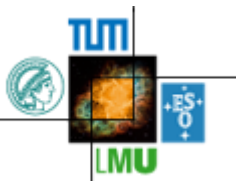


Towards the Identification of New Physics through Correlations between Flavour Observables

Andrzej J. Buras

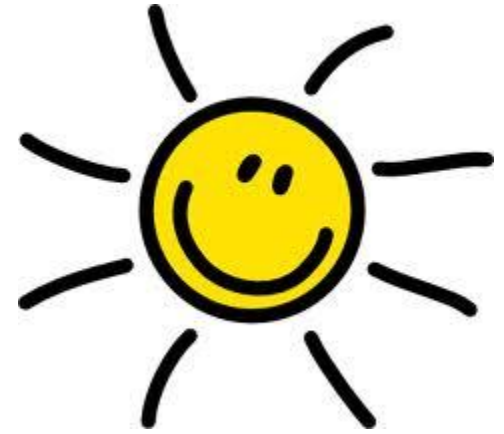
(Technical University Munich, TUM-IAS)



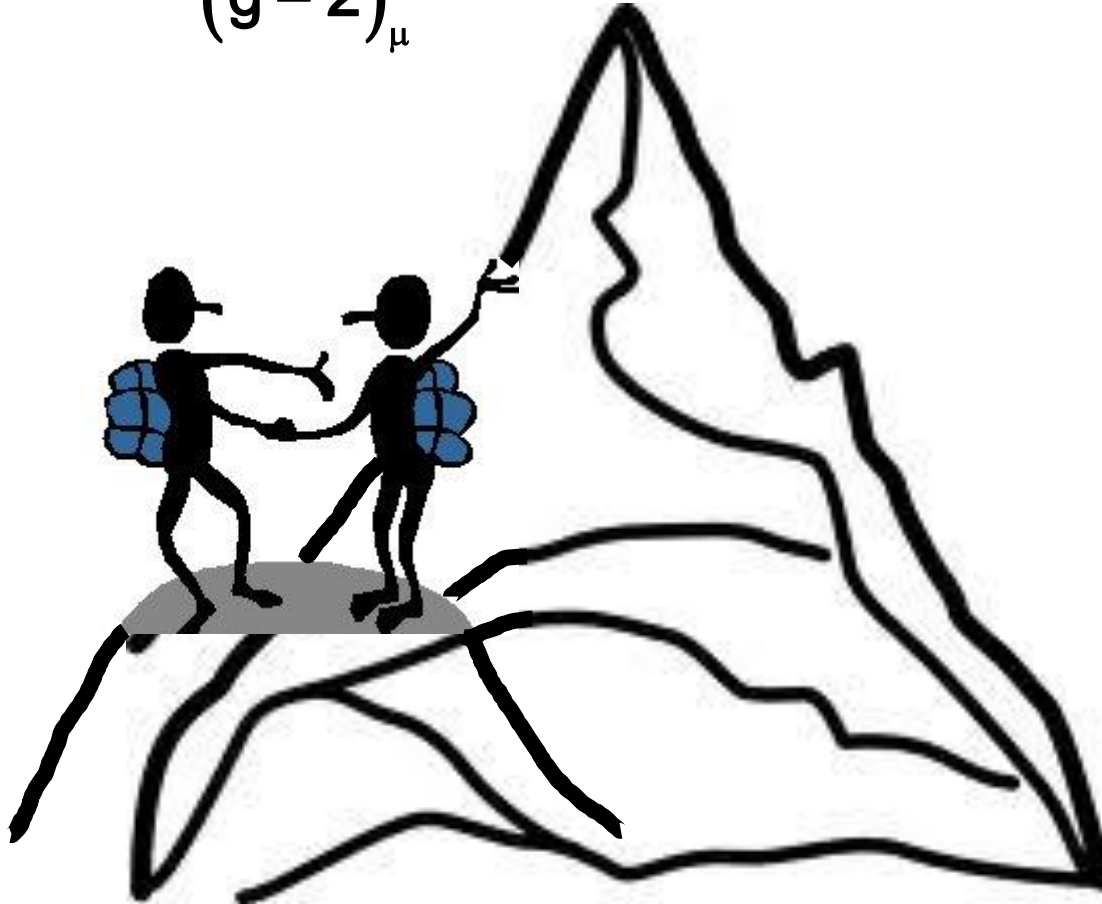
**EPS-HEP Stockholm
July 2013**



SUSY



$(g-2)_\mu$



SUSY

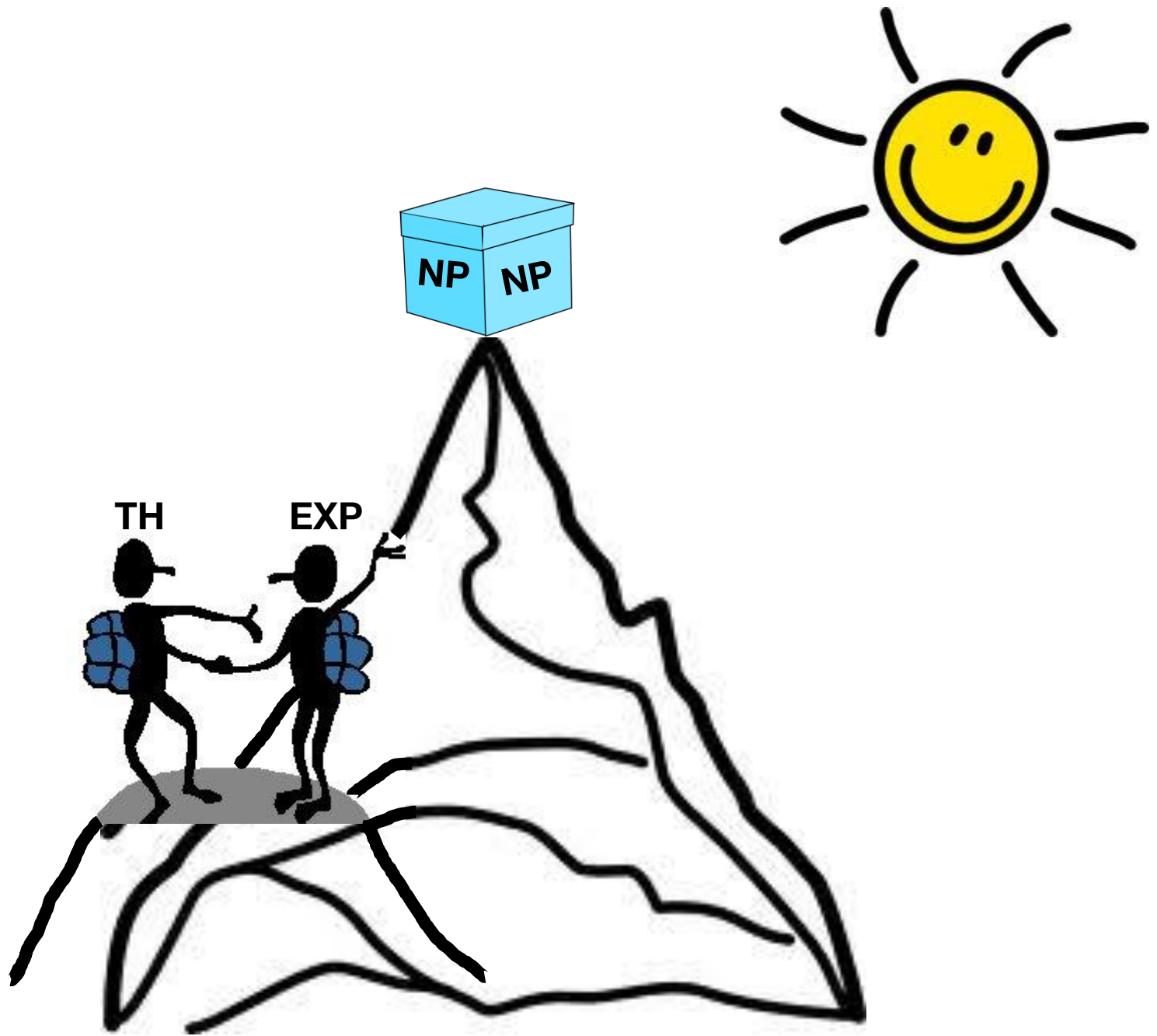


$$(g - 2)_\mu$$

TH

EXP





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

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**

$5 \cdot 10^{-20}\text{m}$

**Frontiers of Elementary
Particle Physics in 2010's**

**High Precision Measurements
of Rare Processes (Europe,
Japan, USA)**

10^{-21}m

Zeptouniverse



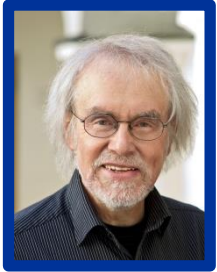
Advanced ERC Grant at the TUM Institute for Advanced Study Zeptouniverse Base Camp



**HEADQUARTERS
ERC-Flavour**



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

In Order to identify New Physics through Flavour Physics

We need

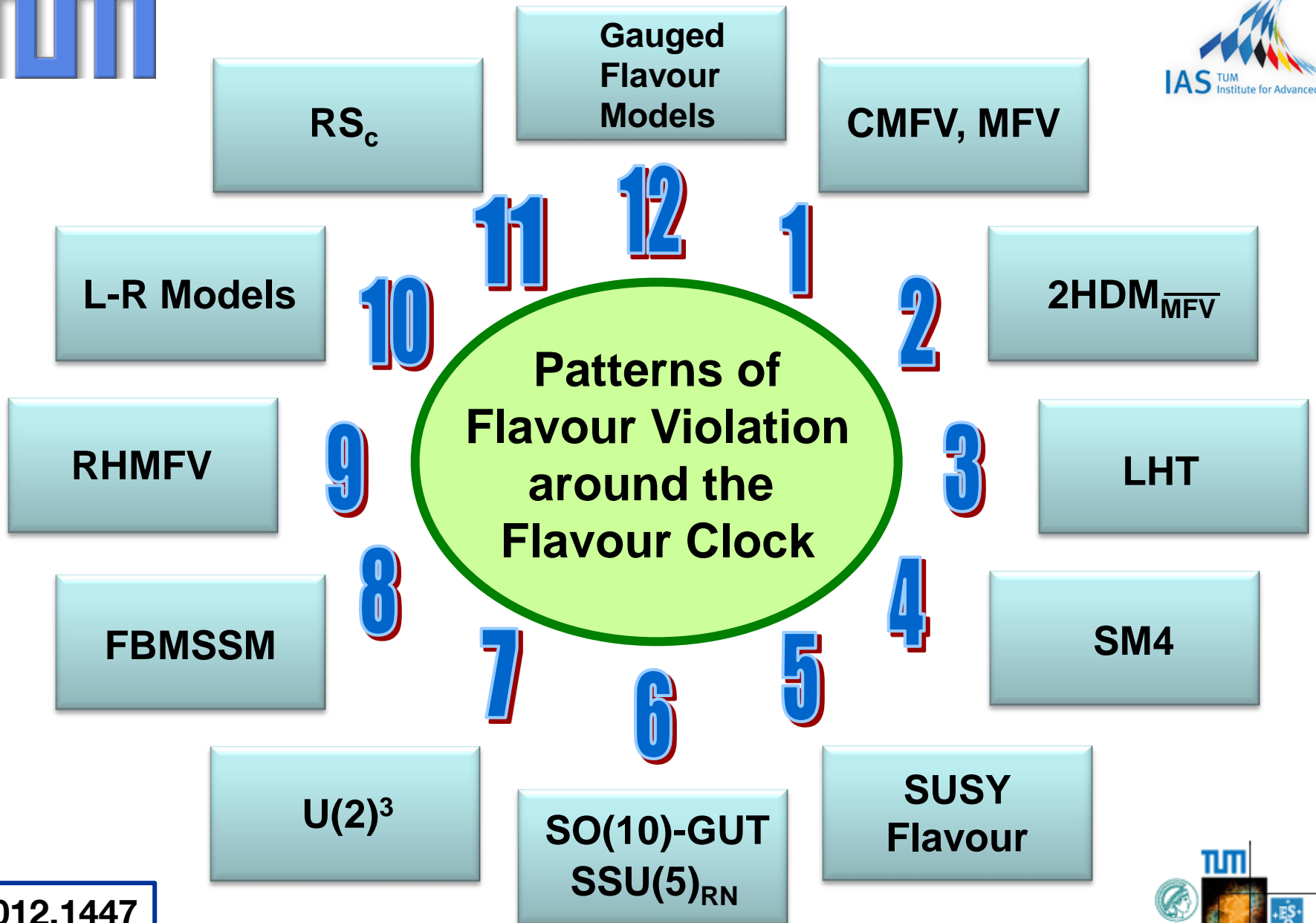
- 1.** Many precision measurements of many observables and precise theory.
- 2.** Study Patterns on Flavour Violation in various New Physics models (correlations between many flavour observables).

...and

3.

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

**Here top-down approach more
powerful in flavour physics**



1012.1447
1204.5065

1.

Z' and Z FCNCs (tree level)

AJB, De Fazio, Girschbach: 1211.1896 (General)

AJB, De Fazio, Girschbach, Carlucci: 1211.1237 (331-Model)

AJB, Girschbach, Ziegler: 1301.5498 (Minimal Theory of Fermion Masses)

AJB, Girschbach, 1201.1302 (NLO QCD)

2.

Neutral Scalars FCNCs (tree level)

AJB, De Fazio, Girschbach, Kneijens, Nagai (1303.3723)

AJB, Girschbach, 1201.1302 (NLO QCD)

3.

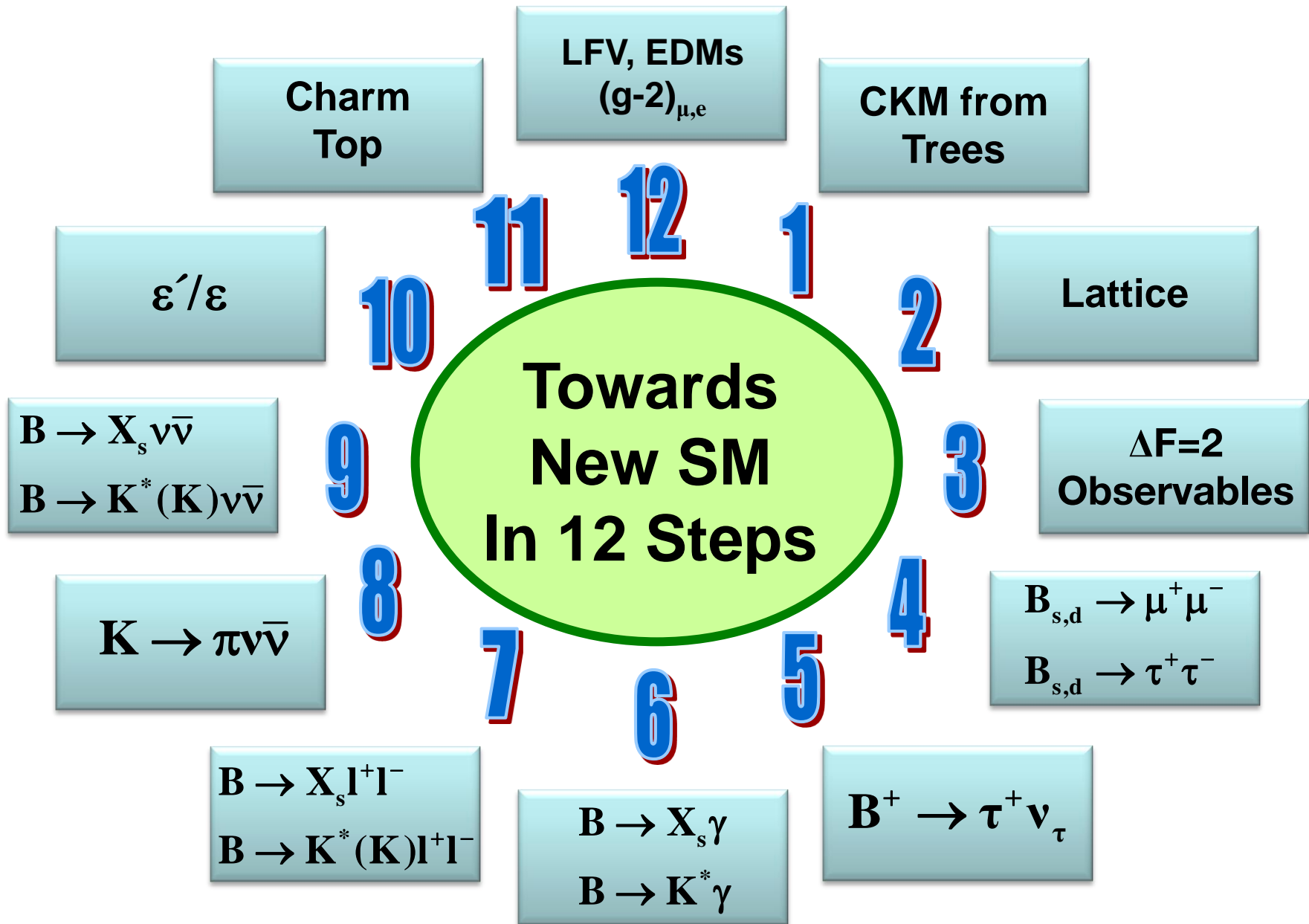
$B_{s,d} \rightarrow \mu^+ \mu^-$ Phenomenology

AJB, Fleischer, Girschbach, Kneijens (1303.3820)

AJB, Girschbach, Guadagnoli, Isidori (1208.0934)

Towards New SM in 12 Steps

AJB + Girrbach (1306.3755)

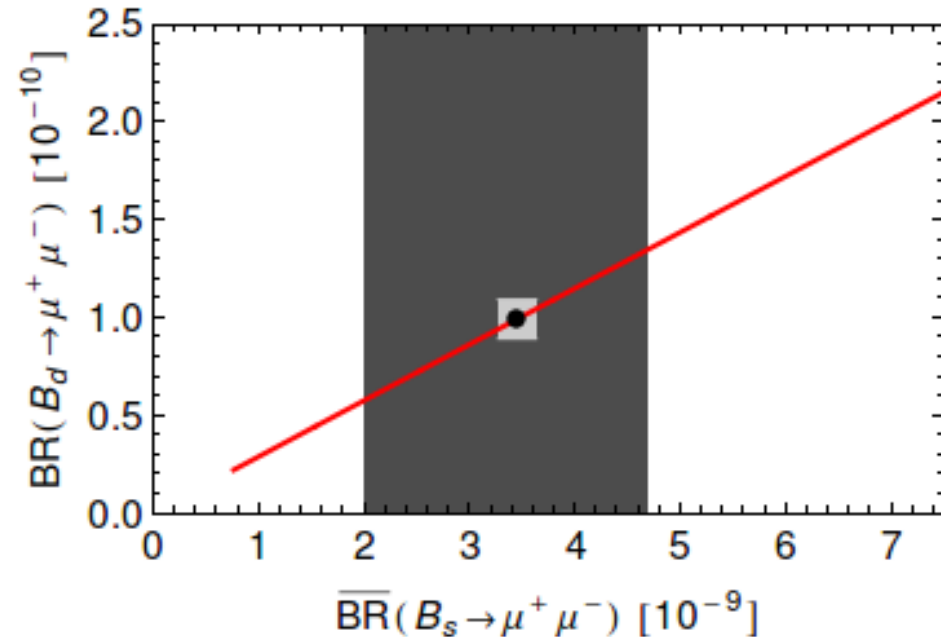


Simplest Correlations

Constrained Minimal Flavour Violation

AJB

Hurth, Isidori, Kamenik, Mescia



Golden Relation

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

AJB 2003

No CKM

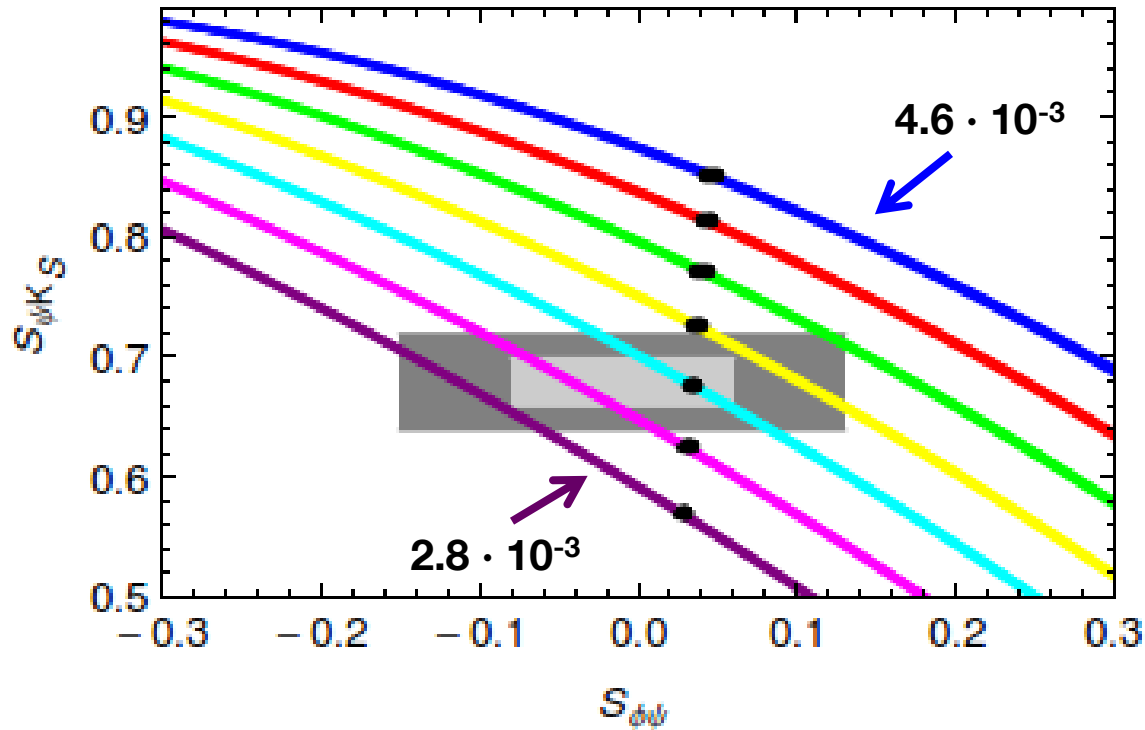
No weak decay constants

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

(LHCb)

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

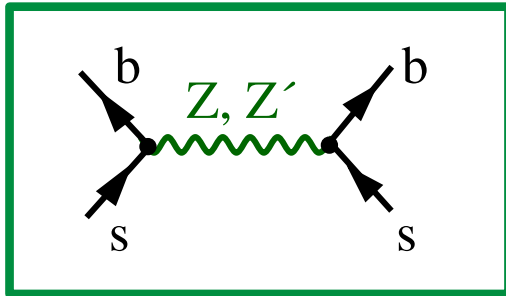
Important test of $U(2)^3$ Models



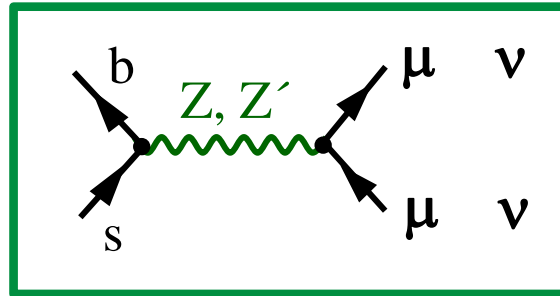
In the $U(2)^3$ Symmetric World we could determine $|V_{ub}|$ without significant hadronic uncertainties (QCD penguins)

Correlations between Flavour Observables in Tree Level FCNCs

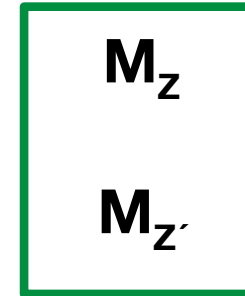
Basics of Correlations in Tree-Level (Z, Z') FCNCs



$$\Delta F = 2$$



$$\Delta F = 1$$



Z, Z' couplings:

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

only two new quark parameters!

For fixed lepton couplings

$$\mathbf{B}_s^0 : \Delta M_s, \mathbf{S}_{\psi\phi}, \mathbf{B}_s \rightarrow \mu^+ \mu^-, \mathbf{S}_{\mu\mu}^s, \mathbf{B} \rightarrow \mathbf{K}^*(\mathbf{K})v\bar{v}, \mathbf{B} \rightarrow \mathbf{X}_s v\bar{v}, b \rightarrow sll$$

$$\mathbf{B}_d^0 : \Delta M_d, \mathbf{S}_{\psi K_s}, \mathbf{B}_d \rightarrow \mu^+ \mu^-, \mathbf{S}_{\mu\mu}^d \leftarrow \Delta_{L,R}^{bd} \equiv \tilde{s}_{13} e^{-i\delta_{13}} \quad \Delta_{L,R}^{sd} \equiv \tilde{s}_{12} e^{-i\delta_{12}}$$

$$\mathbf{K} : \varepsilon_K, \mathbf{K}^+ \rightarrow \pi^+ v\bar{v}, \mathbf{K}_L \rightarrow \pi^0 v\bar{v}, \mathbf{K}_L \rightarrow \mu^+ \mu^-, \mathbf{K}_L \rightarrow \pi^0 l^+ l^-, \varepsilon'/\varepsilon$$

$M_{Z'}$ Dependence of $\Delta F=2$ and $\Delta F=1$ Transitions

$\Delta F=2$
Amplitude

$$: \frac{(\Delta_{L,R}^{ij})^2}{M_{Z'}^2}$$

$\Delta F=1$
Amplitude

$$: \frac{\Delta_{L,R}^{ij}}{M_{Z'}^2}$$

$\Delta_{L,R}^{ij}$
from $\Delta F=2$

$$= \Delta_{L,R}^{ij} \sim M_{Z'}$$



$\Delta F=1$
Amplitude

$$\sim \frac{1}{M_{Z'}}$$



For $M_{Z'} > 1\text{TeV}$

: NP in $\Delta F=2$ more important than in $\Delta F=1$

For Z

: NP in $\Delta F=1$ more important than in $\Delta F=2$

Correlations depend strongly on the allowed Size of NP Contributions

SM


Data

ΔM_s	19.0 / ps	17.7 / ps
$S_{\psi\phi}$	0.04	$-0.20 \leq S_{\psi\phi} \leq 0.20$ 95% C.L.
$\text{Br}(B_s \rightarrow \mu^+ \mu^-)$	$3.5 \cdot 10^{-9}$	$1.10^{-9} \leq \text{Br}(B_s \rightarrow \mu^+ \mu^-) \leq 6.0 \cdot 10^{-9}$

ΔM_d	0.56 / ps	0.51 / 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

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

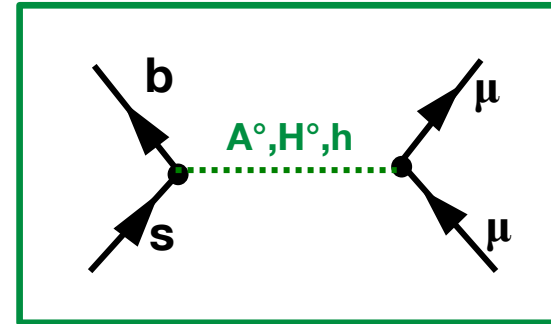
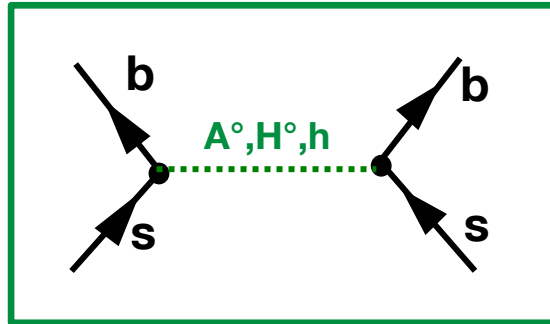
- 1.** All tensions in $\Delta F=2$ observables can be removed.
- 2.** For $M_{Z'} > 5 \text{ TeV}$ NP effects in B_s, B_d systems very small
But: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L \rightarrow \pi^0 \nu \bar{\nu}$ still sensitive to $M_{Z'} \approx 10 - 20 \text{ TeV}$ 

Lessons from Z Studies

- 1.** $\text{Br}(B_d \rightarrow \mu^+ \mu^-)$ and $\text{Br}(B_s \rightarrow \mu^+ \mu^-)$ can only be enhanced.
(both up to the present bounds)
- 2.** $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L \rightarrow \pi^0 \nu \bar{\nu}$: much larger effects than for Z'.
(Bounded by $K_L \rightarrow \mu^+ \mu^-$)

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


(pseudo) scalar SM Higgs



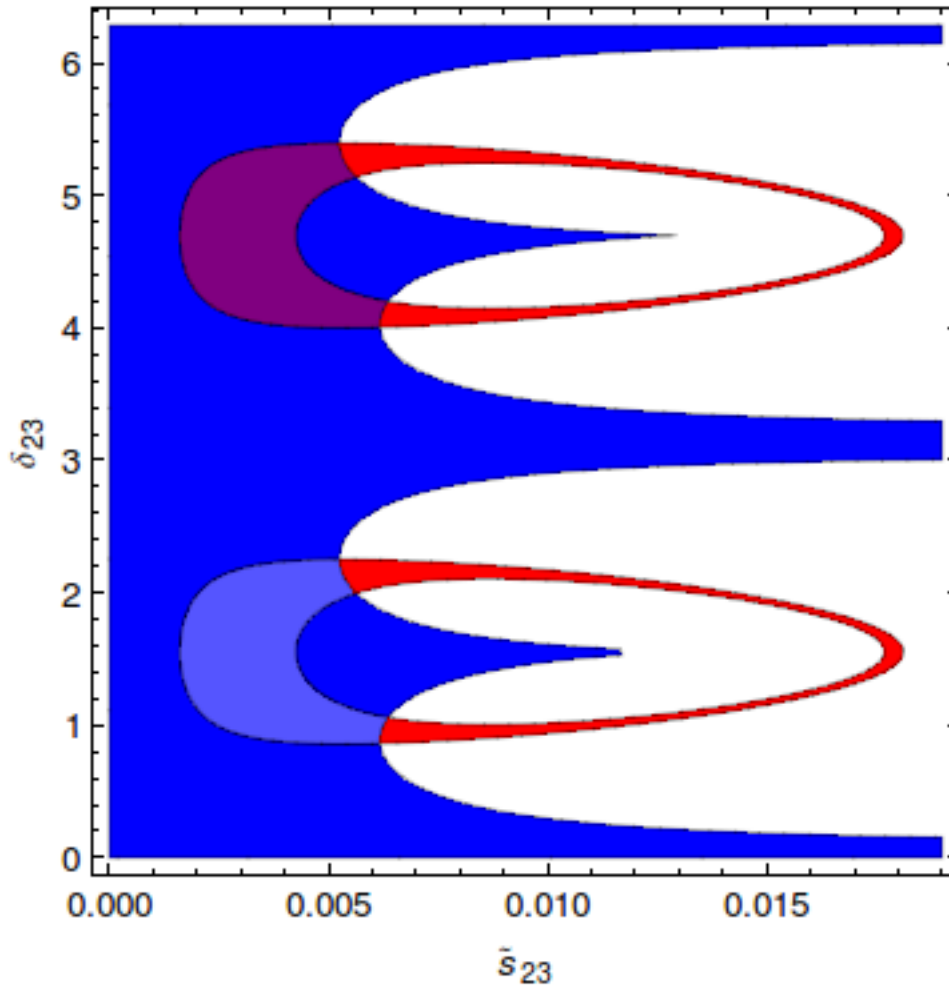
- 1.** Correlations between $\Delta F=1$ and $\Delta F=2$ observables for A° differ from Z' case because of pseudoscalar coupling $i\gamma_5$.
- 2.** Correlations between $\Delta F=1$ and $\Delta F=2$ observables for H° differ from Z' case because of absence of interference with SM part.
(only enhancements 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.

Oases in B_s -System

 ΔM_s

 $S_{\psi\phi}$

ΔM_s & $S_{\psi\phi}$, LHS1



$$\bar{\text{Br}}(B_s \rightarrow \mu^+ \mu^-), S_{\mu\mu}^s, \text{Br}(B_d \rightarrow \mu^+ \mu^-), S_{\mu\mu}^d$$

SM

Data (LHCb)

$$\begin{aligned} \bar{\text{Br}}(B_s \rightarrow \mu^+ \mu^-) &: (3.56 \pm 0.18) \cdot 10^{-9} && (3.2^{+1.5}_{-1.2}) \cdot 10^{-9} \\ \text{Br}(B_d \rightarrow \mu^+ \mu^-) &: (1.05 \pm 0.07) \cdot 10^{-10} && \leq 9.4 \cdot 10^{-10} \end{aligned}$$

$$S_{\mu\mu}^s = S_{\mu\mu}^d = 0$$

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

AJB, Fleischer, Girrbach, Knegjens (1303.3820)

AJB, Girrbach, Guadagnoli, Isidori (1208.0934)

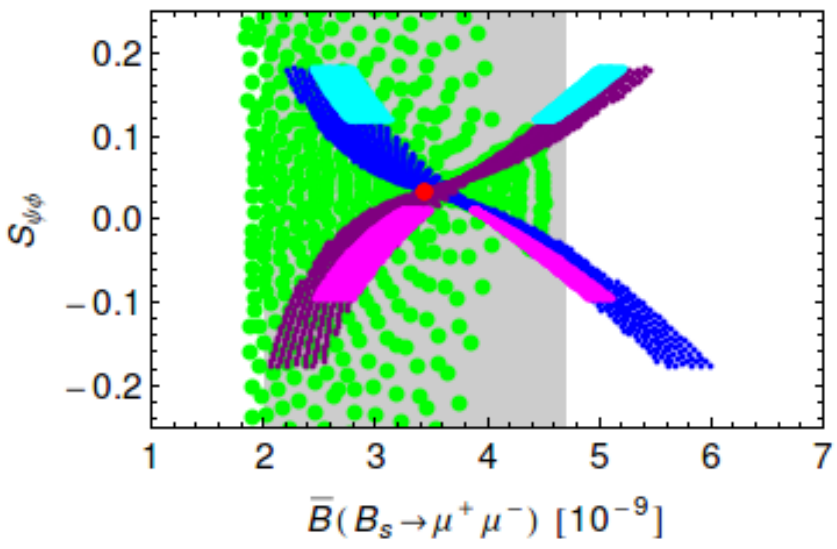
$$S_{\psi\phi} = 0.035 \pm 0.002$$

$$S_{\psi\phi} = -0.01 \pm 0.07$$

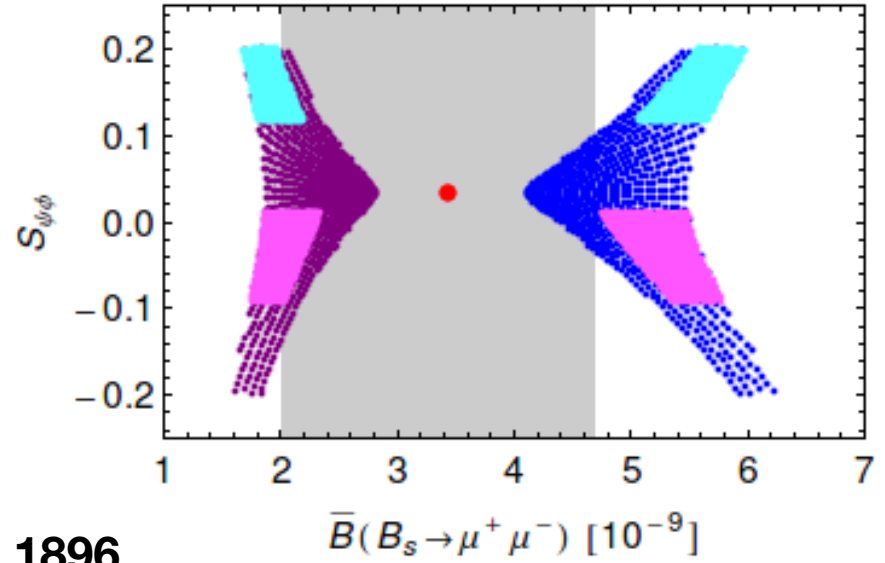
Still New Physics could be discovered in these observables, in particular through correlations between them.



LHS & Z'



LHS & A^0



1211.1896
1303.3723
1303.3820

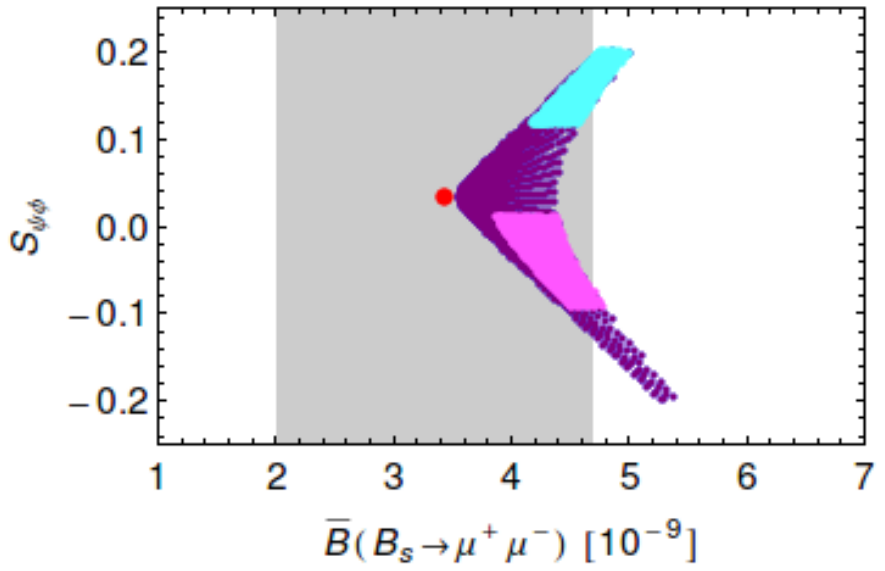
$S_{\psi K_s} - B_s \rightarrow \mu^+ \mu^-$
Correlations for
Z', A⁰, H⁰

1 TeV

: allowed by $b \rightarrow sll$

}
 } U(2)³

LHS & H^0



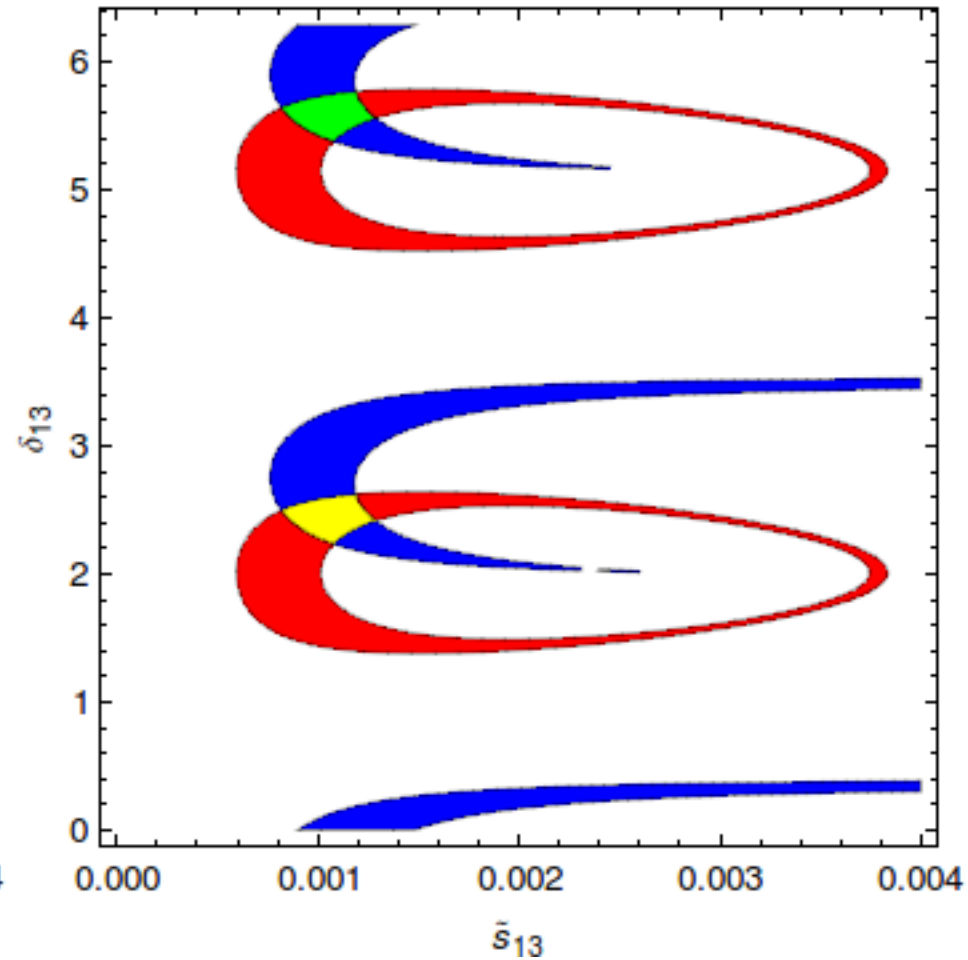
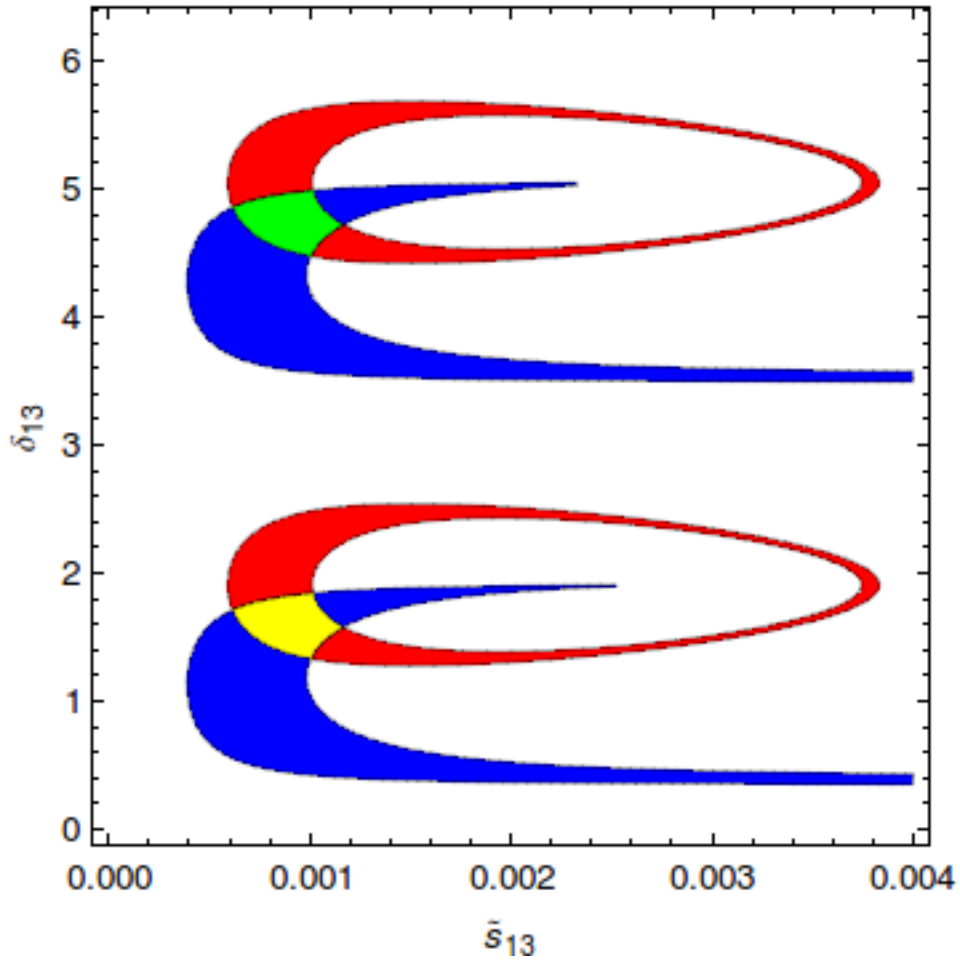
Oases in B_d -System

 ΔM_d

 $S_{\psi K}$

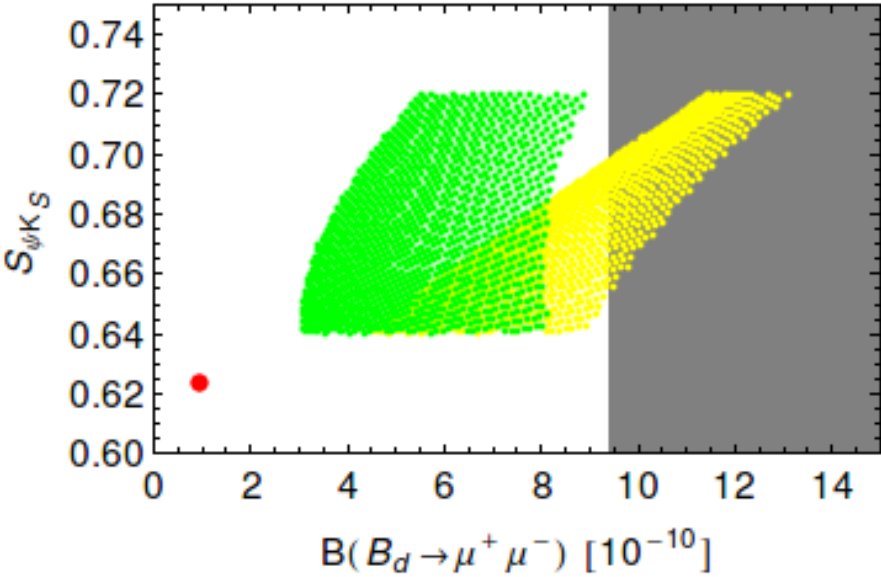
ΔM_d & $S_{\psi K_S}$, LHS1

ΔM_d & $S_{\psi K_S}$, LHS2



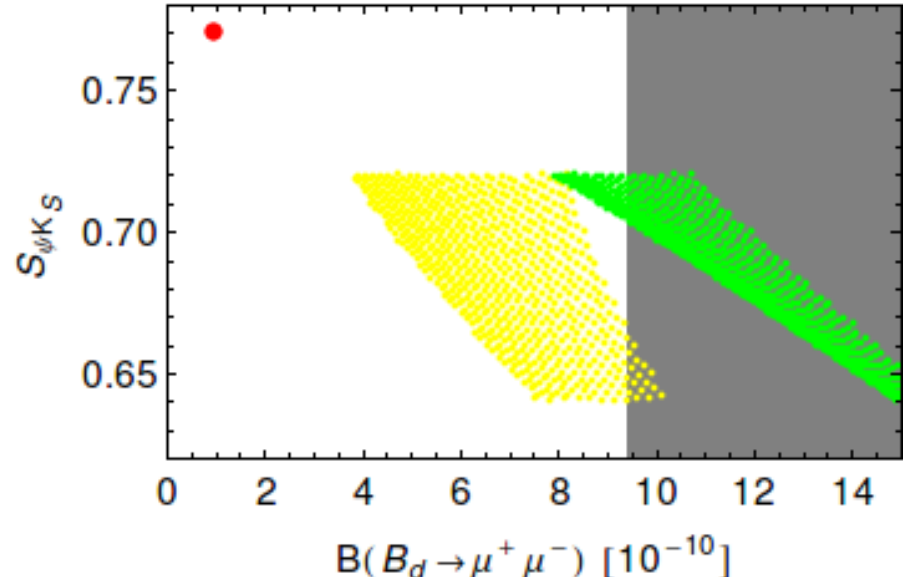
S_{ψK_s} - B_d → μ⁺μ⁻ Correlation for Z

LHS1 & Z



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

LHS2 & Z

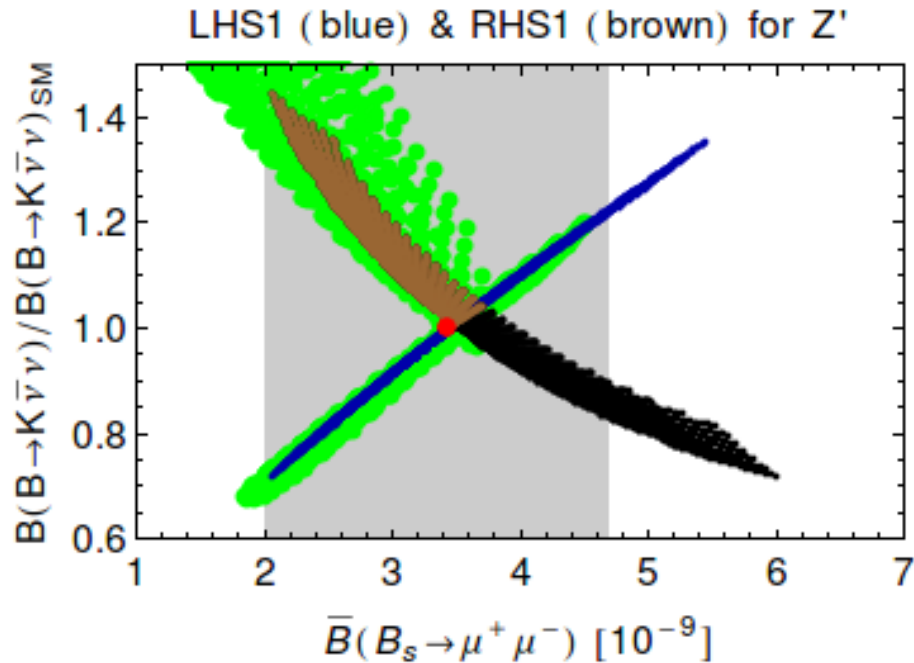


$$|V_{ub}| = 4.0 \cdot 10^{-3}$$

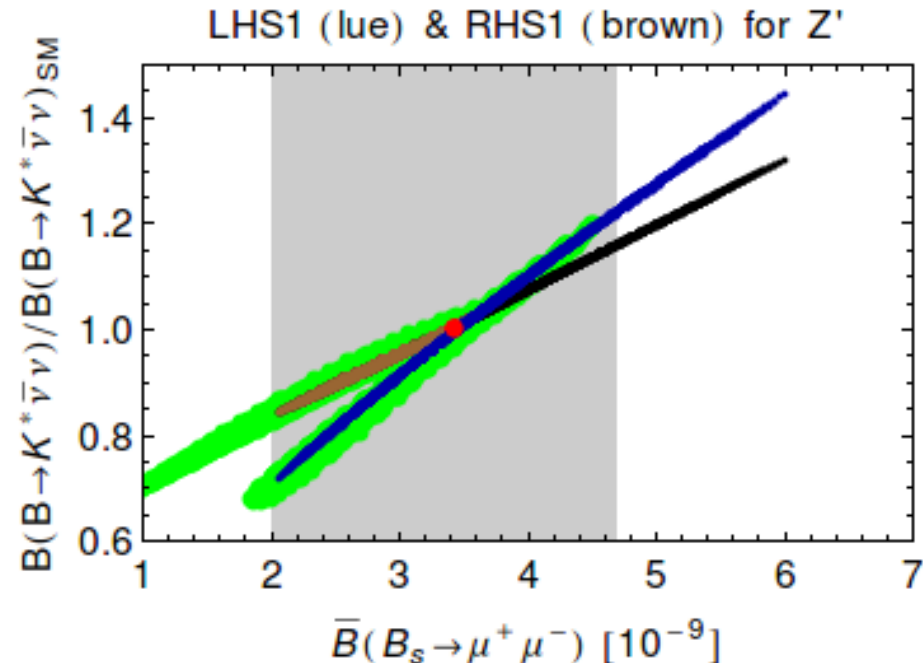
1211.1896

NP-effects can still be large !

Distinguishing Left-Handed Currents from Right-Handed Currents



AJB, De Fazio, Girrbach
1211.1896



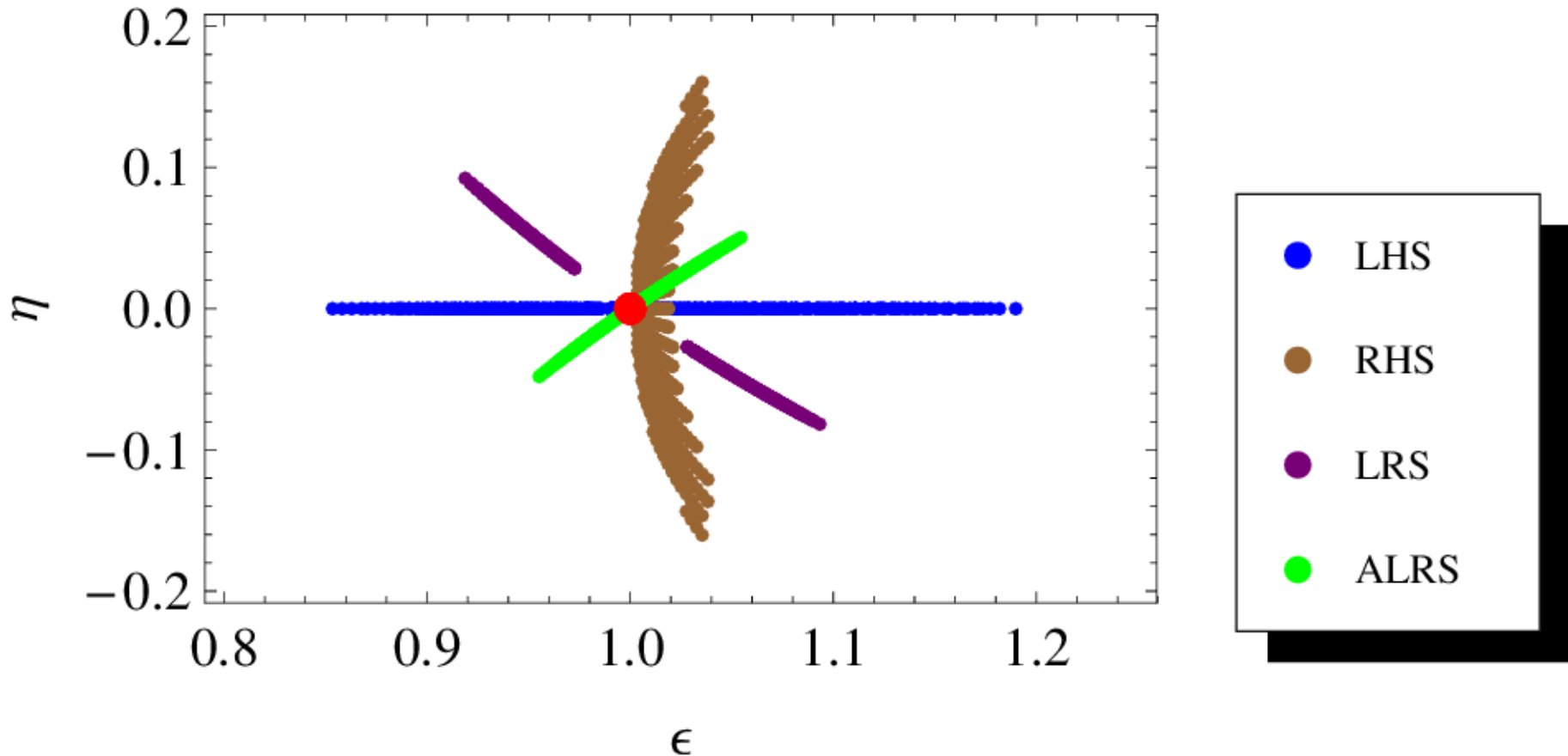
Altmannshofer et al.
0902.0160

■ : forbidden by
 $b \rightarrow sll$

■ : allowed by
 $b \rightarrow sll$

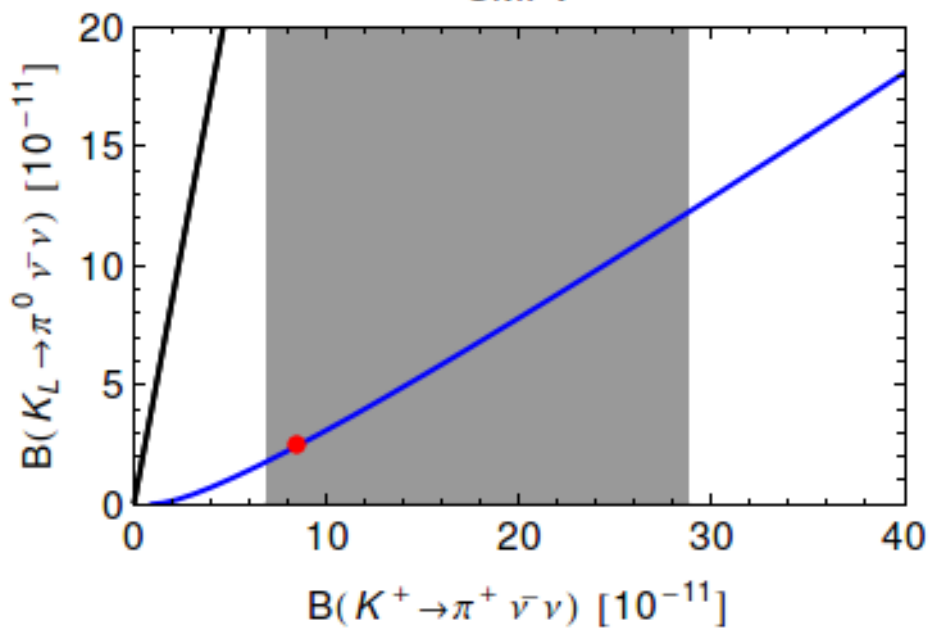
(ϵ, η) : Parameters for $b \rightarrow s\nu\bar{\nu}$ Transitions

1211.1896

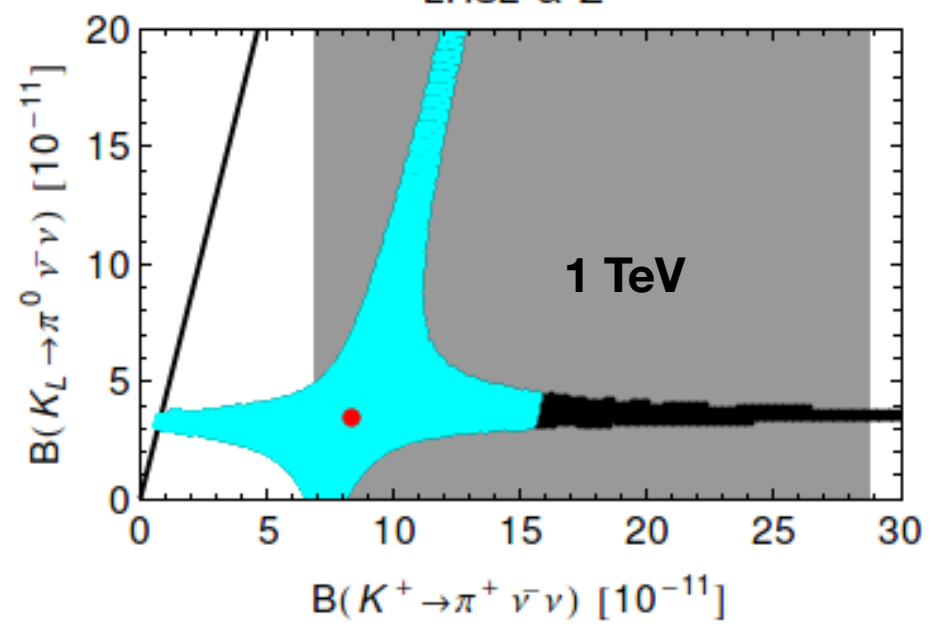


Altmannshofer, AJB, Straub, Wick
0902.0160

CMFV



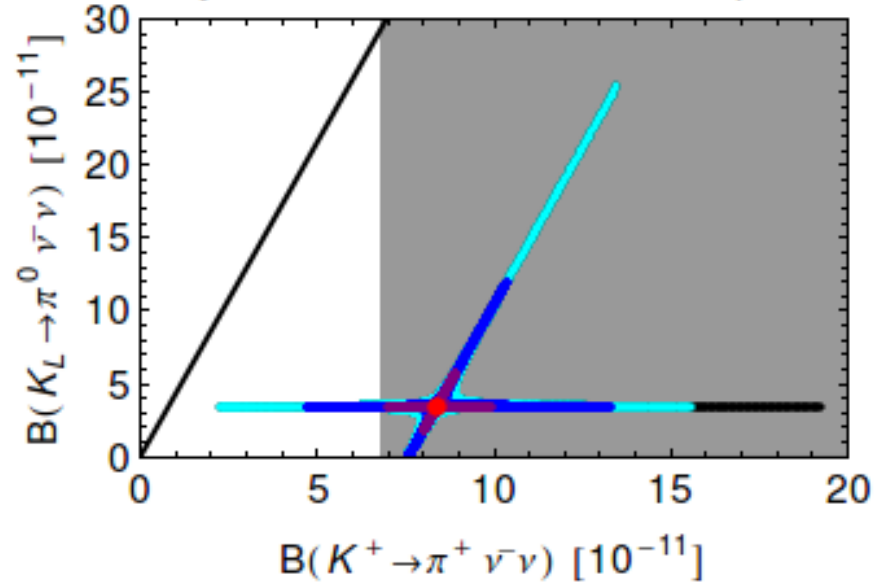
LHS2 & Z'



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

■ : forbidden by $K_L \rightarrow \mu^+ \mu^-$

LHS2, Cyan: 5TeV, Blue: 10TeV, Purple: 30TeV



DNA - Charts

1306.3755

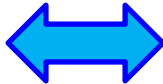
AJB + Girrbach



- suppression relative to SM



- enhancement relative to SM



correlation



anti-correlation

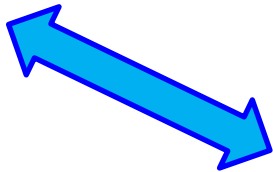
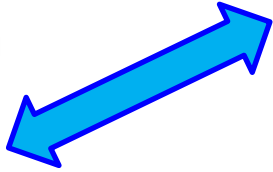
Previous proposals: DNA tables: Altmannshofer, AJB, Gori,
Paradisi, Straub 0909.1333
Flavour codes: AJB 1012.1447

CMFV

ϵ_K

ΔM_s

ΔM_d



$S_{\psi\phi}$

$S_{\psi K_S}$

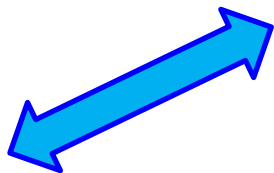
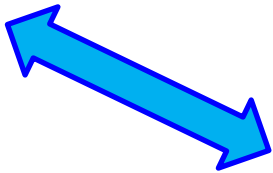
$B_s \rightarrow \mu\bar{\mu}$

$B_d \rightarrow \mu\bar{\mu}$



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

$K_L \rightarrow \pi^0 \nu\bar{\nu}$



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

$U(2)^3$

ϵ_K

ΔM_s



ΔM_d

$S_{\psi\phi}$



$S_{\psi K_s}$

$B_s \rightarrow \mu\bar{\mu}$



$B_d \rightarrow \mu\bar{\mu}$

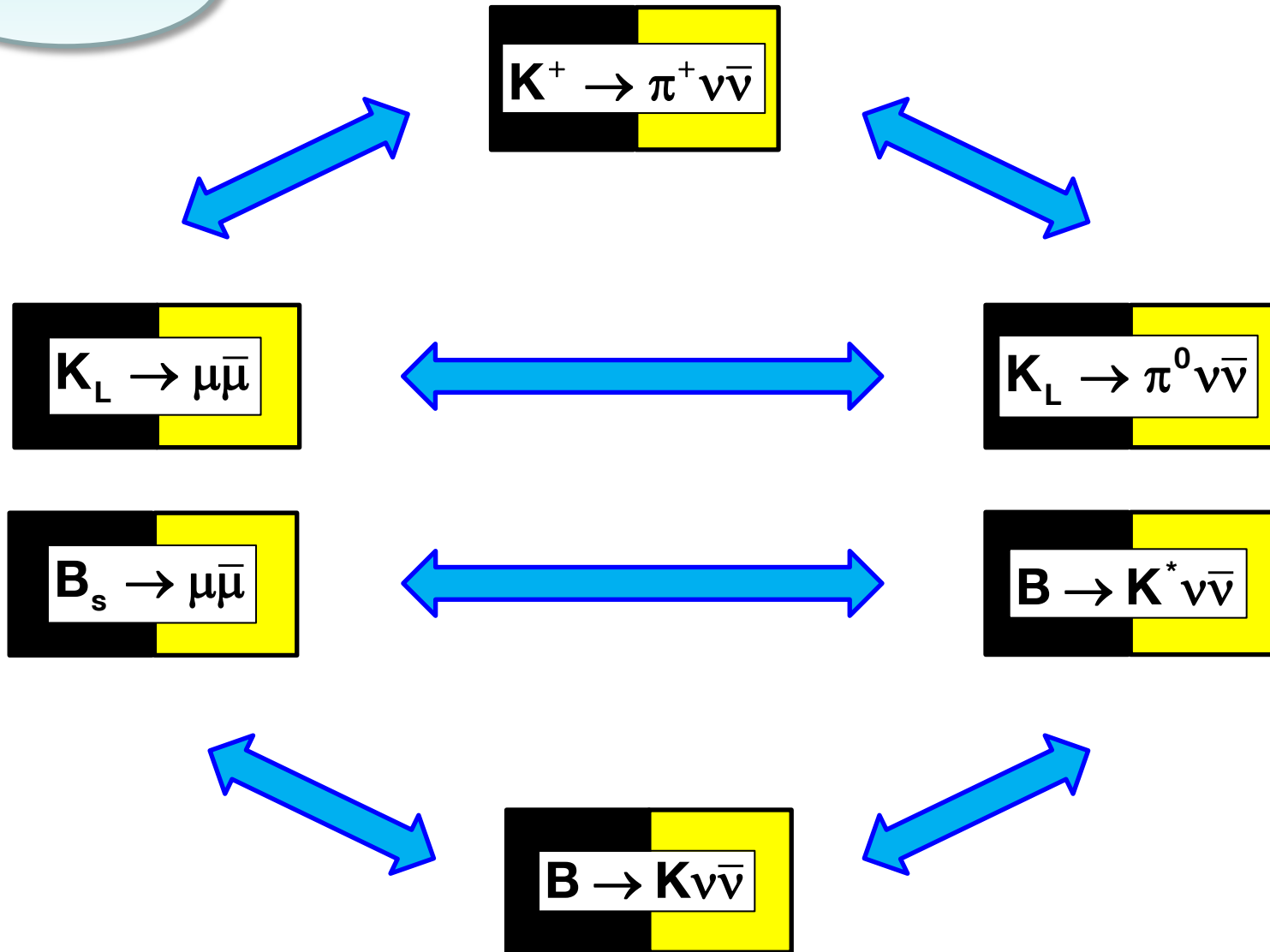
$K^+ \rightarrow \pi^+ \nu\bar{\nu}$



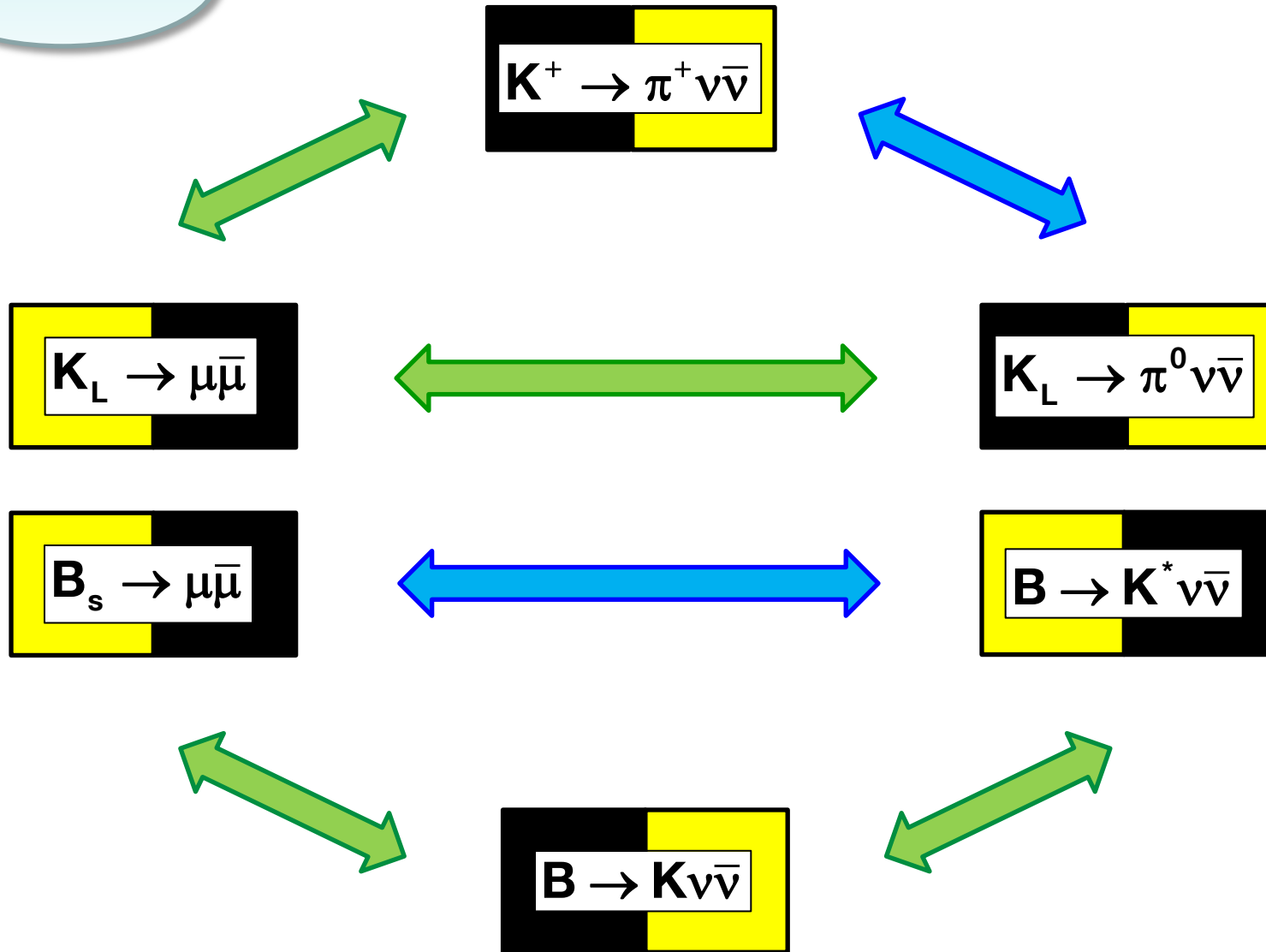
$K_L \rightarrow \pi^0 \nu\bar{\nu}$

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

Z'/Z LHS

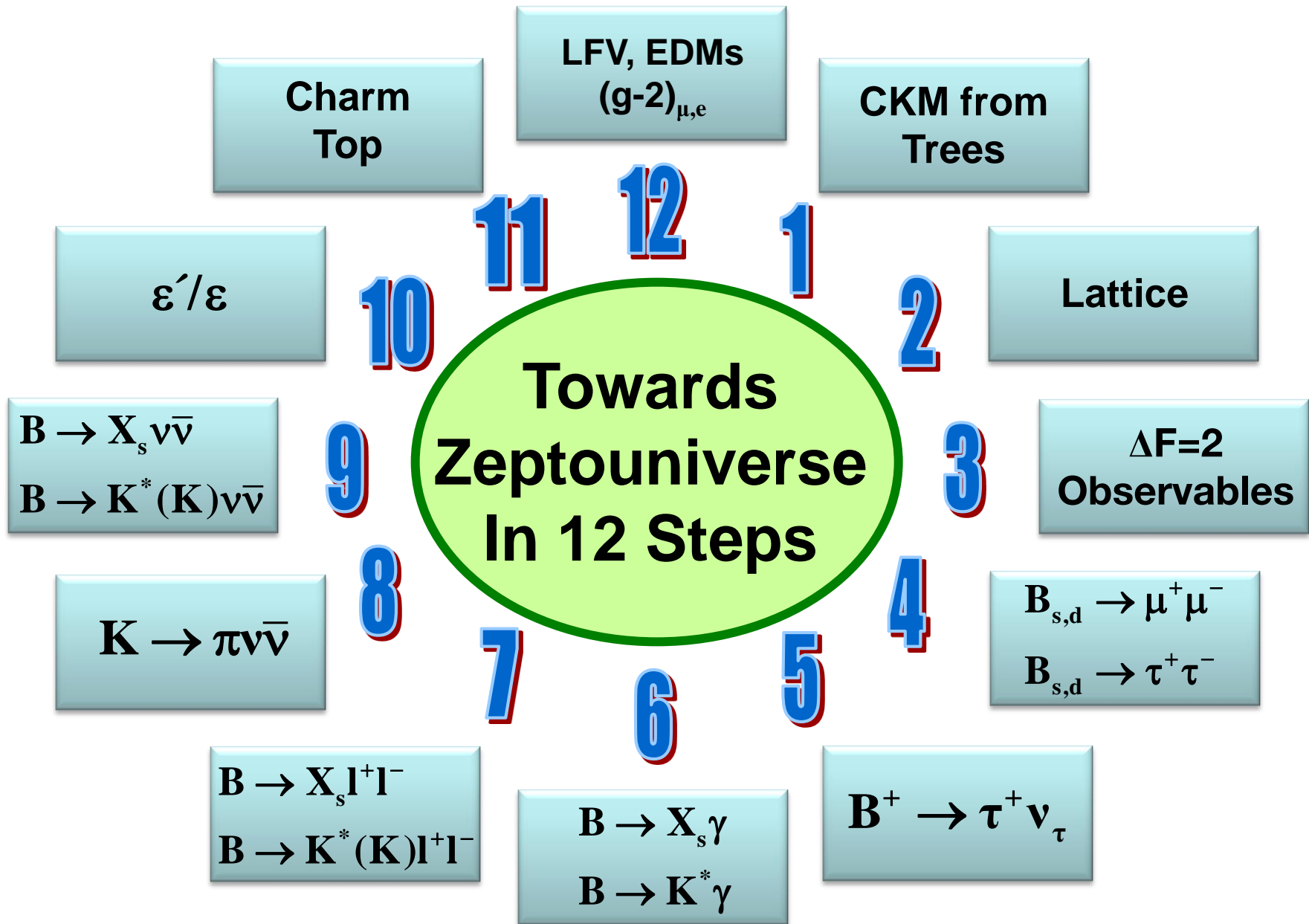


Z'/Z RHS



Finale: Vivace !

**Exciting Times are just
ahead of us !!!**



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

Charm
Top

CKM from
Trees

Lattice

ε'/ε

THANK
YOU!

$\Delta F=2$
Observables

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

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

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

$B \rightarrow X_s l^+ l^-$
 $B \rightarrow K^* (K) l^+ l^-$

$B \rightarrow X_s \gamma$
 $B \rightarrow K^* \gamma$

$B^+ \rightarrow \tau^+ \nu_\tau$

10

11

12

1

2

3

9

8

7

6

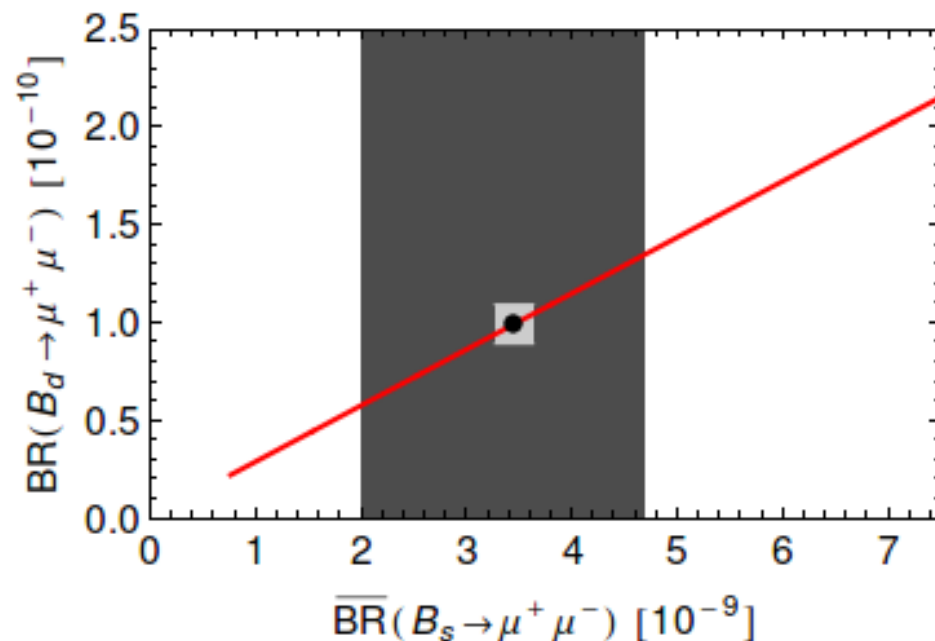
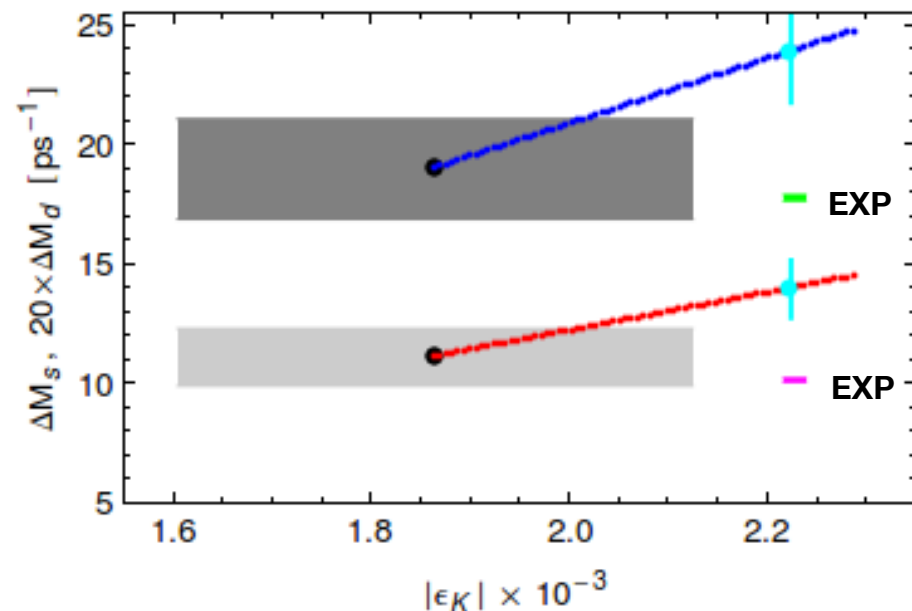
5

4

Backup

Constrained Minimal Flavour Violation

AJB + J. Girrbach (2012)



Tension within CMFV

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

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

(LHCb)

Departures from Standard Model Expectations

$$\begin{array}{l}
 \text{CP} \left\{ \begin{array}{l}
 \mathbf{K}^0 - \bar{\mathbf{K}}^0 \quad (\varepsilon_K) \quad \frac{|\varepsilon_K|_{\text{SM}}}{|\varepsilon_K|_{\text{exp}}} \approx \mathbf{0.80 \pm 0.10} \quad \begin{array}{l} \text{(AJB, Guadagnoli)} \\ \text{(Brod, Gorbahn)} \end{array} \\
 \\
 \mathbf{B}_d^0 - \bar{\mathbf{B}}_d^0 \quad (\mathbf{S}_{\psi K_s}) \quad (\mathbf{S}_{\psi K_s}) \cong \begin{array}{l} \mathbf{0.82 \pm 0.04 \quad (SM)} \\ \mathbf{0.678 \pm 0.022 \quad (exp)} \end{array} \quad \begin{array}{l} \text{(Lunghi, Soni)} \\ \end{array} \\
 \\
 \mathbf{B}_s^0 - \bar{\mathbf{B}}_s^0 \quad (\mathbf{S}_{\psi\phi}) \quad \mathbf{S}_{\psi\phi} = \begin{array}{l} \mathbf{0.035 \pm 0.002 \quad (SM)} \\ \mathbf{-0.01 \pm 0.07 \quad (LHCb)} \end{array} \\
 \\
 \frac{\text{Br}(\mathbf{B}^+ \rightarrow \tau^+ \nu)_{\text{exp}}}{\text{Br}(\mathbf{B}^+ \rightarrow \tau^+ \nu)_{\text{SM}}} \cong \mathbf{1.5 \pm 0.3} \\
 \\
 |\mathbf{V}_{ub}| = \begin{cases} \mathbf{4.3 \cdot 10^{-3}} & \text{Inclusive Decays } (\mathbf{B} \rightarrow X_u l \nu) \\ \mathbf{3.1 \cdot 10^{-3}} & \text{Exclusive Decays } (\mathbf{B} \rightarrow \rho l \nu) \end{cases} \quad \begin{array}{l} \text{(Right-handed} \\ \text{currents?} \\ \text{Crivellin;} \\ \text{Mannel et al.} \\ \text{AJB, Gemmler,} \\ \text{Isidori)} \end{array} \\
 \text{and SM-CKM fit}
 \end{array}
 \right.
 \end{array}$$

Two Scenarios for $|V_{ub}|$

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

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

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

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

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 $|V_{ub}|$

Important Messages on K Physics

1.

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

$$\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \sim 2 \text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{SM}}$$
$$\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \sim 3 \text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu})_{\text{SM}}$$

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 $S_{\psi\phi}$



$$\frac{\text{Br}(\mathbf{B}_d \rightarrow \mu^+ \mu^-)}{\text{Br}(\mathbf{B}_s \rightarrow \mu^+ \mu^-)} = \frac{\tau(\mathbf{B}_d) m_{\mathbf{B}_d} F_{\mathbf{B}_d}^2}{\tau(\mathbf{B}_s) m_{\mathbf{B}_s} F_{\mathbf{B}_s}^2} \left| \frac{\mathbf{V}_{td}}{\mathbf{V}_{ts}} \right|^2$$



$$\frac{\text{Br}(\mathbf{B}_s \rightarrow \mu^+ \mu^-)}{\text{Br}(\mathbf{B}_d \rightarrow \mu^+ \mu^-)} = \frac{\hat{\mathbf{B}}_d \tau(\mathbf{B}_s) \Delta M_s}{\hat{\mathbf{B}}_s \tau(\mathbf{B}_d) \Delta M_d}$$



$$\text{Br}(\mathbf{K}^+ \rightarrow \pi^+ \nu \bar{\nu}); \quad \text{Br}(\mathbf{K}_L \rightarrow \pi^0 \nu \bar{\nu})$$



Lepton Flavour Violation

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

$$\tau \rightarrow e\gamma, \quad \tau \rightarrow 3e$$

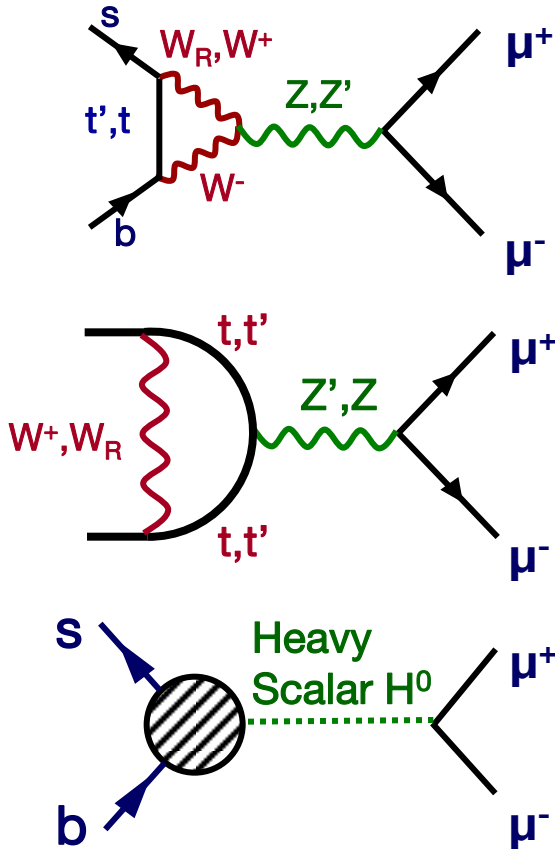
$$\tau \rightarrow \mu\gamma$$



ε'/ε provided QCD Penguin hadronic matrix under control

Standard
Candles
of
Flavour
Physics

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



Other Z-Penguins
and Boxes

$$\text{SM: } (3.2 \pm 0.2) \cdot 10^{-9}$$

**Model Independent
Limit (95% C.L.)**

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

**Altmannshofer, Paradisi,
Straub 1111.1257**

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

in SUSY

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

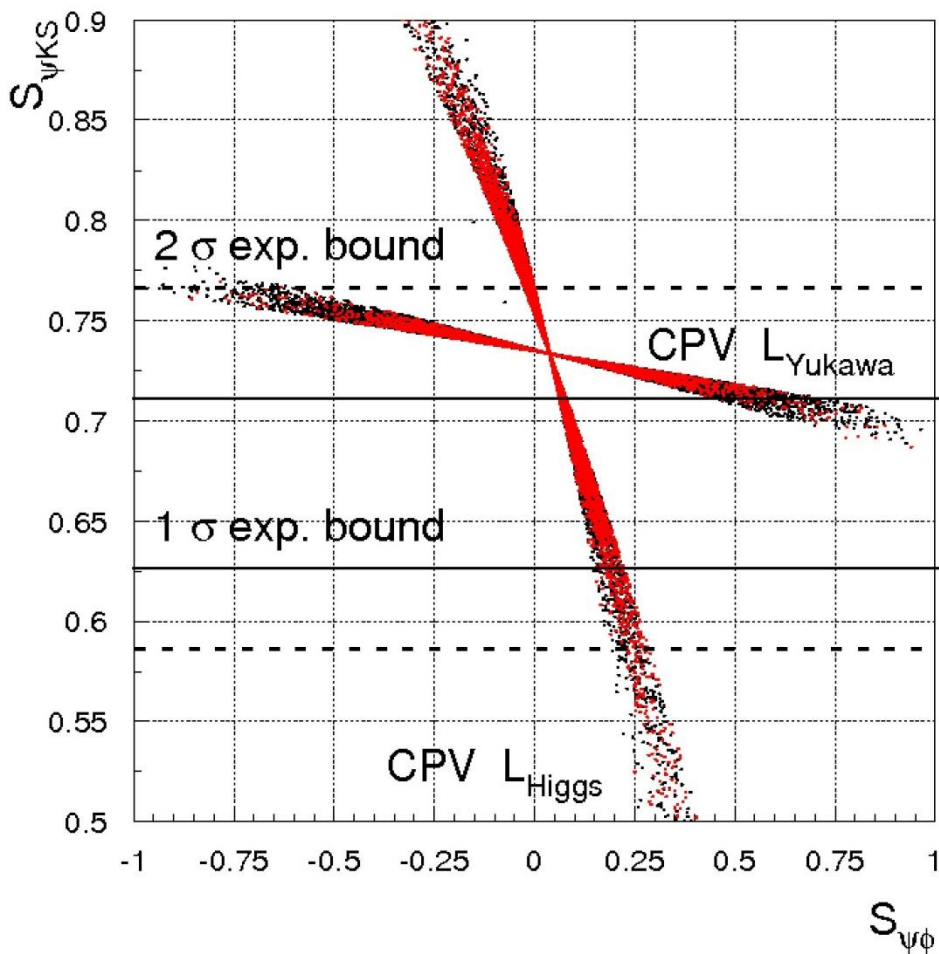
In the case of

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

**distinction between Z, Z' and H^0
possible**

More on 2HDM with MFV and Flavour Blind Phases

Correlation between \mathcal{CP} Effects



$$S_{\psi K_S} = \sin(2\beta - \theta_d^H) \quad S_{\psi\phi} \cong \sin(\theta_s^H)$$

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 $|V_{ub}|_{\text{excl}} \neq |V_{ub}|_{\text{incl}}$
- Softens $B^+ \rightarrow \tau^+ \nu_\tau$ problem (large V_{ub})

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

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

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

SM-like $\text{Br}(B_s \rightarrow \mu^+ \mu^-)$, $\text{Br}(B_d \rightarrow \mu^+ \mu^-)$, $S_{\psi K_s}$ ok
can be large

$$\mathbf{K^+ \rightarrow \pi^+ \nu\bar{\nu} \text{ and } K_L \rightarrow \pi^0 \nu\bar{\nu}} \quad (\mathbf{Z^0\text{-penguins}})$$

(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 $K_L \rightarrow \pi^0 \nu\bar{\nu}$)**

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

SM

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

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

Exp

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

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

(E787, E949 Brookhaven)

(E391a, KEK)

Future :

**NA62
ORCA (FNAL)**



**Both very
sensitive to
New Physics**

J-PARC KOTO



**CP-conserving
TH uncertainty 2-3%**

**CP-Violation in Decay
TH uncertainty 1-2%**



Littlest Higgs Model with T-Parity

$$\mathbf{SU}(3)_c \otimes [\mathbf{SU}(2) \otimes \mathbf{U}(1)]_1 \otimes [\mathbf{SU}(2) \otimes \mathbf{U}(1)]_2$$

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

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

LHT after LHCb Data

**Our 2006
Predictions**
(Blanke et al.)

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

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

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

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

ABGPS

$\text{Br}(B_d \rightarrow \mu^+ \mu^-)$ vs $\text{Br}(B_s \rightarrow \mu^+ \mu^-)$

SUSY
(Flavour)

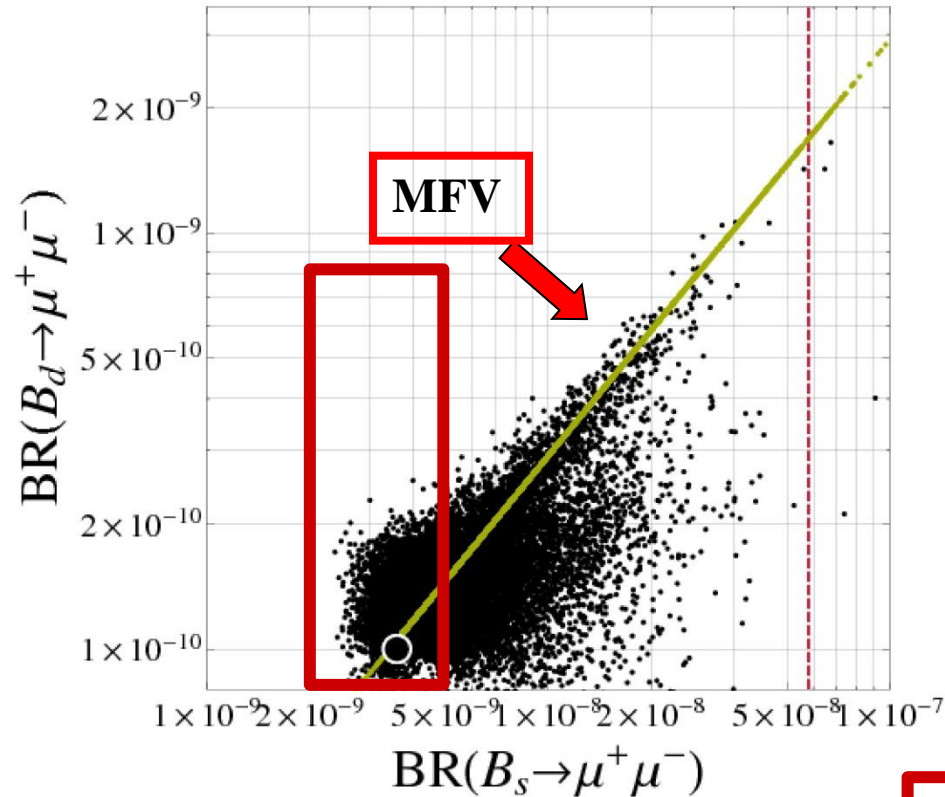
(0909.1333)

Altmannshofer, AJB, Gori, Paradisi, Straub

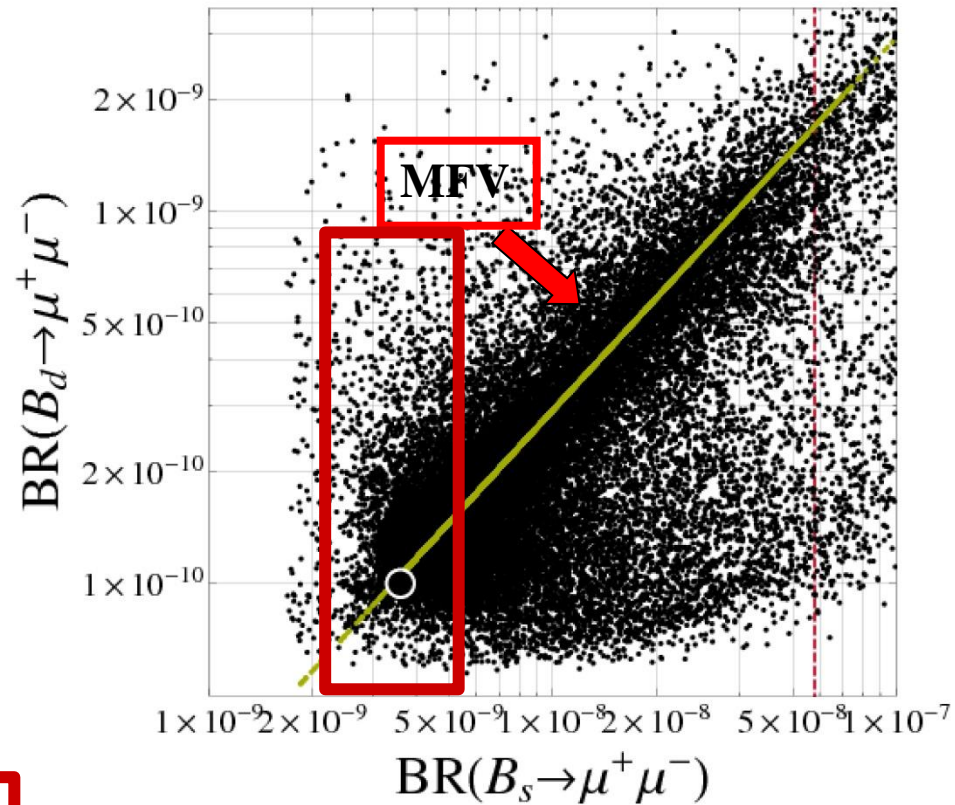
● = SM

MFV

AJB; Hurth, Isidori, Kamenik, Mescia



RVV2 (RH currents)



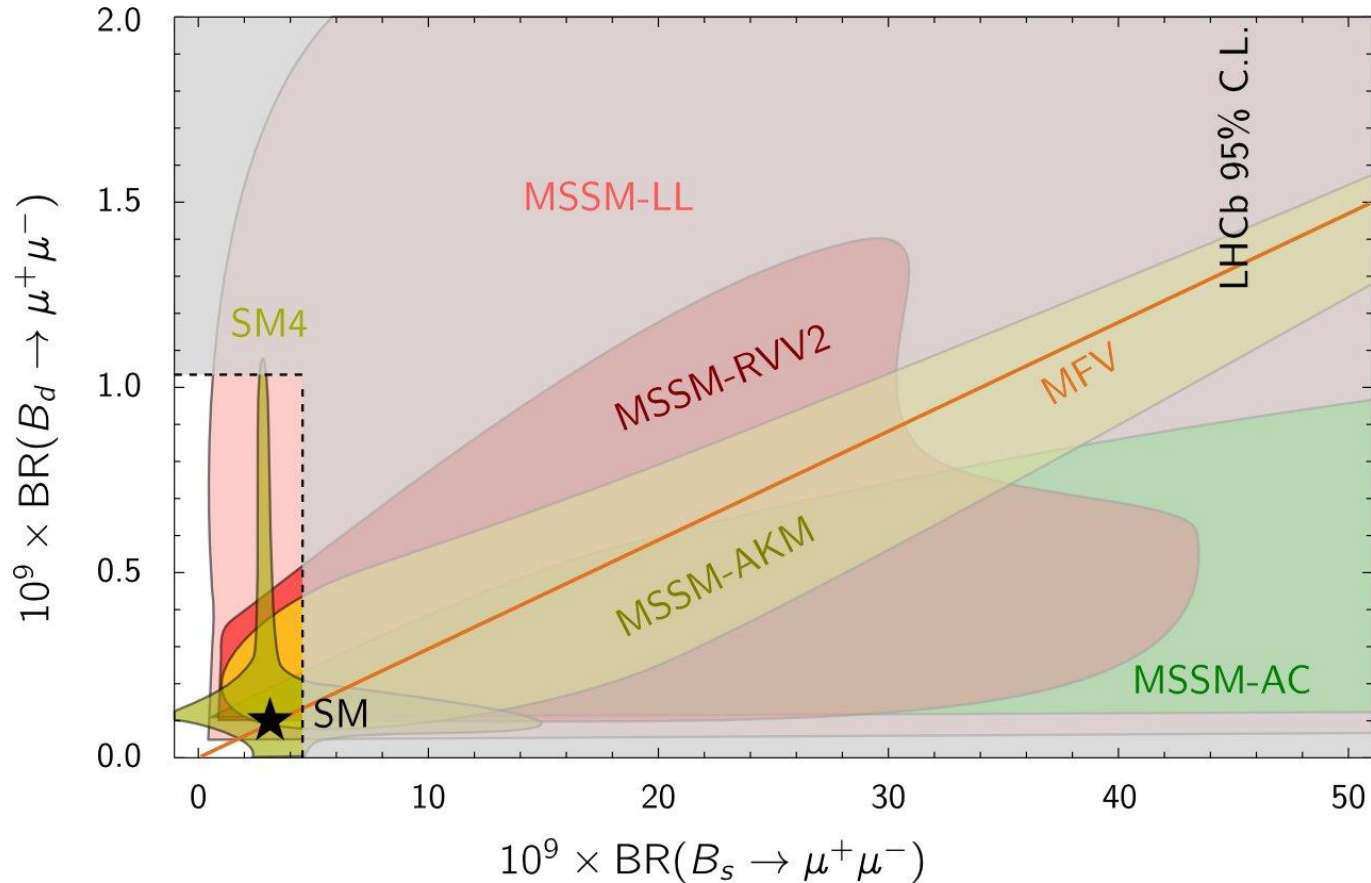
LH currents

LHCb

Supersymmetric Models Facing LHCb Data

ABGPS

Straub 1012.3893



Models with new left-handed currents favoured

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

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

RHMFV

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

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

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

$$\varepsilon \approx \frac{v_L}{v_R}$$

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

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

Generally: in principle yes

But a very detailed analysis of $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ 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 \varepsilon_K $	ΔM_d	ΔM_s	$\Delta S_{\psi K_s}$	$\Delta S_{\psi\phi}$	Favoured $ V_{ub} $
CMFV	+	+	+	0	0	exclusive
2HDM_{MFV}	0	\pm	\pm	-	+	inclusive
U(2)³	+	\pm	\pm	- 0 +	+ 0 -	inclusive exclusive

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

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

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

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

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

(weak)

Impose Constraints

Set all input parameters at central values but require:

($\pm 5\%$)

$$16.9 / \text{ps} \leq \Delta M_s \leq 18.7 / \text{ps}$$
$$0.48 / \text{ps} \leq \Delta M_d \leq 0.53 / \text{ps}$$

($\pm 2\sigma$)

$$-0.20 \leq S_{\psi\phi} \leq 0.20$$
$$0.64 \leq S_{\psi K_s} \leq 0.72$$

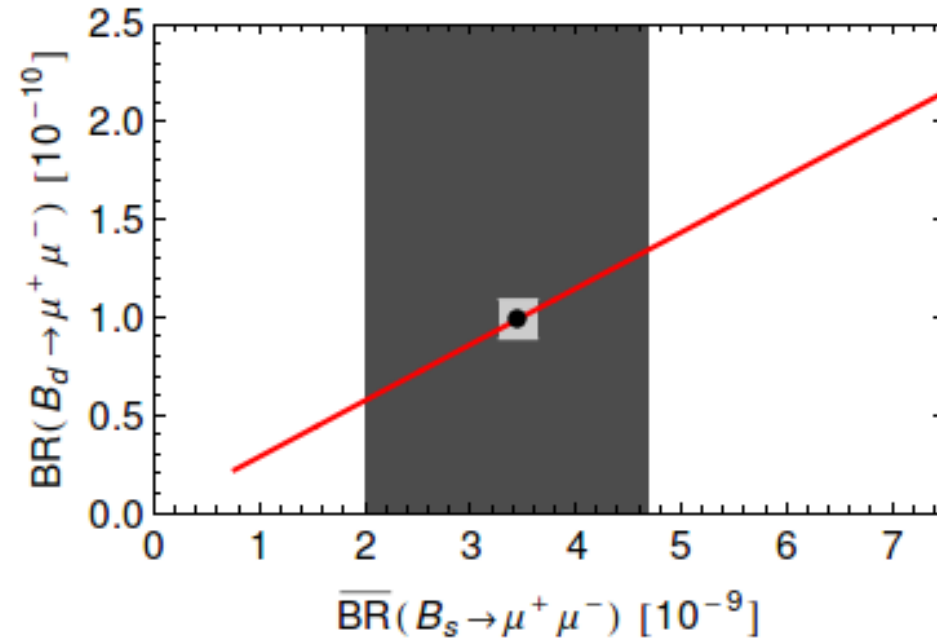
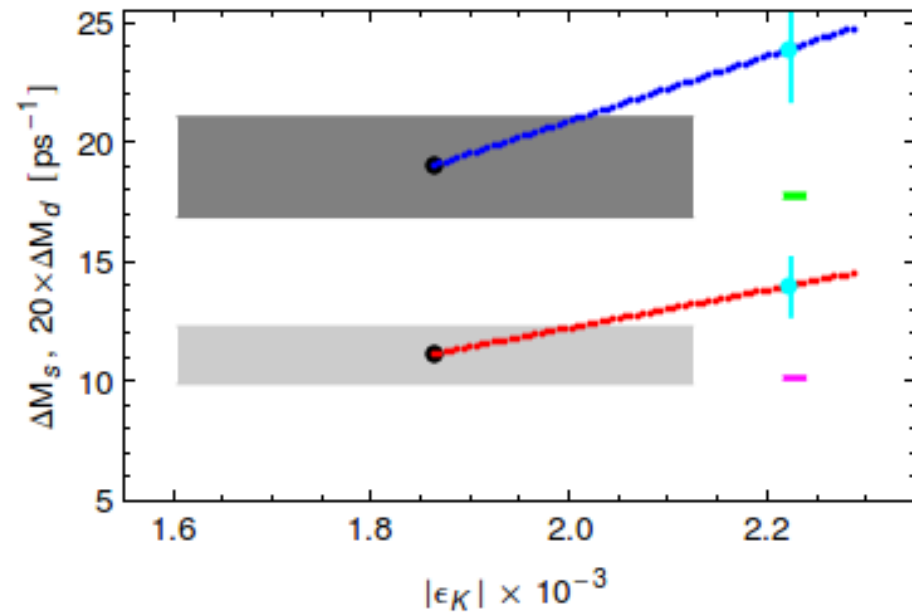
$$0.75 \leq \frac{\Delta M_K}{(\Delta M_K)_{\text{SM}}} \leq 1.25$$

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

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

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

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

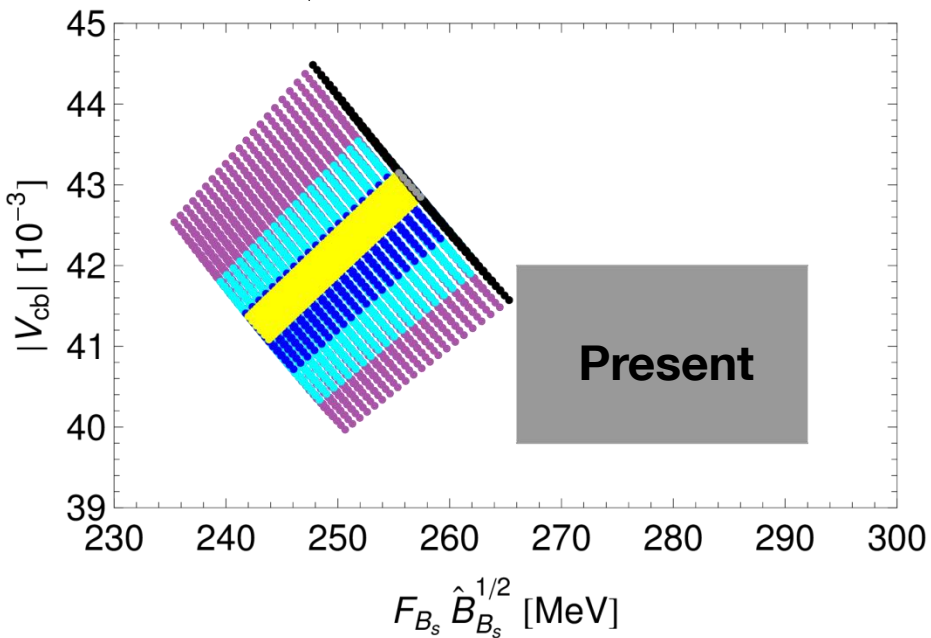
AJB + Girschbach 1304.6835

Which values of

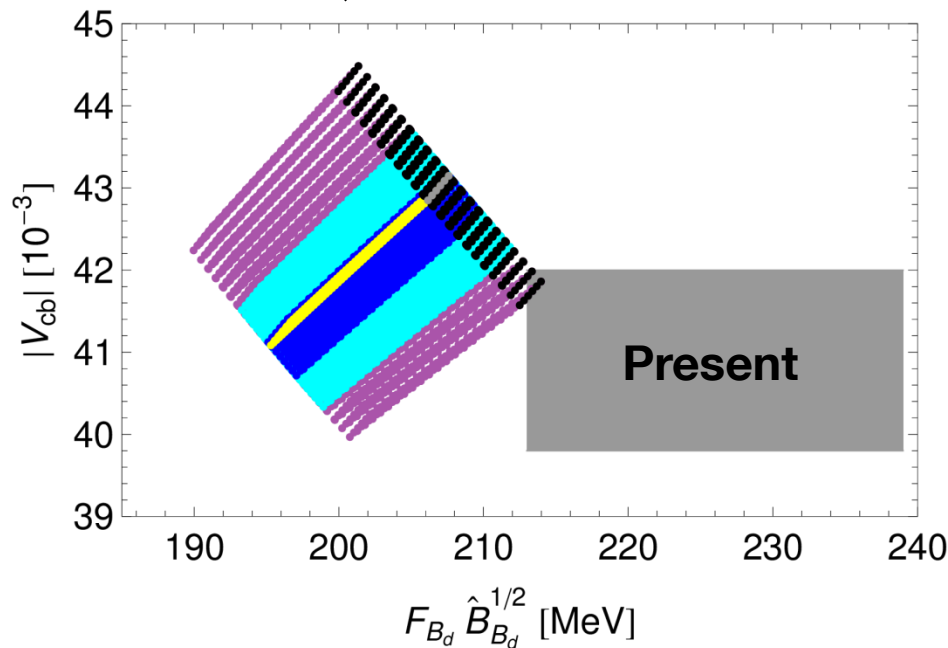
$$|\mathbf{V}_{cb}|, \sqrt{\hat{\mathbf{B}}_d} \mathbf{F}_{B_d}, \sqrt{\hat{\mathbf{B}}_s} \mathbf{F}_{B_s}$$

Would save CMFV ?

Required
by CMFV



Required
by CMFV



: SM



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

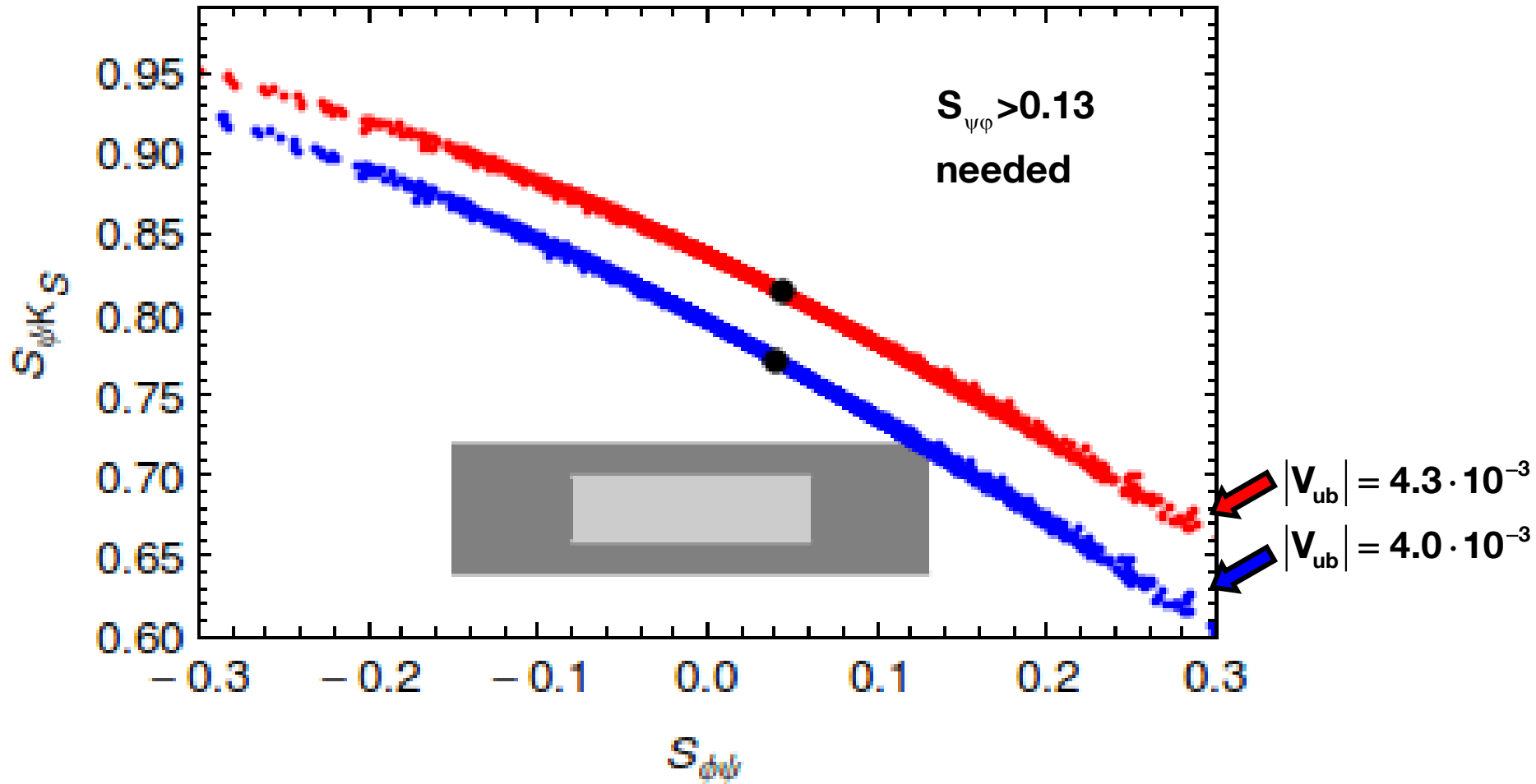


: $\eta_{cc} = 1.70 \pm 0.21$ (using ΔM_K) AJB + Girrbach,

1304.6835

2HDM_{MFV} Facing LHCb Data

AJB, Girschbach, Nagai (2013)



AJB, Carlucci, Gori, Isidori; 1005.5310

AJB, Isidori, Paradisi; 1007.5291

Conclusion on 2HDM_{MFV}

Still alive but finding

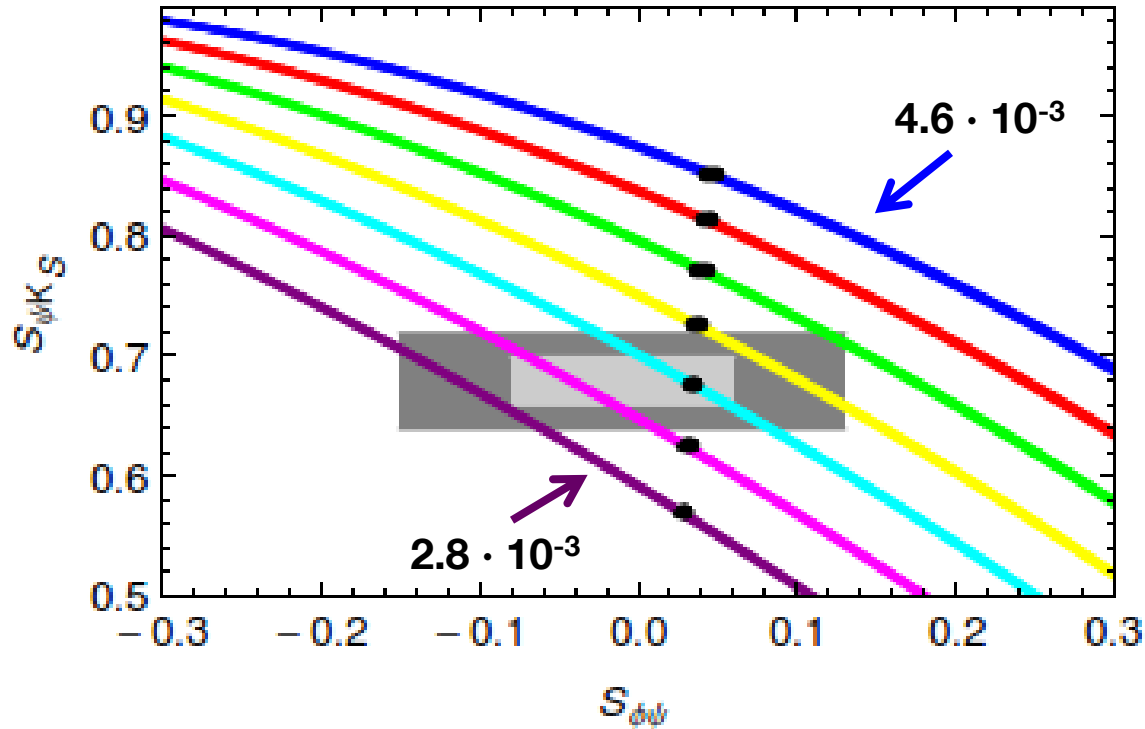
$S_{\psi\phi} < 0$ or very close to SM

will rule it out.

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

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

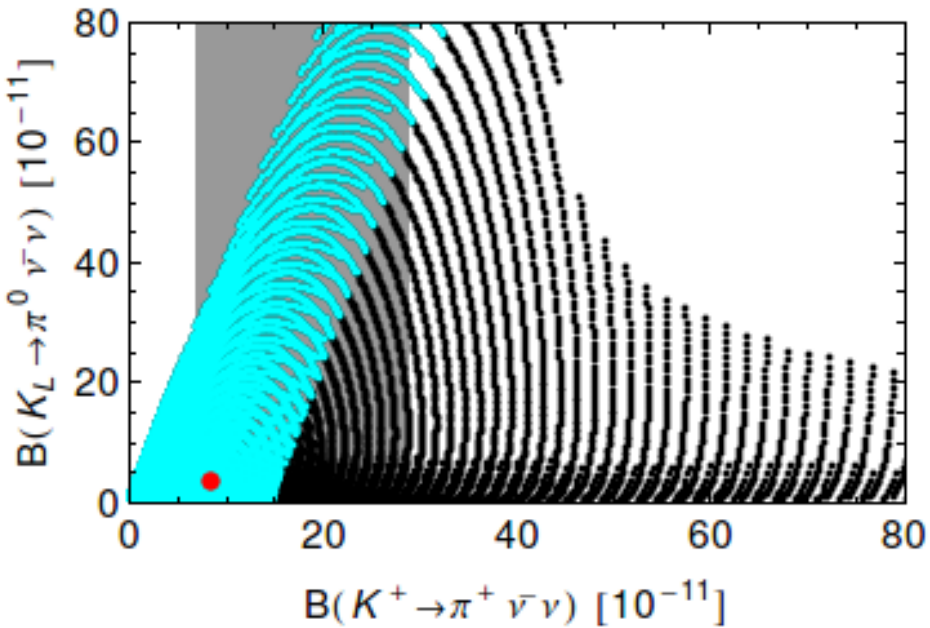
Important test of $U(2)^3$ Models



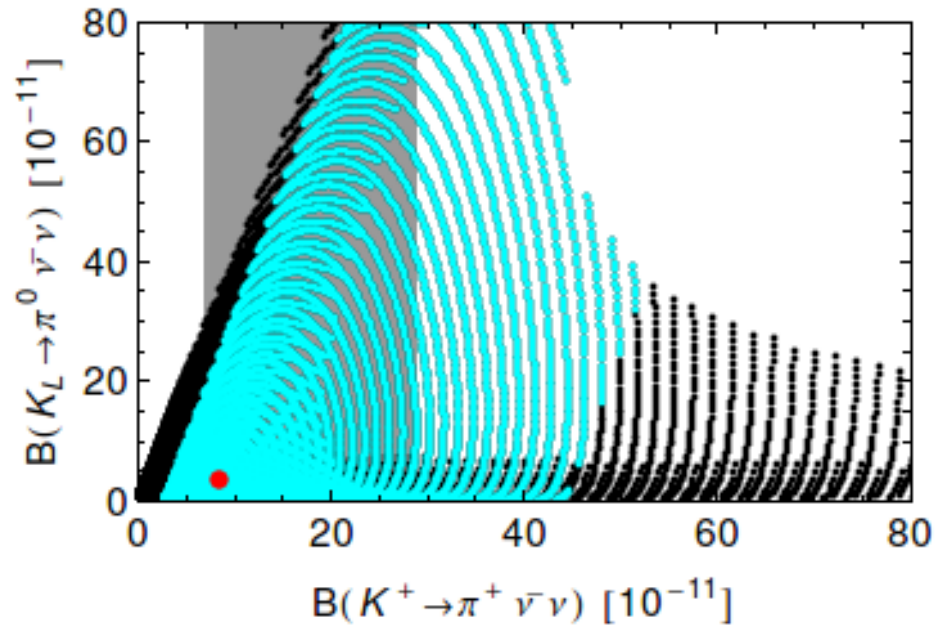
$\gamma = 68^\circ$

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

LHS2 & Z



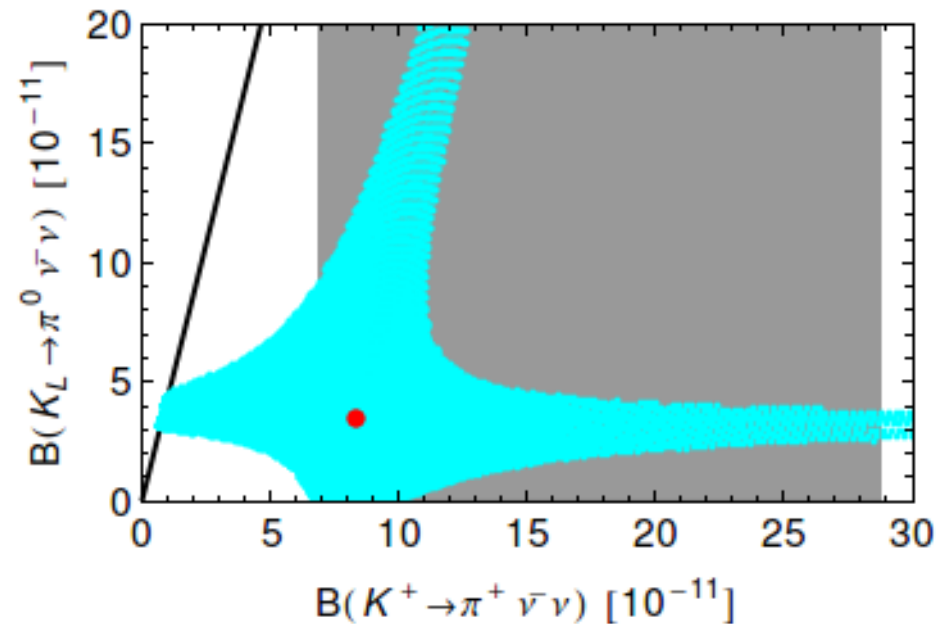
RHS2 & Z



■ : forbidden by
 $K_L \rightarrow \mu^+ \mu^-$

LHS, RHS
 LRHS

LRS2 & Z



$$\bar{\text{Br}}(B_s \rightarrow \mu^+ \mu^-), S_{\mu\mu}^s, \text{Br}(B_d \rightarrow \mu^+ \mu^-), S_{\mu\mu}^d$$

SM

Data

$$\begin{aligned} \bar{\text{Br}}(B_s \rightarrow \mu^+ \mu^-) &: (3.56 \pm 0.18) \cdot 10^{-9} & \left(3.2^{+1.5}_{-1.2}\right) \cdot 10^{-9} \\ \text{Br}(B_d \rightarrow \mu^+ \mu^-) &: (1.05 \pm 0.07) \cdot 10^{-10} & \leq 9.4 \cdot 10^{-10} \end{aligned}$$

$$S_{\mu\mu}^s = S_{\mu\mu}^d = 0$$

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

AJB, Fleischer, Girrbach, Knegjens (1303.3820)

AJB, Girrbach, Guadagnoli, Isidori (1208.0934)

$$S_{\psi\phi} = 0.035 \pm 0.002$$

$$S_{\psi\phi} = -0.01 \pm 0.07$$

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) $\Delta_L^{ij} \neq 0$ $\Delta_R^{ij} = 0$

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

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

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

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