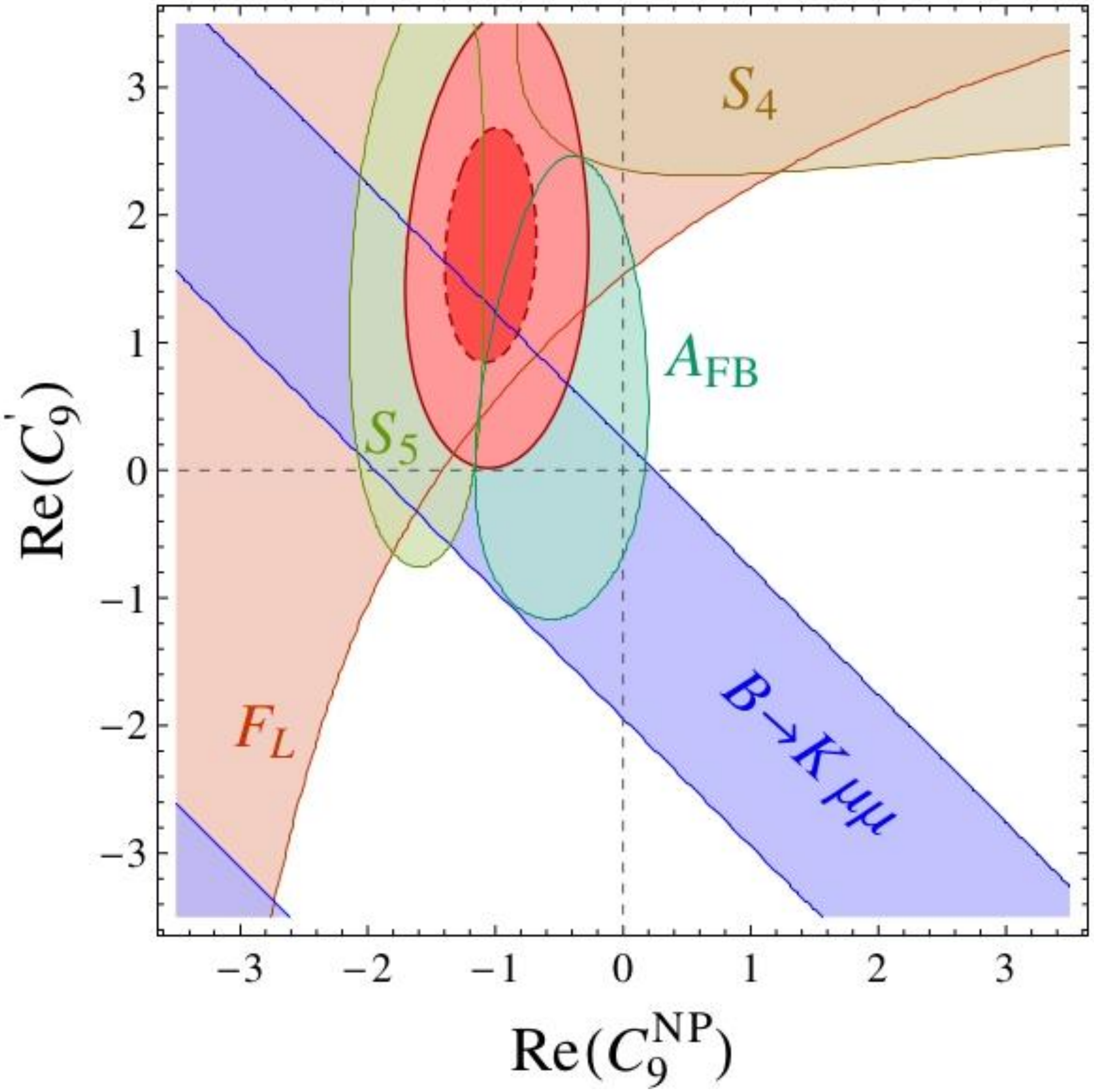
$$C_{7\gamma}^{NP} < 0, \quad C_9^{NP} < 0$$

or

AS

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

($C_9^{'}$: 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)

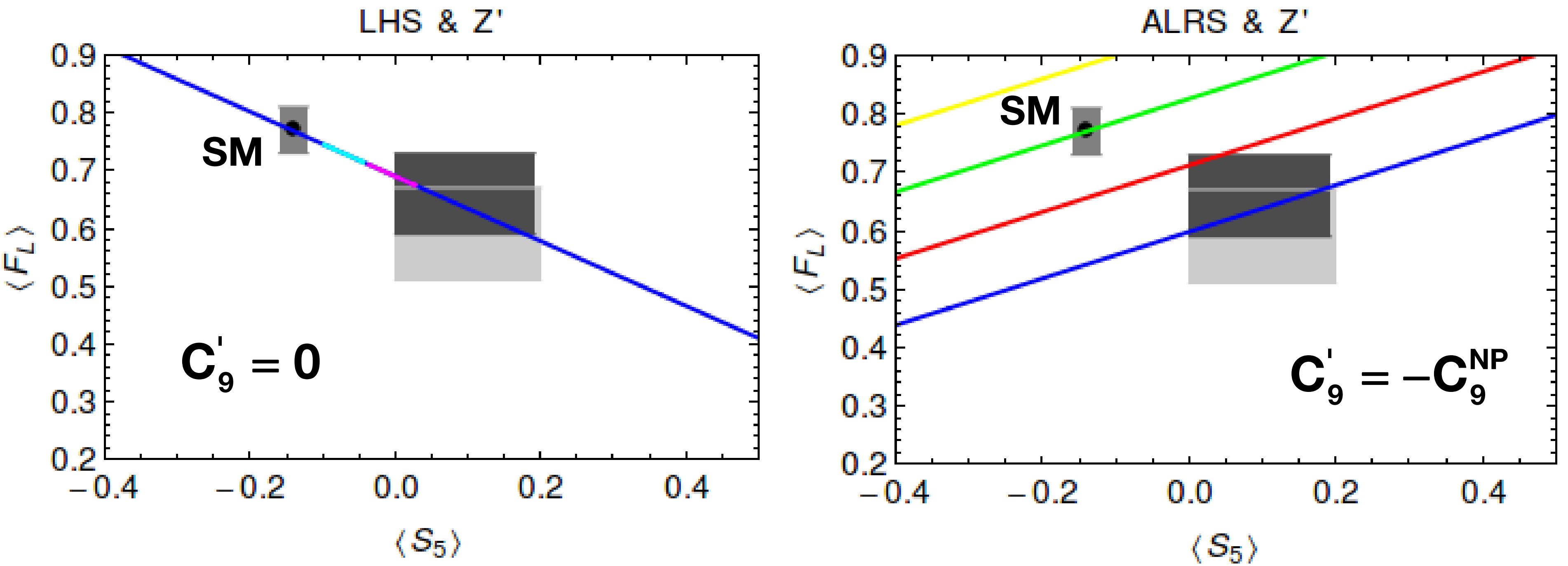
$C_9^{NP} \neq 0, \quad C_9' \approx -C_9^{NP}$ (ALRS)

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

New Correlations

(General Z´)

(AJB + Girrbach, 1309.2466)



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

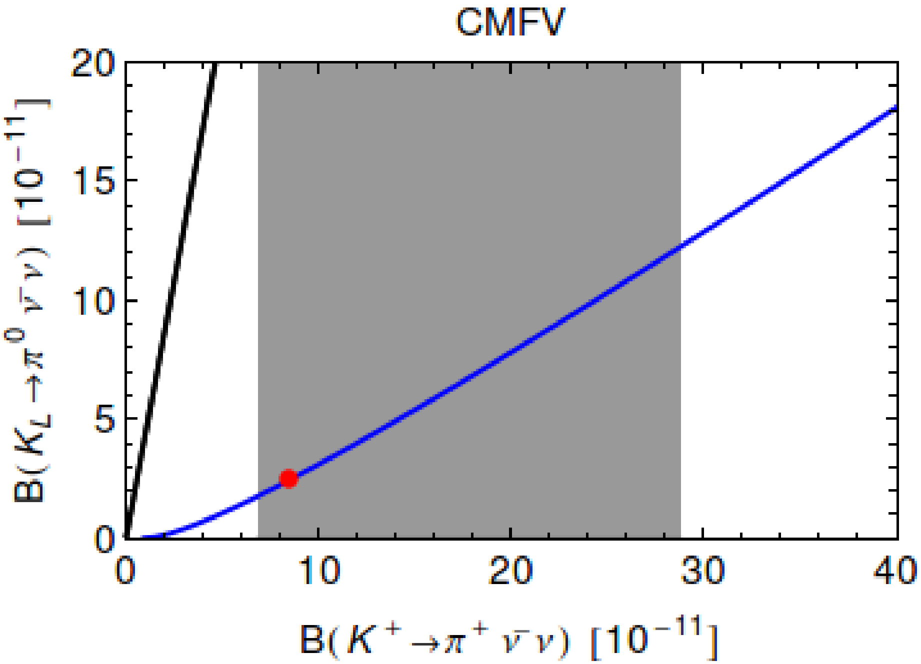
$C_9^{NP} = -(1.6 \pm 0.3)$

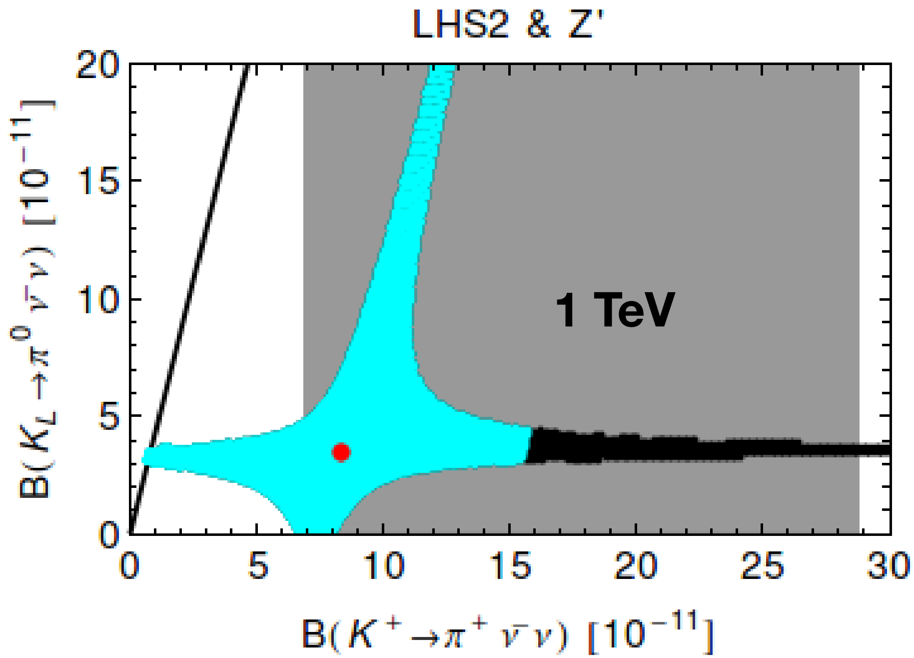
$C_9^{NP} = -1.0$

$C_9^{NP} = -2.0$

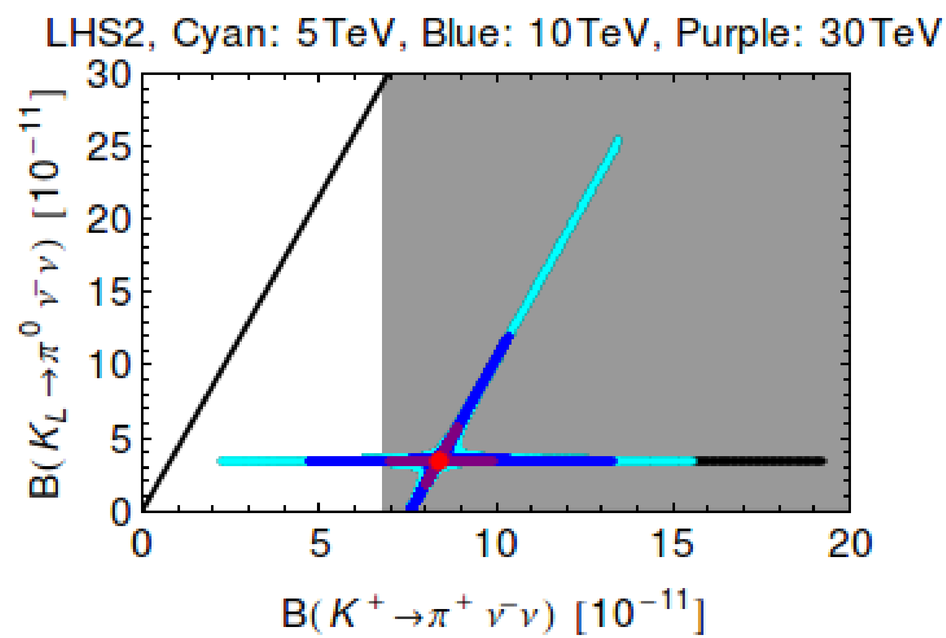
$C_9^{NP} = 0$

1211.1896

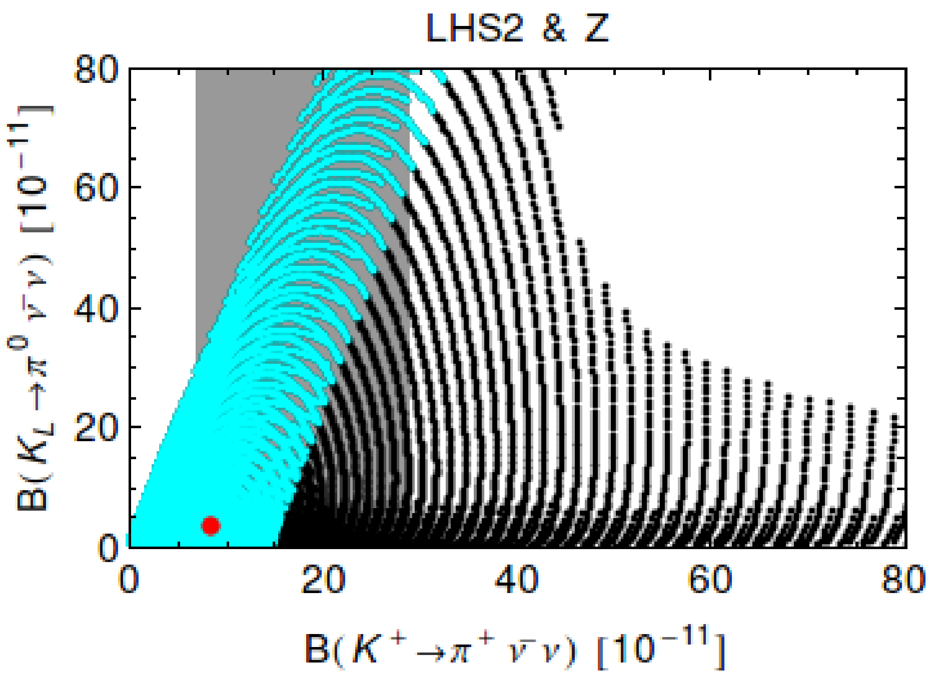


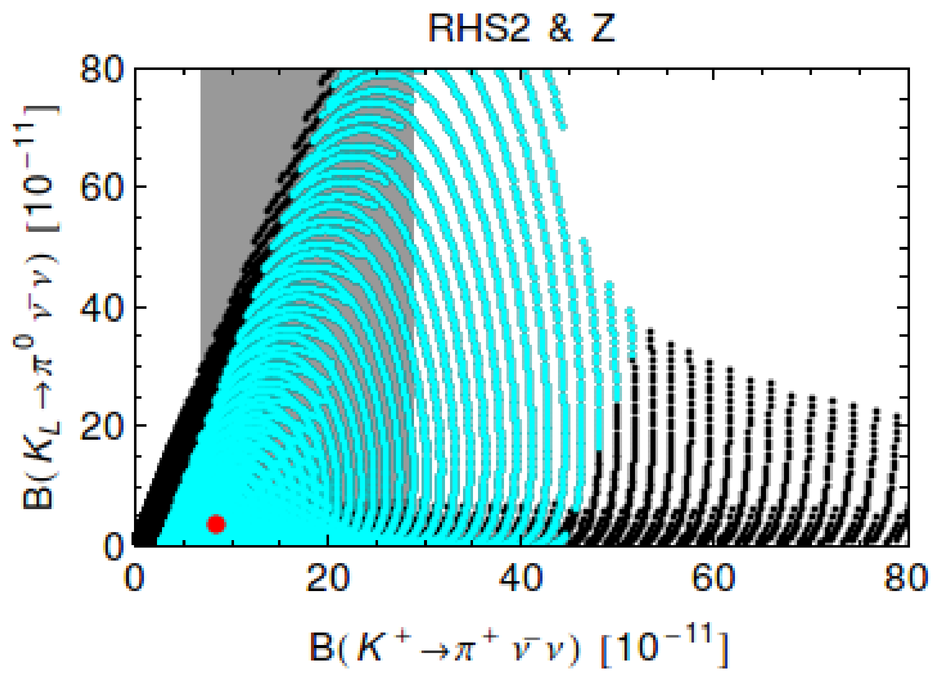


Sensitivity to $M_{Z'}$ beyond the LHC



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

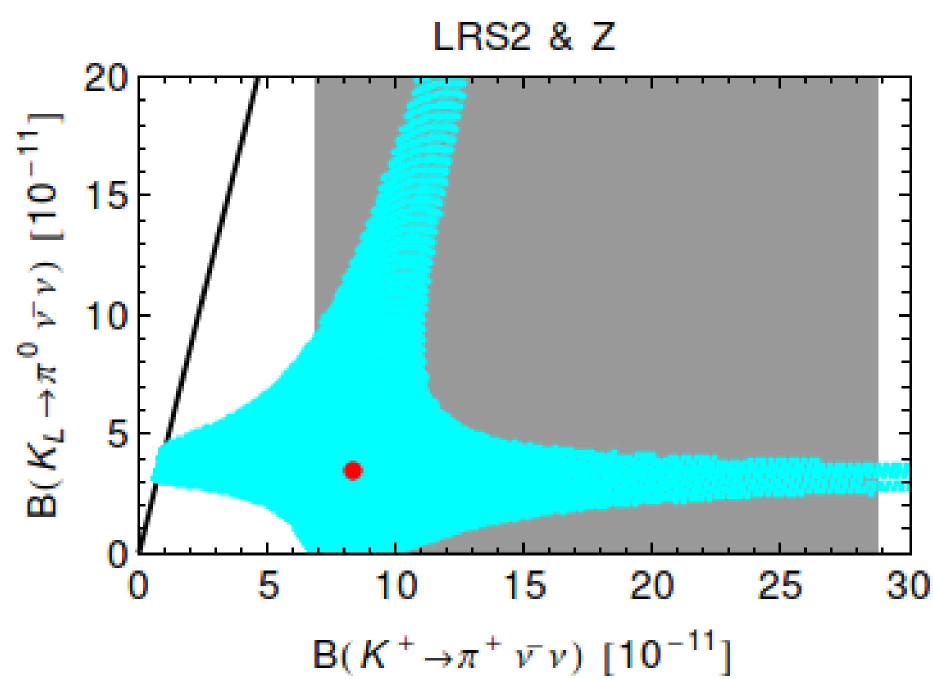




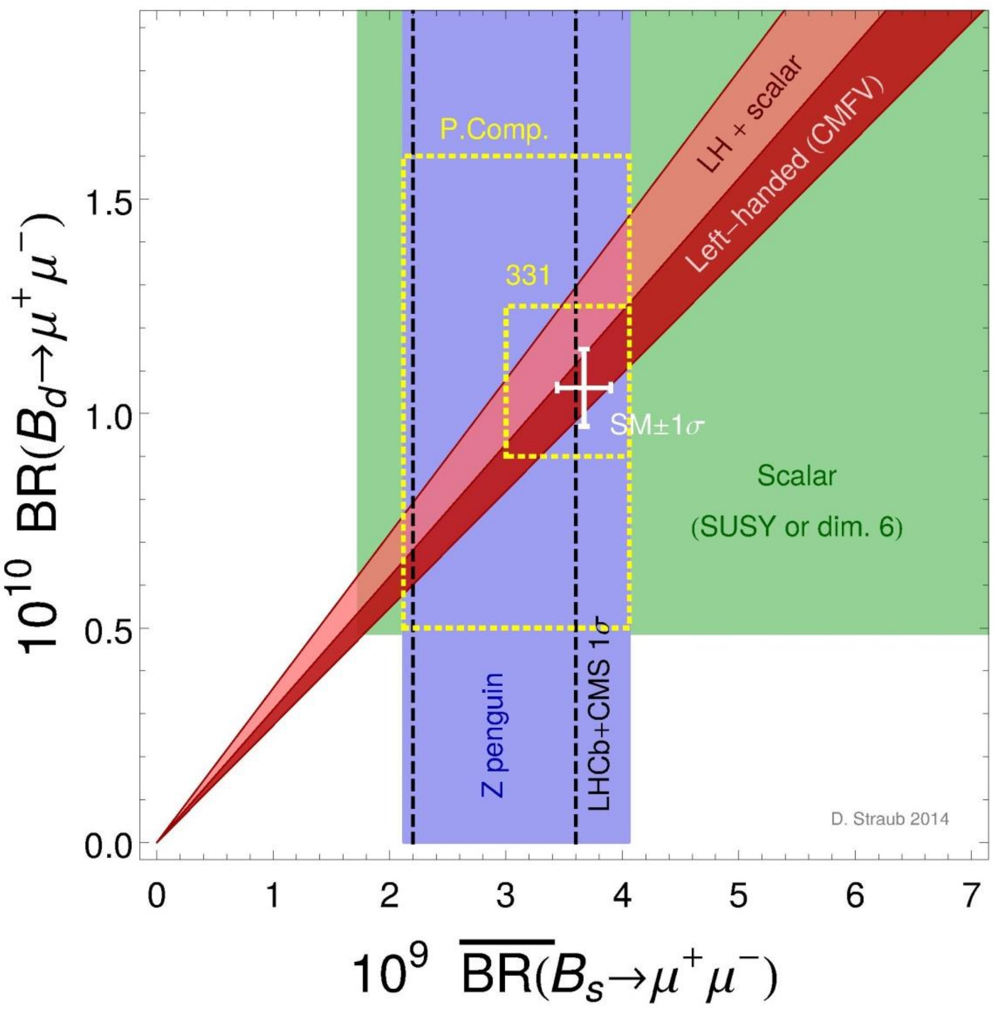
: **forbidden by**

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

LHS, RHS
LRHS



Straub´s Plot 2014



Two Versions of Effective Theories

Wilson Coefficients → c_i ; Local operators → Q_i

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 $(U(3))^3$, $U(2)^3$,…