Towards the Zeptouniverse with the Help of Correlations between Flavour Observables

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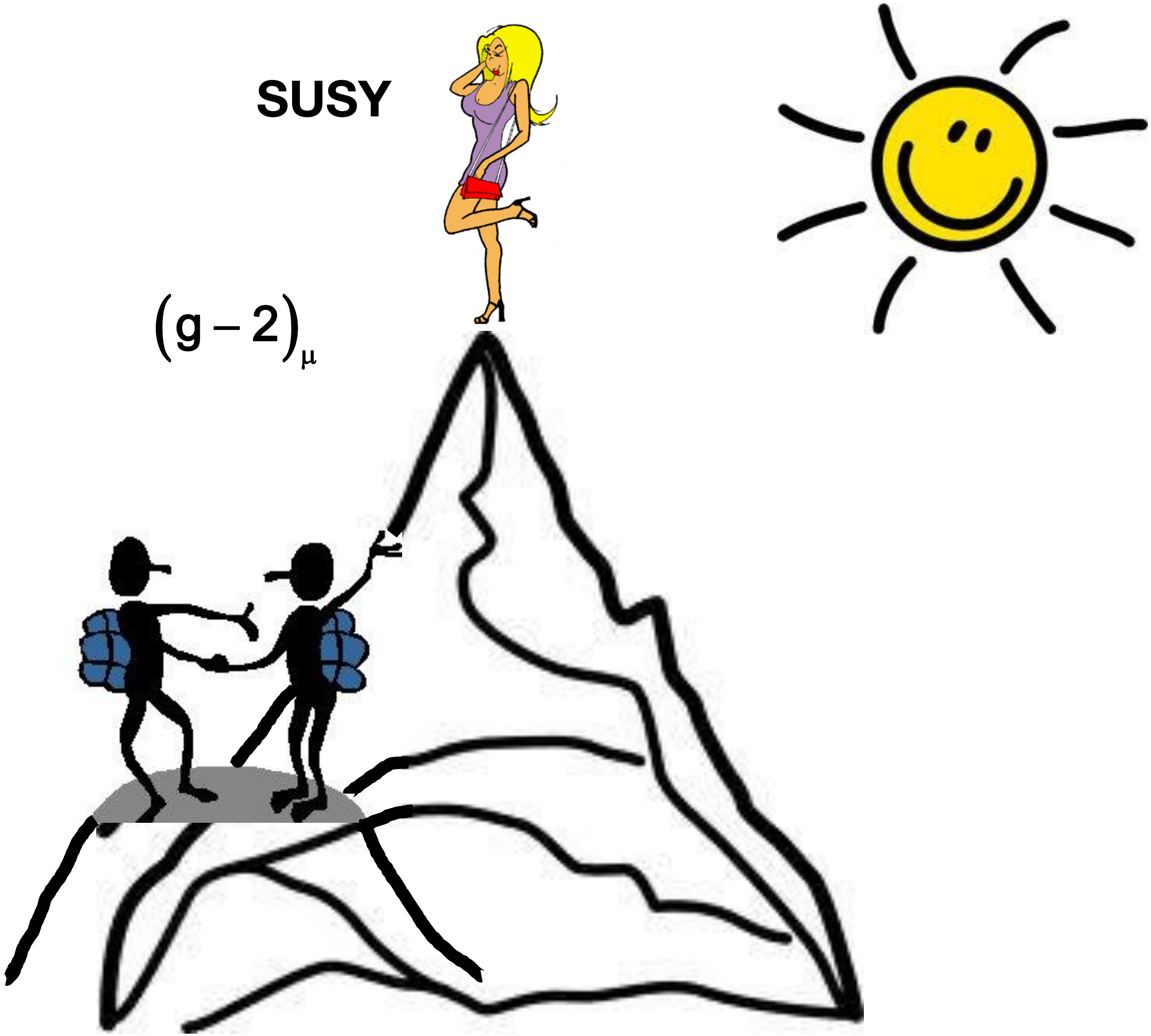
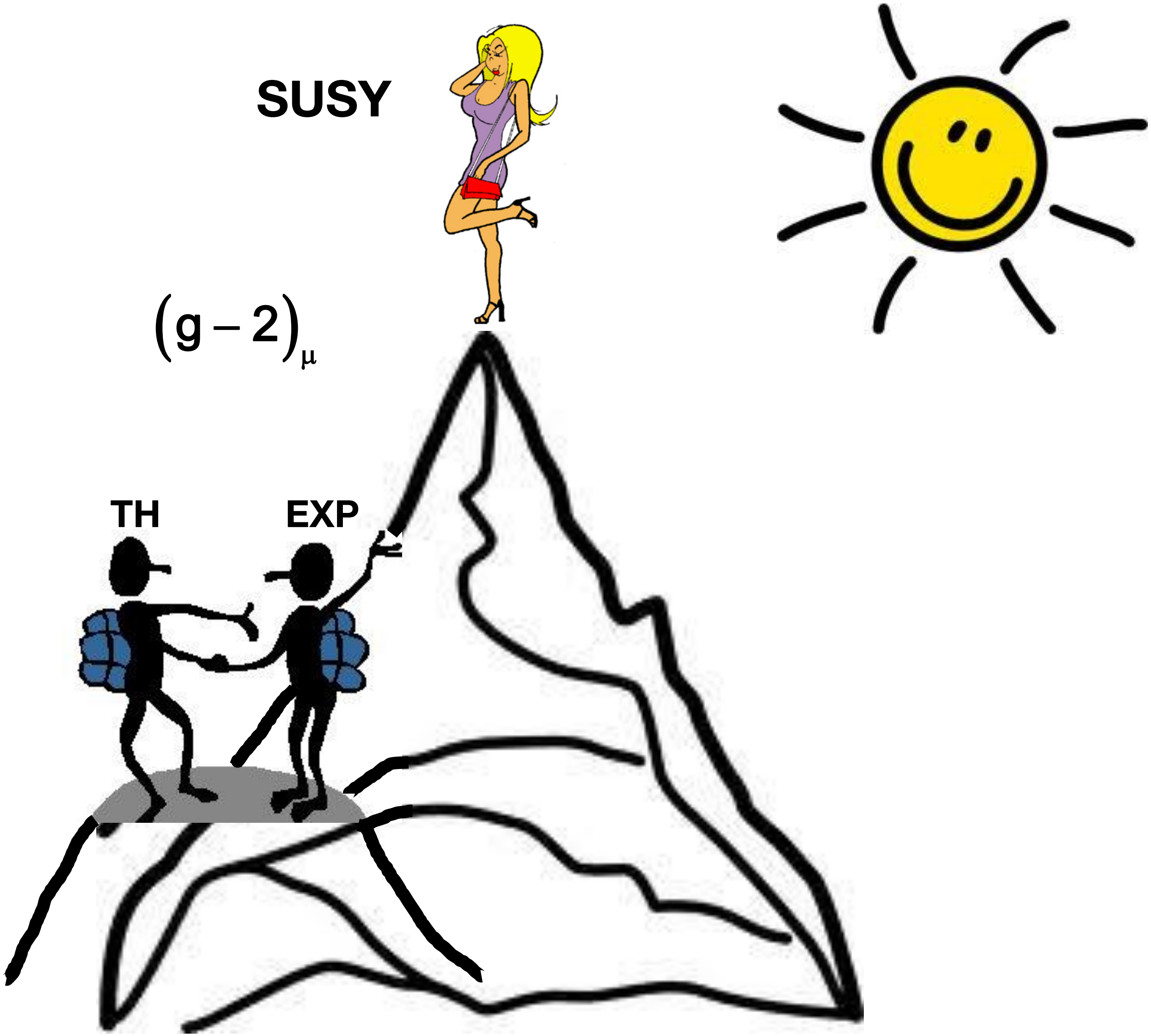
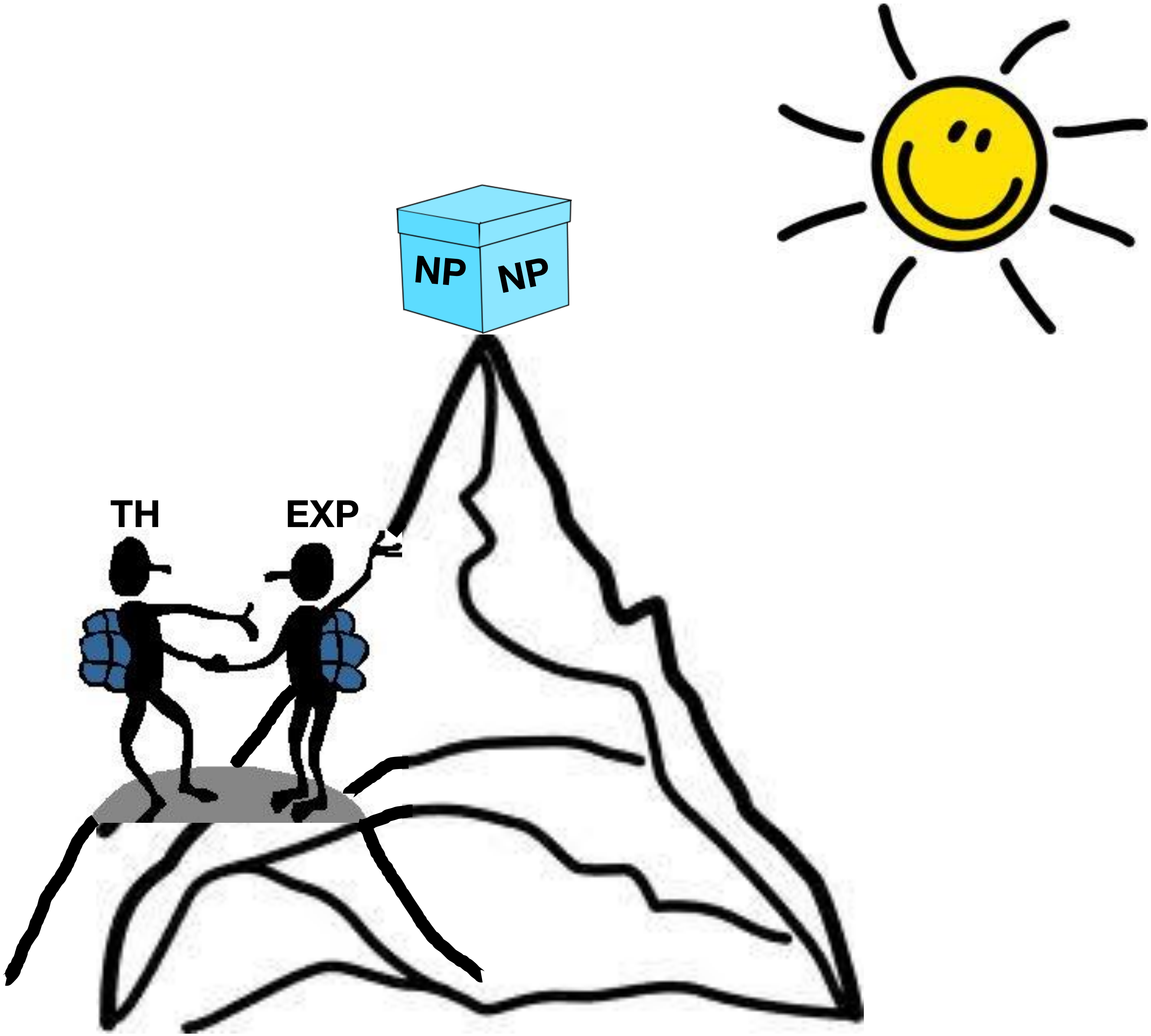
Warsaw
September 2013


SUSY
$(g-2)_\mu$


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


NP NP
TH
EXP

June 2013

July 2013

EPS 2013 Flavour Highlights

1.

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

(LHCb, CMS)

2.

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

3.

$B \to D^*\tau\nu$ **(not in this talk)**

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

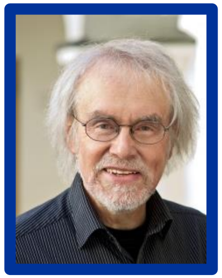
A Journey to the Very Short Distance Scales:

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

ERC Flavour Team


AJB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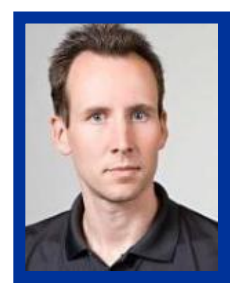
G.Buchalla


A.Ibarra


M.Ratz

In Order to identify New Physics through Flavour Physics

We need

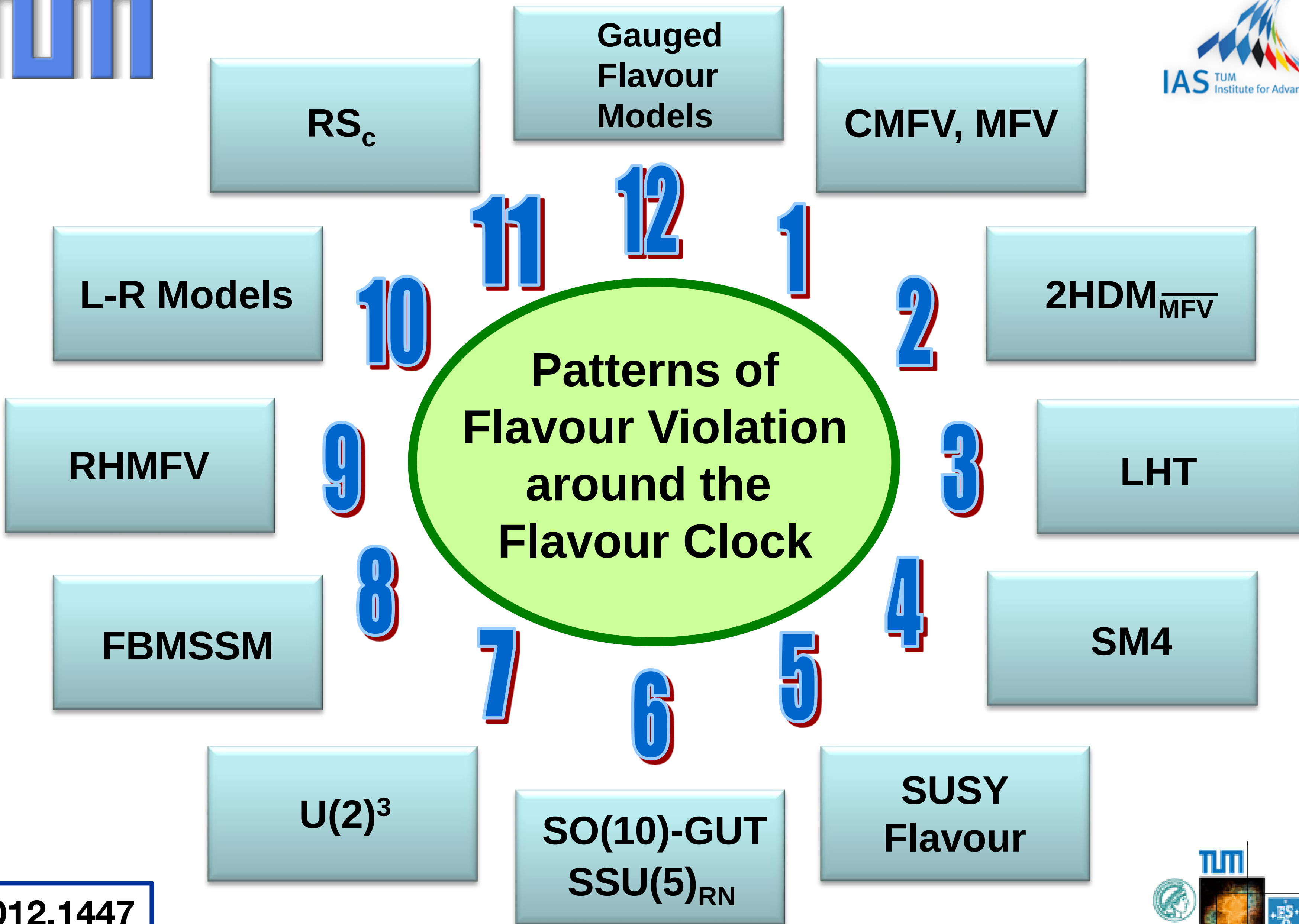
1. Many precision measurements of many observables and precise theory.

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

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)
AJB, Girrbach, 1201.1302 (NLO QCD)
AJB, Girrbach, 1309.2466 (Facing new data)

2. Neutral Scalars FCNCs (tree level)

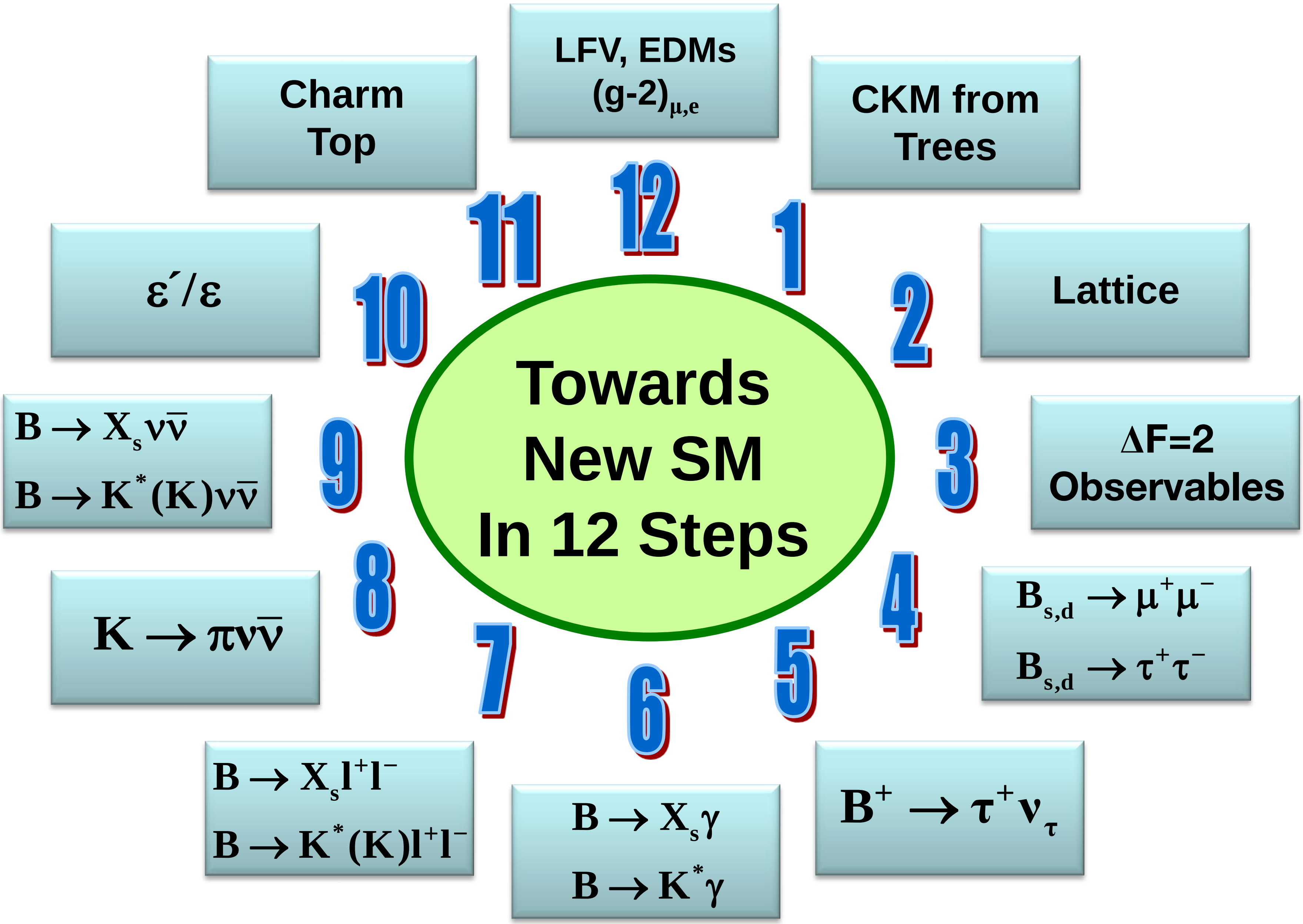
AJB, De Fazio, Girrbach, Knegjens, Nagai (1303.3723)
AJB, Girrbach, 1201.1302 (NLO QCD)

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

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

Towards New SM in 12 Steps

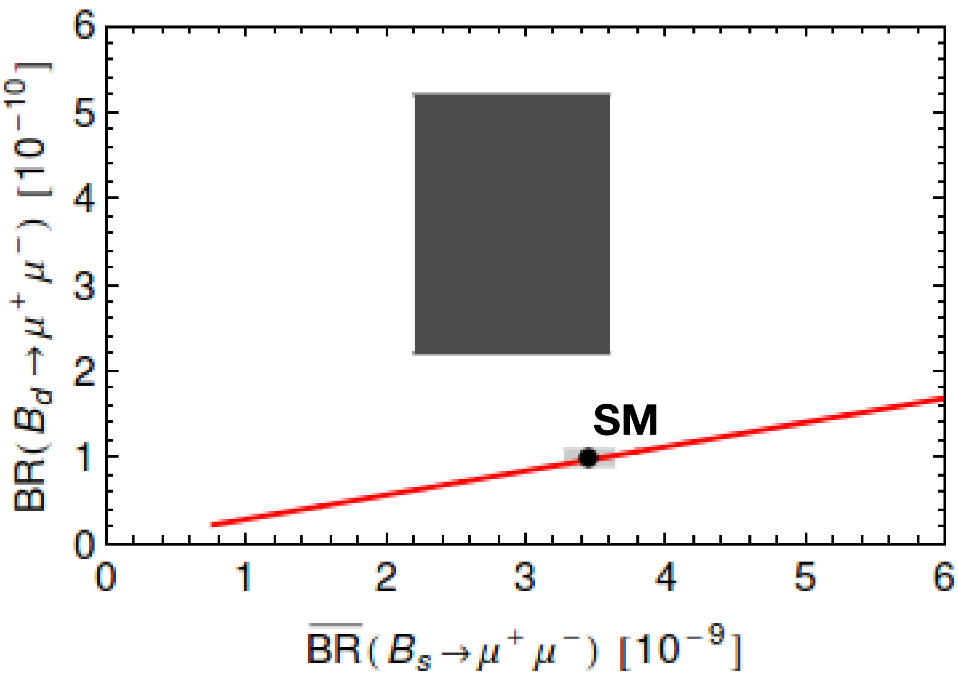
AJB + Girrbach (1306.3755)


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

Simplest Correlations

Constrained Minimal Flavour Violation

AJB
Hurth, Isidori, Kamenik, Mescia



Golden Relation

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

AJB 2003

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

No CKM
No weak decay constants

$$\overline{\mathrm{Br}}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \cdot 10^{-9}$$

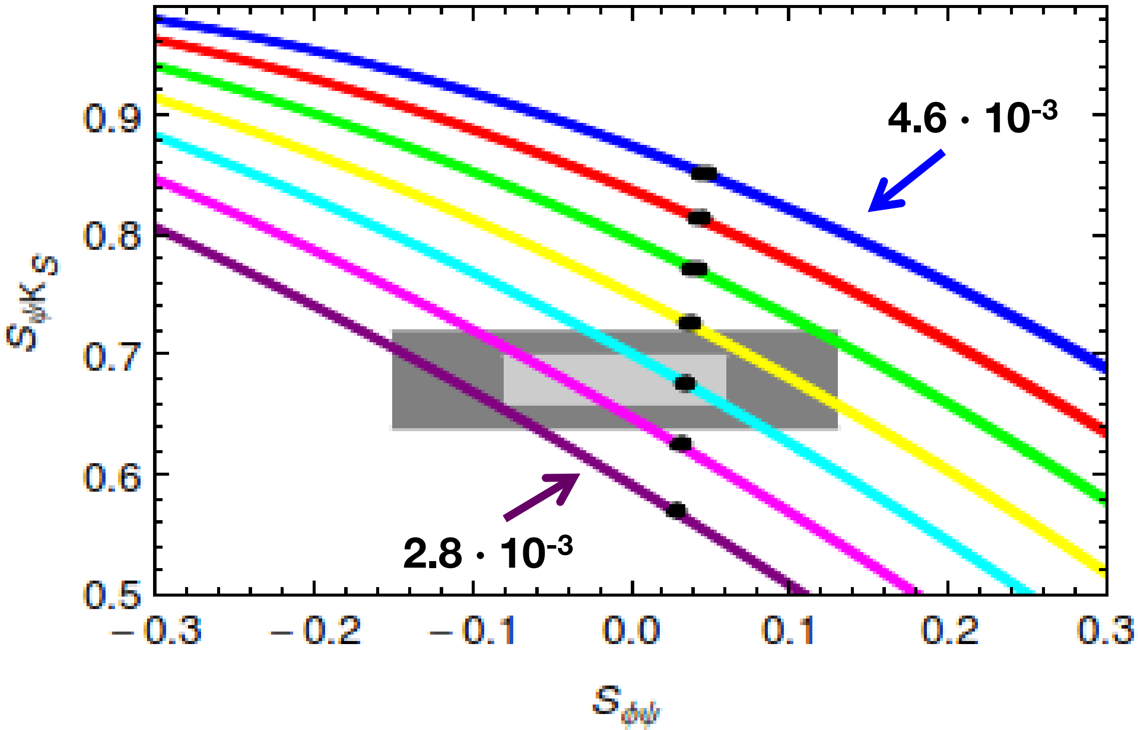
$$\mathrm{Br}(B_d \to \mu^+\mu^-) = \left(3.6^{+1.6}_{-1.4}\right) \cdot 10^{-10}$$

(LHCb + CMS)

AJB
Girrbach
(1206.3878)

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

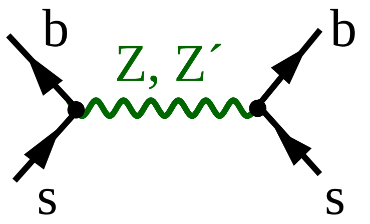
Important test of $U(2)^3$ Models



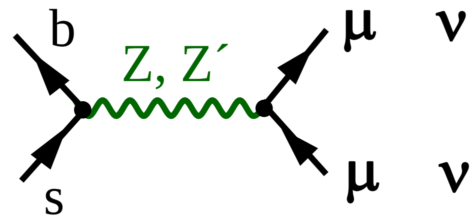
In the $U(2)^3$ Symmetric World we could determine $|V_{ub}|$ without significant hadronic uncertainties (QCD penguins)

Correlations between Flavour Observables in Tree Level FCNCs

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!

For fixed lepton couplings

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

B_d^0 : $\Delta M_d,\ S_{\psi K_s},\ B_d \to \mu^+\mu^-,\ S_{\mu\mu}^d$ ⟸ $\Delta_{L,R}^{bd} \equiv \tilde{s}_{13} e^{-i\delta_{13}}$ $\Delta_{L,R}^{sd} \equiv \tilde{s}_{12} e^{-i\delta_{12}}$

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

Correlations depend strongly on the allowed Size of NP Contributions

	SM	Data	
ΔM_s	$(18.0 \pm 1.8)\,/\,\text{ps}$	$17.7\,/\,\text{ps}$	
$S_{\psi\varphi}$	0.04	$-0.15 \leq S_{\psi\varphi} \leq 0.15$	95% C.L.
$\overline{\text{Br}}(B_s \to \mu^+\mu^-)$	$(3.5 \pm 0.2) \cdot 10^{-9}$	$(2.9 \pm 0.7) \cdot 10^{-9}$	

	SM	Data
ΔM_d	$(0.52 \pm 0.05)\,/\,\text{ps}$	$0.51\,/\,\text{ps}$
$S_{\psi K_s}$	0.67 (excl. V_{ub}) (S1)	0.68 ± 0.02
	0.81 (incl. V_{ub}) (S2)	0.68 ± 0.02
$\text{Br}(B_d \to \mu^+\mu^-)$	$(1.1 \pm 0.1) \cdot 10^{-10}$	$(3.6 \pm 1.5) \cdot 10^{-10}$

	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 ΔF=2 observables can be removed.

2. The present data on $B_{s,d} \to \mu^+\mu^-$ and $B_d \to K^*\mu^+\mu^-$ can be reproduced with $M_{Z'} \sim 0(\text{few TeV})$

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

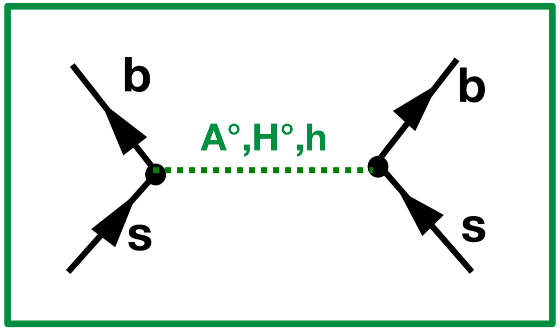
Lessons from Z Studies

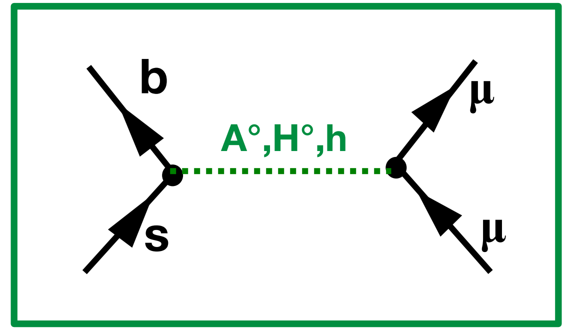
1. Data on $\text{Br}(B_{s,d} \to \mu^+\mu^-)$ can be understood but not $B_d \to K^*\mu^+\mu^-$ (vector coupling to $\mu^+\mu^-$ too small)

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



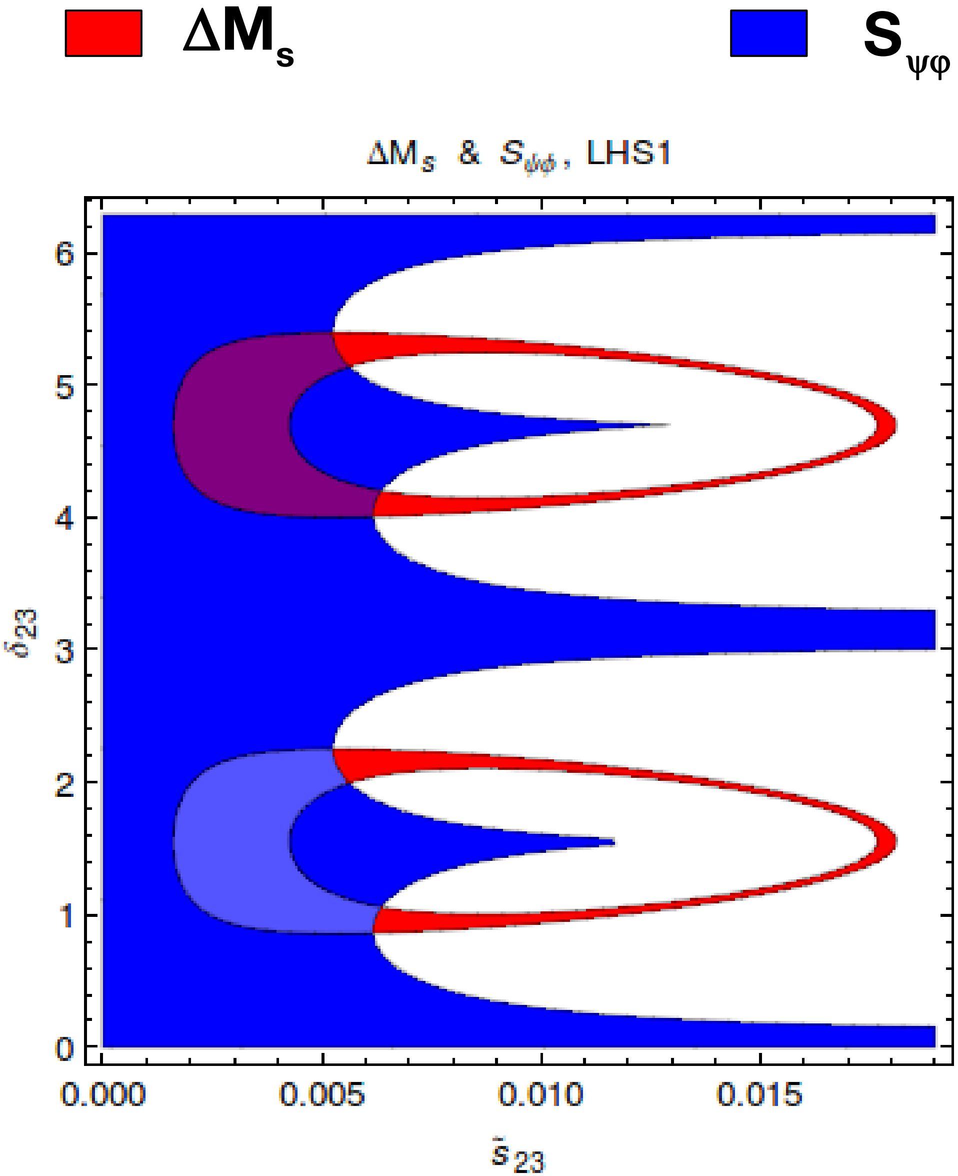


1. Correlations between ΔF=1 and ΔF=2 observables for A° differ from Z´ case because of pseudoscalar coupling $i\gamma_5$.

2. Correlations between ΔF=1 and ΔF=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 ΔF=1 transitions negligible once ΔF=2 constraints satisfied because of small μμ coupling.

Oases in B_s-System



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

	SM	Data (LHCb)
$\bar{Br}(B_s \to \mu^+\mu^-)$:	$(3.56 \pm 0.18) \cdot 10^{-9}$	$(2.9 \pm 0.7) \cdot 10^{-9}$
$Br(B_d \to \mu^+\mu^-)$:	$(1.05 \pm 0.07) \cdot 10^{-10}$	$\left(3.6^{+1.6}_{-1.4}\right) \cdot 10^{-10}$

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

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.

Historical Remarks

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

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

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

Values of $$Br(B_s \to \mu^+\mu^-)_{SM} \sim 3-4\cdot 10^{-9}$$ $$Br(B_d \to \mu^+\mu^-)_{SM} \sim 1\cdot 10^{-10}$$ were with us for last 15 years

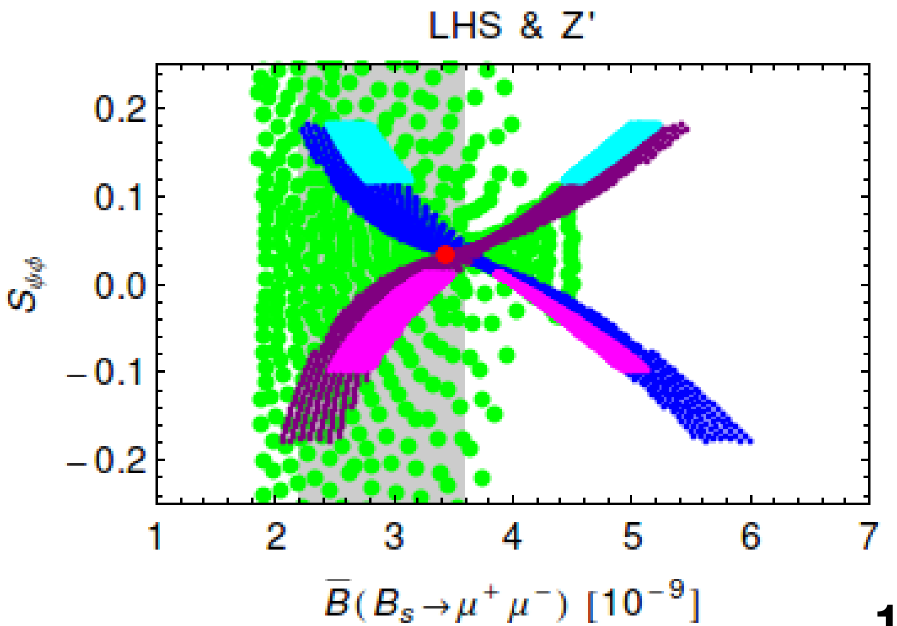
Theoretical Improvements over years : **Buchalla, AJB; Misiak, Urban (~1998)**

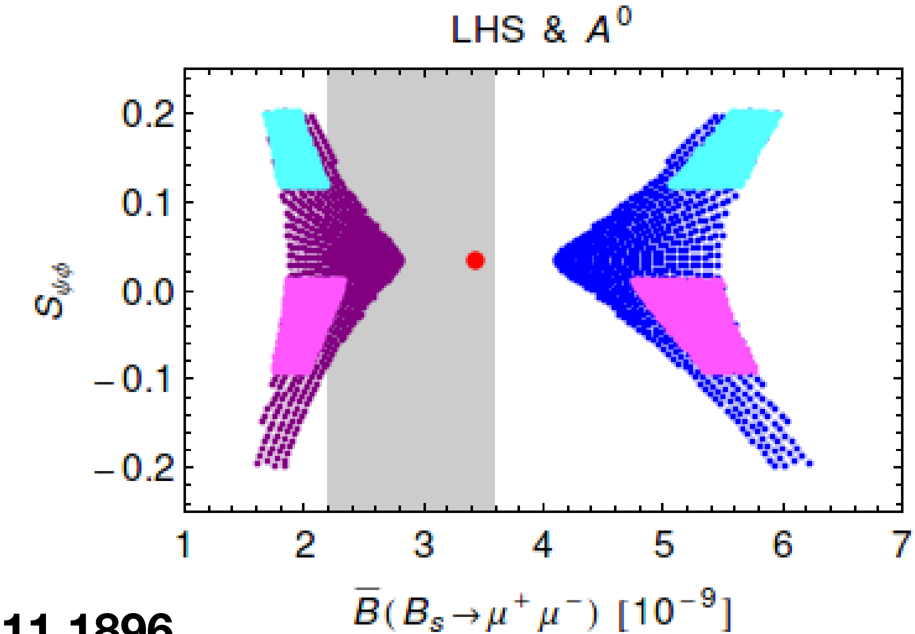
September 2013

<u>Recently</u>: full NLO Electroweak, NNLO QCD

Bobeth, Gorbahn, Hermann, Misiak, Stamou, Steinhauser

$$Br(B_s \to \mu^+\mu^-)_{SM} = (\;\fbox{}\;\pm 0.16(\text{par}) \pm 0.02(\text{theo}))\cdot 10^{-9}$$
$$Br(B_d \to \mu^+\mu^-)_{SM} = (\;\fbox{}\;\pm 0.07(\text{par}) \pm 0.01(\text{theo}))\cdot 10^{-10}$$

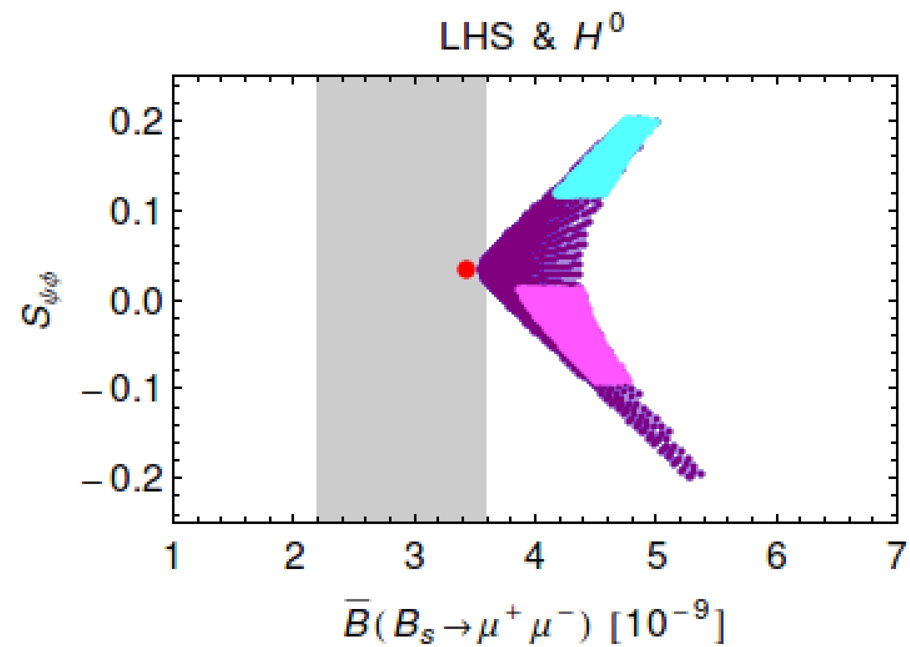




1211.1896
1303.3723
1303.3820

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

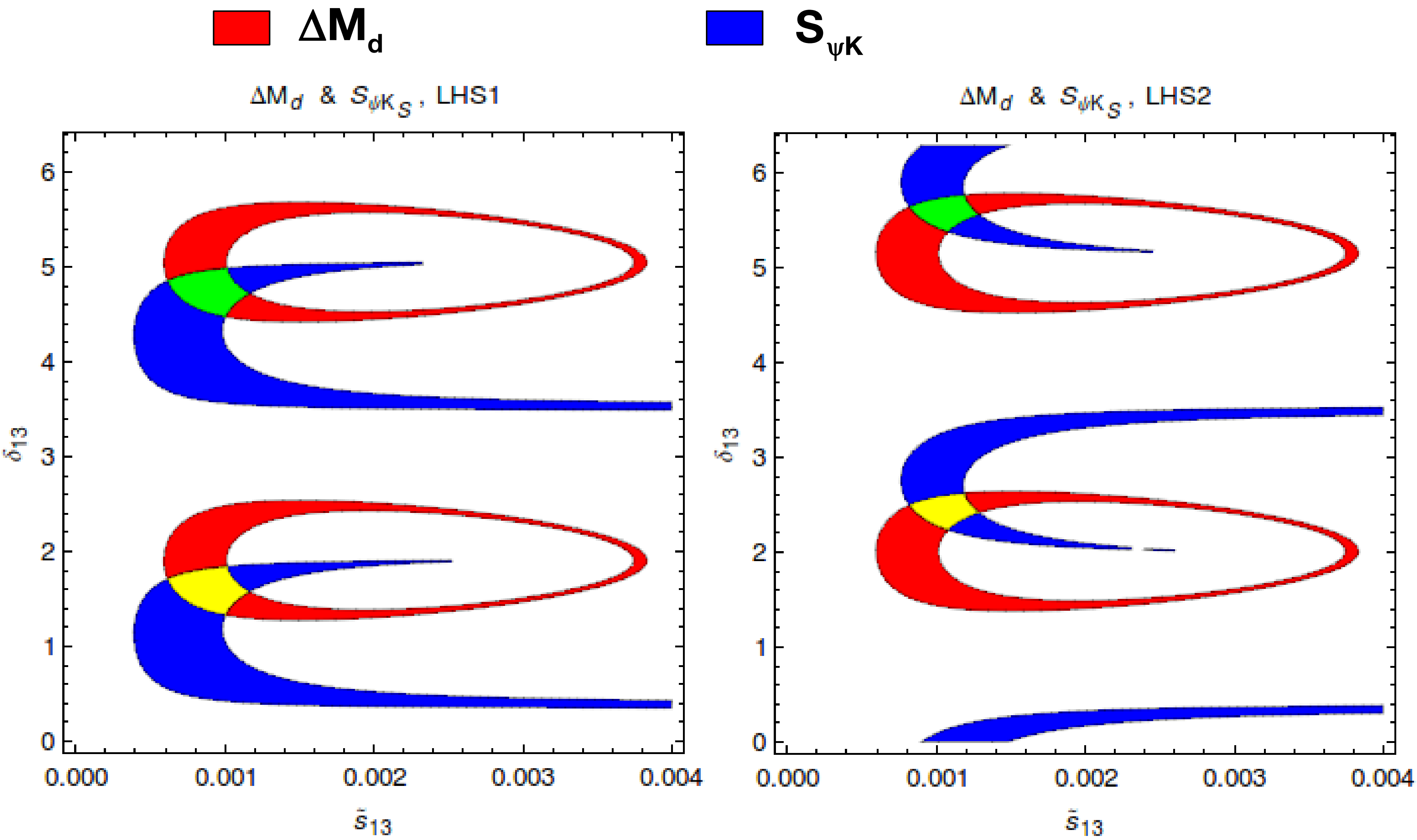
1 TeV



: **allowed by $b \to sll$**

$U(2)^3$

Oases in B_d-System

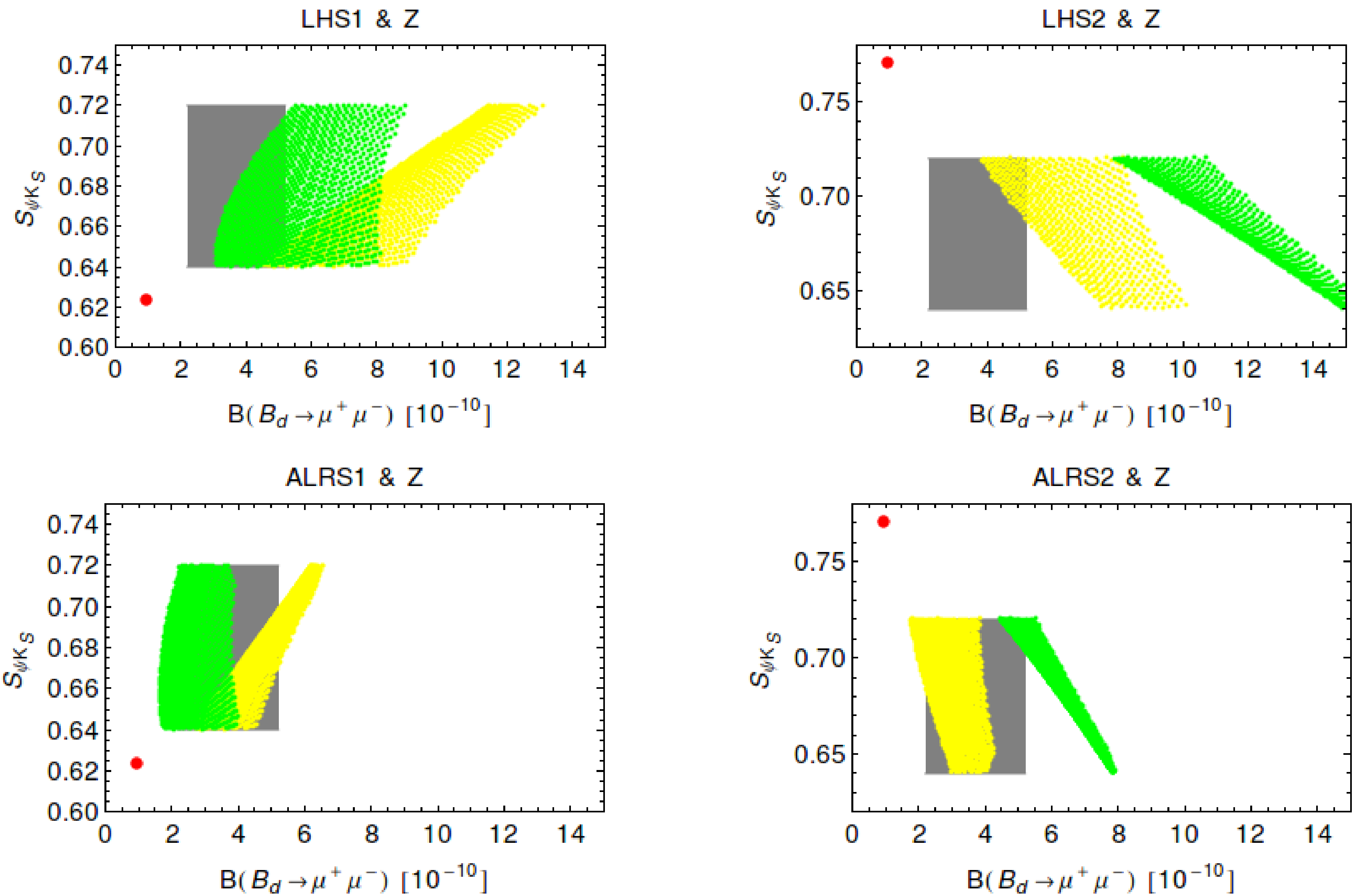


1211.1896

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

NP-effects can still be large !

"Confirmation" by LHCb + CMS



$|V_{ub}| = 3.1 \cdot 10^{-3}$ $|V_{ub}| = 4.0 \cdot 10^{-3}$

Left-handed Z´ and Z FCNC Couplings Facing New $B_{s,d} \to \mu^+\mu^-$ Data

Correlation with $\Delta F=2$

(AJB + Girrbach, 1309.2466)

Both branching ratios can be put to agree with CMS + LHCb for Z and Z´

Z´

Favoured :

$$\frac{\Delta M_s}{(\Delta M_s)_{SM}} \approx 1.00 \pm 0.01 \qquad \frac{\Delta M_d}{(\Delta M_d)_{SM}} \approx 1.04 \pm 0.01$$

$$S_{\psi\varphi} \neq (S_{\psi\varphi})_{SM} \qquad \text{coupling} \rightarrow \frac{\Delta_A^{\mu\bar{\mu}}(Z')}{M_{Z'}} \approx \frac{1.0 - 2.0}{1\text{TeV}}$$

Z

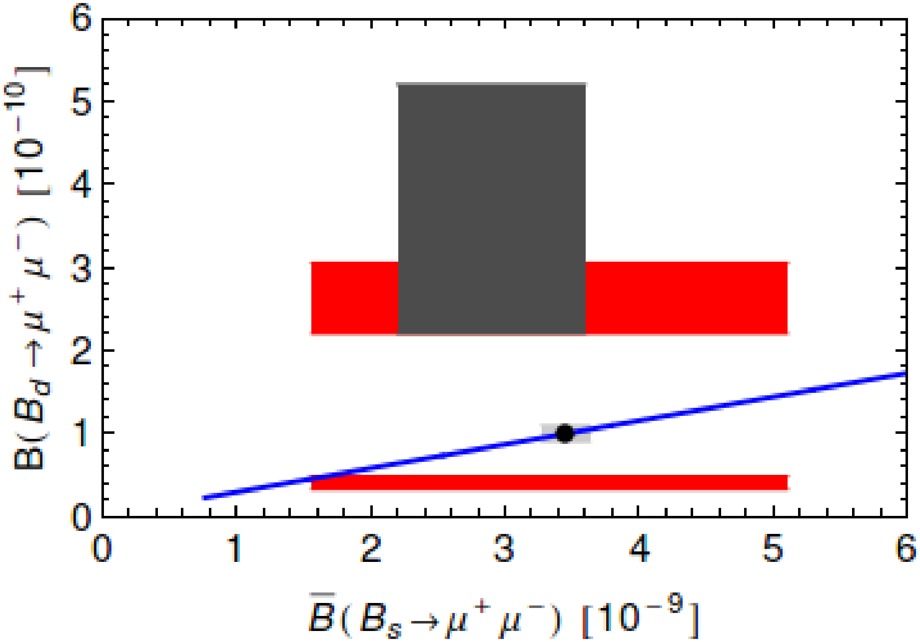
Favoured :

$$\frac{\Delta M_s}{(\Delta M_s)_{SM}} \approx 1.00 \pm 0.01 \qquad \frac{\Delta M_d}{(\Delta M_d)_{SM}} \approx 0.96 \pm 0.01$$

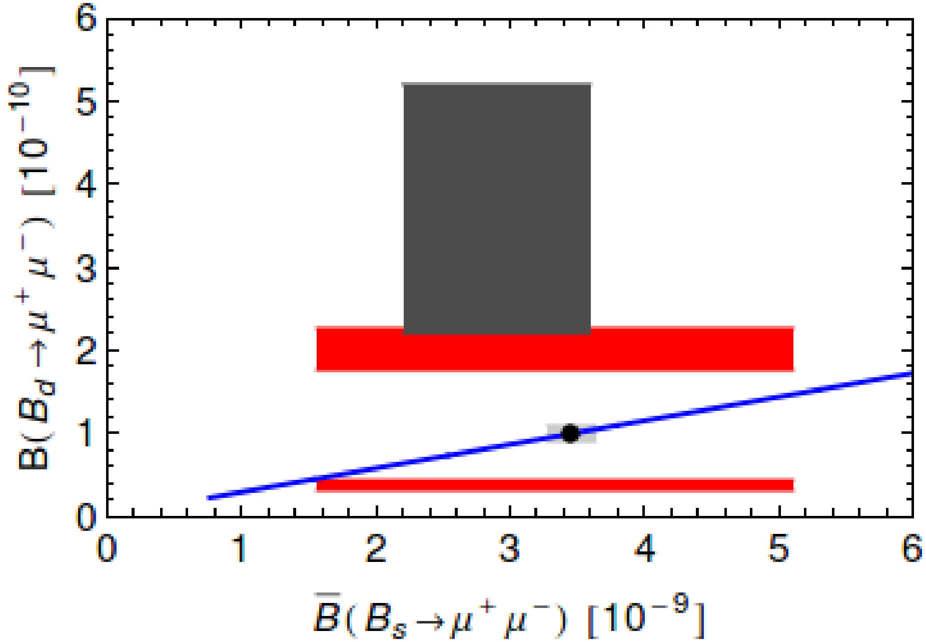
$$S_{\psi\varphi} \approx (S_{\psi\varphi})_{SM} \qquad \text{Note: } \frac{\Delta_A^{\mu\bar{\mu}}(Z)}{M_Z} = \frac{4.0}{1\text{TeV}} \text{ fixed}$$

Violation of CMFV (Z′)

High V_{ub}



Low V_{ub}



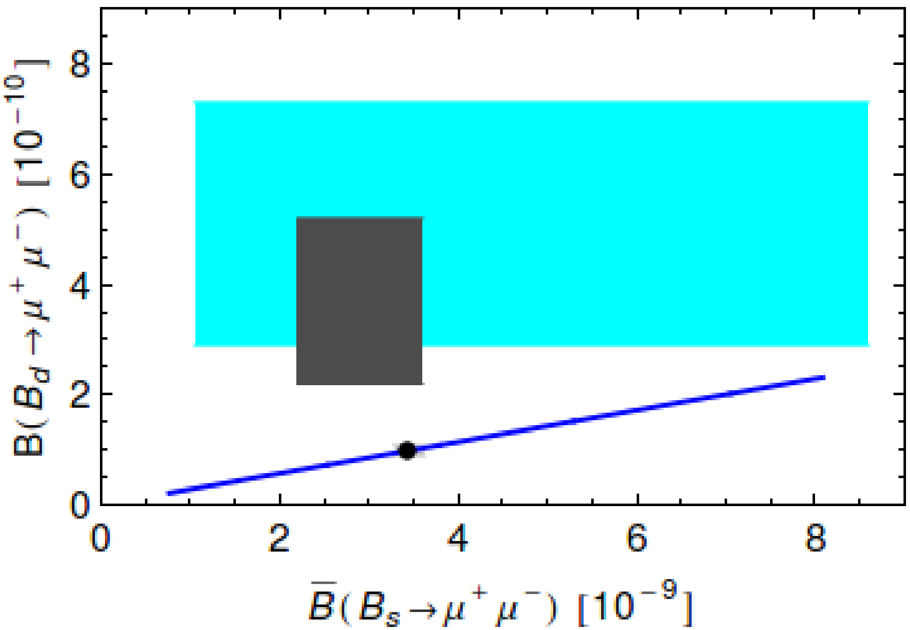
CMS + LHCb

SM

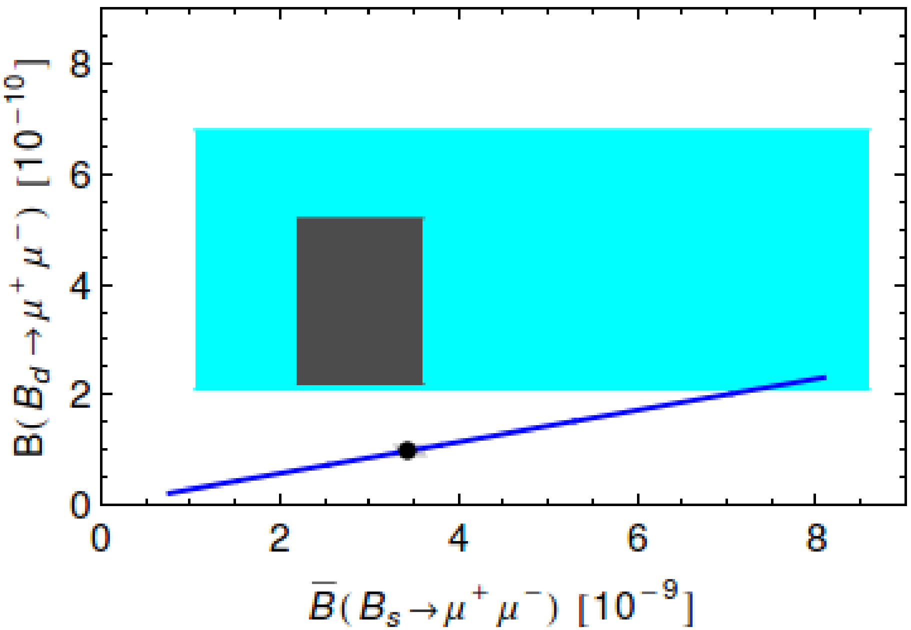
 BurasScalar2013

Violation of CMFV (Z)

High V_{ub}



Low V_{ub}



■ **CMS + LHCb**

● **SM**

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

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

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

Extensive Analyses:

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

DMV
AS

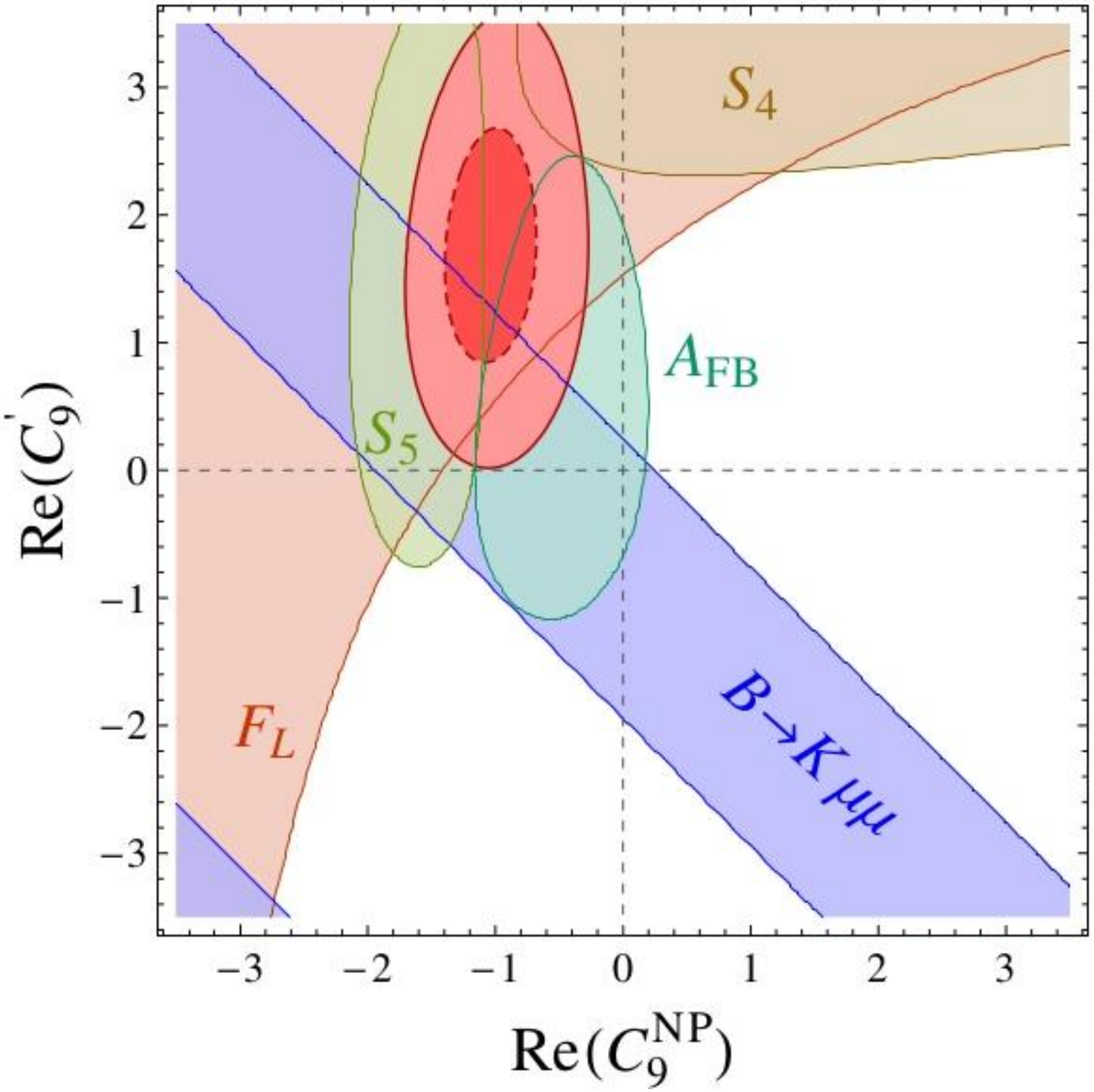
$$C_{7\gamma}^{NP} < 0, \quad C_9^{NP} < 0$$

or

AS

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

right-handed



Altmannshofer
Straub
(1308.1501)

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

(AJB + Girrbach, 1309.2466)

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

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

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

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

See also Altmannshofer Straub (1308.1501)

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

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

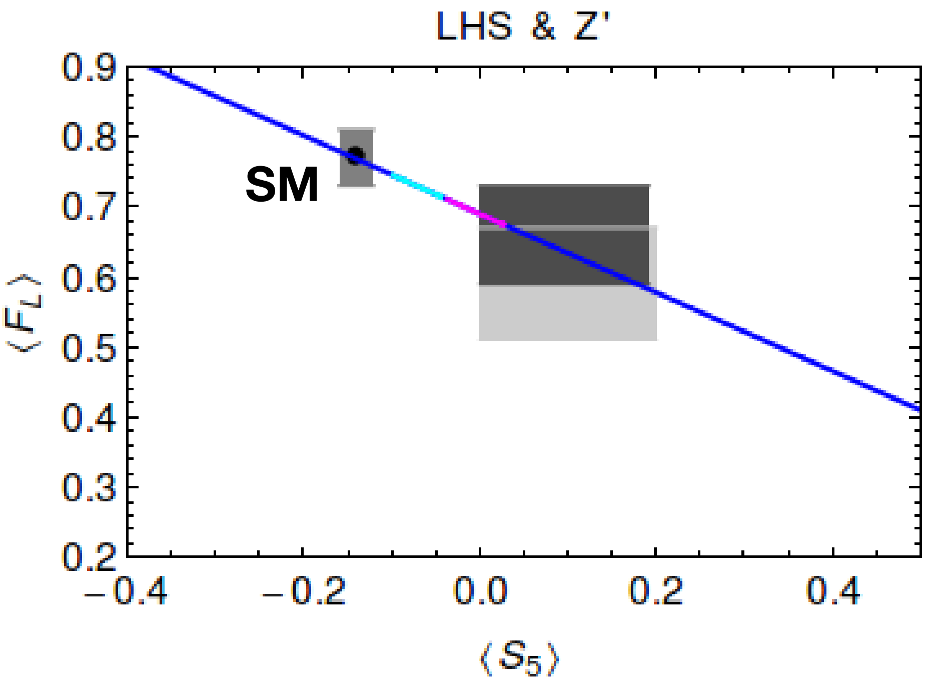
$C_9^{NP} \neq 0, \quad C_9' = 0$ (LHS)

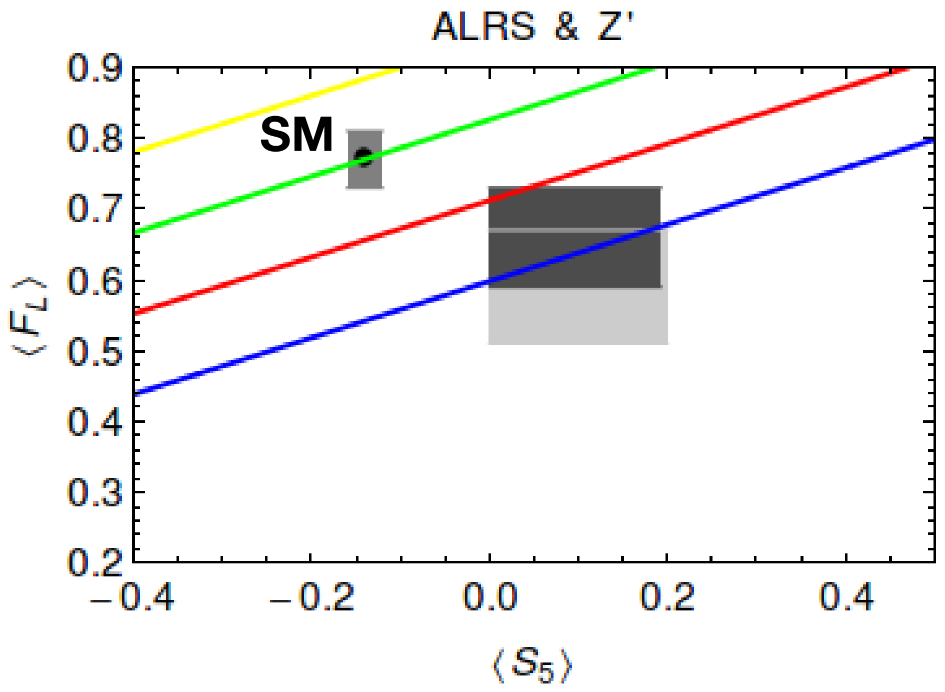
$C_9^{NP} \neq 0, \quad C_9' \approx -C_9^{NP}$ (ALRS)

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

New Correlations

(AJB + Girrbach, 1309.2466)





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

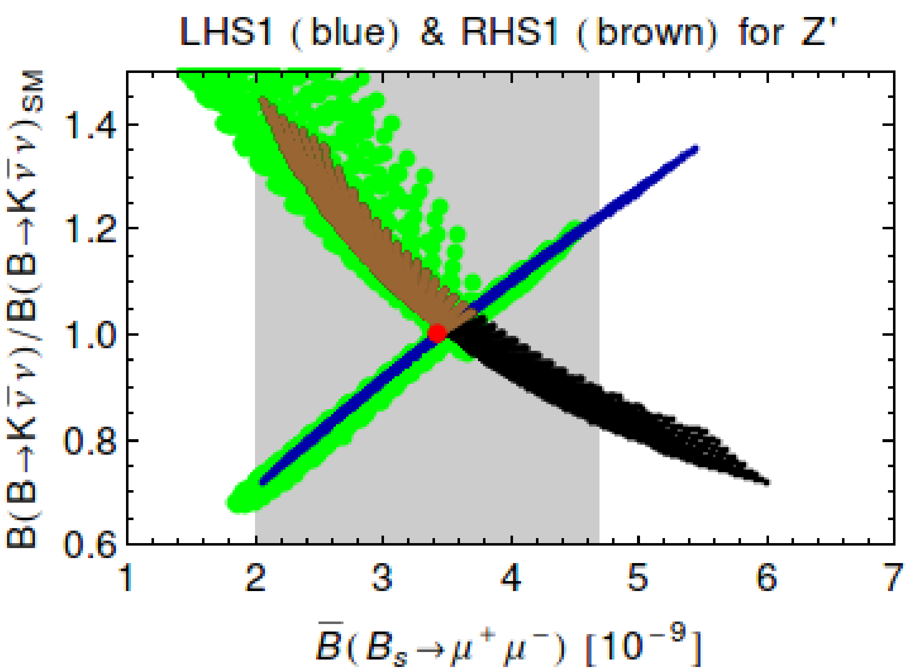
$C_9^{NP} = -(1.6 \pm 0.3)$

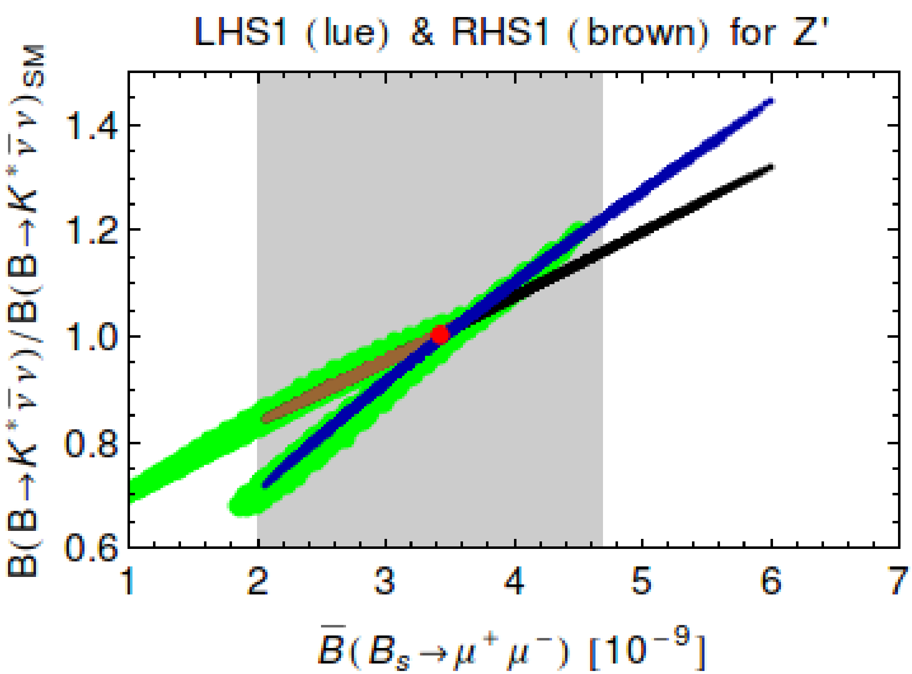
$C_9^{NP} = -1.0$

$C_9^{NP} = -2.0$

$C_9^{NP} = 0$

Distinguishing Left-Handed Currents from Right-Handed Currents

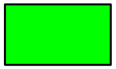




AJB, De Fazio, Girrbach
1211.1896

Altmannshofer et al.
0902.0160

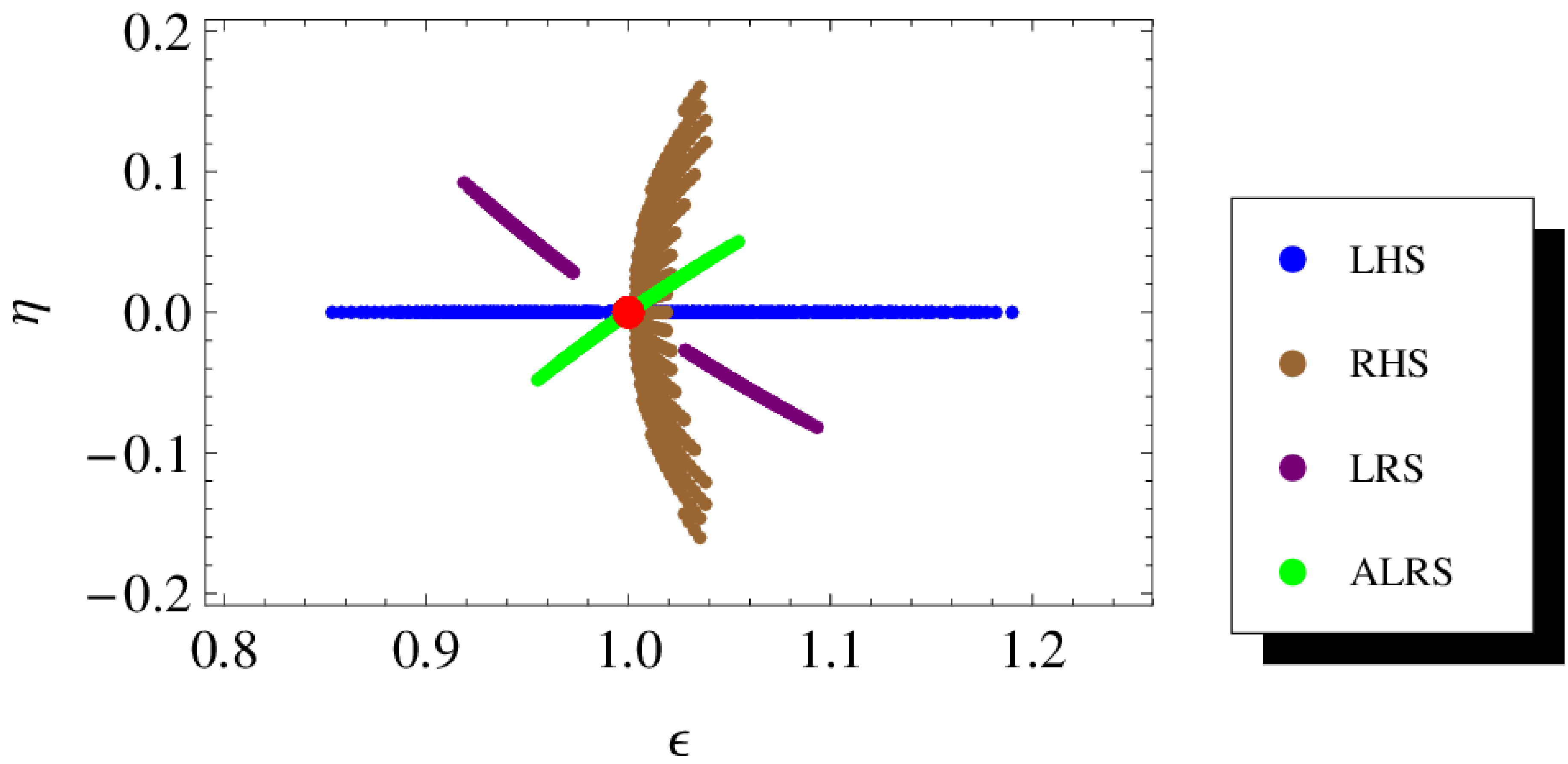
: forbidden by $b \to sll$



: allowed by $b \to sll$

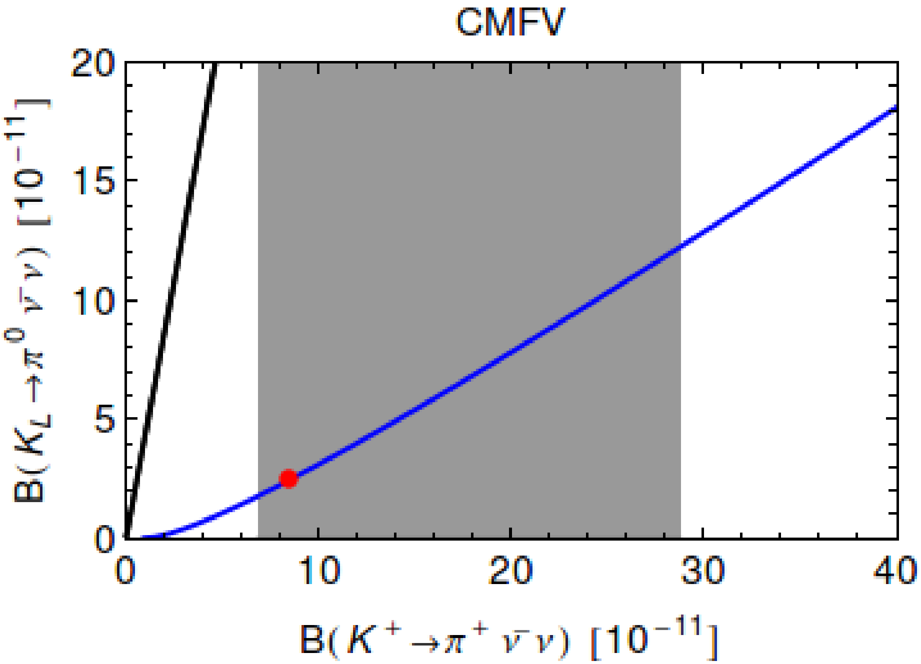
(ε, η) : Parameters for $b \to s\nu\bar{\nu}$ Transitions

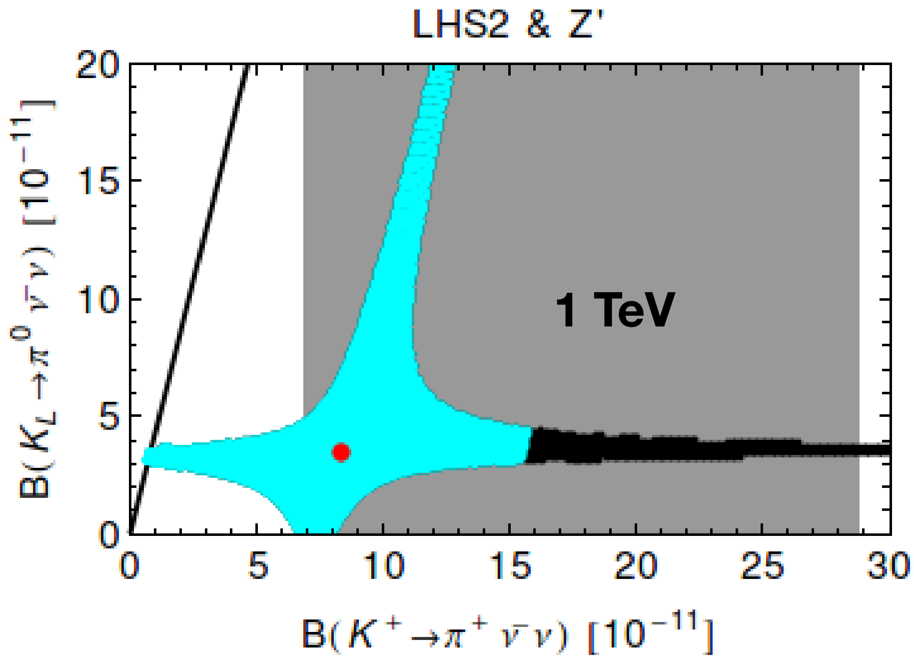
1211.1896



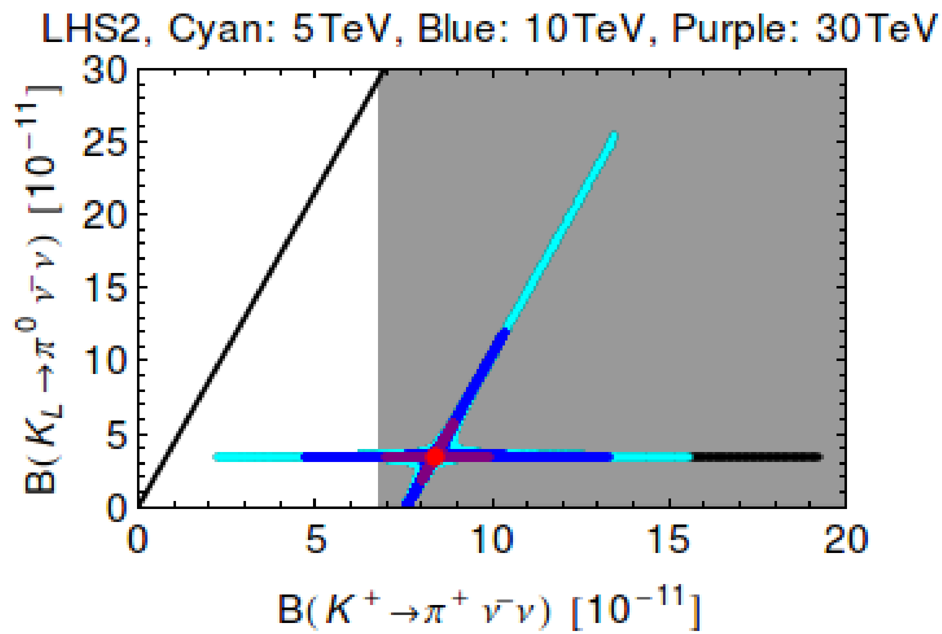
Altmannshofer, AJB, Straub, Wick
0902.0160

1211.1896

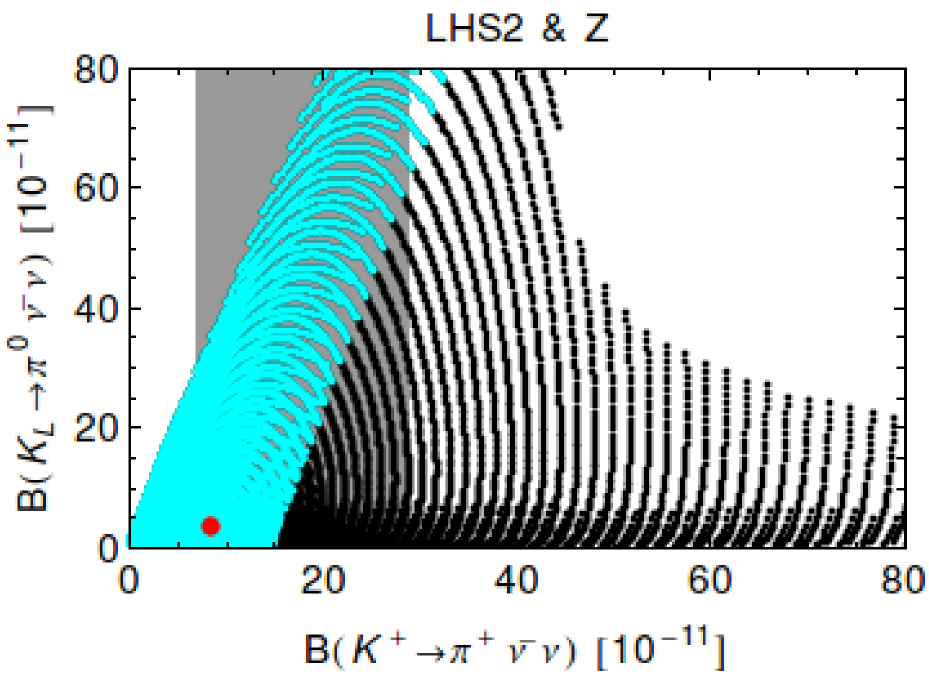


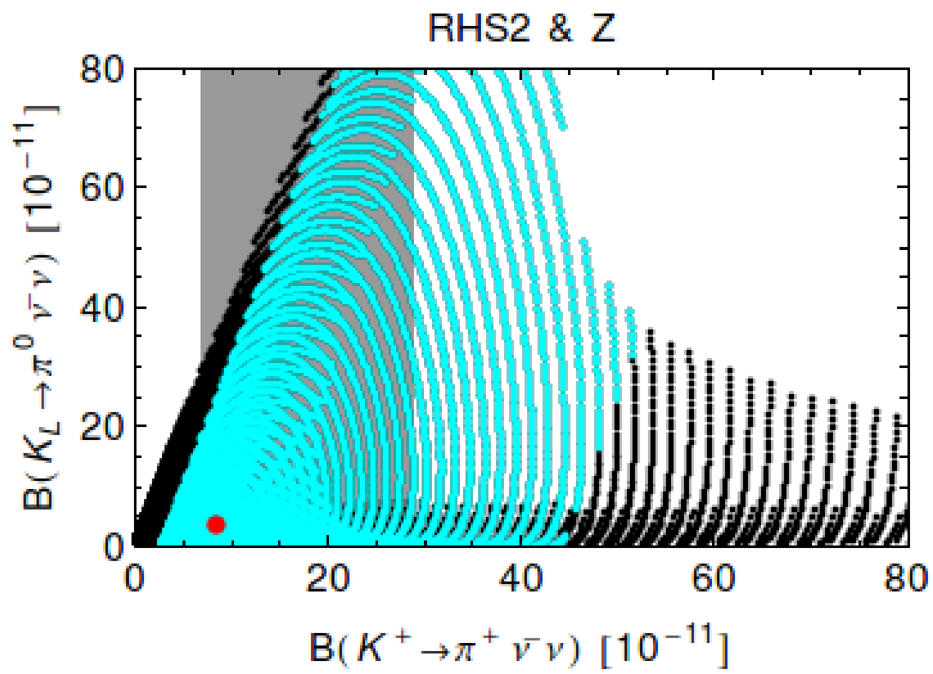


Sensitivity to $M_{Z'}$ beyond the LHC



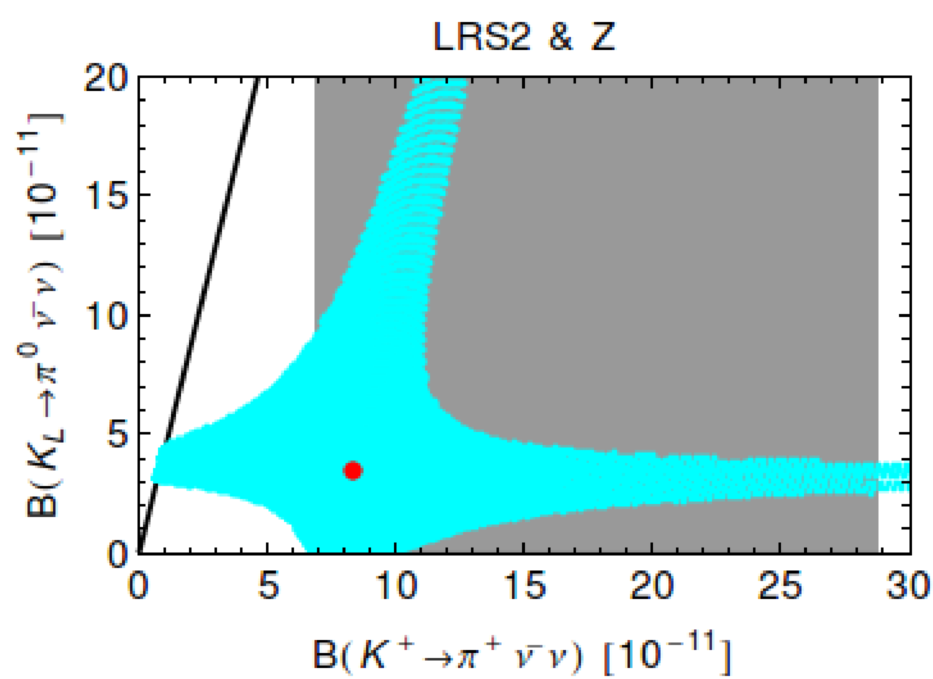
■ : **forbidden by $K_L \to \mu^+\mu^-$**





■ : **forbidden by**

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



LHS, RHS
LRHS

DNA - Charts

1306.3755

AJB + Girrbach

- suppression relative to SM

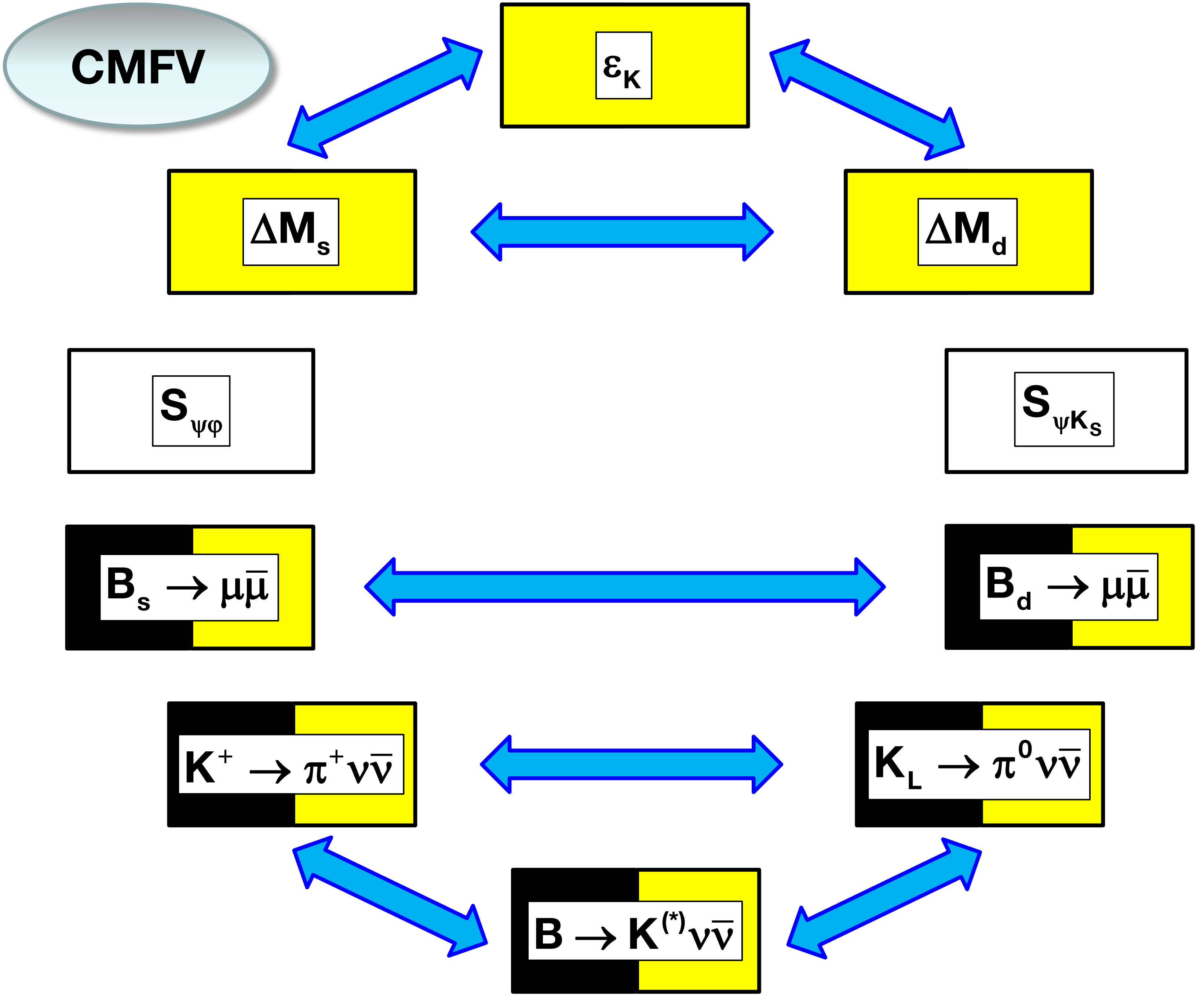
- enhancement relative to SM

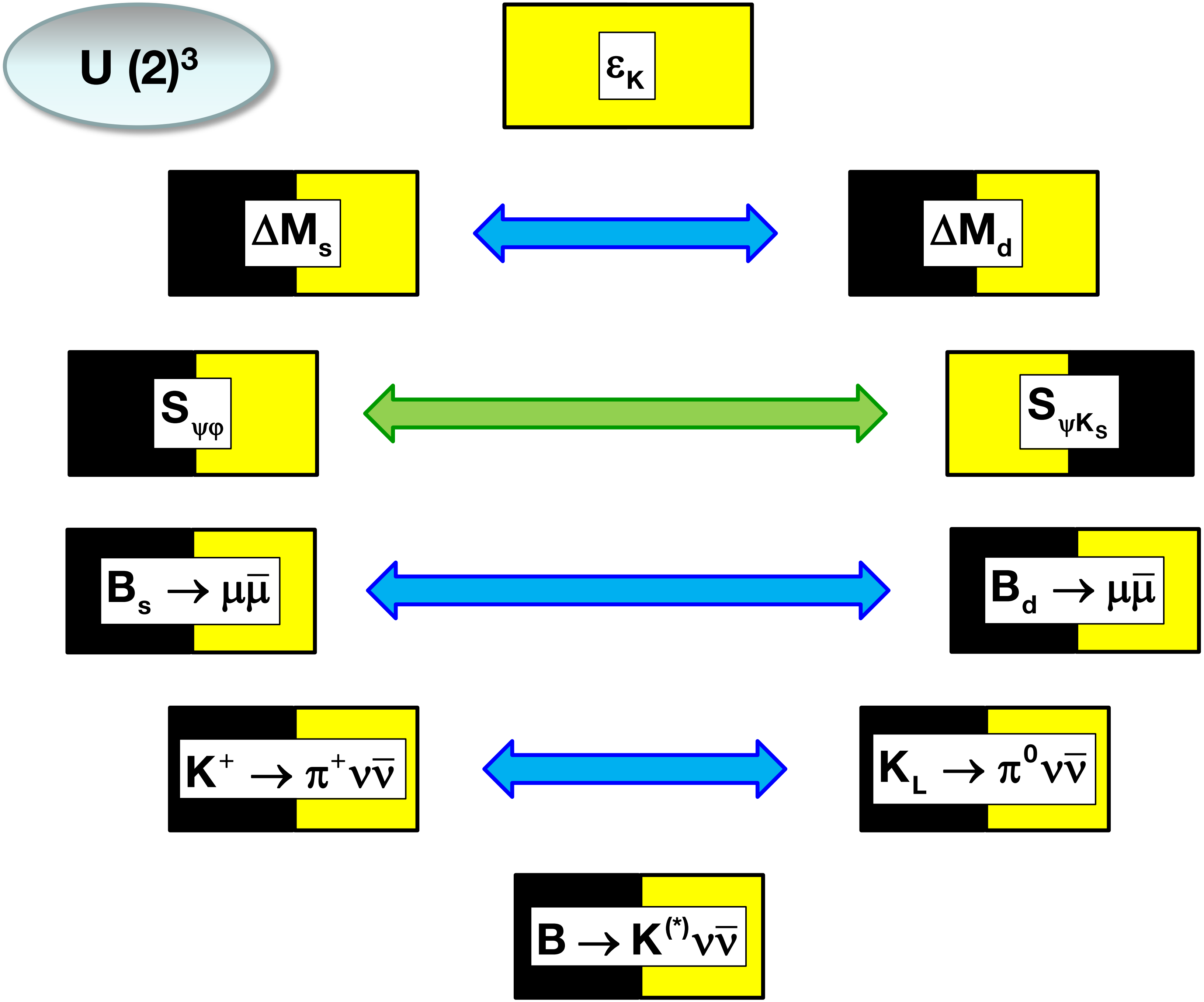
correlation

anti-correlation

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

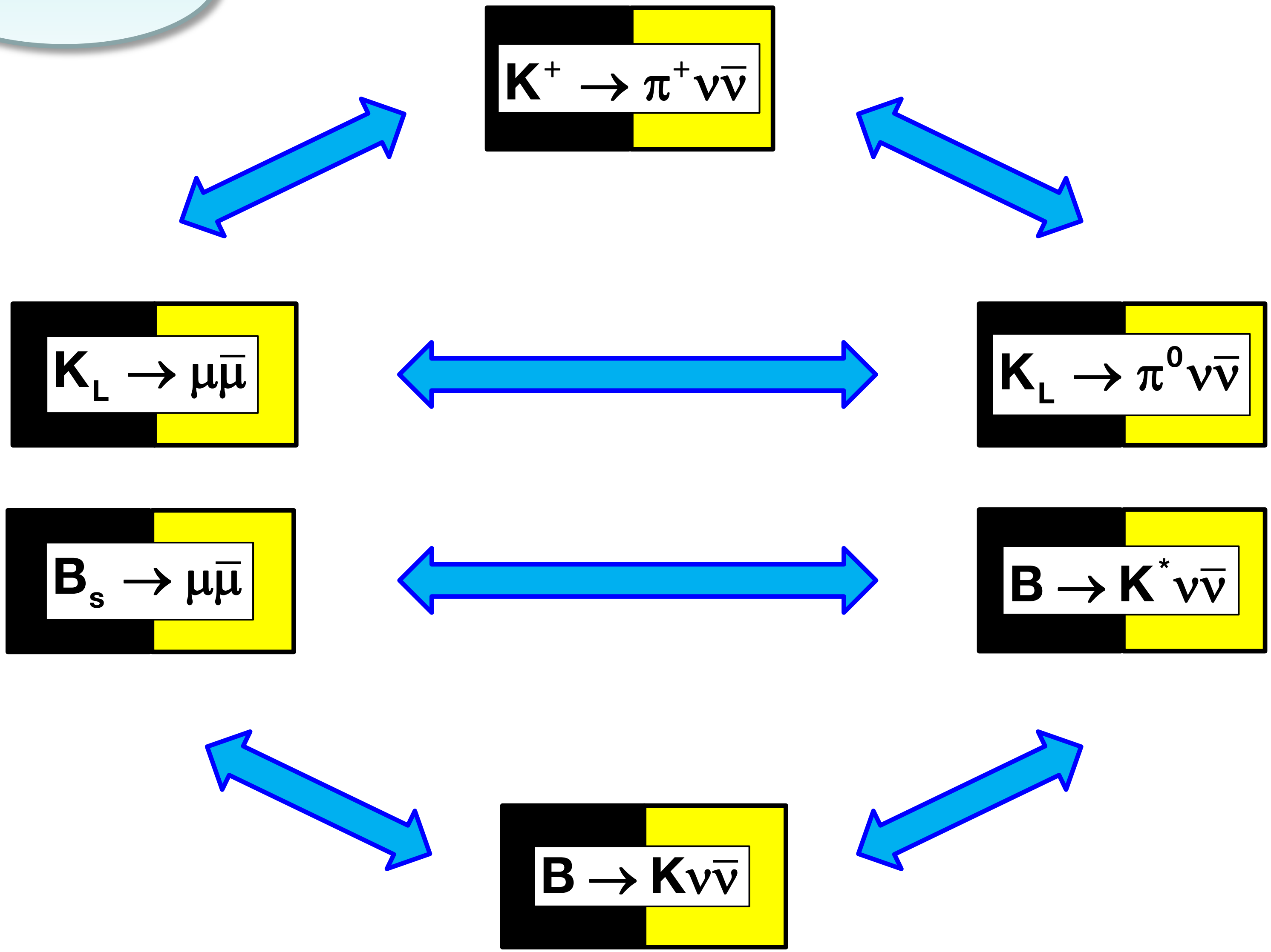
Flavour codes: AJB 1012.1447


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



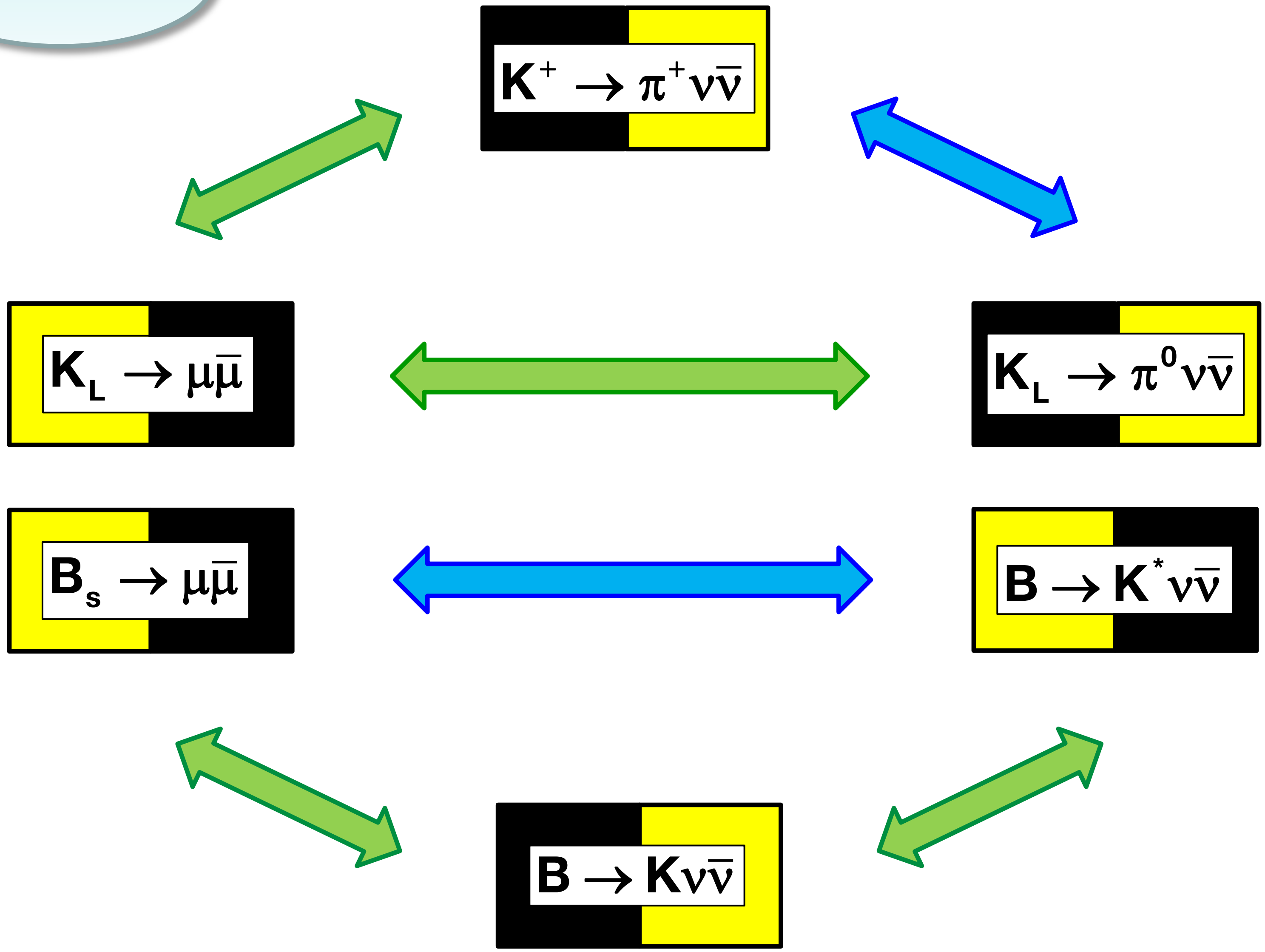
$U(2)^3$
ε_K
ΔM_s
ΔM_d
$S_{\psi\phi}$
$S_{\psi K_S}$
$B_s \to \mu\bar{\mu}$
$B_d \to \mu\bar{\mu}$
$K^+ \to \pi^+ \nu\bar{\nu}$
$K_L \to \pi^0 \nu\bar{\nu}$
$B \to K^{(*)} \nu\bar{\nu}$

Z′/Z LHS



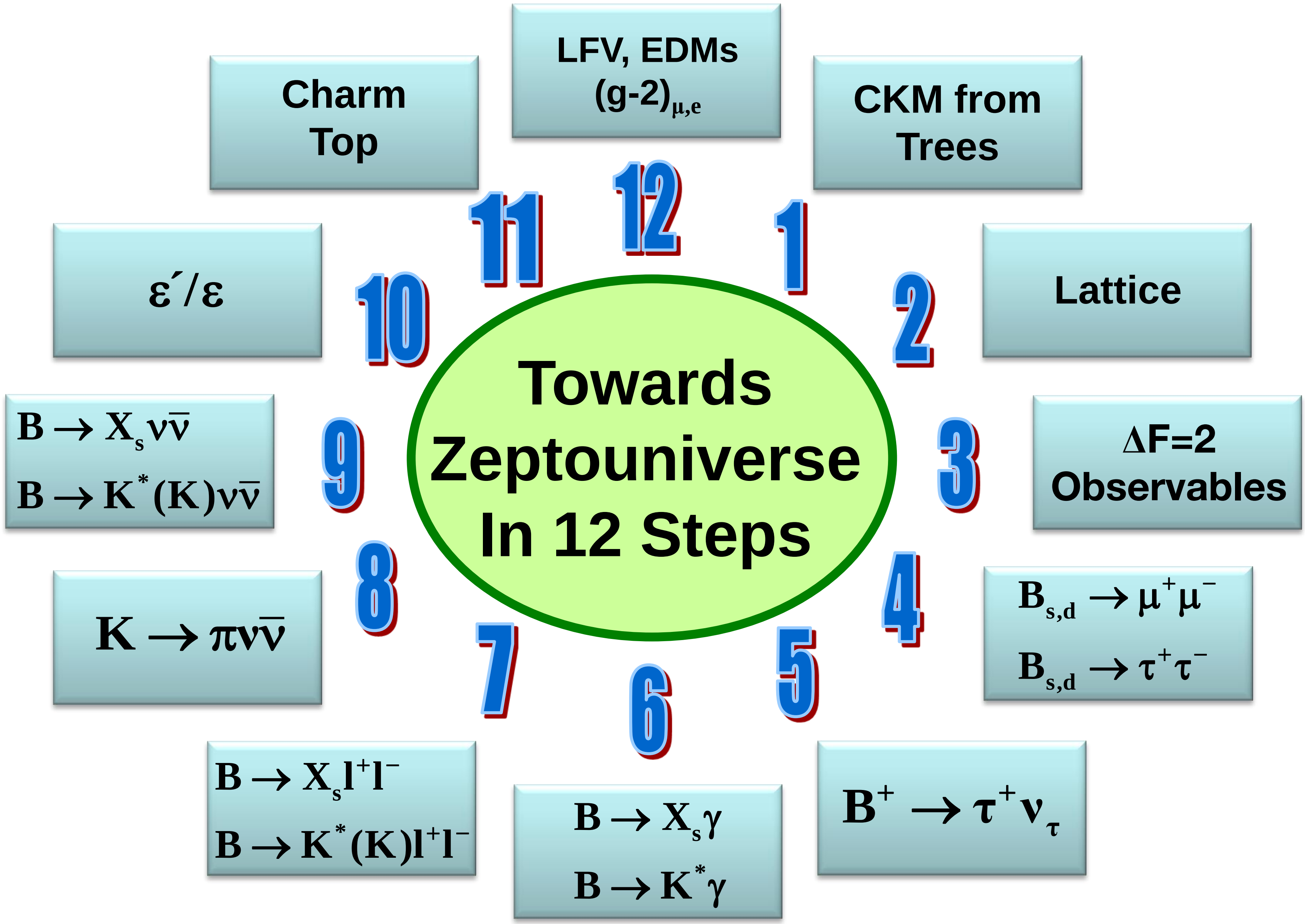
$K^+ \to \pi^+ \nu\bar{\nu}$
$K_L \to \mu\bar{\mu}$
$K_L \to \pi^0 \nu\bar{\nu}$
$B_s \to \mu\bar{\mu}$
$B \to K^* \nu\bar{\nu}$
$B \to K \nu\bar{\nu}$

Z′/Z RHS

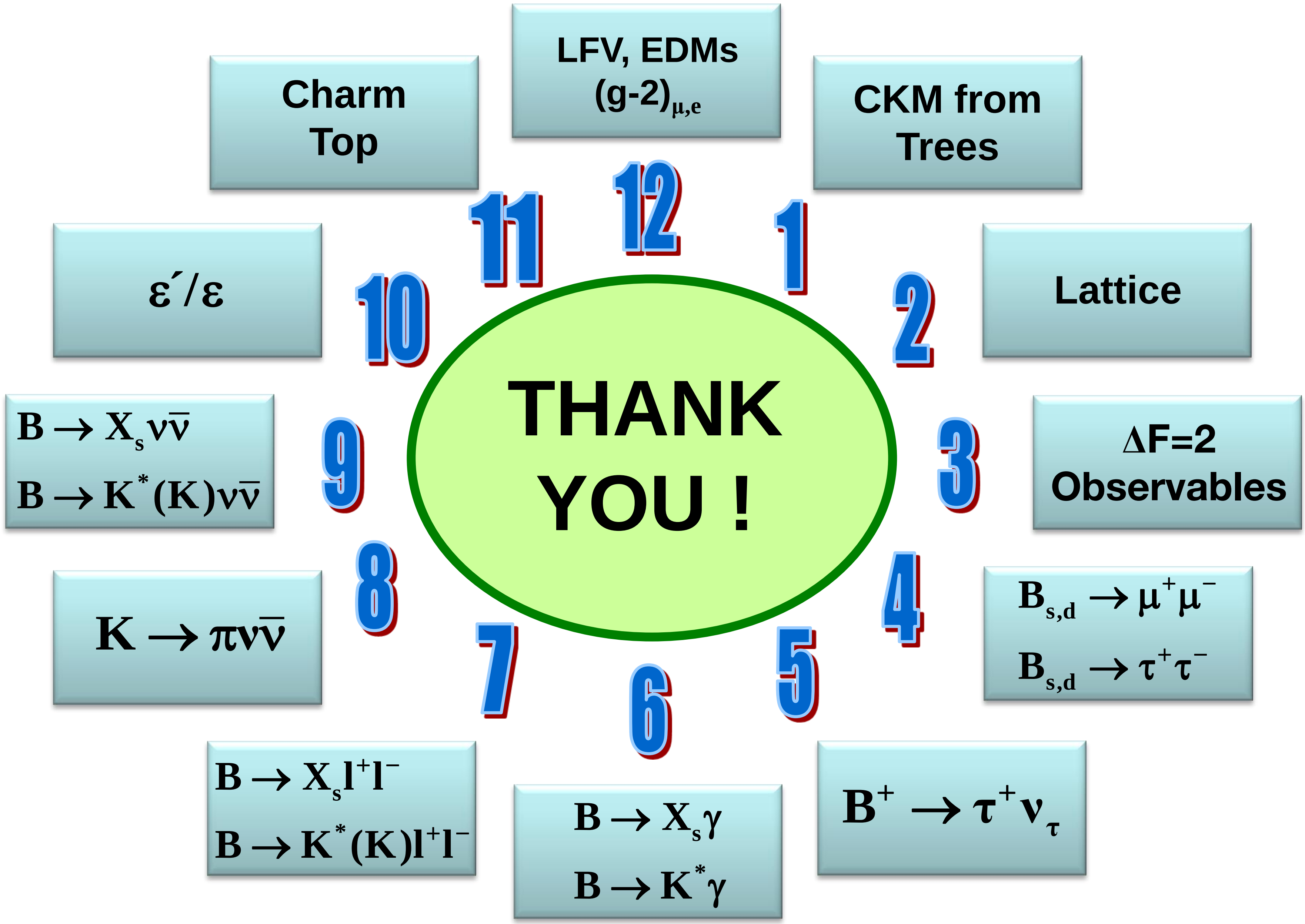

$K^+ \to \pi^+ \nu\bar{\nu}$
$K_L \to \mu\bar{\mu}$
$K_L \to \pi^0 \nu\bar{\nu}$
$B_s \to \mu\bar{\mu}$
$B \to K^* \nu\bar{\nu}$
$B \to K \nu\bar{\nu}$

Finale: Vivace !

Exciting Times are just ahead of us !!!



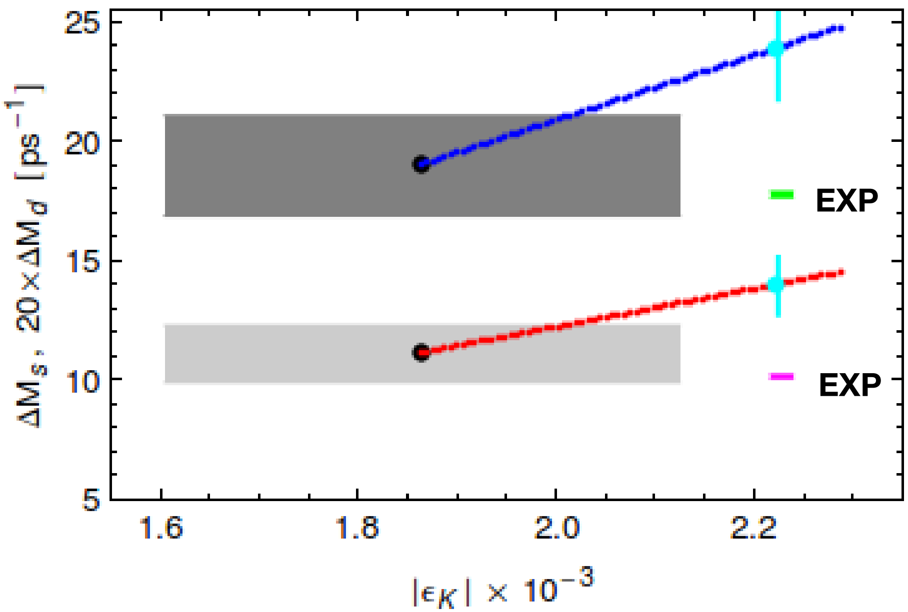
Towards Zeptouniverse In 12 Steps
12
LFV, EDMs $(g\text{-}2)_{\mu,e}$
1
CKM from Trees
2
Lattice
3
$\Delta F=2$ Observables
4
$B_{s,d} \to \mu^+\mu^-$
$B_{s,d} \to \tau^+\tau^-$
5
$B^+ \to \tau^+\nu_\tau$
6
$B \to X_s\gamma$
$B \to K^*\gamma$
7
$B \to X_s l^+l^-$
$B \to K^*(K) l^+l^-$
8
$K \to \pi\nu\bar{\nu}$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

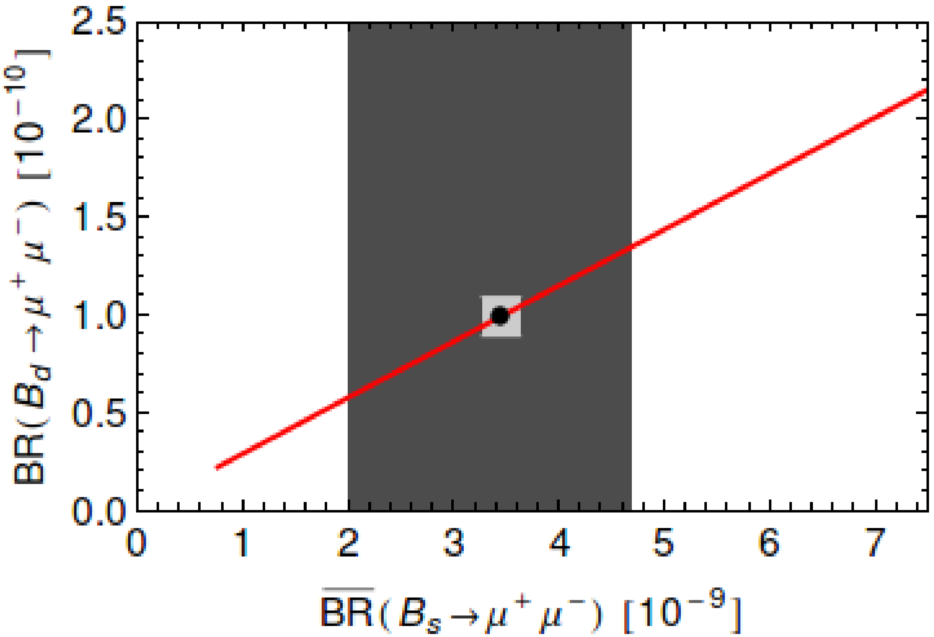

LFV, EDMs
$(g\text{-}2)_{\mu,e}$
CKM from Trees
Lattice
$\Delta F=2$ Observables
$B_{s,d} \to \mu^+\mu^-$
$B_{s,d} \to \tau^+\tau^-$
$B^+ \to \tau^+\nu_\tau$
$B \to X_s\gamma$
$B \to K^*\gamma$
$B \to X_s l^+ l^-$
$B \to K^*(K) l^+ l^-$
$K \to \pi\nu\bar{\nu}$
$B \to X_s\nu\bar{\nu}$
$B \to K^*(K)\nu\bar{\nu}$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

Backup

Constrained Minimal Flavour Violation

AJB + J. Girrbach (2012)





Tension within CMFV

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

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

(LHCb)

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)

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

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

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

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

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

Two Scenarios for $|V_{ub}|$

(Taking into account $\Delta M_s, \Delta M_d \leftarrow B^0_{d,s} - \bar{B}^0_{d,s}$ 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 $B^0_d - \bar{B}^0_d$ 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 $|V_{ub}|$

Important Messages on K Physics

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

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

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

2. Even if no significant New Physics would be seen in B-decays large effects in $K \to \pi\nu\bar{\nu}$ 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 $S_{\psi\varphi}$

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

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

- $Br(K^+ \to \pi^+\nu\bar{\nu})$; $Br(K_L \to \pi^0\nu\bar{\nu})$

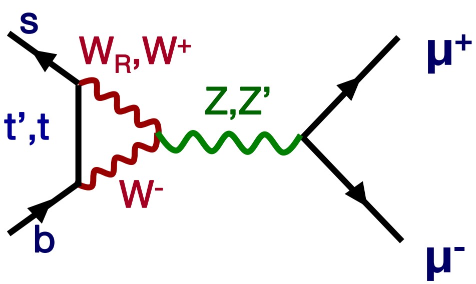
- **Lepton Flavour Violation**

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

- ε'/ε provided QCD Penguin hadronic matrix under control

Standard Candles of Flavour Physics

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



+

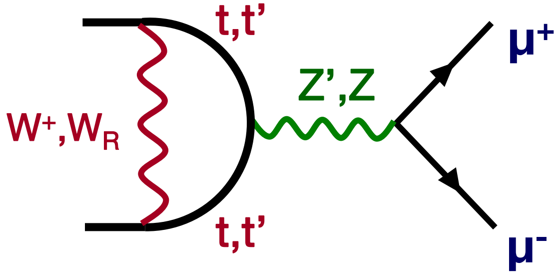
Other Z-Penguins and Boxes

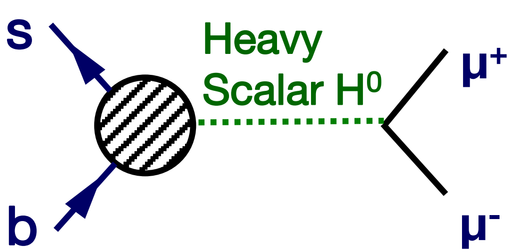
SM: (3.2 ± 0.2) · 10⁻⁹

Model Independent Limit (95% C.L.)

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

Altmannshofer, Paradisi, Straub 1111.1257





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

in SUSY

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

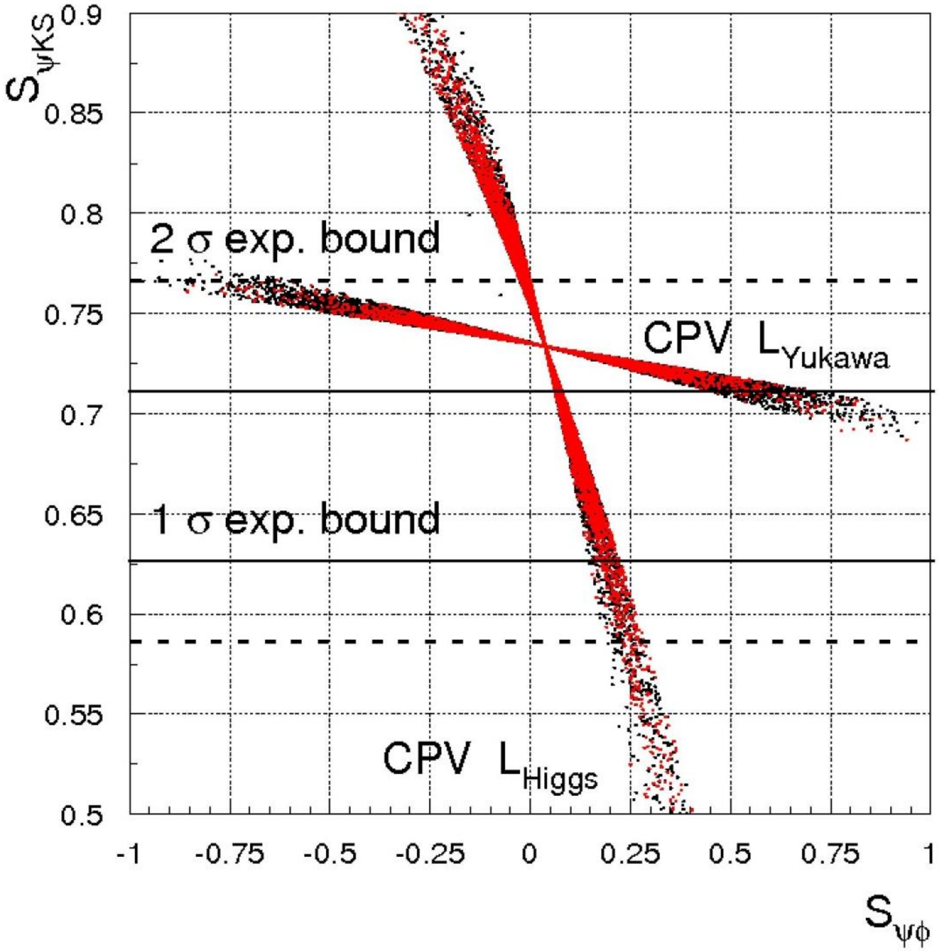
In the case of

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

distinction between Z,Z' and H^0 possible

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)

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

(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

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

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

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

$Br(B_d \to \mu^+\mu^-)$ vs $Br(B_s \to \mu^+\mu^-)$

ABGPS

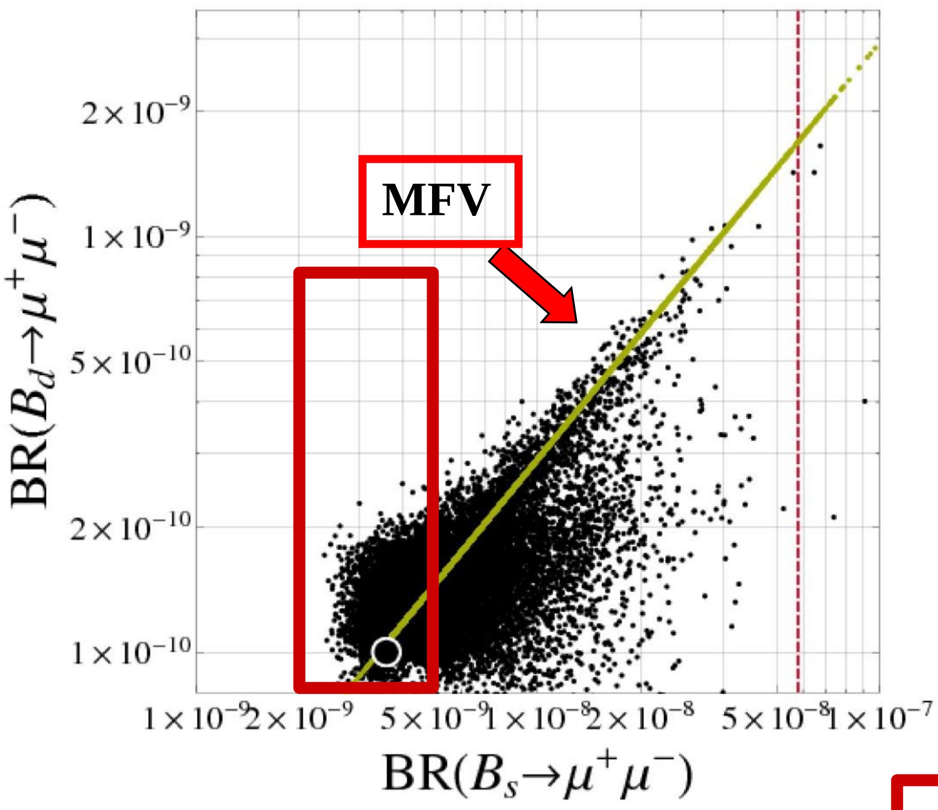
(0909.1333)

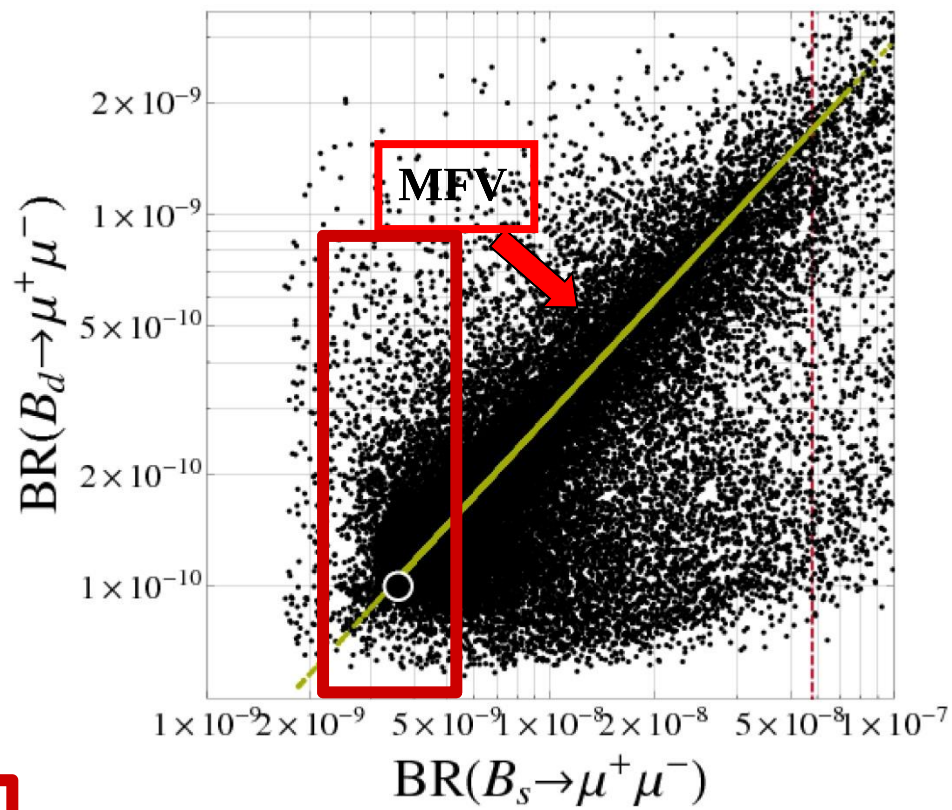
SUSY (Flavour)

Altmannshofer, AJB, Gori, Paradisi, Straub

● = SM

MFV AJB; Hurth, Isidori, Kamenik, Mescia





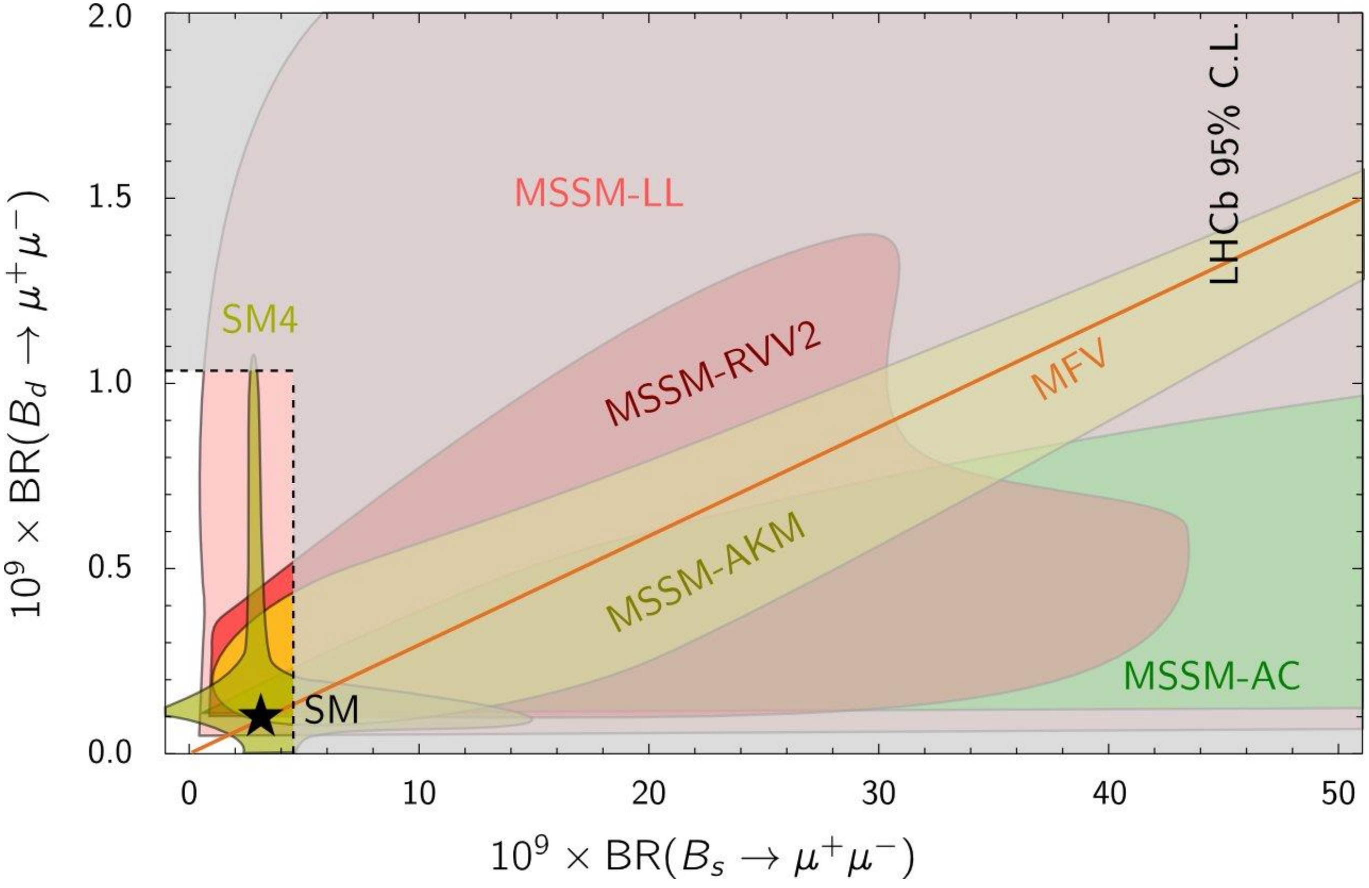
RVV2 **(RH currents)**

LHCb

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:

$(\pm 5\%)$

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

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

$(\pm 2\sigma)$

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

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

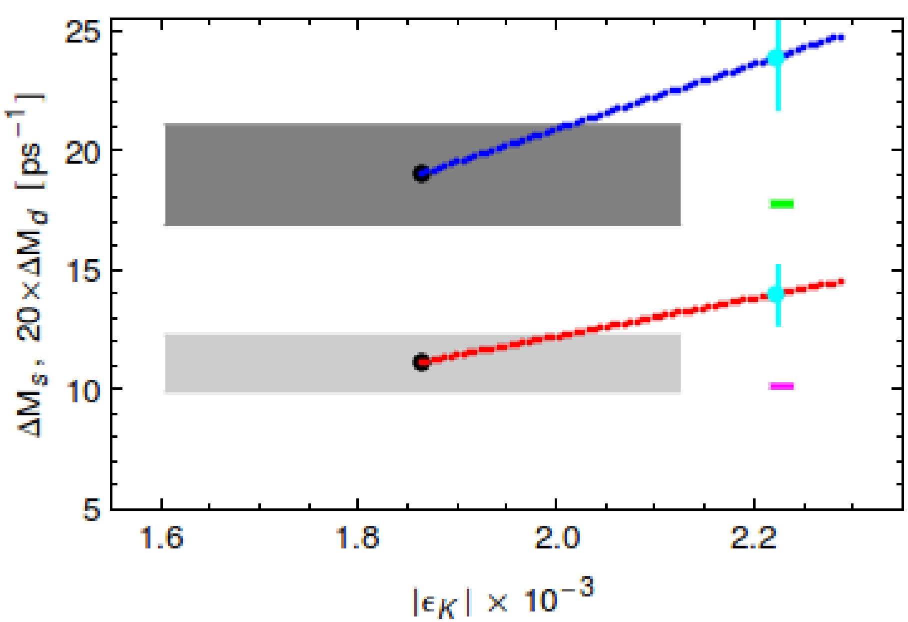
$$0.75 \le \frac{\Delta M_K}{(\Delta M_K)_{SM}} \le 1.25$$

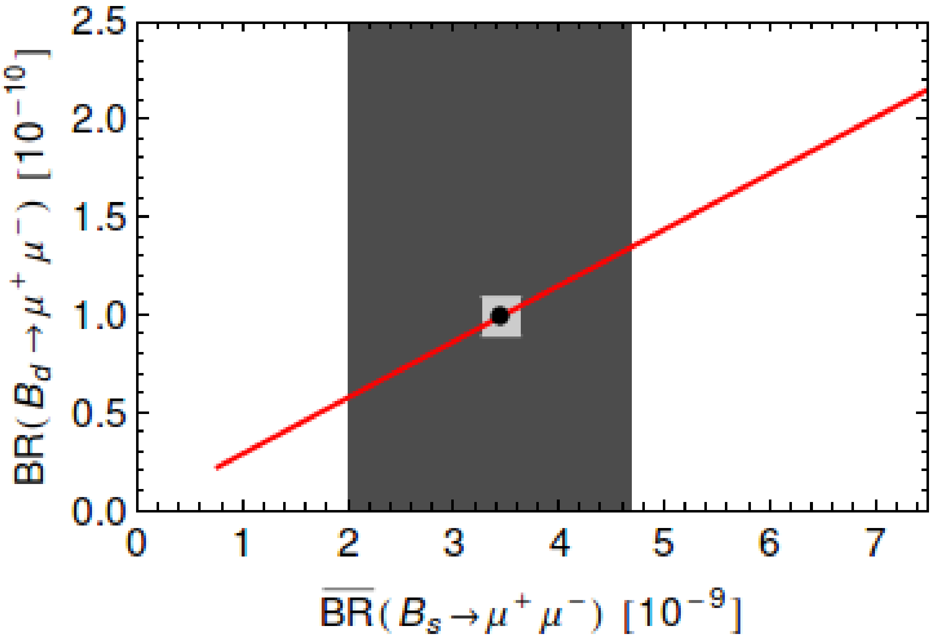
$$2.0 \cdot 10^{-3} \le \varepsilon_K \le 2.5 \cdot 10^{-3}$$

Constrained Minimal Flavour Violation

0007085
0310208
0604057

AJB + J. Girrbach (2012)





Tension within CMFV EXP

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

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

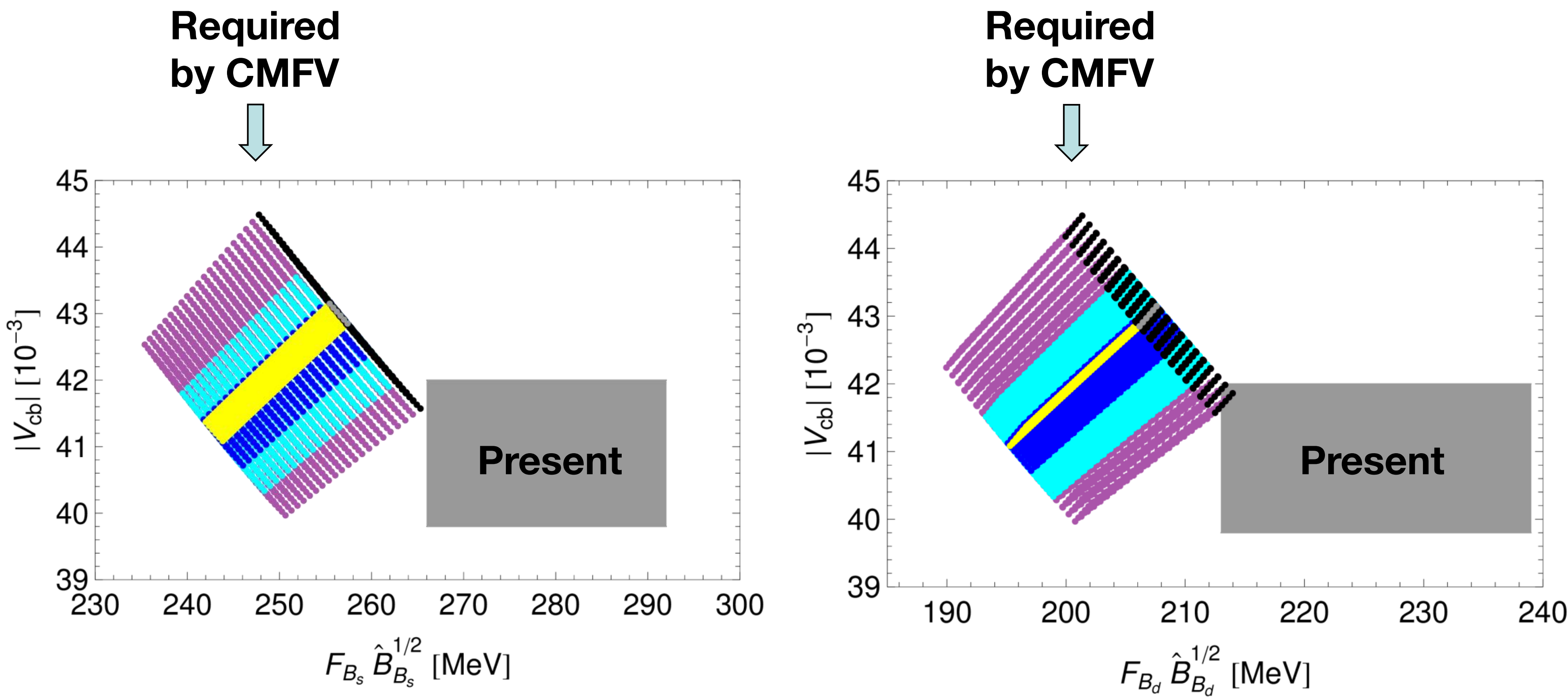
Stringent Tests of CMFV through $\Delta F=2$ Processes

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 ?



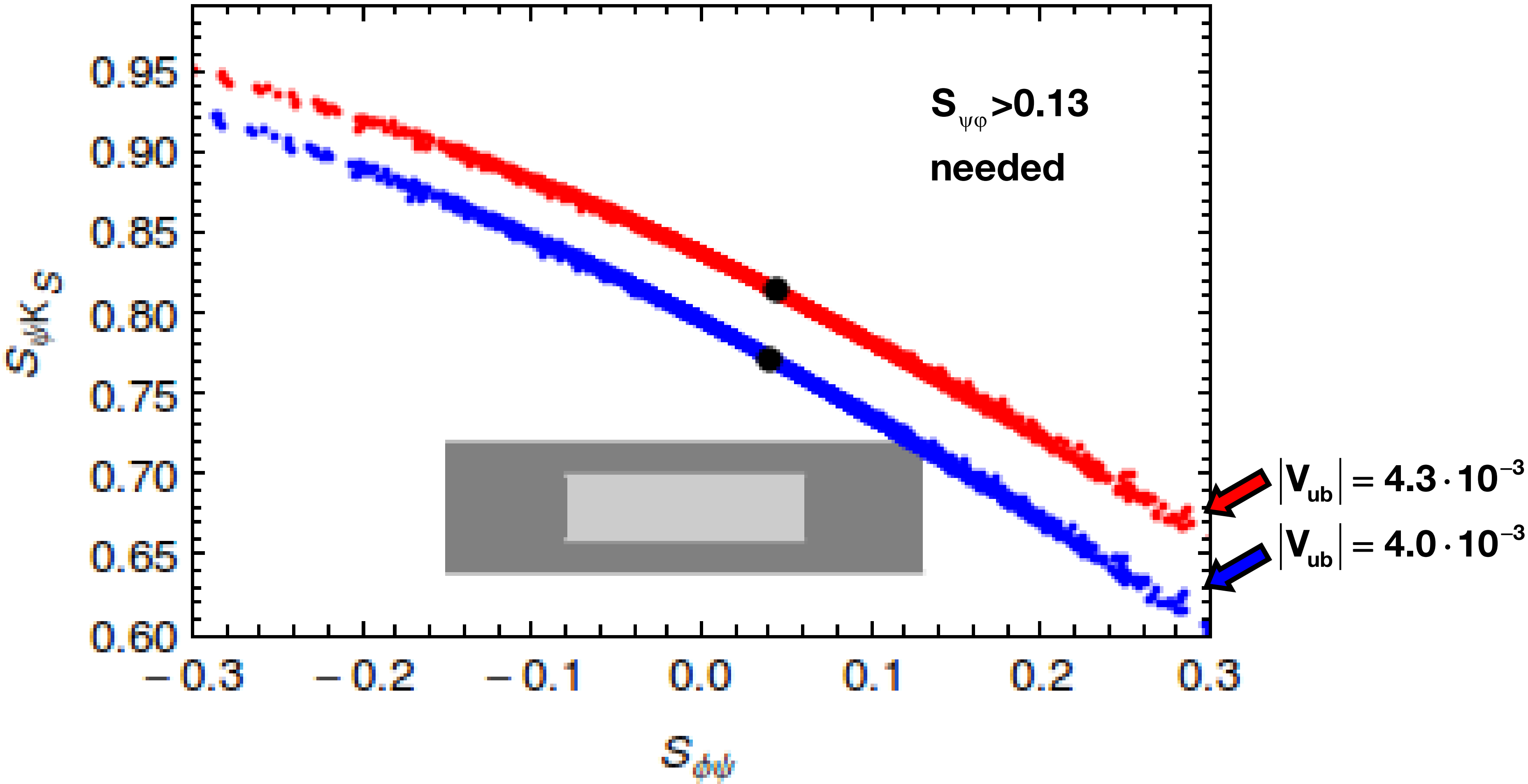
: SM

: $\eta_{cc} = 1.87 \pm 76$ (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

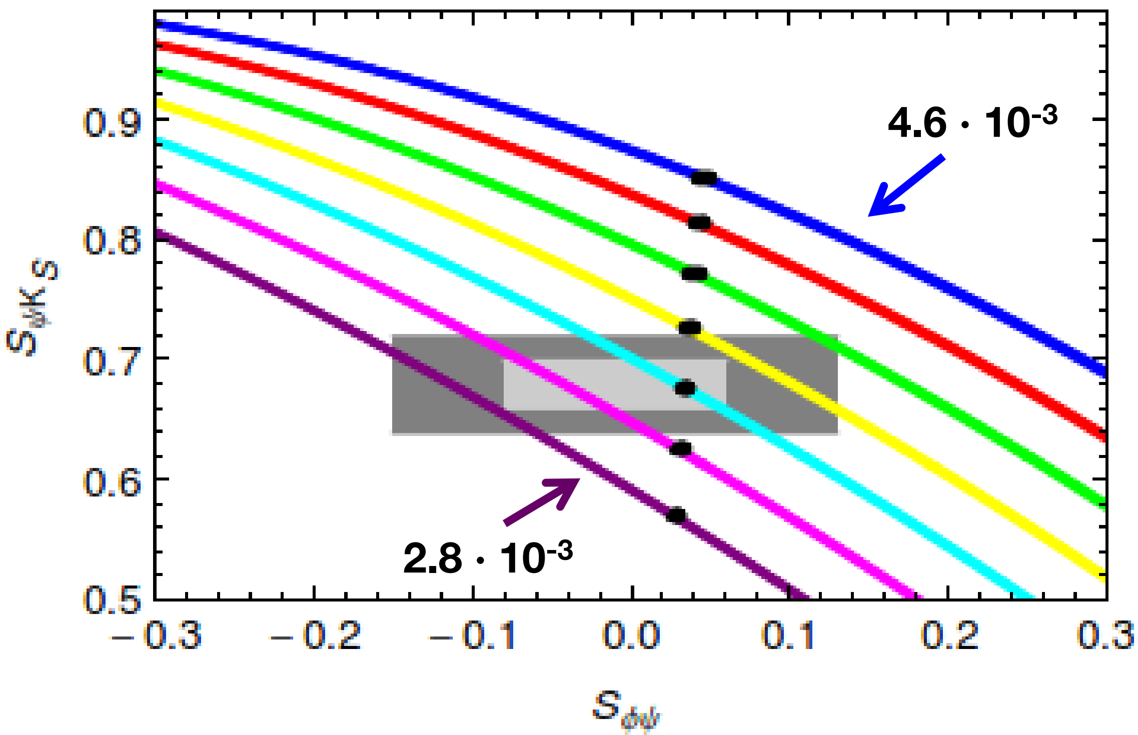
will rule it out.

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



$\gamma = 68°$

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

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

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

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

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