Towards the Identification of New Physics through Flavour Physics

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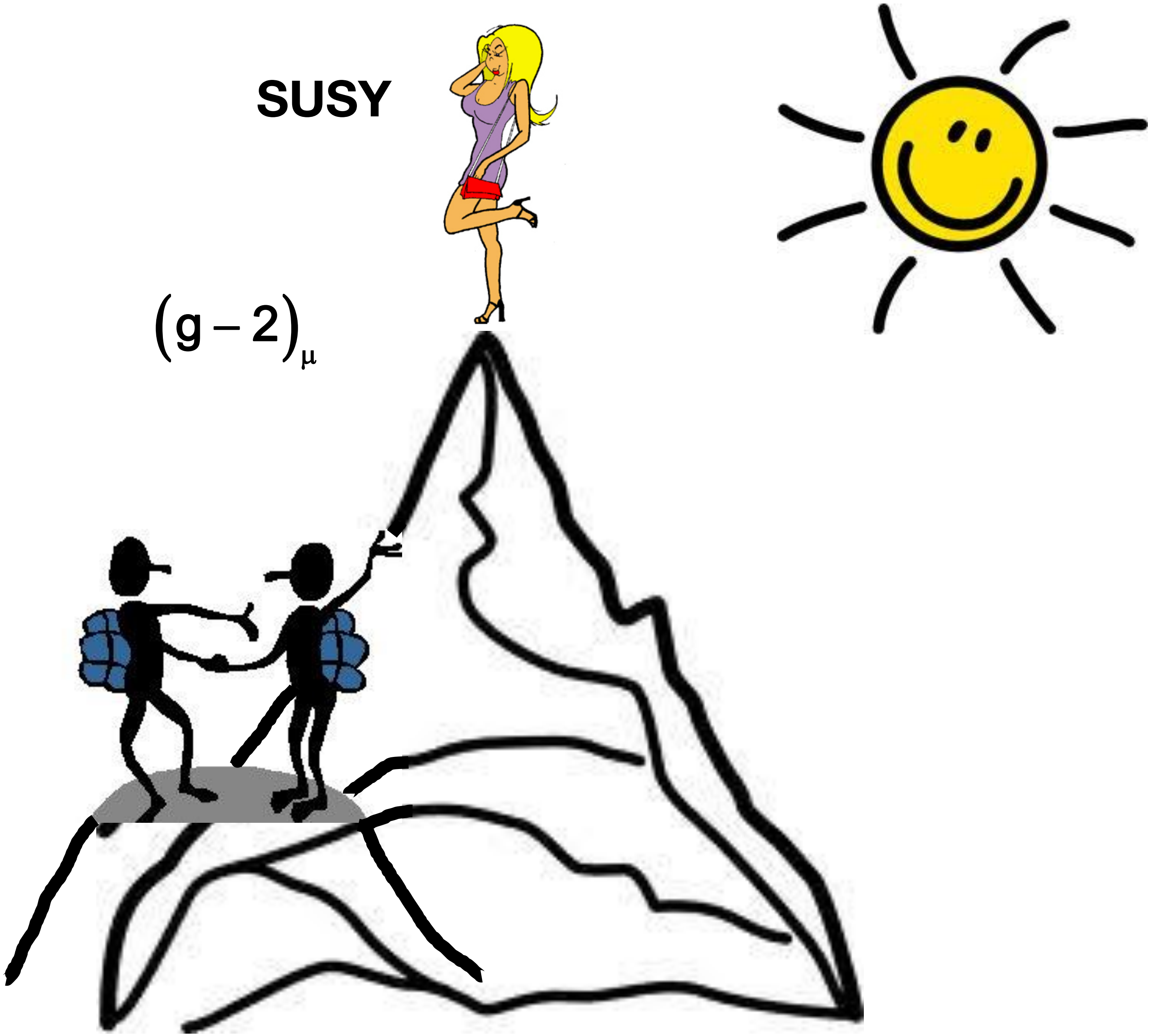
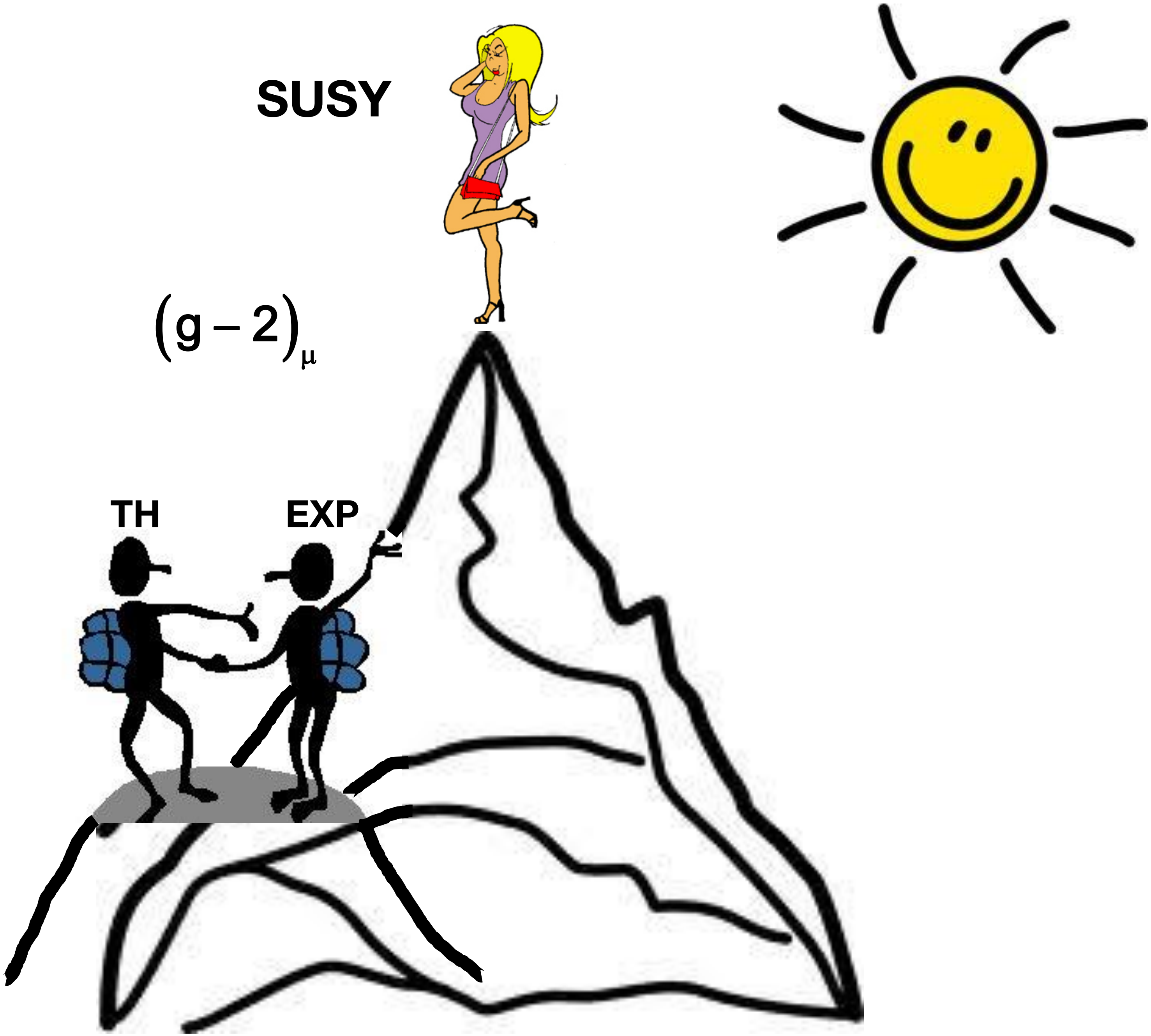
Santa Barbara
July 2013

Overture


SUSY
$(g-2)_\mu$


SUSY
$(g-2)_\mu$
TH
EXP

June 2012

July 2013

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

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	$5 \cdot 10^{-20}$m	Frontiers of Elementary Particle Physics in 2010´s
High Precision Measurements of Rare Processes (Europe, Japan, USA)	10^{-21}m	Zeptouniverse

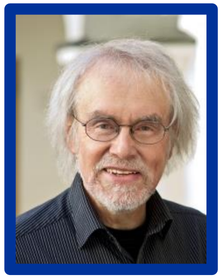
Expedition

Attouniverse → Zeptouniverse

10^{-18}m → 10^{-21}m

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

ERC Flavour Team


AJB


D.Buttazzo


F. De Fazio


J.Drobnak


K.Gemmler


J.Girrbach


G.Isidori


L.Merlo


Y.Omura

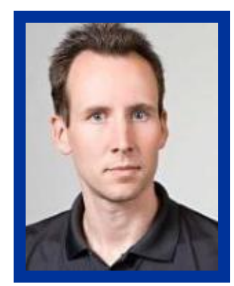

S.Pokorski


E.Stamou


R.Ziegler


G.Buchalla


A.Ibarra


M.Ratz

Strategy for the Next 28 min

1. Searching for New Physics (Rare Decays, CP Violation)

2. Towards New SM in 12 Steps

3. Correlations between Flavour Observables: DNA Charts

4. Finale Vivace !

AJB + Girrbach: hep-ph/1306.3755

1.

Searching for New Physics (Rare Decays and CP Violation)

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

Patterns of Flavour Violation around the Flavour Clock

12. Gauged Flavour Models
1. CMFV, MFV
2. $2HDM_{\overline{MFV}}$
3. LHT
4. SM4
5. SUSY Flavour
6. SO(10)-GUT $SSU(5)_{RN}$
7. $U(2)^3$
8. FBMSSM
9. RHMFV
10. L-R Models
11. RS_c

1204.5065

Studies 2012-2013

1. **Z´and Z FCNCs (tree level)**

AJB, De Fazio, Girrbach: 1211.1896 (General)
AJB, De Fazio, Girrbach, Carlucci: 1211.1237 (331-Model)
AJB, Girrbach, Ziegler: 1301.5498 (Minimal Theory of Fermion Masses)

2. **Neutral Scalars FCNCs (tree level)**

AJB, De Fazio, Girrbach, Knegjens, Nagai (1303.3723)

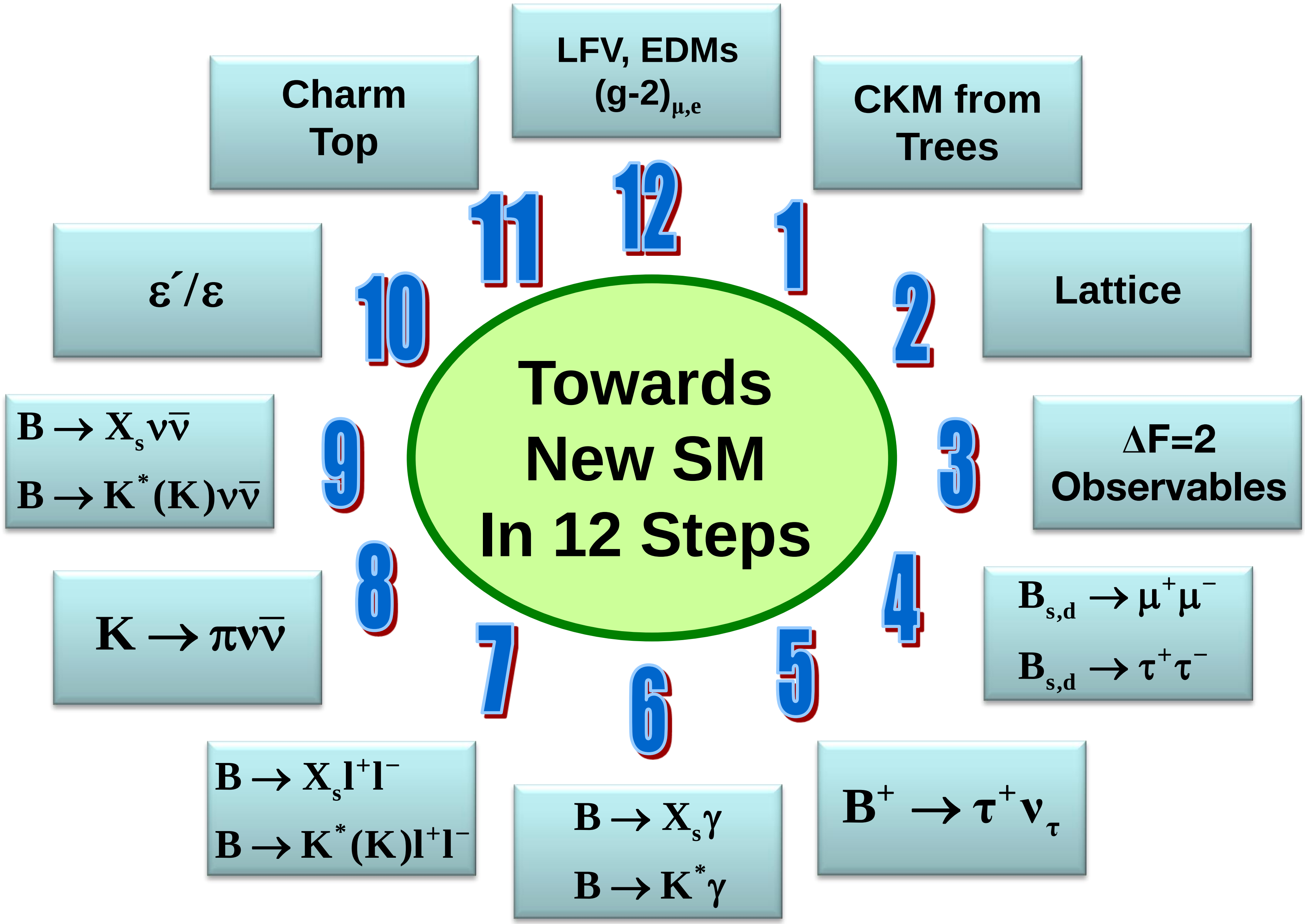
3. **$B_{s,d} \to \mu^+\mu^-$ Phenomenology**

AJB, Fleischer, Girrbach, Knegjens (1303.3820)
AJB, Girrbach, Guadagnoli, Isidori (1208.0934)

2.

Towards New SM in 12 Steps

AJB + Girrbach (1306.3755)


Towards
New SM
In 12 Steps
12
LFV, EDMs
$(g\text{-}2)_{\mu,e}$
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

Departures from Standard Model Expectations

$\not{CP}$

$K^0 - \bar{K}^0$ (ε_K) $\frac{|\varepsilon_K|_{SM}}{|\varepsilon_K|_{exp}} \approx 0.80 \pm 0.10$ (AJB, Guadagnoli) (Brod, Gorbahn)

$B_d^0 - \bar{B}_d^0$ $(S_{\psi K_s})$ $(S_{\psi K_s}) \cong \begin{matrix} 0.82 \pm 0.04 & \text{(SM)} \\ 0.678 \pm 0.022 & \text{(exp)} \end{matrix}$ (Lunghi,Soni)

$B_s^0 - \bar{B}_s^0$ $(S_{\psi\varphi})$ $S_{\psi\varphi} = \begin{matrix} 0.035 \pm 0.002 & \text{(SM)} \\ -0.01 \pm 0.07 & \text{(LHCb)} \end{matrix}$

$$\frac{Br(B^+ \to \tau^+\nu)_{exp}}{Br(B^+ \to \tau^+\nu)_{SM}} \cong 1.5 \pm 0.3$$

$$|V_{ub}| = \begin{cases} 4.3 \cdot 10^{-3} & \text{Inclusive Decays } (B \to X_u l\nu) \\ 3.1 \cdot 10^{-3} & \text{Exclusive Decays } (B \to \rho l\nu) \\ & \text{and SM-CKM fit} \end{cases}$$

(Right-handed currents? Crivellin; Mannel et al. AJB, Gemmler, Isidori)

Two Scenarios for $|V_{ub}|$

(Taking into account $\Delta M_s, \Delta M_d \leftarrow B^0_{d,s} - \overline{B}^0_{d,s}$ Mixing)

$$\left\{|V_{ub}| \cong 4.3 \cdot 10^{-3}\right\} \Rightarrow \left\{\frac{\left(S_{\psi K_s}\right)_{SM}}{\left(S_{\psi K_s}\right)_{exp}}\right\} \cong 1.2 \qquad \frac{|\varepsilon_K|_{SM}}{|\varepsilon_K|_{exp}} \cong 1.0$$

New Physics in $B^0_d - \overline{B}^0_d$ required

$$\left\{|V_{ub}| \cong 3.1 \cdot 10^{-3}\right\} \Rightarrow \left\{\frac{\left(S_{\psi K_s}\right)_{SM}}{\left(S_{\psi K_s}\right)_{exp}}\right\} \cong 1.0 \qquad \frac{|\varepsilon_K|_{SM}}{|\varepsilon_K|_{exp}} \cong 0.8$$

New Physics in ε_K required

Unfortunately to resolve this issue we have to wait for Belle II, Super-B and smarter Theorists

The size of CP Violation depends on the size of CKM elements: here $|V_{ub}|$

Good Agreement of SM With ΔM_s and ΔM_d

(for both $|V_{ub}|$ scenarios)

Data

$$\left(\Delta M_d\right)^{SM} = \left(0.55 \pm 0.06\right) / \text{ps} \qquad \left(0.507 \pm 0.004\right) / \text{ps}$$

$$\left(\Delta M_s\right)^{SM} = \left(19.0 \pm 2.1\right) / \text{ps} \qquad \left(17.7 \pm 0.1\right) / \text{ps}$$

$$\left(\frac{\Delta M_s}{\Delta M_d}\right)^{SM} = 34.5 \pm 3.0 \qquad 34.9 \pm 0.3$$

Further Lattice Improvements crucial

But tendency:

$$\left(\Delta M_{s,d}\right)^{SM} > \left(\Delta M_{s,d}\right)^{exp}$$

Models with Constrained MFV

SM Operators + CKM   but new particles in loops

$S_{\psi K_s}$, $S_{\psi\varphi}$ **o.k.**   **LH, UED**

$$\frac{\Delta M_s}{\Delta M_d} = \left(\frac{\Delta M_s}{\Delta M_d}\right)^{SM}$$

o.k.   **Exclusive V_{ub} to get correct $S_{\psi K_s}$**

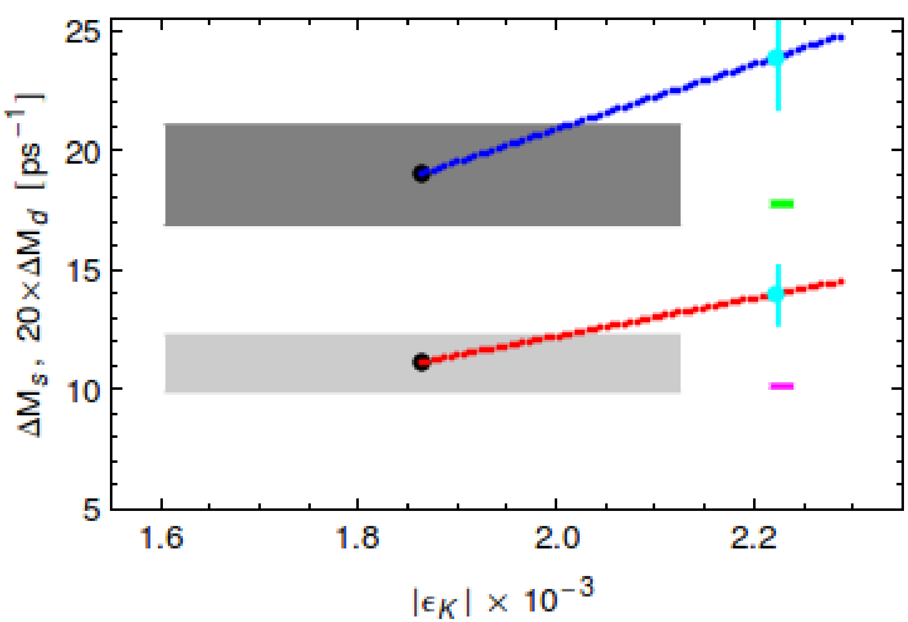
But necessary enhancement of $|\varepsilon_K|$ implies automatically enhancements Of ΔM_s and ΔM_d spoiling the agreement with data*)

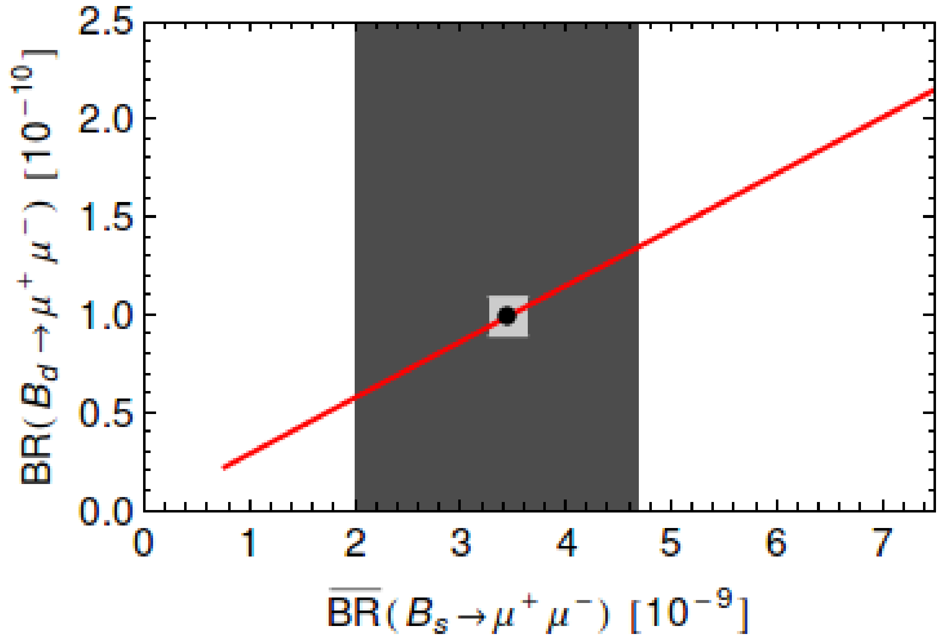
Conclusion: **CMFV under pressure**

***) Only enhancements of $|\varepsilon_K|$, $\Delta M_{s,d}$ are possible in CMFV   (Blanke + AJB)**

Constrained Minimal Flavour Violation

AJB + J. Girrbach (2012)





Tension within CMFV **EXP**

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

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

(LHCb)

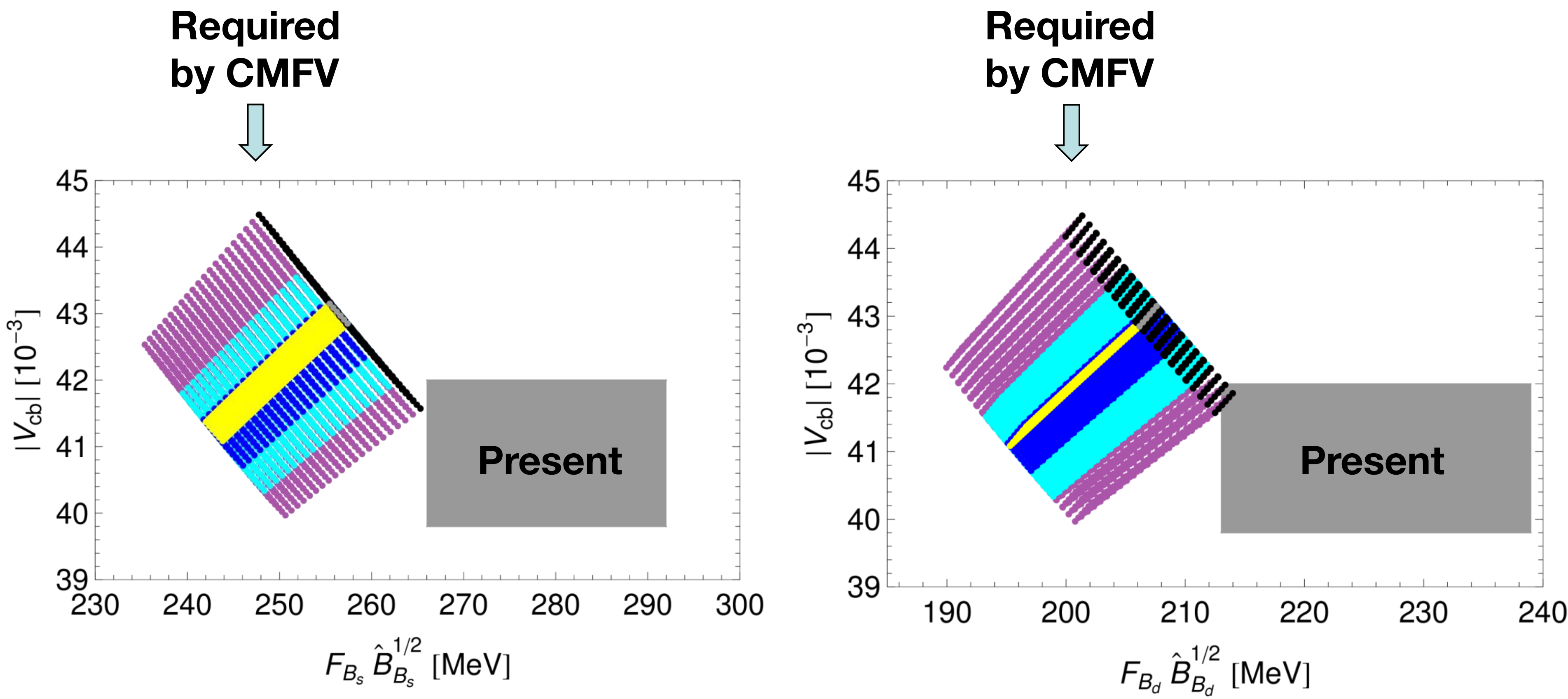
Stringent Tests of CMFV through $\Delta F=2$ Processes

AJB + Girrbach 1304.6835

Which values of

$$|V_{cb}|,\ \sqrt{\hat{B}_d}F_{B_d},\ \sqrt{\hat{B}_s}F_{B_s}$$

Would save CMFV ?



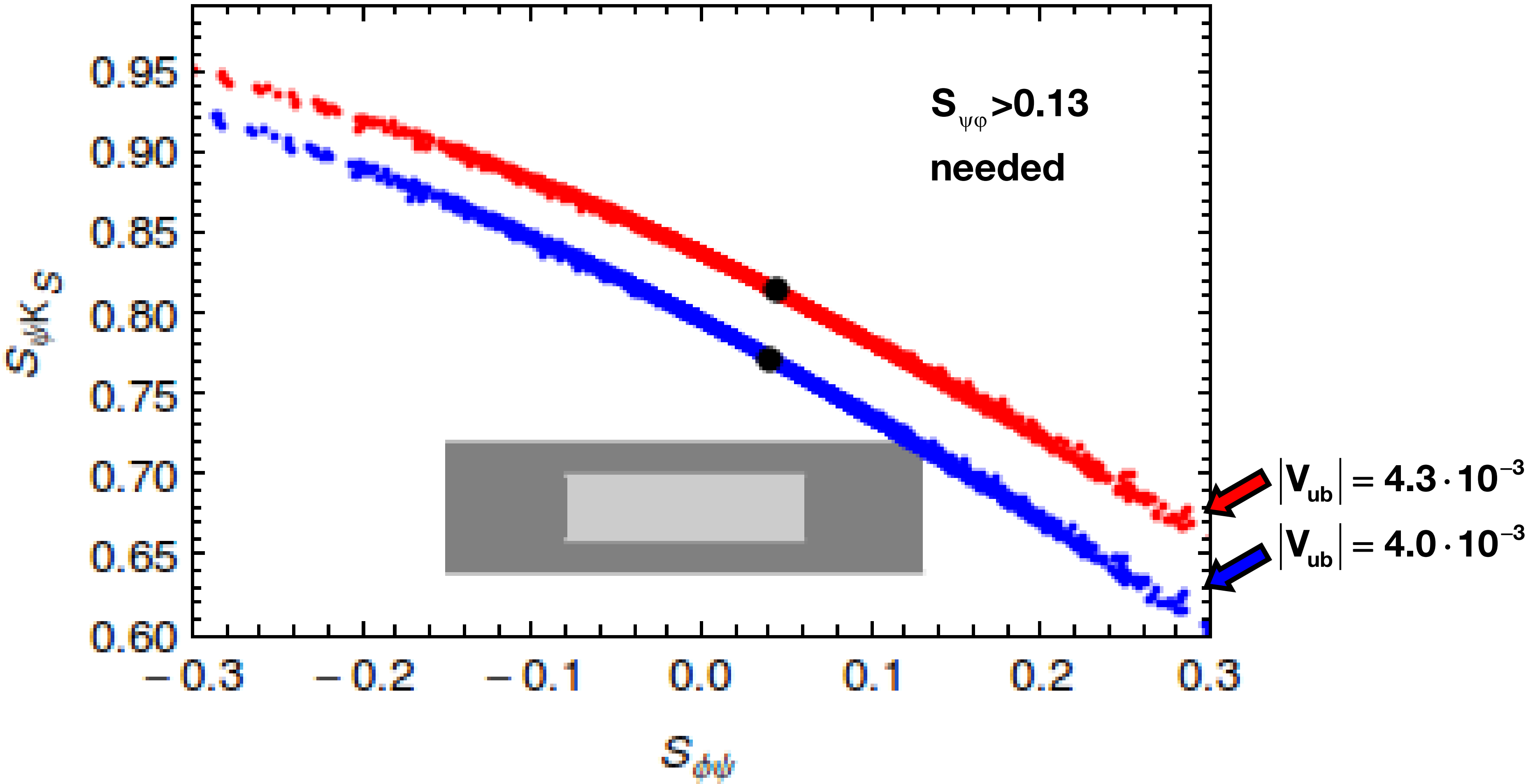
: SM

: $\eta_{cc} = 1.87 \pm 76$ (Brod + Gorbahn)

: $\eta_{cc} = 1.70 \pm 0.21$ (using ΔM_K) AJB + Girrbach, 1304.6835

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

AJB, Girrbach, Nagai (2013)



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

Conclusion on $2HDM_{\overline{MFV}}$

Still alive but finding

$S_{\psi\varphi} < 0$ or very close to SM

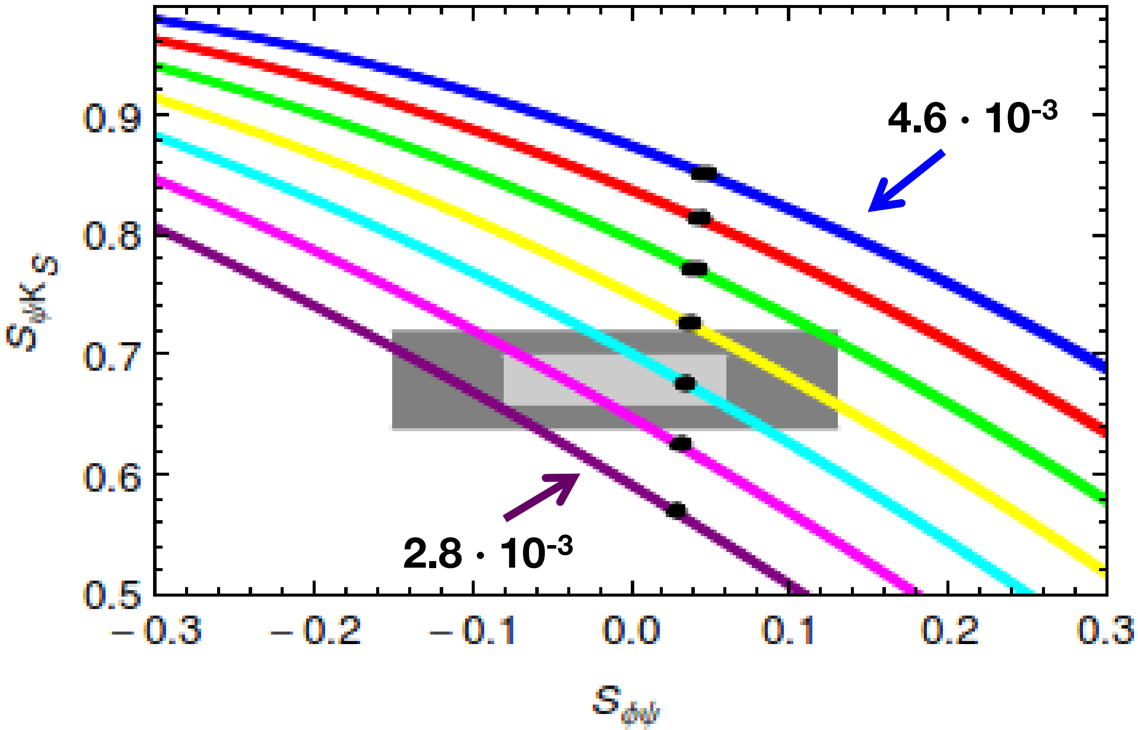
will rule it out.

Let us see what $U(2)^3$ symmetry can do for us ? (Barbieri et al. Nierste et al.)

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

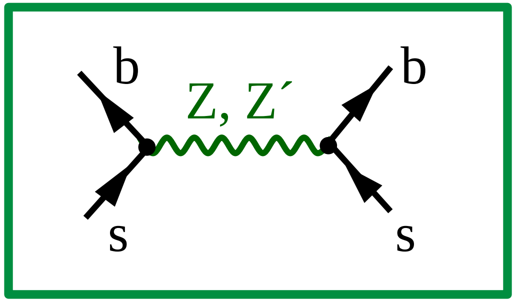


In the $U(2)^3$ Symmetric World we could determine $|V_{ub}|$ without significant hadronic uncertainties (QCD penguins)

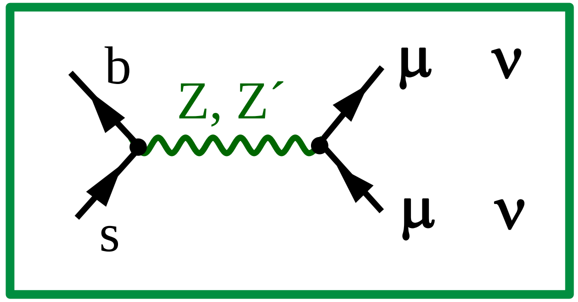
3.

Correlations between Flavour Observables: DNA Charts

Basics of Correlations in Tree-Level (Z,Z´) FCNCs



$\Delta F = 2$



$\Delta F = 1$

M_Z

$M_{Z'}$

Z, Z´ couplings: $\Delta_{L,R}^{bs} \equiv \tilde{s}_{23} e^{-i\delta_{23}}$

only two new quark parameters!

B_s^0 : ΔM_s, $S_{\psi\varphi}$, $B_s \to \mu^+\mu^-$, $S_{\mu\mu}^s$, $B \to K^*(K)\nu\bar{\nu}$, $B \to X_s\nu\bar{\nu}$, $b \to sll$

B_d^0 : ΔM_d, $S_{\psi K_S}$, $B_d \to \mu^+\mu^-$, $S_{\mu\mu}^d$ ⇐ $\Delta_{L,R}^{bd} \equiv \tilde{s}_{13} e^{-i\delta_{13}}$ | $\Delta_{L,R}^{sd} \equiv \tilde{s}_{12} e^{-i\delta_{12}}$

K : ε_K, $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$, $K_L \to \mu^+\mu^-$, $K_L \to \pi^0 l^+ l^-$, ε'/ε

$M_{Z'}$ Dependence of ΔF=2 and ΔF=1 Transitions

ΔF=2 Amplitude : $\frac{\left(\Delta_{L,R}^{ij}\right)^2}{M_{Z'}^2}$ **ΔF=1 Amplitude** : $\frac{\Delta_{L,R}^{ij}}{M_{Z'}^2}$

$\Delta_{L,R}^{ij}$ from ΔF=2 = $\Delta_{L,R}^{ij} \sim M_{Z'}$ → **ΔF=1 Amplitude** ~ $\frac{1}{M_{Z'}}$

↓

For $M_{Z'}$ > 1TeV : **NP in ΔF=2 more important than in ΔF=1**

For Z : **NP in ΔF=1 more important than in ΔF=2**

Correlations depend strongly on the allowed Size of NP Contributions

	SM	Data
ΔM_s	$19.0\,/\,\mathrm{ps}$	$17.7\,/\,\mathrm{ps}$
$S_{\psi\varphi}$	0.04	$-0.20 \le S_{\psi\varphi} \le 0.20$ 95% C.L.
$Br(B_s \to \mu^+\mu^-)$	$3.5 \cdot 10^{-9}$	$1.10^{-9} \le Br(B_s \to \mu^+\mu^-) \le 6.0 \cdot 10^{-9}$

	SM	Data
ΔM_d	$0.56\,/\,\mathrm{ps}$	$0.51\,/\,\mathrm{ps}$
$S_{\psi K_s}$	0.67 (excl. V_{ub}) (S1)	0.68 ± 0.02
	0.81 (incl. V_{ub}) (S2)	0.68 ± 0.02

	SM	Data
ε_K	$1.80 \cdot 10^{-3}$ (excl. V_{ub}) (S1)	$2.23 \cdot 10^{-3}$
	$2.20 \cdot 10^{-3}$ (incl. V_{ub}) (S2)	$2.23 \cdot 10^{-3}$

Lessons from Z´ Studies

1. All tensions in $\Delta F=2$ observables can be removed.

2. For $M_{Z'} > 5$ TeV NP effects in B_s, B_d systems very small

But: $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ still sensitive to $M_{Z'} \approx 10 - 20\,\text{TeV}$

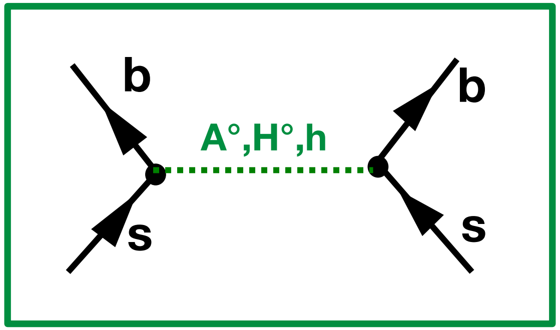
Lessons from Z Studies

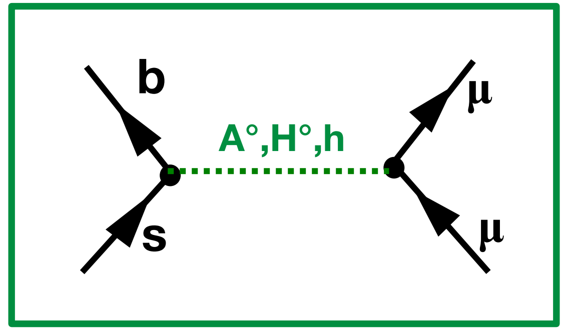
1. $\text{Br}(B_d \to \mu^+\mu^-)$ and $\text{Br}(B_s \to \mu^+\mu^-)$ can only be enhanced. (both up to the present bounds)

2. $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$: much larger effects than for Z'. (Bounded by $K_L \to \mu^+\mu^-$)

Lessons from Tree-Level (A°, H°, h) FCNC´s

(pseudo) scalar SM Higgs





1. Correlations between $\Delta F=1$ and $\Delta F=2$ observables for A° differ from Z´ case because of pseudoscalar coupling γ_5.

2. Correlations between $\Delta F=1$ and $\Delta F=2$ observables for H° differ from Z´ case because of absence of interference with SM part.
(only enhancements of branching ratios possible)

3. SM Higgs contributions to $\Delta F=1$ transitions negligible once $\Delta F=2$ constraints satisfied because of small $\mu\mu$ coupling.

$\overline{Br}(B_s \to \mu^+\mu^-),\ S^s_{\mu\mu},\ Br(B_d \to \mu^+\mu^-),\ S^d_{\mu\mu}$

	SM	Data (LHCb)
$\overline{Br}(B_s \to \mu^+\mu^-)$	$(3.56 \pm 0.18)\cdot 10^{-9}$	$\left(3.2^{+1.5}_{-1.2}\right)\cdot 10^{-9}$
$Br(B_d \to \mu^+\mu^-)$	$(1.05 \pm 0.07)\cdot 10^{-10}$	$\leq 9.4 \cdot 10^{-10}$

$$S^s_{\mu\mu} = S^d_{\mu\mu} = 0$$

De Bruyn, Fleischer, Knegjens et al. (1204.1735; 1204.1737)

AJB, Fleischer, Girrbach, Knegjens (1303.3820)
AJB, Girrbach, Guadagnoli, Isidori (1208.0934)

$S_{\psi\varphi} = 0.035 \pm 0.002$ $\qquad$ $S_{\psi\varphi} = -0.01 \pm 0.07$

Still New Physics could be discovered in these observables, in particular through correlations between them.

Scenarios for Z´and Z Couplings

Left-handed scenario (LHS) $\Delta_L^{ij} \neq 0 \qquad \Delta_R^{ij} = 0$

Right-handed scenario (RHS) $\Delta_R^{ij} \neq 0 \qquad \Delta_L^{ij} = 0$

Left-right symmetric scenario (LRS) $\Delta_L^{ij} = \Delta_R^{ij} \neq 0$

Left-right asymmetric scenario (ALRS) $\Delta_L^{ij} = -\Delta_R^{ij} \neq 0$

LRS : no New Physics contributions to $K_L \to \mu^+\mu^-$, $B_{s,d} \to \mu^+\mu^-$

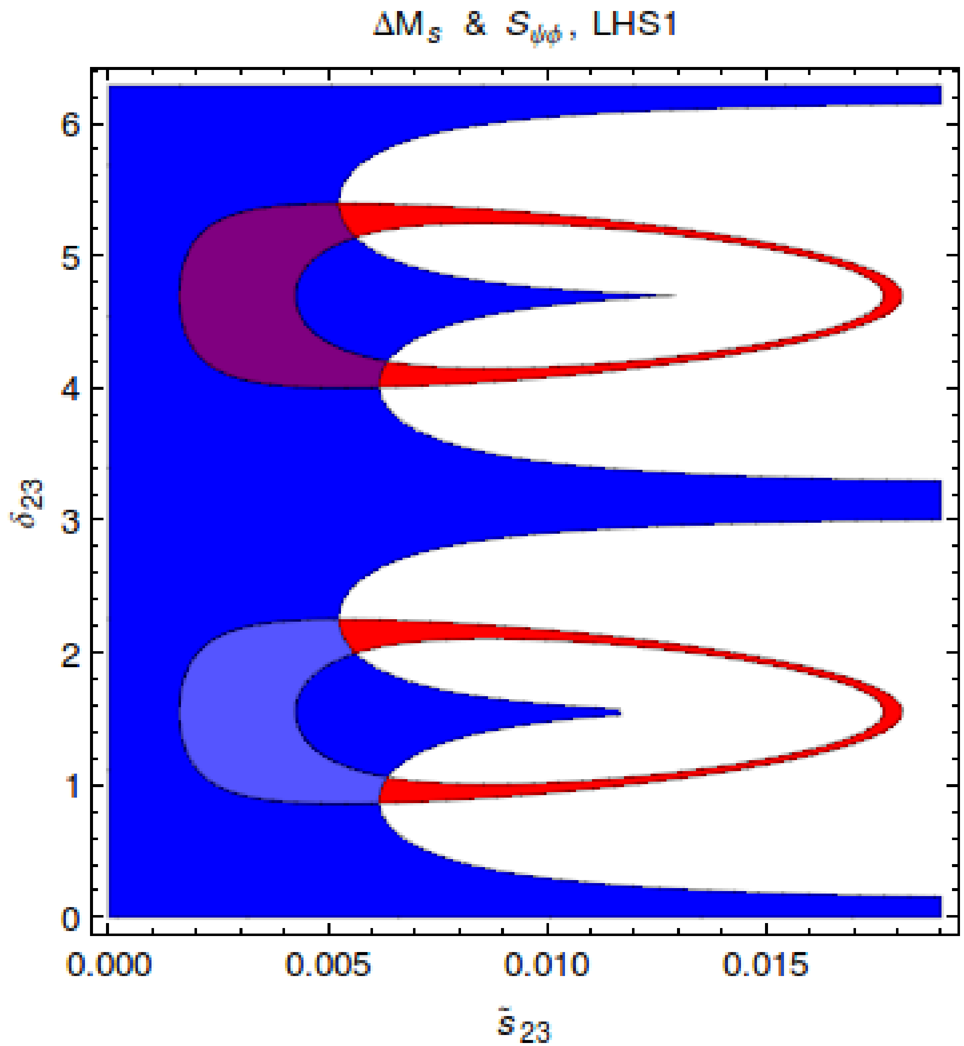
ALRS : no New Physics contributions to $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$

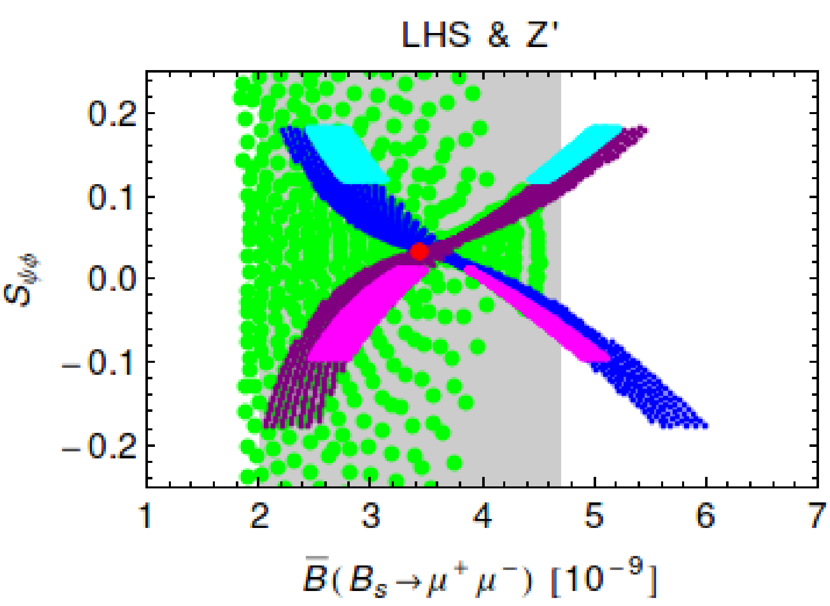
See also:

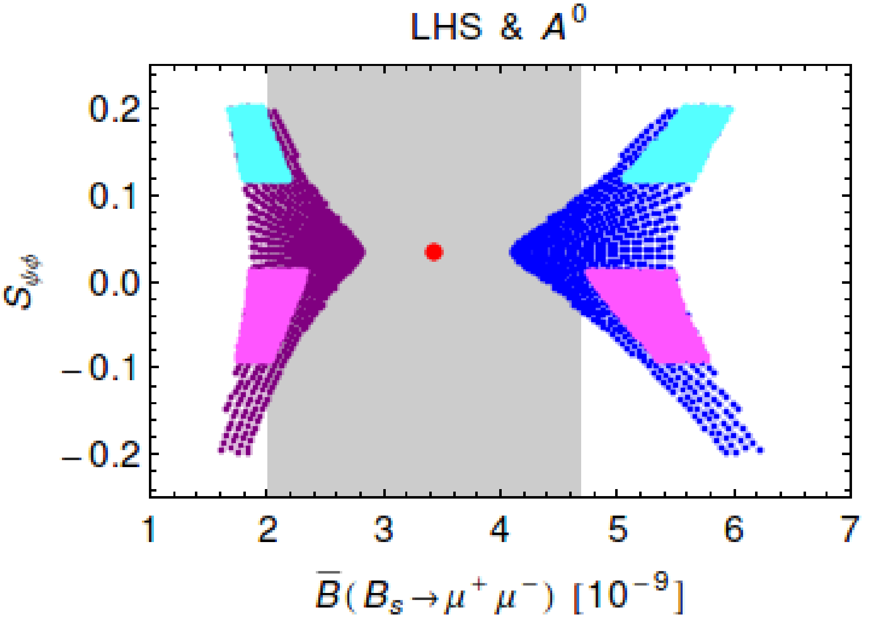
Altmannshofer, AJB, Straub, Wick 0902.0160
Altmannshofer, AJB, Gori, Paradisi, Straub (Flavour SUSY) 0909.1333
Altmannshofer, Paradisi, Straub 1111.1257
Altmannshofer, Straub 1206.0273

Oases in B_s-System

ΔM_s (red) $S_{\psi\varphi}$ (blue)



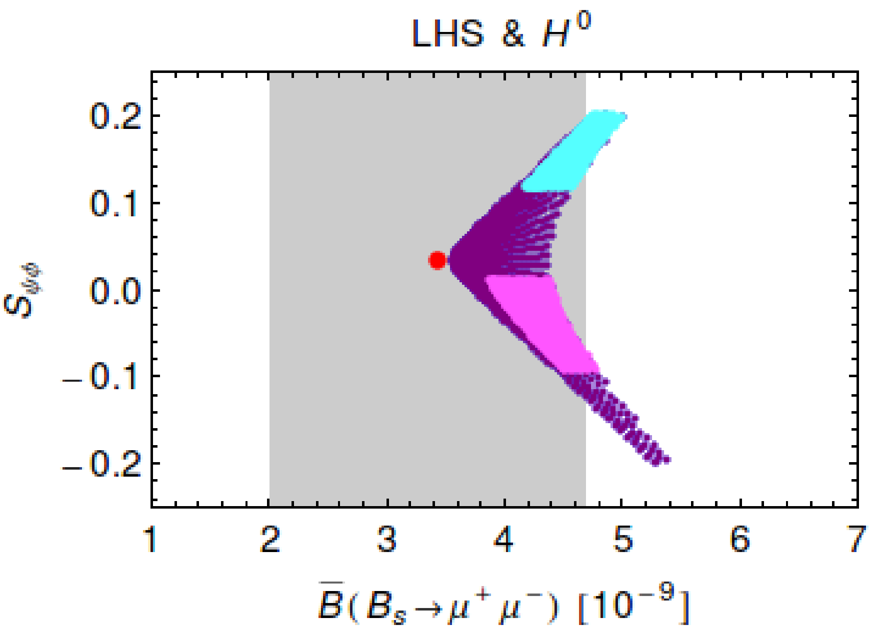




1211.1896
1303.3723

$S_{\psi K_s}$ – $B_s \to \mu^+\mu^-$
Correlations for
Z', A°, H°

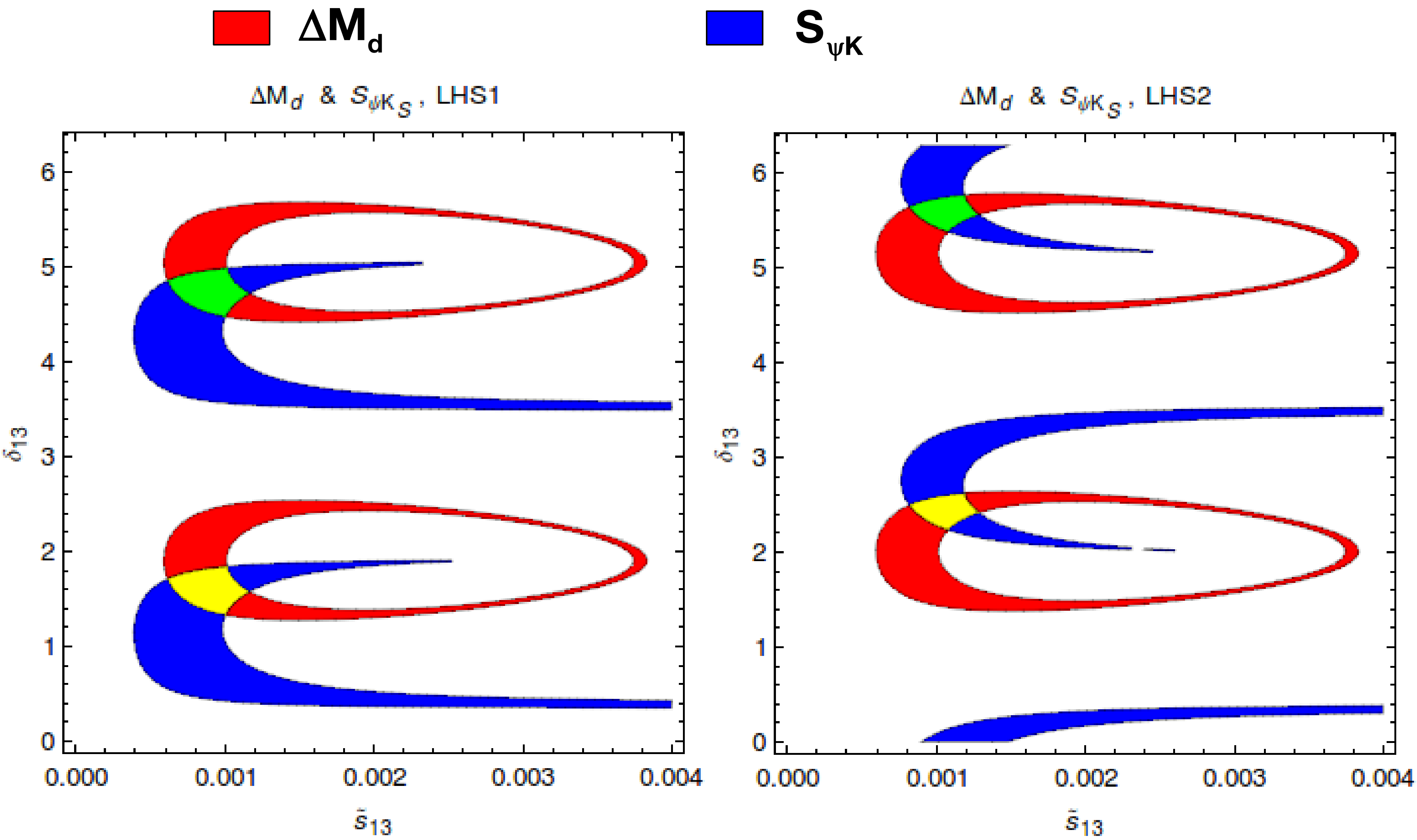
1 TeV



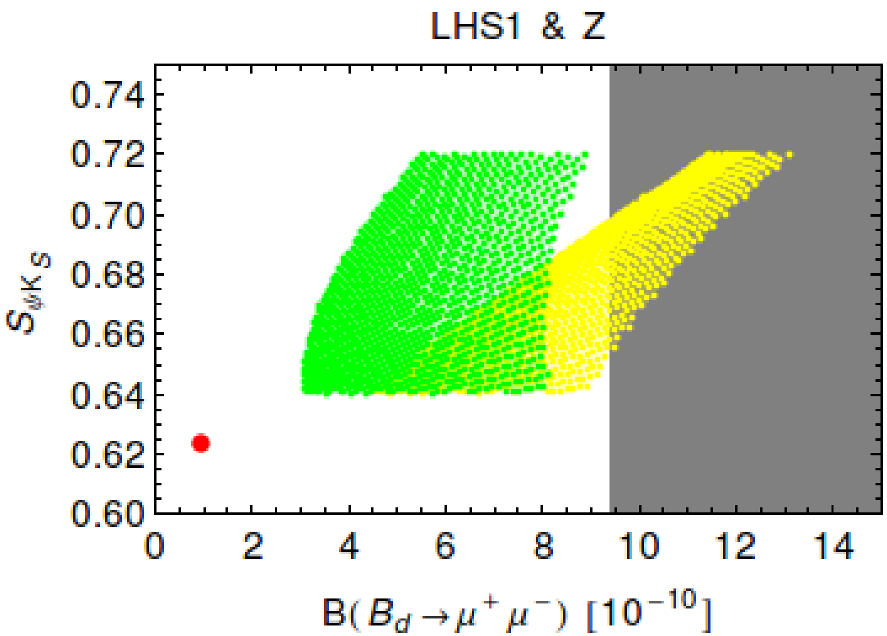
: allowed by $b \to sll$

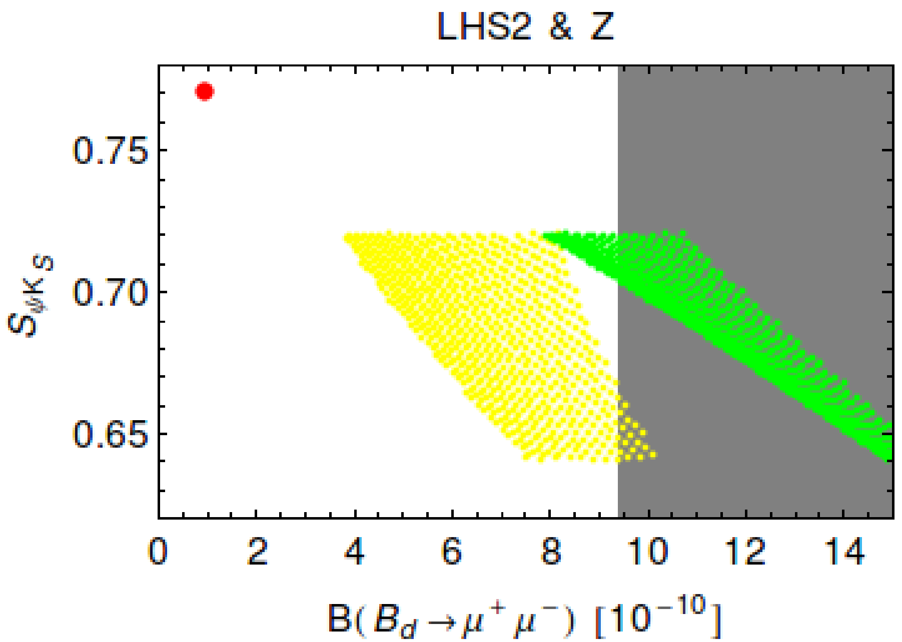
$U(2)^3$

Oases in B_d-System



$S_{\psi K_s} - B_d \to \mu^+\mu^-$ Correlation for Z





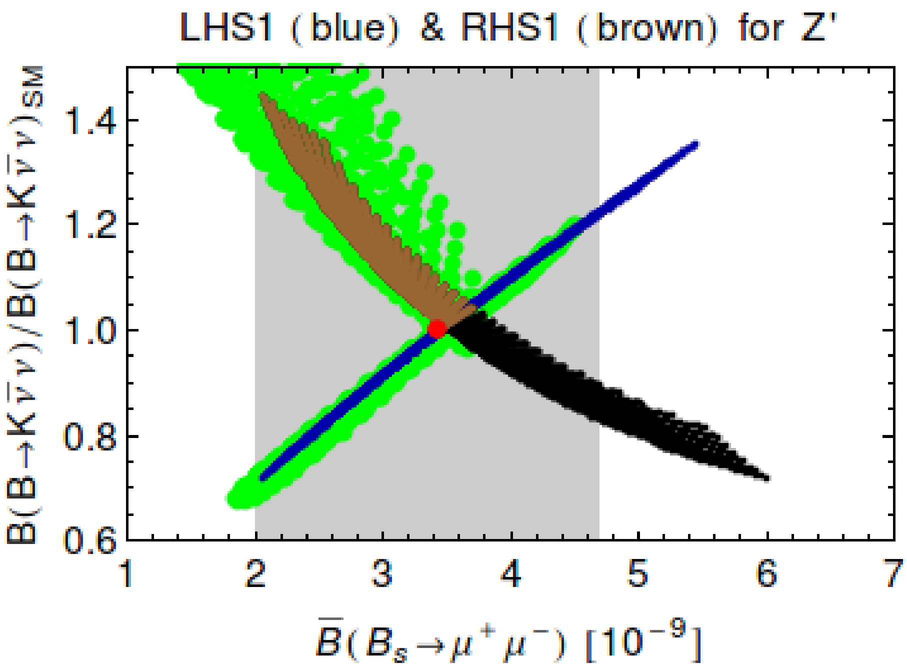
$|V_{ub}| = 3.1 \cdot 10^{-3}$

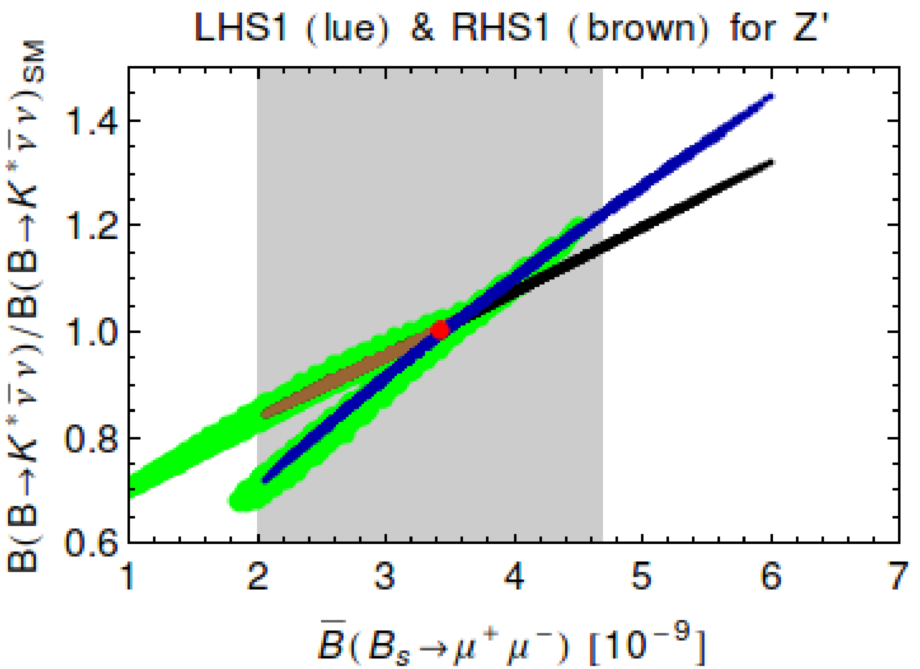
$|V_{ub}| = 4.0 \cdot 10^{-3}$

1211.1896

NP-effects can still be large !

Distinguishing Left-Handed Currents from Right-Handed Currents





AJB, De Fazio, Girrbach
1211.1896

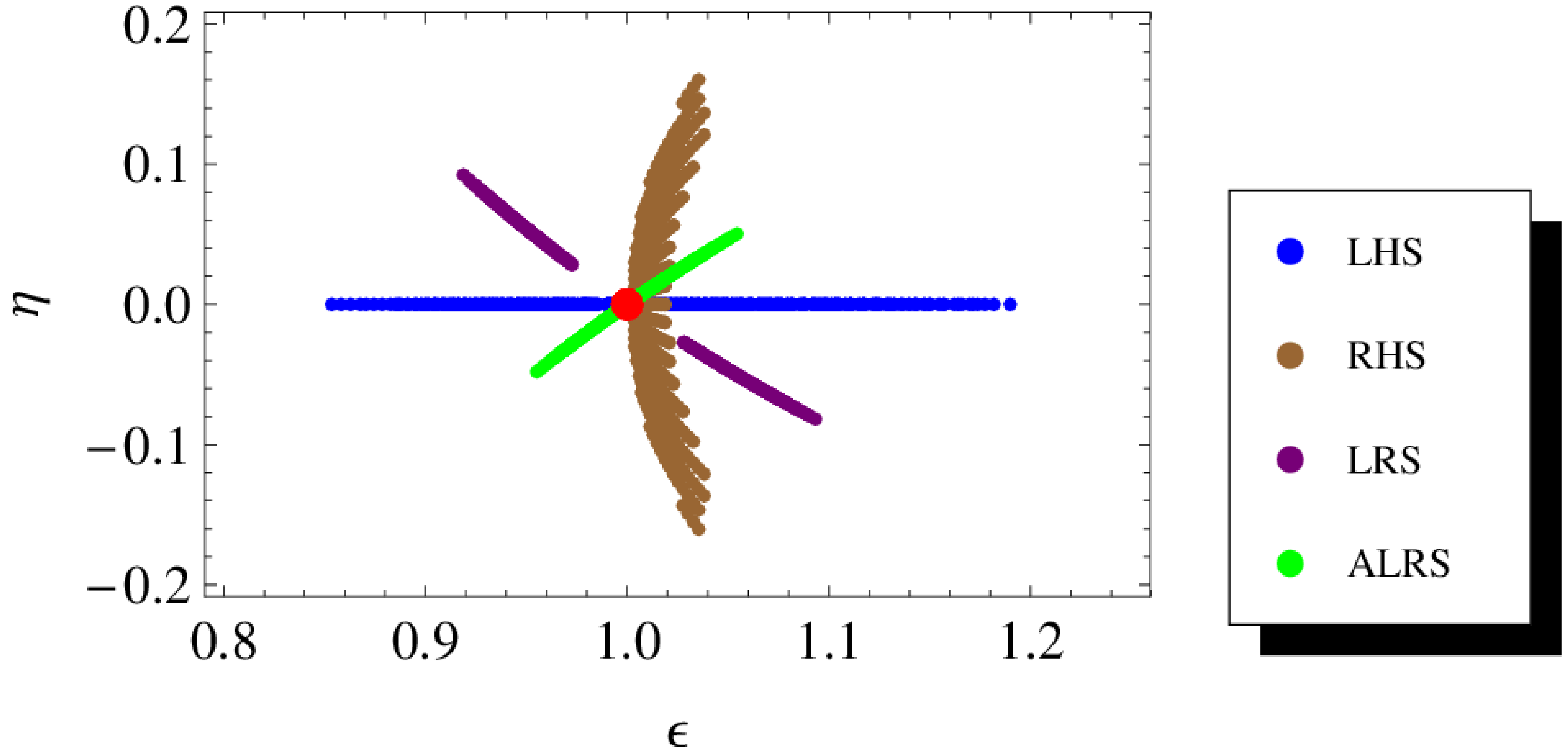
Altmannshofer et al.
0902.0160

■ : **forbidden by $b \to sll$**

■ : **allowed by $b \to sll$**

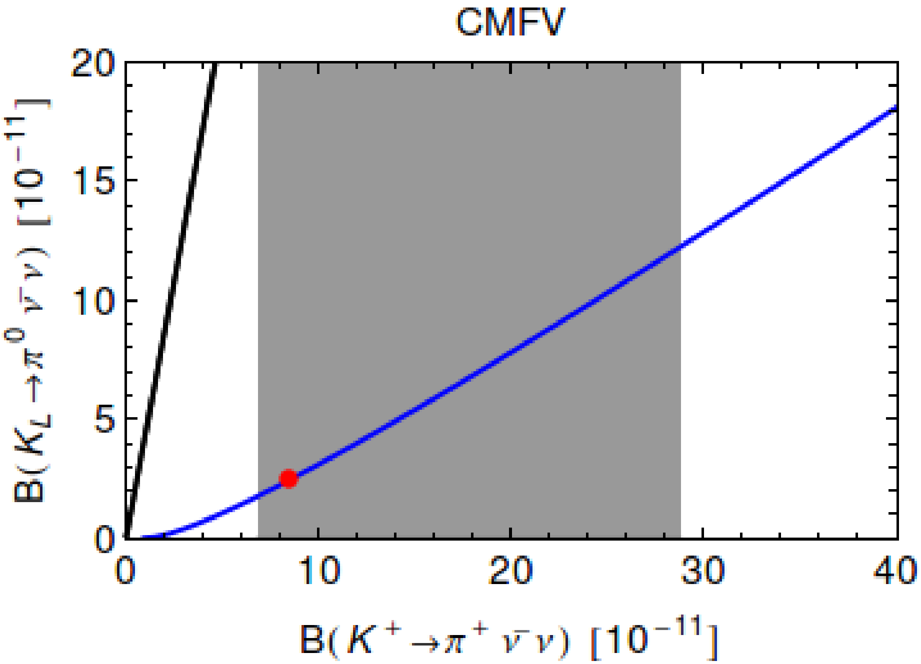
(ε, η) : Parameters for $b \to s\nu\bar{\nu}$ Transitions

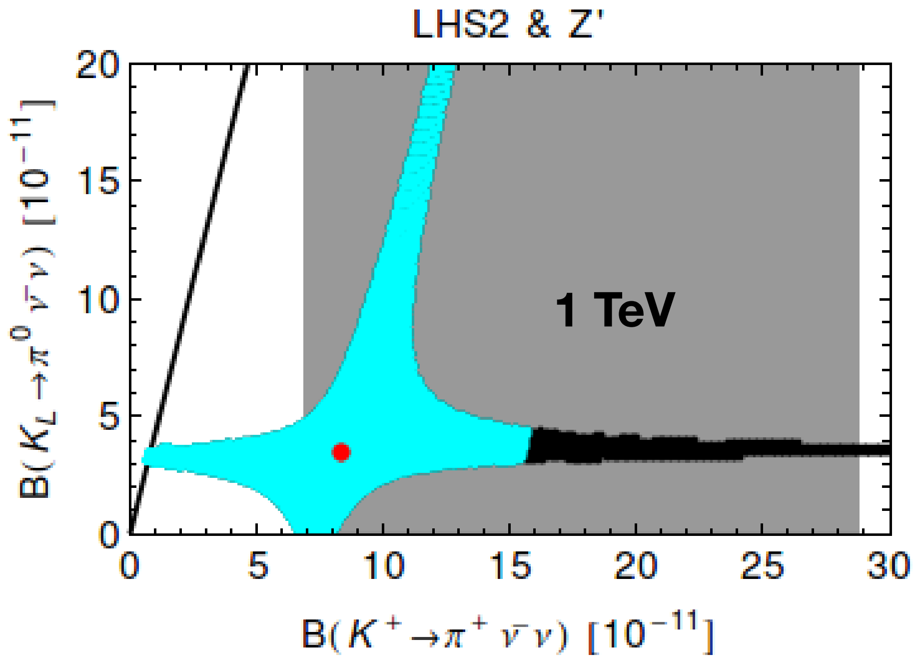
1211.1896

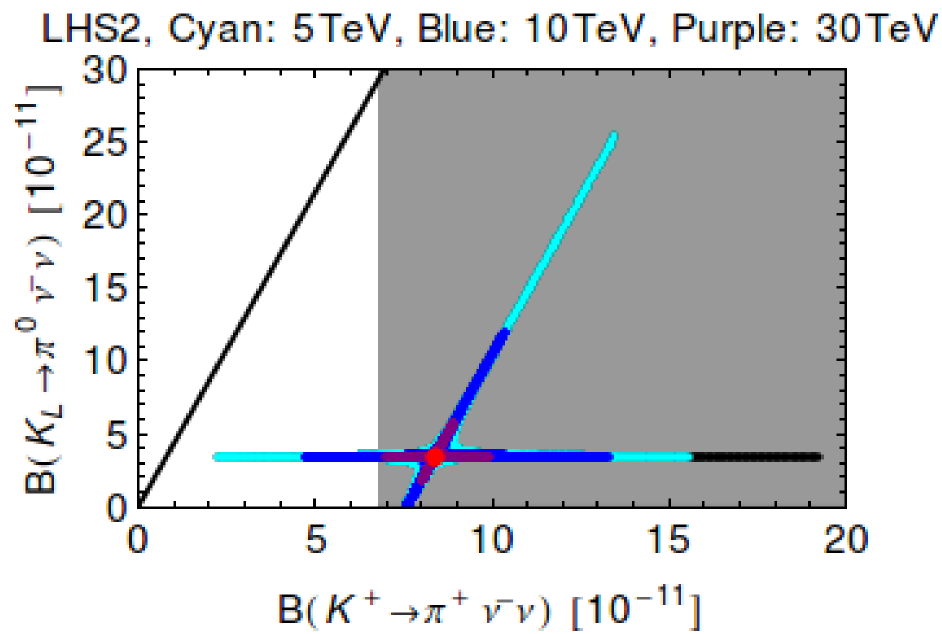


Altmannshofer, AJB, Straub, Wick
0902.0160

1211.1896

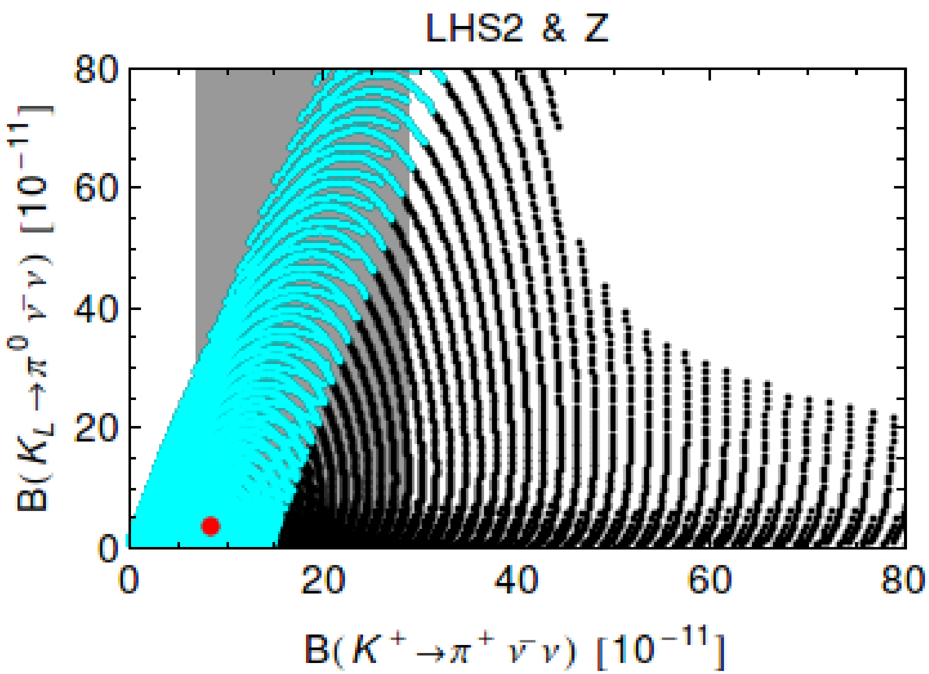


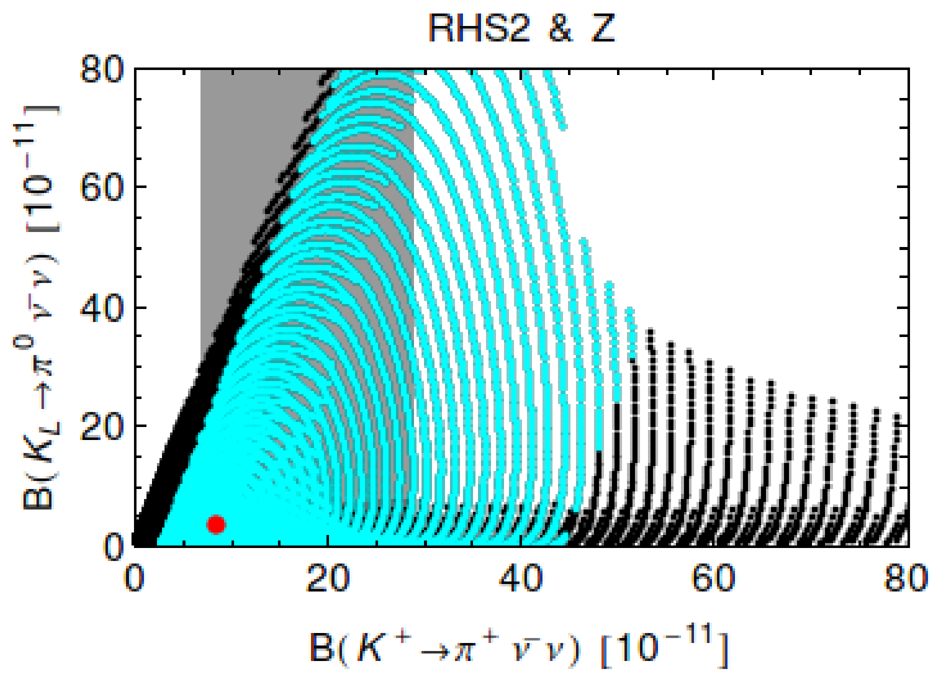


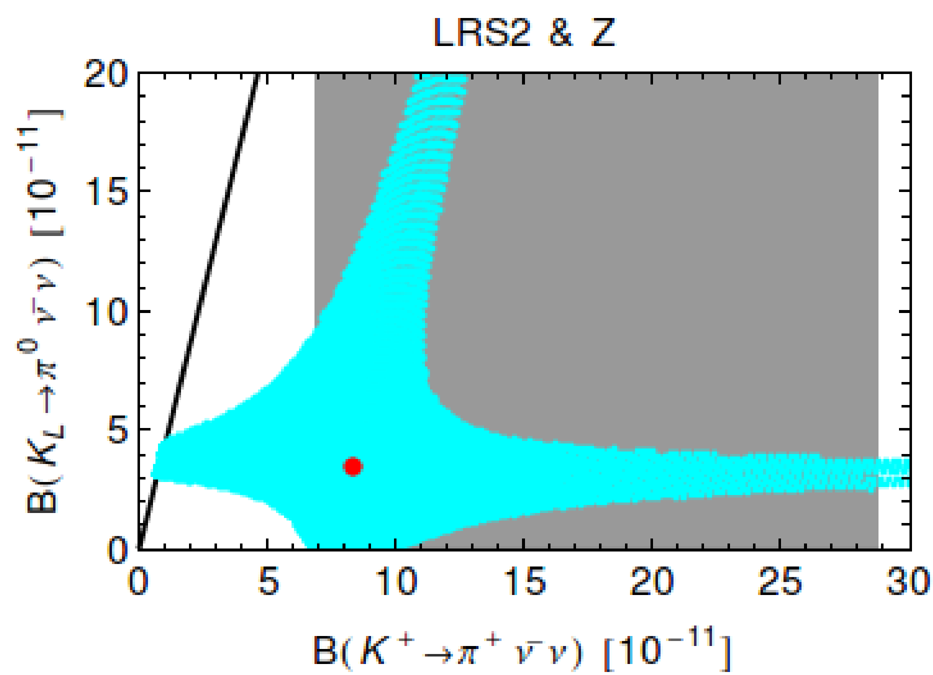


Sensitivity to $M_{Z'}$ beyond the LHC

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







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

LHS, RHS
LRHS

DNA - Charts

1306.3755

AJB + Girrbach

- suppression relative to SM

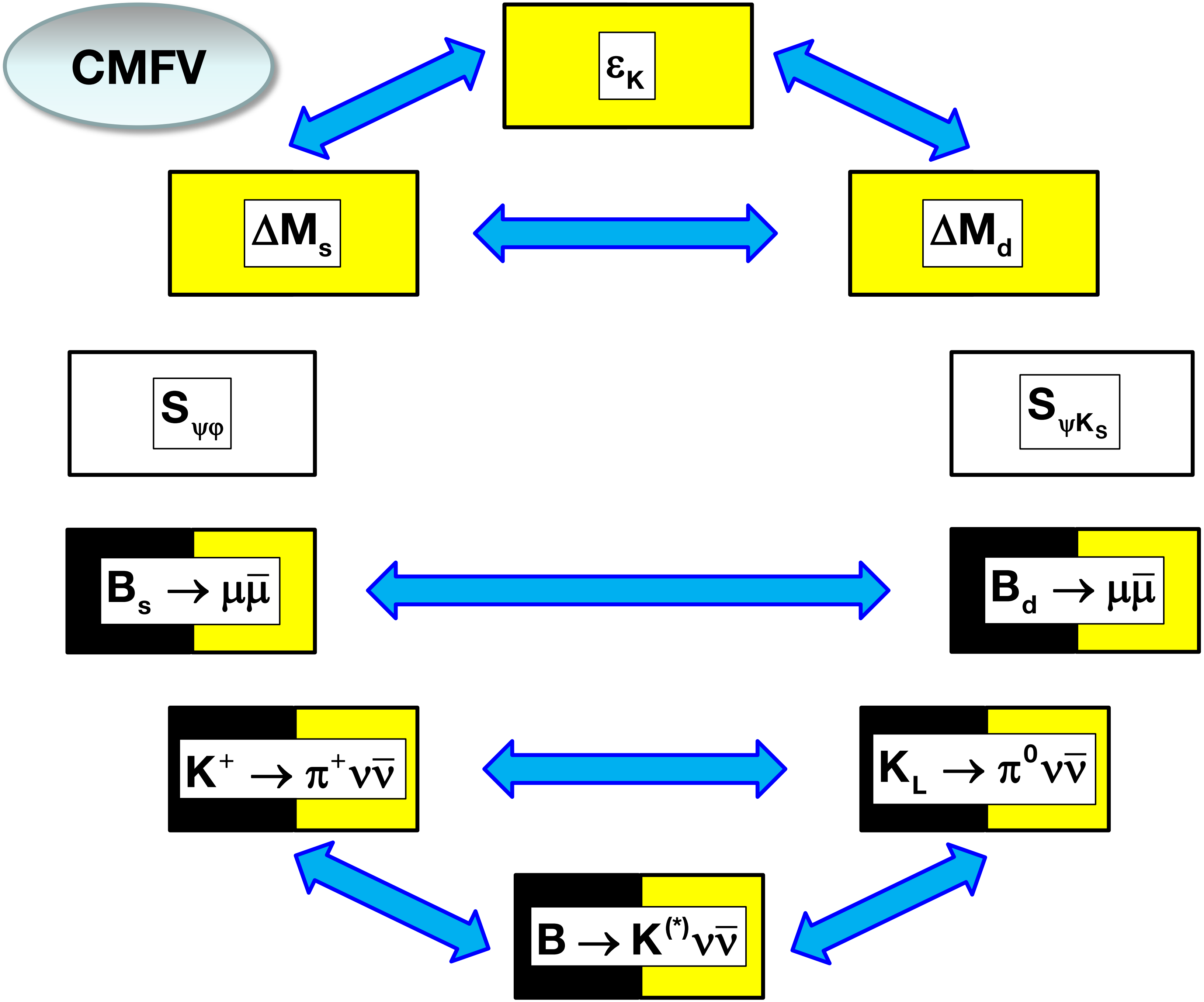
- enhancement relative to SM

correlation

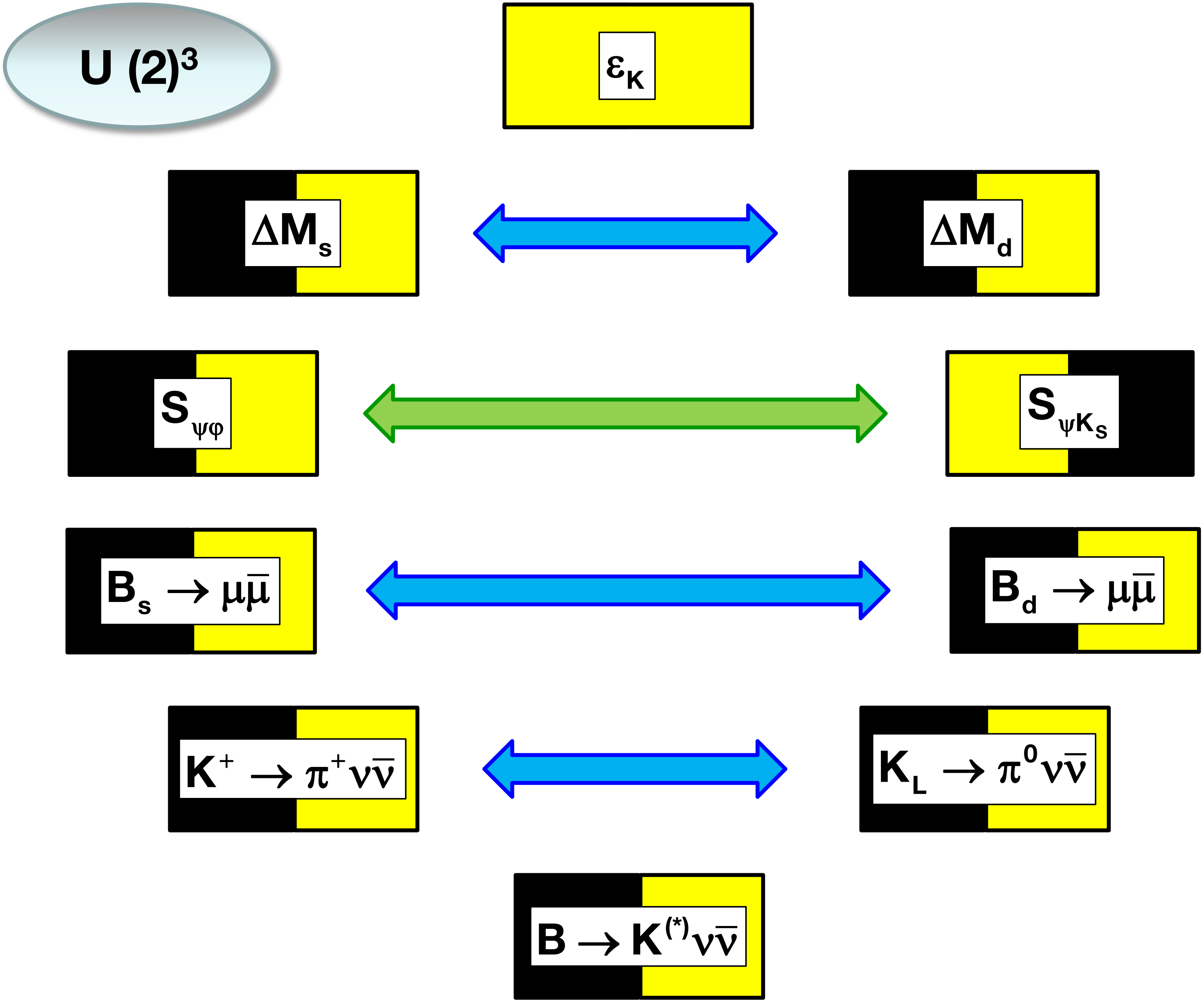
anti-correlation

Previous proposals: DNA tables: Altmannshofer, AJB, Gori, Paradisi, Straub 0909.1333

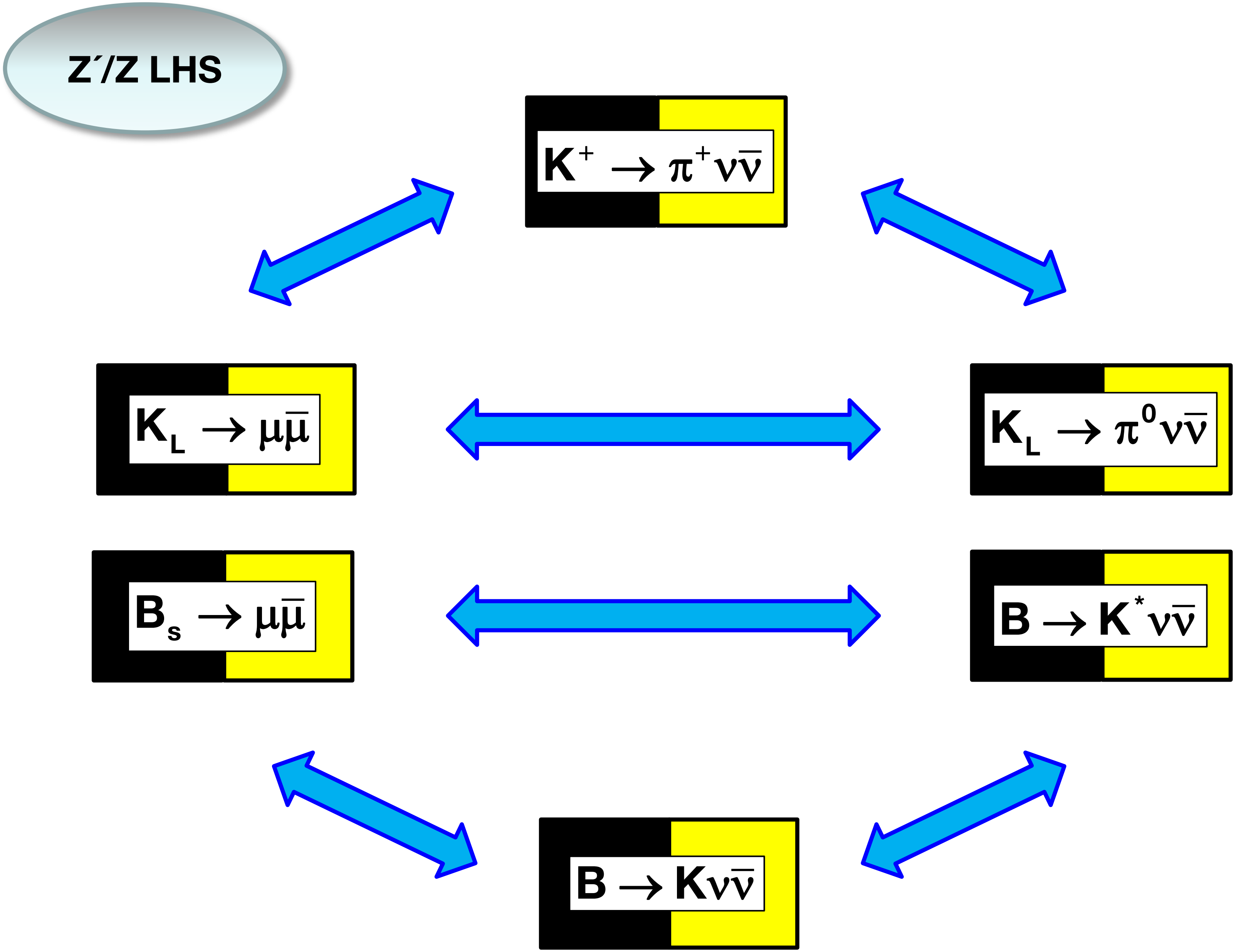
Flavour codes: AJB 1012.1447

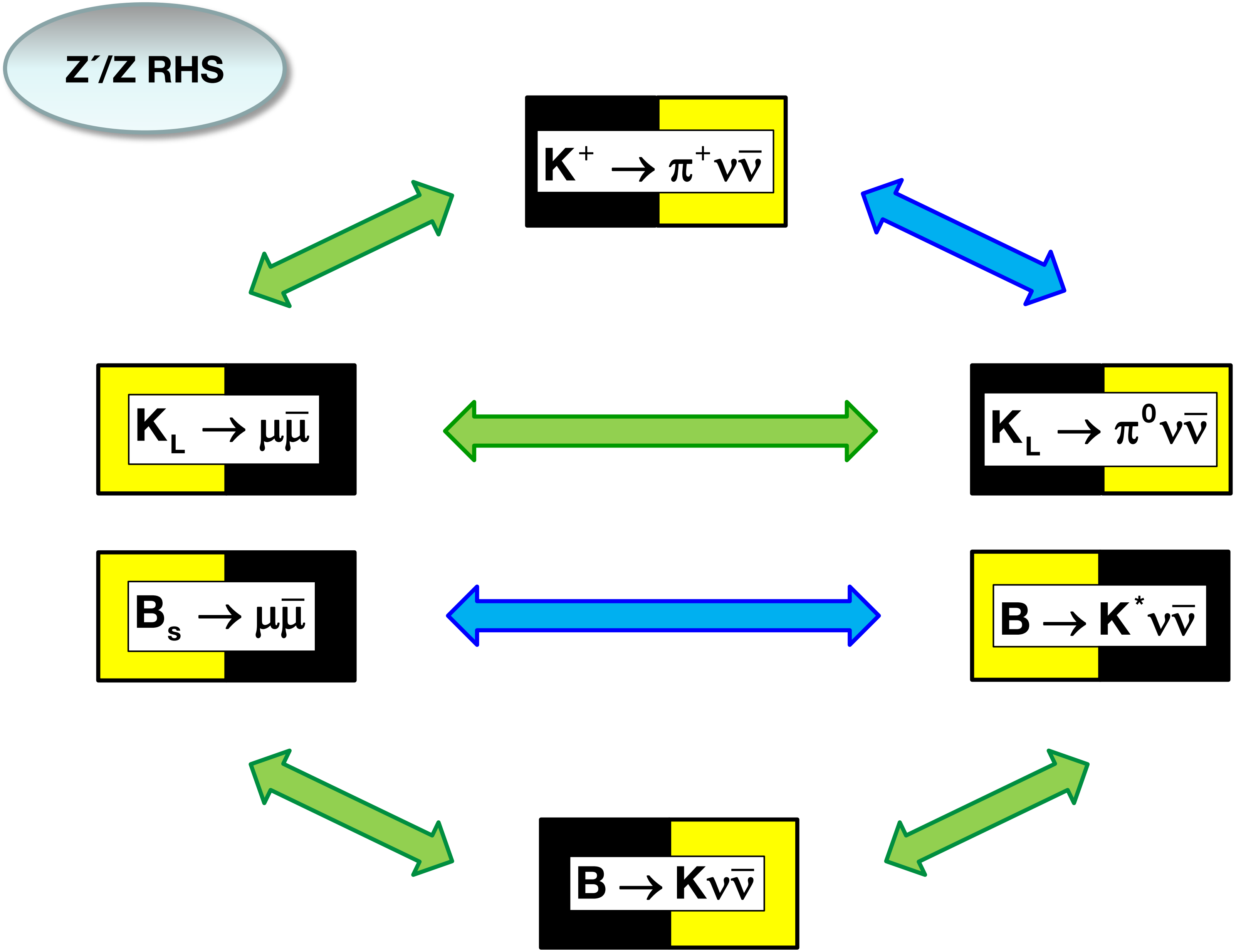


CMFV
ε_K
ΔM_s
ΔM_d
$S_{\psi\varphi}$
$S_{\psi K_S}$
$B_s \to \mu\bar{\mu}$
$B_d \to \mu\bar{\mu}$
$K^+ \to \pi^+\nu\bar{\nu}$
$K_L \to \pi^0\nu\bar{\nu}$
$B \to K^{(*)}\nu\bar{\nu}$



U (2)^3
ε_K
ΔM_s
ΔM_d
$S_{\psi\varphi}$
$S_{\psi K_S}$
$B_s \to \mu\bar{\mu}$
$B_d \to \mu\bar{\mu}$
$K^+ \to \pi^+ \nu\bar{\nu}$
$K_L \to \pi^0 \nu\bar{\nu}$
$B \to K^{(*)} \nu\bar{\nu}$


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

4.

Finale: Vivace !

LHCb Data had profound impact on various BSM models

1204.5056
1306.3755
AJB + Girrbach

In view of stronger bounds on NP effects precise lattice calculations and the more precise determination of CKM parameters: γ, $|V_{ub}|$, $|V_{cb}|$ from trees gained in importance.

Already precise determination of $|V_{ub}|$ with precise lattice calculations could distinguish between simplest BSM models:

Small $|V_{ub}|$: CMFV, Gauged Flavour Models

Large $|V_{ub}|$: $2HDM_{\overline{MFV}}$, 331, RHMFV

Final Messages

1. SM does not offer a fully satisfactory description of $\Delta F=2$ observables.

2. CMFV does not improve on this.

3. $2HDM_{\overline{MFV}}$ under pressure because of $S_{\psi K_s} \leftrightarrow S_{\psi\varphi}$ correlation.

   Prediction: $S_{\psi\varphi} > \left(S_{\psi\varphi}\right)^{SM} > 0$

4. Models with non-MFV interactions (LHT, SM4, SUSY, RS, Z´…) can still remove all tensions in the data. In particular both $S_{\psi\varphi} > 0$ and $S_{\psi\varphi} < 0$ possible.

5. $U(2)^3$ an interesting alternative to MFV ($U(3)^3$) $S_{\psi K_s} - S_{\psi\varphi} - |V_{ub}|$ correlation.

Final Messages

6. Precise measurements of several observables combined with studies of various patterns of flavour violation, correlations and DNA charts could one day give us insight into the physics beyond the LHC scales: Zeptouniverse.

7. Sizable New Physics effects in B_d-system and K-decays still possible, less in B_s-system, but also here New Physics could still be identified.

8. Most important will be correlations between B_s, B_d and K-systems and high energy collider data.

Should we be frustrated after LHC, LHCb Data?

Should we be frustrated after LHC, LHCb Data?

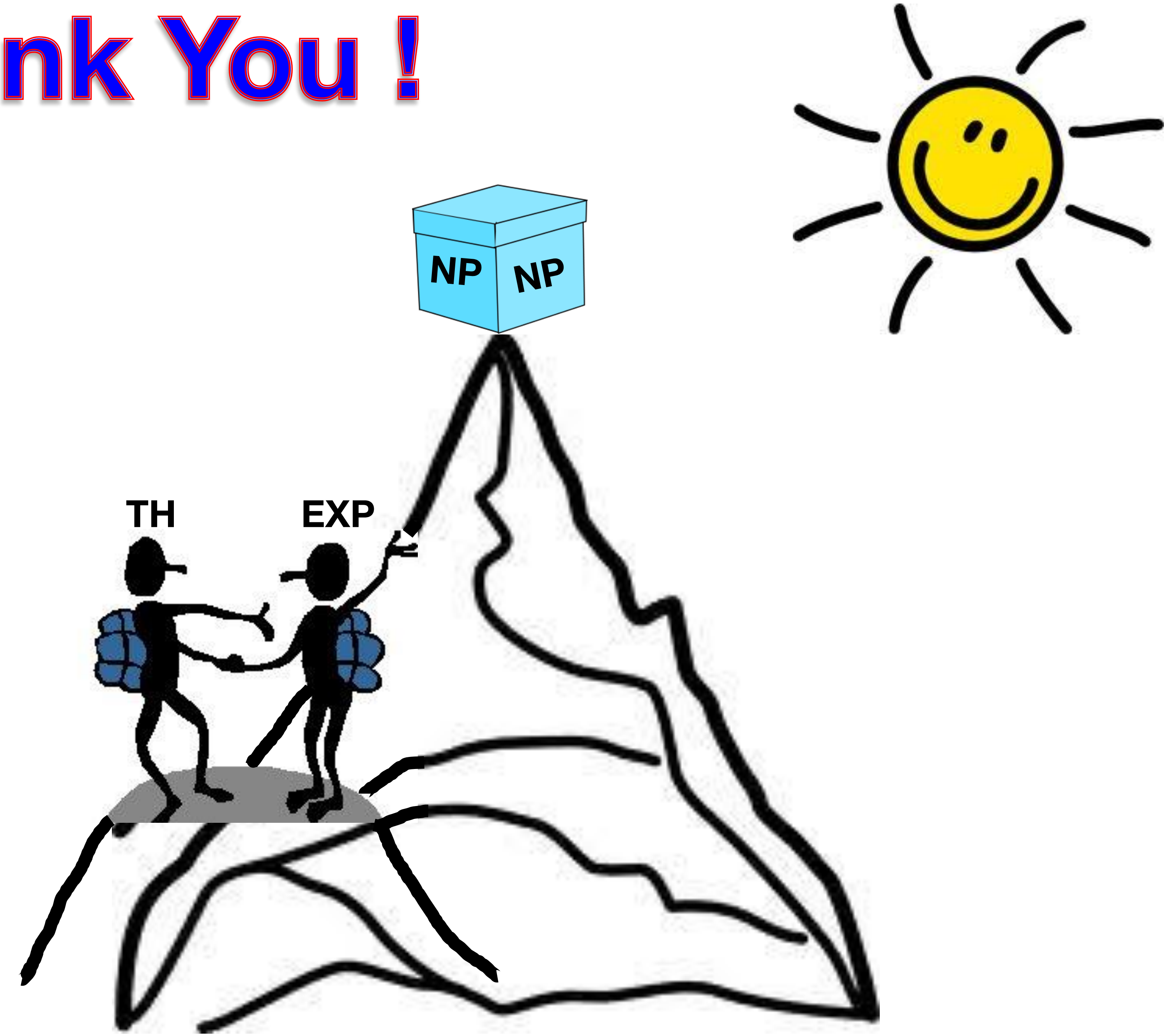
No, no, no !!!

Should we be frustrated after LHC, LHCb Data?

No, no, no !!!

Exciting Times are just ahead of us !!!

Thank You !



Backup

Important Messages on K Physics

1. Many Models (SUSY, 4G, LHT, RS) can still accommodate

$$Br\left(K^+ \rightarrow \pi^+ \nu\bar{\nu}\right) \sim 2Br\left(K^+ \rightarrow \pi^+ \nu\bar{\nu}\right)_{SM}$$

$$Br\left(K_L \rightarrow \pi^0 \nu\bar{\nu}\right) \sim 3Br\left(K_L \rightarrow \pi^0 \nu\bar{\nu}\right)_{SM}$$

2. Even if no significant New Physics would be seen in B-decays large effects in $K \rightarrow \pi\nu\bar{\nu}$ are possible.

3. LHCb opened the road for large effects in LHT, RSc.

4. ε'/ε very important provided QCD Penguin hadronic matrix under control

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**

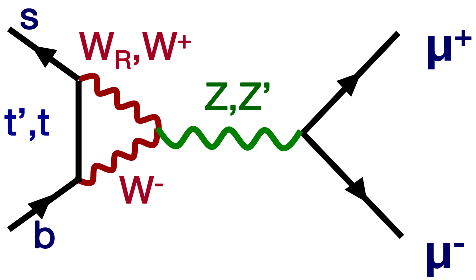
  $\mu \to e\gamma$, $\mu \to 3e$, $\tau \to 3\mu$

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

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

Standard Candles of Flavour Physics

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



+

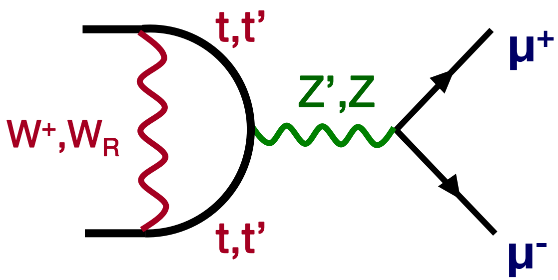
Other Z-Penguins and Boxes

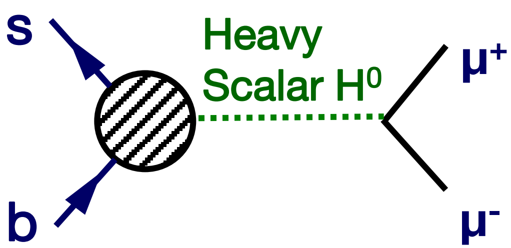
SM: (3.2 ± 0.2) · 10^{-9}

Model Independent Limit (95% C.L.)

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

Altmannshofer, Paradisi, Straub 1111.1257





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

in SUSY

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

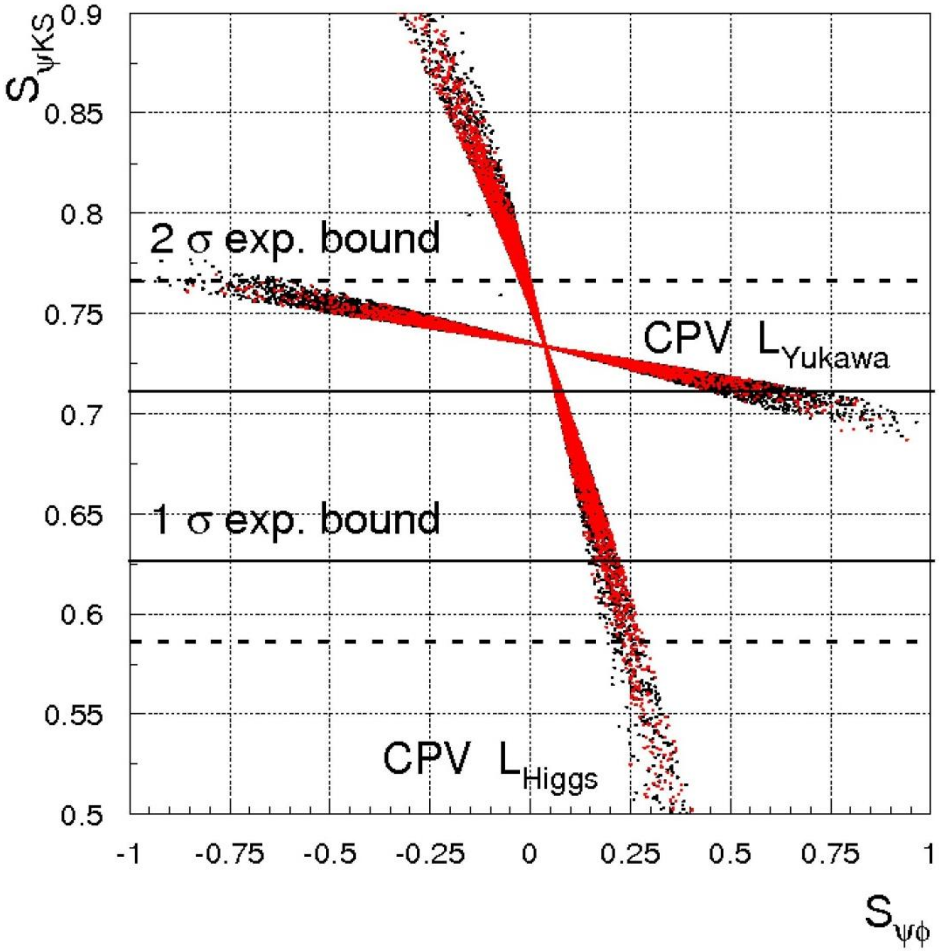
In the case of

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

distinction between Z,Z' and H^0 possible

More on 2HDM with MFV and Flavour Blind Phases

Correlation between CP Effects



$$S_{\psi K_s} = \sin\left(2\beta - \theta_d^H\right) \qquad S_{\psi\varphi} \cong \sin\left(\theta_s^H\right)$$

L_{Yukawa} : $\frac{\theta_d^H}{\theta_s^H} \approx \frac{m_d}{m_s} \approx \frac{1}{17}$ **BCGI**

L_{Higgs} : (potential) $\frac{\theta_d^H}{\theta_s^H} = 1$

After LHCb

Kagan, Perez, Volansky, Zupan
Paradisi, Straub
Dobrescu, Fox, Martin
Blum, Hochberg, Nir
Ligeti, Papucci, Perez, Zupan

AJB, Isidori, Paradisi 1007.5291

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 $K_L \to \pi^0 \nu\bar{\nu}$)

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

SM :

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

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

Exp :

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

(E787, E949 Brookhaven)

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

(E391a, KEK)

Future :

NA62
ORCA (FNAL)

CP-conserving
TH uncertainty 2-3%

Both very sensitive to New Physics

J-PARC KOTO

CP-Violation in Decay
TH uncertainty 1-2%

Littlest Higgs Model with T-Parity

$$SU(3)_c \otimes \left[SU(2) \otimes U(1)\right]_1 \otimes \left[SU(2) \otimes U(1)\right]_2$$

Non-MFV sources in interactions between SM-quarks, Mirror Fermions and new Gauge Bosons.

Can remove ΔF=2 tensions and have $S_{\psi\phi} < 0$

LHT after LHCb Data

Our 2006 Predictions
(Blanke et al.) :

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

$|S_{\psi\varphi}| \leq 0.25$

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

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

$\mathrm{Br}\left(B_d \to \mu^+\mu^-\right)$ vs $\mathrm{Br}\left(B_s \to \mu^+\mu^-\right)$

ABGPS

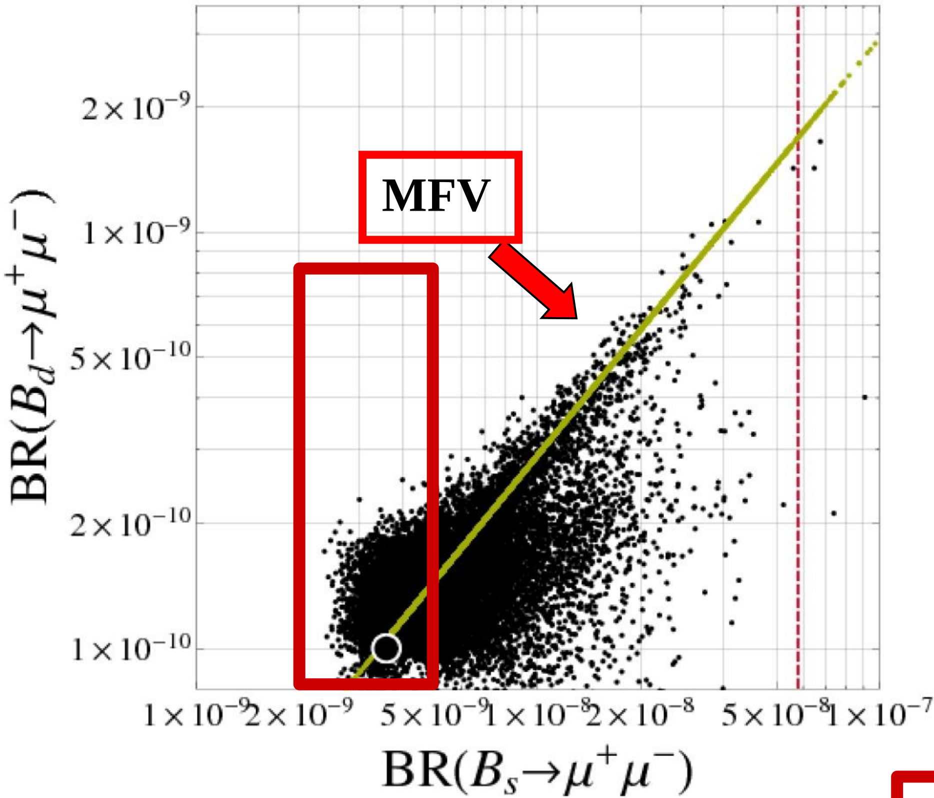
(0909.1333)

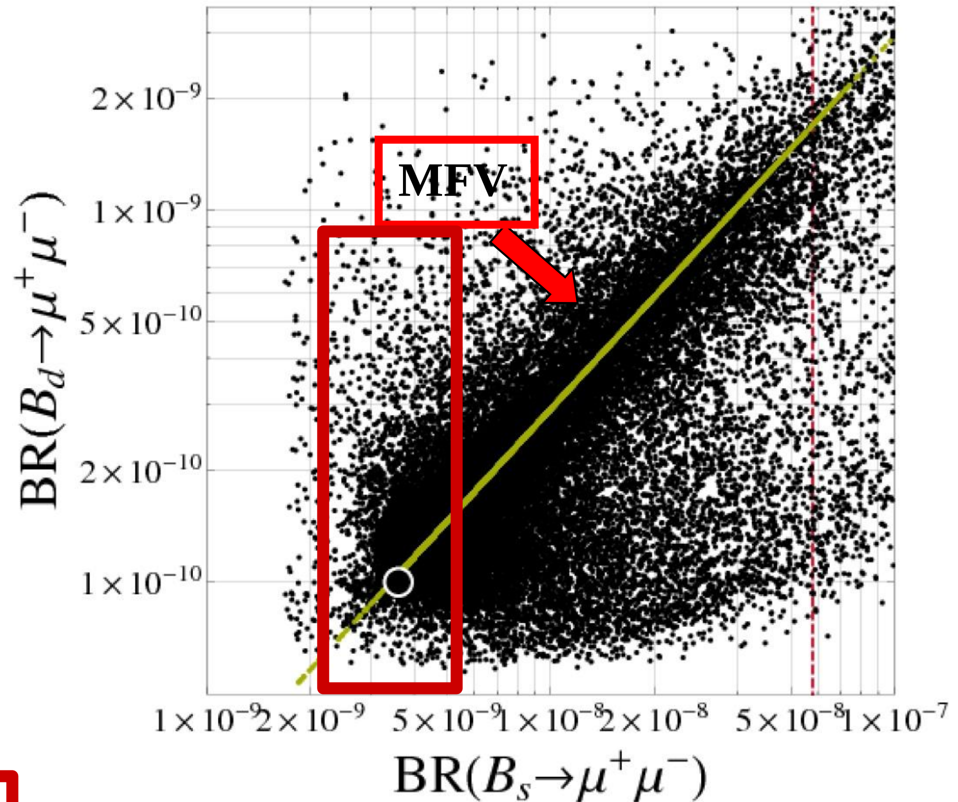
Altmannshofer, AJB, Gori, Paradisi, Straub

SUSY (Flavour)

● = SM

MFV AJB; Hurth, Isidori, Kamenik, Mescia





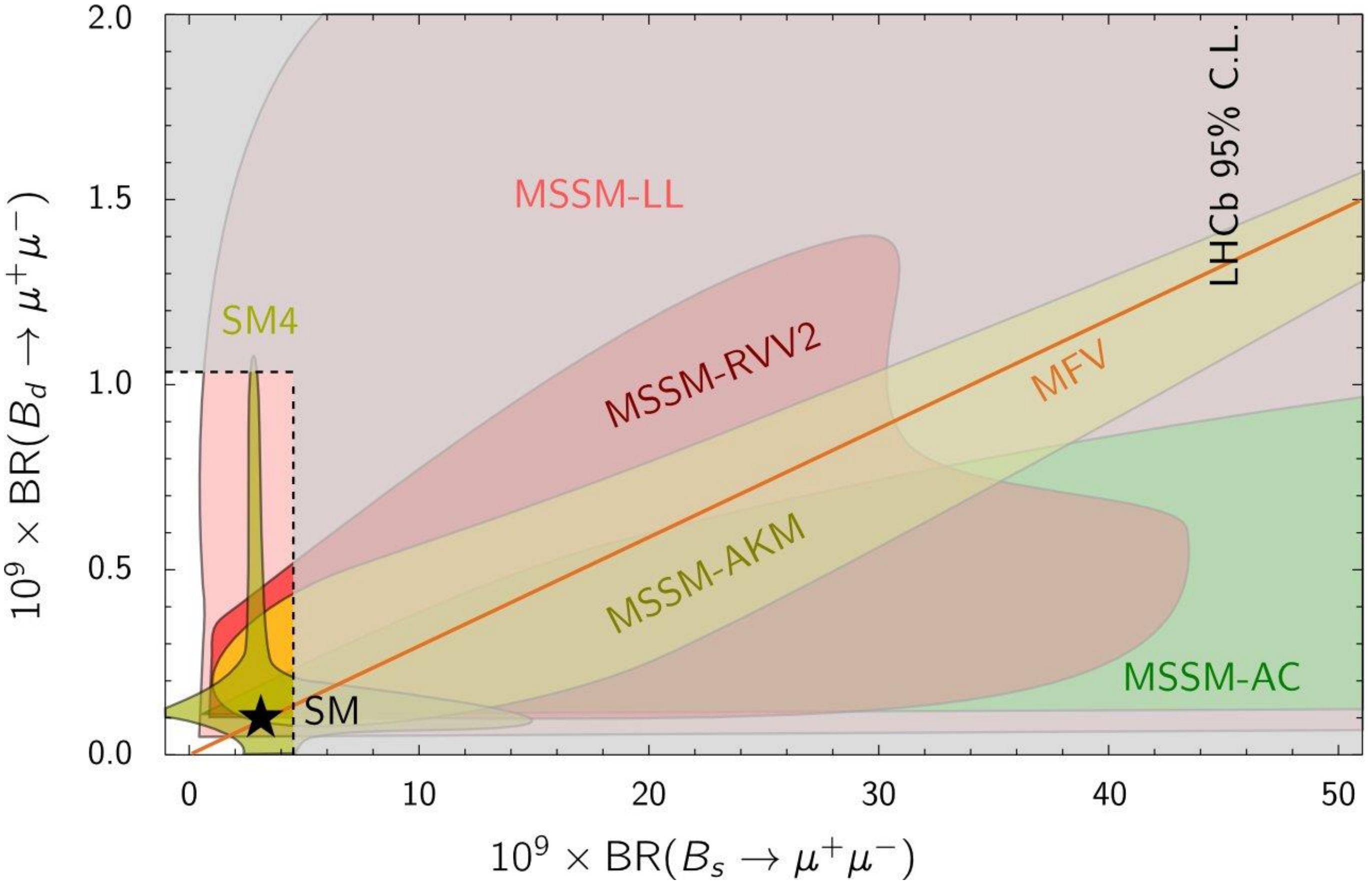
LHCb

RVV2 (RH currents)

LH currents

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

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

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

(weak)

Impose Constraints

Set all input parameters at central values but require:

$(\pm 5\%)$

$$16.9\,/\,\mathrm{ps} \le \Delta M_s \le 18.7\,/\,\mathrm{ps}$$

$$0.48\,/\,\mathrm{ps} \le \Delta M_d \le 0.53\,/\,\mathrm{ps}$$

$(\pm 2\sigma)$

$$-0.20 \le S_{\psi\varphi} \le 0.20$$

$$0.64 \le S_{\psi K_s} \le 0.72$$

$$0.75 \le \frac{\Delta M_K}{\left(\Delta M_K\right)_{SM}} \le 1.25$$

$$2.0 \cdot 10^{-3} \le \varepsilon_K \le 2.5 \cdot 10^{-3}$$

AJB
Girrbach
(1204.5064)

Relations of Constrained Minimal Flavour Violation (CMFV)*) as Standard Candles of Flavour Physics

AJB, Gambino, Gorbahn, Jäger, Silvestrini (0007085)
AJB (0310208); Blanke, AJB, Guadagnoli , Tarantino (0604057)

CMFV :

(A) Only SM operators relevant at the Electroweak Scale

(B) CKM the only source of flavour and CP Violation

Pragmatic very effective approach

MFV :

D´Ambrosio, Giudice, Isidori, Strumia (0207036)
(CMFV + New Operators
+ Flavour Blind Phases)

Effective theory approach

Kagan, Perez, Volansky, Zupan
Paradisi, Straub
Dobrescu, Fox, Martin
Blum, Hochberg, Nir
Ligeti, Papucci, Perez, Zupan

*) Earlier: Ciuchini et al.
Ali et al.

CMFV Candles of Flavour Physics

1. $S_{\psi K_s} = \left(S_{\psi K_s}\right)^{SM}$ $\qquad$ $S_{\psi\varphi} = \left(S_{\psi\varphi}\right)^{SM}$

2. ε_K, ΔM_s, ΔM_d can only be enhanced over SM, moreover in a correlated manner. (Blanke, AJB: 2006)

3.

$$\frac{Br(B_d \to \mu^+\mu^-)}{Br(B_s \to \mu^+\mu^-)} = \frac{\tau(B_d)}{\tau(B_s)} \frac{m_{B_d}}{m_{B_s}} \frac{F^2_{B_d}}{F^2_{B_s}} \left|\frac{V_{td}}{V_{ts}}\right|^2$$

(MFV, CMFV)

4.

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

(CMFV)

5. All FCNC Processes can be described by 7 real and flavour universal gauge independent master functions.
S, X, Y, Z, E, D´, E´ ⇒ Stringent Correlations between CPV and Rare Decays in K, B_d and B_s systems