BSM Models Facing LHCb Data

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(Technical University Munich, TUM-IAS)

Planck 2012
Warsaw

Overture

An Excursion towards the Very Short Distance Scales:

1676 - 2020

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

Prime Goals in Flavour Physics

1. **Search for New Physics** ★

2. **Construction of the Theory of Flavour**

Main Targets in Quark Flavour Physics in the Last Six Years

A $B_s^0 - \bar{B}_s^0$ mixing induced CP asymmetry $S_{\psi\varphi}$

SM: $S_{\psi\varphi}^{SM} = 0.035 \pm 0.002$

$S_{\psi\varphi} \approx 0\ (1\ )$ (SUSY, RS, ...)

B $B_s \to \mu^+\mu^-$

SM: $Br^{SM}\left(B_s \to \mu^+\mu^-\right) = \left(3.1 \pm 0.2\right) \cdot 10^{-9}$

$Br\left(B_s \to \mu^+\mu^-\right) \simeq 0\left(10^{-8} - 10^{-7}\right)$ (SUSY, 2HDM, ...)

A

March 2012 LHCb News

$$\text{LHCb} : S_{\psi\varphi} = 0.002 \pm 0.087$$

$$\text{SM} : S^{SM}_{\psi\varphi} = 0.035 \pm 0.002$$

★

2σ Range : $-0.18 \lesssim S_{\psi\varphi} \leq 0.18$ $S_{\psi K_s} = 0.68 \pm 0.02$

CPV : $B_s^0 - \bar{B}_s^0$ Mixing   CPV : $B_d^0 - \bar{B}_d^0$ Mixing

Message from Nature : **$B_s^0 - \bar{B}_s^0$ Mixing induced CP-Violation much smaller than in $B_d^0 - \bar{B}_d^0$ Mixing as predicted by CKM Matrix**

B

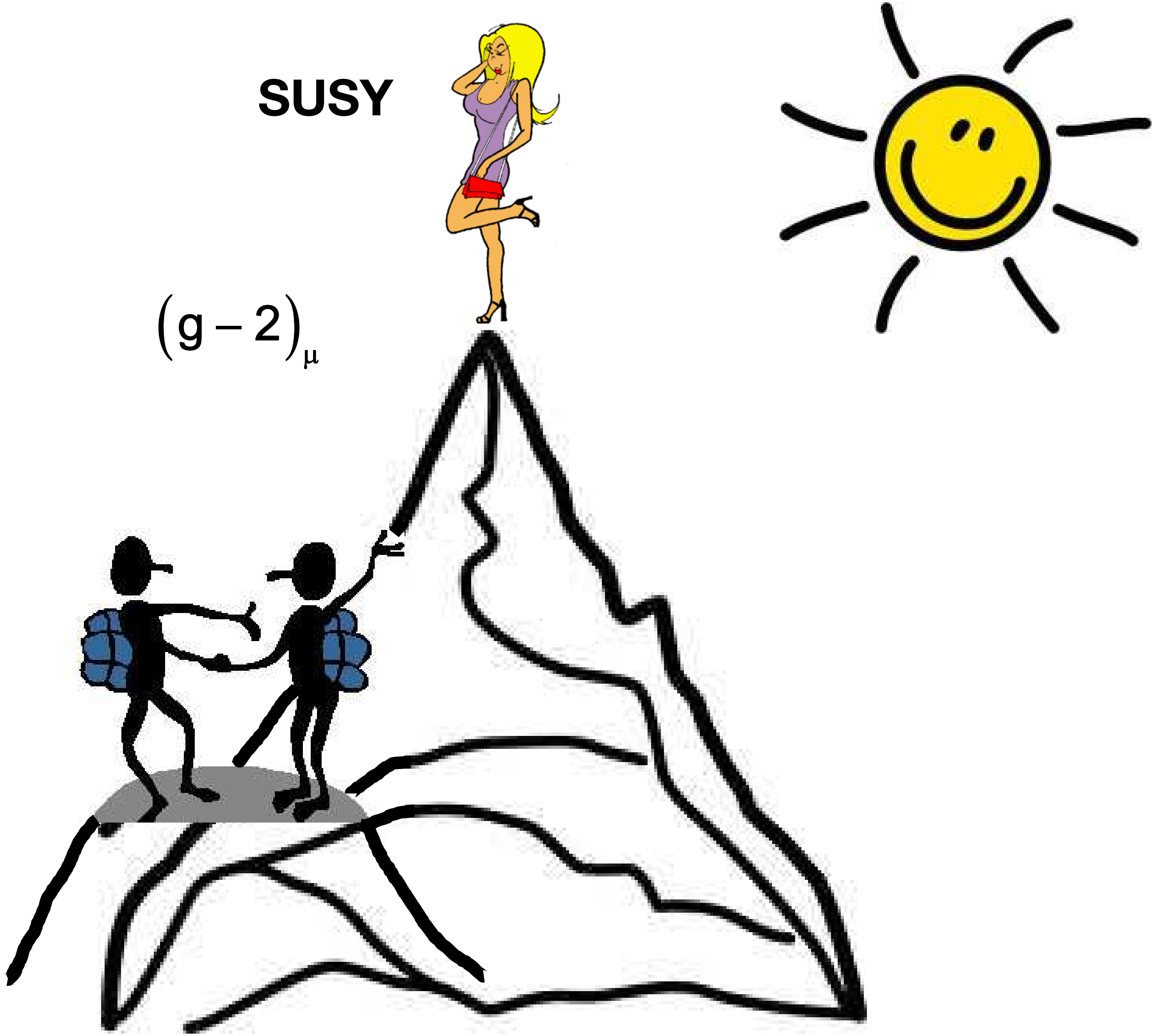
March 2012 LHCb News

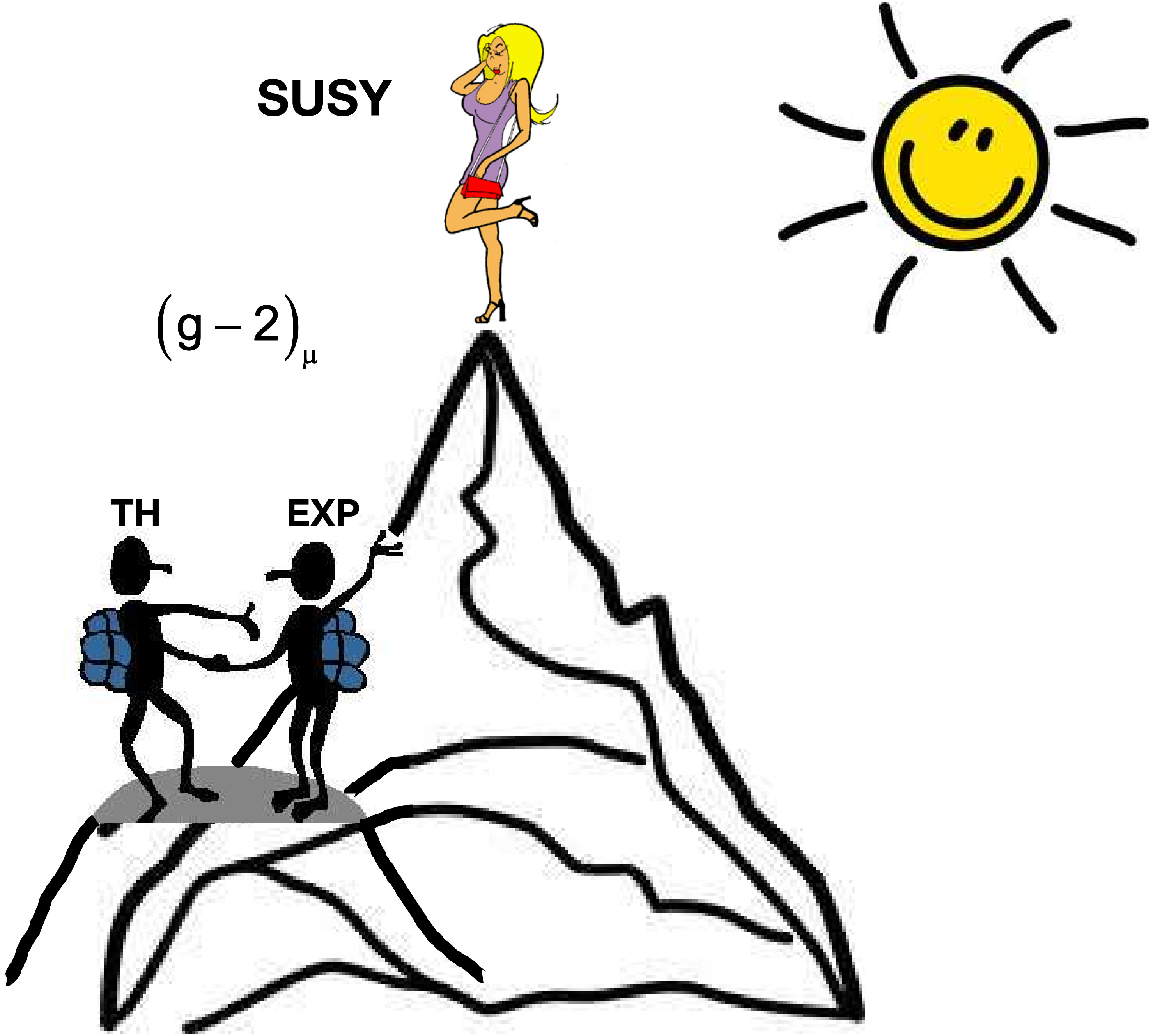
$$\text{LHCb} \quad : \quad \text{Br}\left(B_s \to \mu^+\mu^-\right) \le 4.5 \cdot 10^{-9} \quad 95\%\ \text{C.L.}$$

$$\text{SM} \quad : \quad \text{Br}\left(B_s \to \mu^+\mu^-\right) = \left(3.1 \pm 0.2\right) \cdot 10^{-9}$$

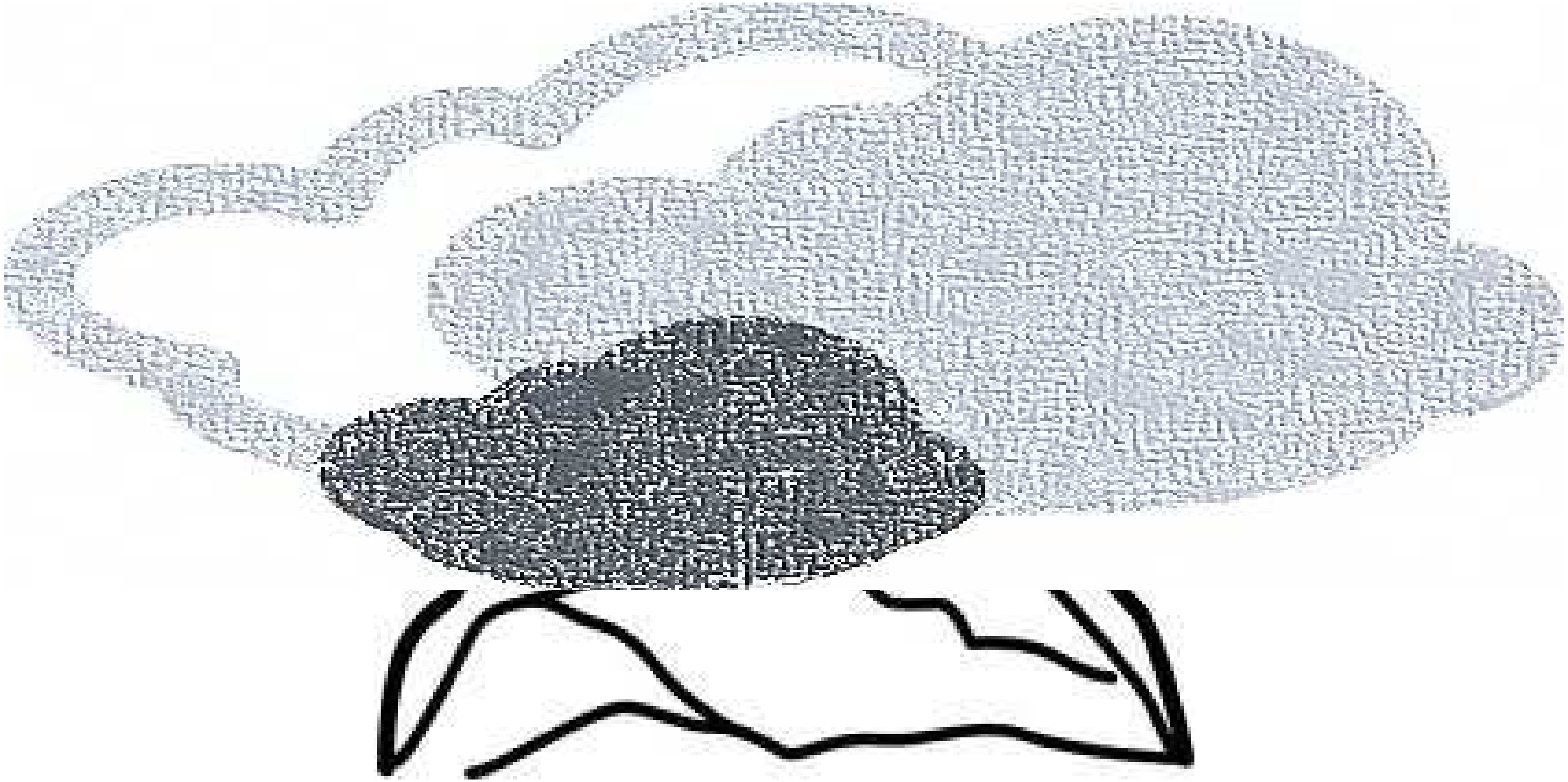
$$\text{LHCb} \quad : \quad \text{Br}\left(B_d \to \mu^+\mu^-\right) \le 8.2 \cdot 10^{-10} \quad 95\%\ \text{C.L.}$$

$$\text{SM} \quad : \quad \text{Br}\left(B_d \to \mu^+\mu^-\right) = \left(1.0 \pm 0.1\right) \cdot 10^{-10}$$


SUSY
$\left(g-2\right)_\mu$


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

May 2012



Credo of a Great Philosopher of the Second Half of the 20th Century and the Beginning of the 21st Century

Credo of a Great Philosopher of the Second Half of the 20th Century and the Beginning of the 21st Century

There is no New Physics !
But as scientists we are obliged to search for it !

Credo of a Great Philosopher of the Second Half of the 20th Century and the Beginning of the 21st Century

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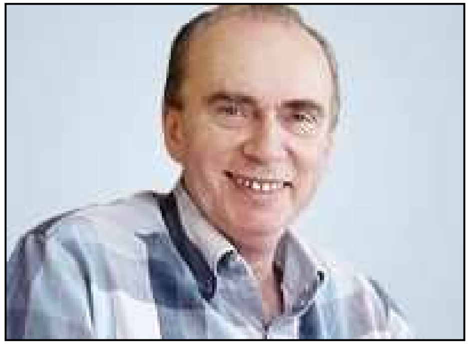
But as scientists we are obliged to search for it !

Stefan Pokorski
CERN Cafeteria
16th April 2012



Strategy for the Next 22 min

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

2. Anomalies in Flavour Data

3. BSM Models Facing LHCb Data

4. Finale Vivace !

AJB { hep-ph/0910.1032 | hep-ph/1204.5064
hep-ph/1012.1447 | (AJB + J. Girrbach)

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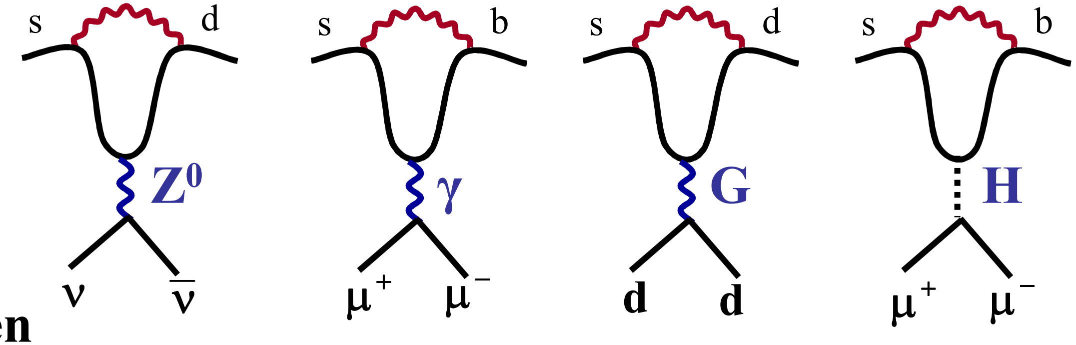
1.

Searching for New Physics (Rare Decays and CP Violation)

Arena of FCNC Processes

Penguin Family :

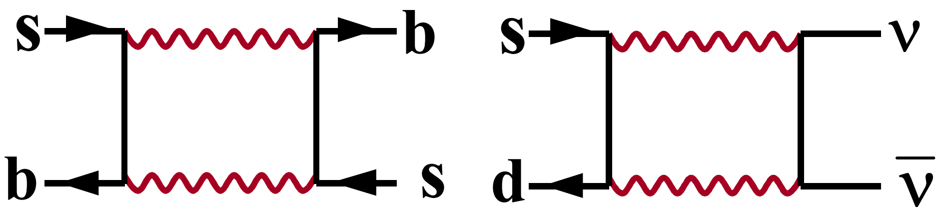


← **New Physics enters here**

Similar diagrams in LFV and EDM´s

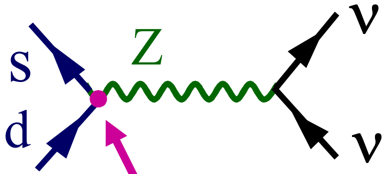
(GIM broken at one loop)

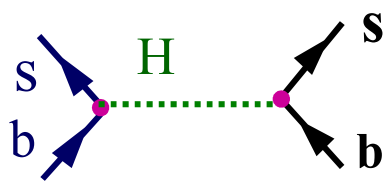
Box Diagrams



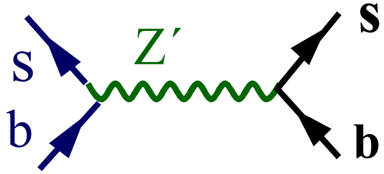
+ **other box diagrams**

Tree Diagrams





(GIM broken at tree level)



RS

Generated through mixing with New Gauge Bosons

Double Higgs Penguin in SUSY

In Order to identify New Physics through Flavour Physics

We need

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

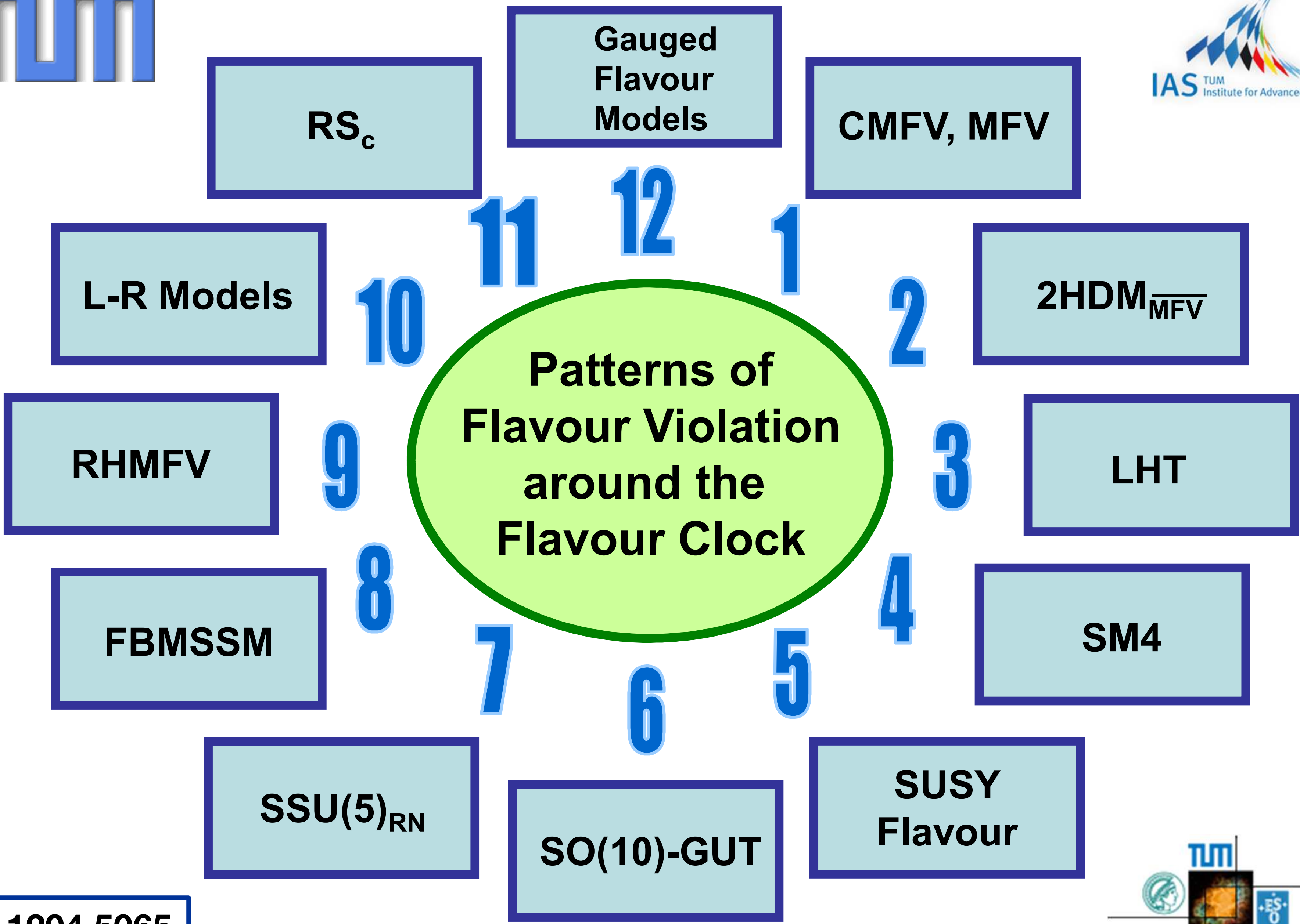
2. **Study Patterns on Flavour Violation in various New Physics models (correlations between many flavour observables).**

...and

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

Here top-down approach more powerful in flavour physics

In the era of precision flavour physics we have to go beyond rough estimates provided by Effective Lagrangians with a multitude of operators with unknown coefficients ($1/\Lambda^2$,...)


Patterns of Flavour Violation around the Flavour Clock
Gauged Flavour Models
12
CMFV, MFV
1
2HDM$_{\overline{MFV}}$
2
LHT
3
SM4
4
SUSY Flavour
5
SO(10)-GUT
6
SSU(5)$_{RN}$
7
FBMSSM
8
RHMFV
9
L-R Models
10
RS$_c$
11

1204.5065

Expedition
Attouniverse $\rightarrow$ Zeptouniverse

Junior BSM Collaborators M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D.Straub


B.Duling


A.Poschenrieder


S.Recksiegel


T.Heidsieck


C.Promberger


T.Feldmann


D.Guadagnoli

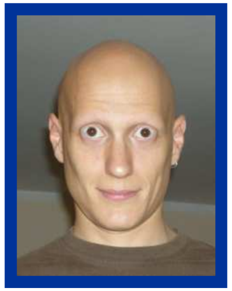

L.Merlo

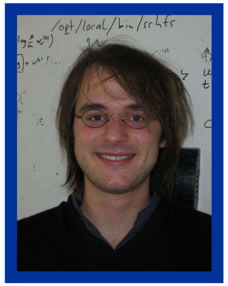

R.Ziegler


A.Weiler


O.Cata


M.Wick


L.Calibbi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M.Nagai

Senior BSM Collaborators M


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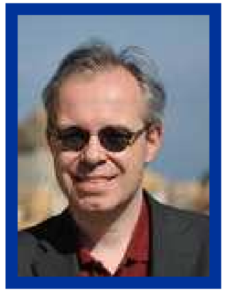
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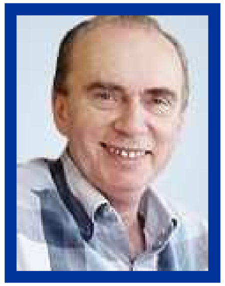
C.Grojean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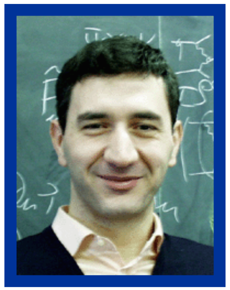
L.Silvestrini


P.Gambino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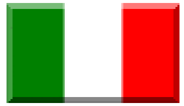
C.Tarantino


F. de Fazio




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

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.

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

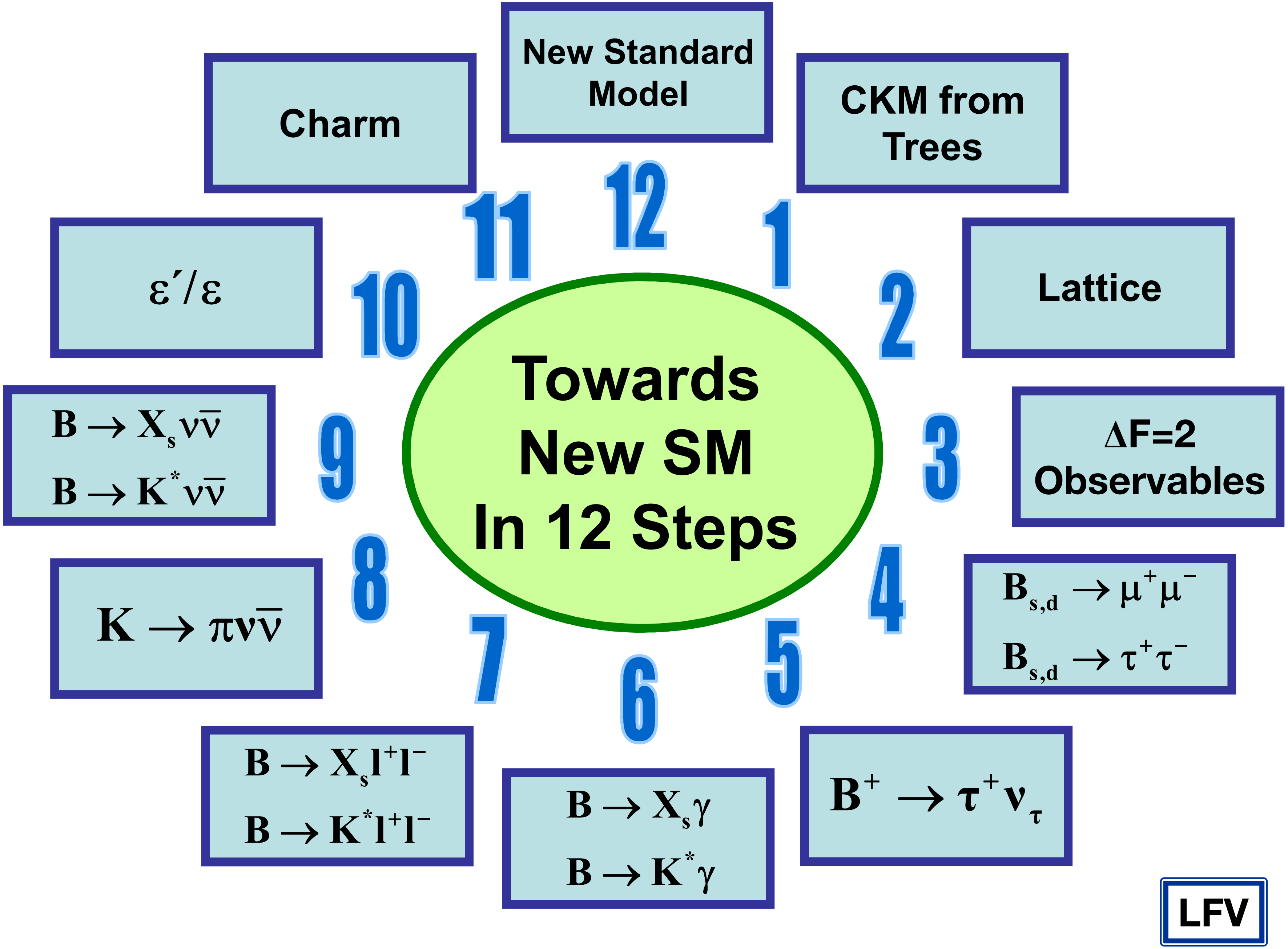
(MFV, CMFV)

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 <u>real</u> 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**


Towards New SM In 12 Steps
1
CKM from Trees
2
Lattice
3
ΔF=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
$B \to X_s l^+l^-$
$B \to K^* l^+l^-$
8
$K \to \pi\nu\bar{\nu}$
9
$B \to X_s\nu\bar{\nu}$
$B \to K^*\nu\bar{\nu}$
10
ε'/ε
11
Charm
12
New Standard Model
LFV

2.

Anomalies in Flavour Data

Departures from Standard Model Expectations

$\not{CP}$

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

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

$B_s^0 - \bar{B}_s^0 \quad (S_{\psi\varphi}) \quad S_{\psi\varphi} = \begin{cases} 0.035 \pm 0.002 & \text{(SM)} \\ 0.002 \pm 0.087 & \text{(LHCb)} \end{cases}$

Ok now

$$\frac{Br(B^+ \to \tau^+ \nu)_{exp}}{Br(B^+ \to \tau^+ \nu)_{SM}} \cong 2.2 \pm 0.5$$

$$|V_{ub}| = \begin{cases} 4.3 \cdot 10^{-3} & \text{Inclusive Decays} \quad (B \to X_u l \nu) \\ 3.4 \cdot 10^{-3} & \text{Exclusive Decays} \quad (B \to \rho l \nu) \\ & \text{and SM-CKM fit} \end{cases}$$

(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)

Favoured by $B^+ \rightarrow \tau^+ \nu$

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

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

$$\{|V_{ub}| \cong 3.4 \cdot 10^{-3}\} \Rightarrow \left\{ \frac{(S_{\psi K_s})_{SM}}{(S_{\psi K_s})_{exp}} \right\} \cong 1.0 \qquad \frac{|\varepsilon_K|_{SM}}{|\varepsilon_K|_{exp}} \cong 0.8$$

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

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

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

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

Further Lattice Improvements crucial

(Using most recent lattice values)

(AJB + Girrbach)

3.

BSM Models Facing LHCb

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. **Small V_{ub}**

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

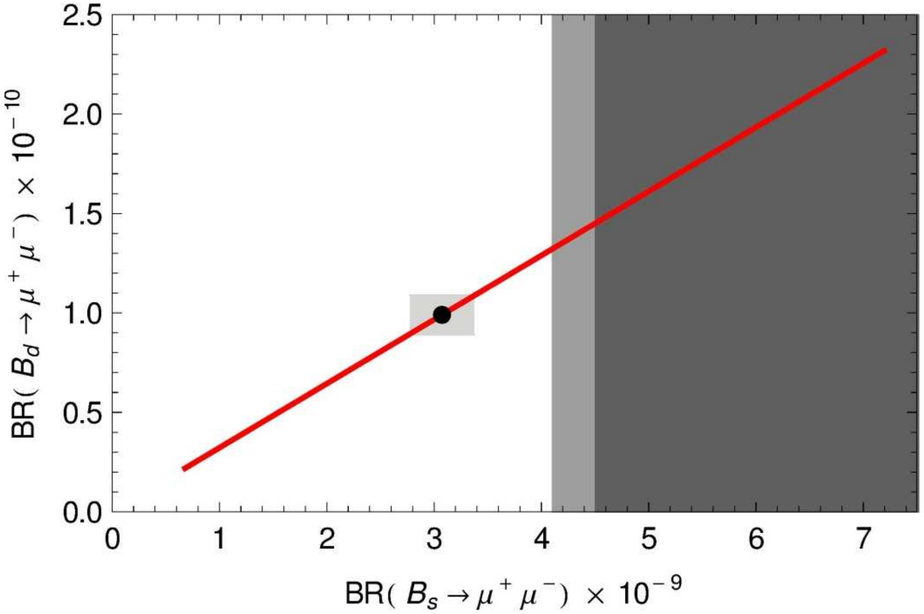
$Br\left(B^+ \to \tau^+ \nu_\tau\right)$ factor 2 below the data

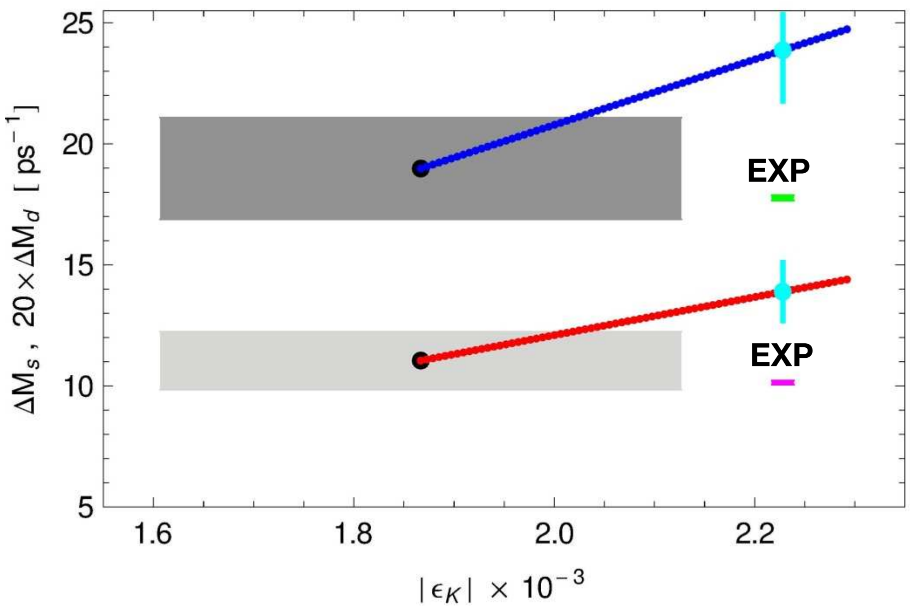
Conclusion: **CMFV under pressure**

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

Constrained Minimal Flavour Violation

AJB + J. Girrbach (2012)





$$\mathbf{Br}\left(B_d \to \mu^+\mu^-\right) \leq 1.3 \cdot 10^{-10}$$

$$\mathbf{LHCb} \leq 8.2 \cdot 10^{-10}$$

Tension within CMFV

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

Non-Supersymmetric 2HDM And Flavour Blind Phases

With MFV

$2HDM_{\overline{MFV}}$

AJB, Carlucci, Gori, Isidori (1005.5310)
AJB, Isidori, Paradisi (1007.5291)

{Tree-Level Higgs Exchanges}

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

$$S_{\psi\varphi} = \sin\left(2\left|\beta_s\right| + \theta_s^H\right)$$

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

Unambiguous Implications of $2HDM_{\overline{MFV}}$

(Stringent Correlations)

Step 1 : Need $|V_{ub}| \approx 4.4 \cdot 10^{-3}$ to get ε_K^{exp}

Step 2 : $Br(B^+ \to \tau^+ \nu_\tau) \Rightarrow 1.3 \cdot 10^{-4}$ (Enhancement by 1.7 over SM value) $(Exp: 1.7 \pm 0.3 \cdot 10^{-4})$

$S_{\psi K_S} = \sin 2\beta \simeq 0.82$ compared to $S_{\psi K_S}^{exp} \simeq 0.68 \pm 0.02$

Step 3 : $S_{\psi K} = \sin(2\beta - \theta_H^d) \to S_{\psi K_S} \simeq 0.68$ $\quad \theta_H^d =$ new phase from Higgs sector

Step 4 : $S_{\psi\varphi} = \sin(\underbrace{2\beta_s}_{\text{small}} + \theta_H^s)$

$$\begin{cases} \theta_H^s \approx \dfrac{m_s}{m_d} \theta_H^d \simeq 17 \theta_H^d & \text{(Yukawa's)} \\ \theta_H^s \simeq \theta_H^d & \text{(Higgs Potential)} \end{cases}$$

Step 5 : With enhanced $S_{\psi\varphi}$: $Br(B_s \to \mu^+\mu^-)$, $Br(B_d \to \mu^+\mu^-)$ still enhanced for small $S_{\psi\varphi}$?

Basic Questions

Can $2HDM_{\overline{MFV}}$ bring down

$$S_{\psi K_s} \simeq 0.82 \to 0.68$$

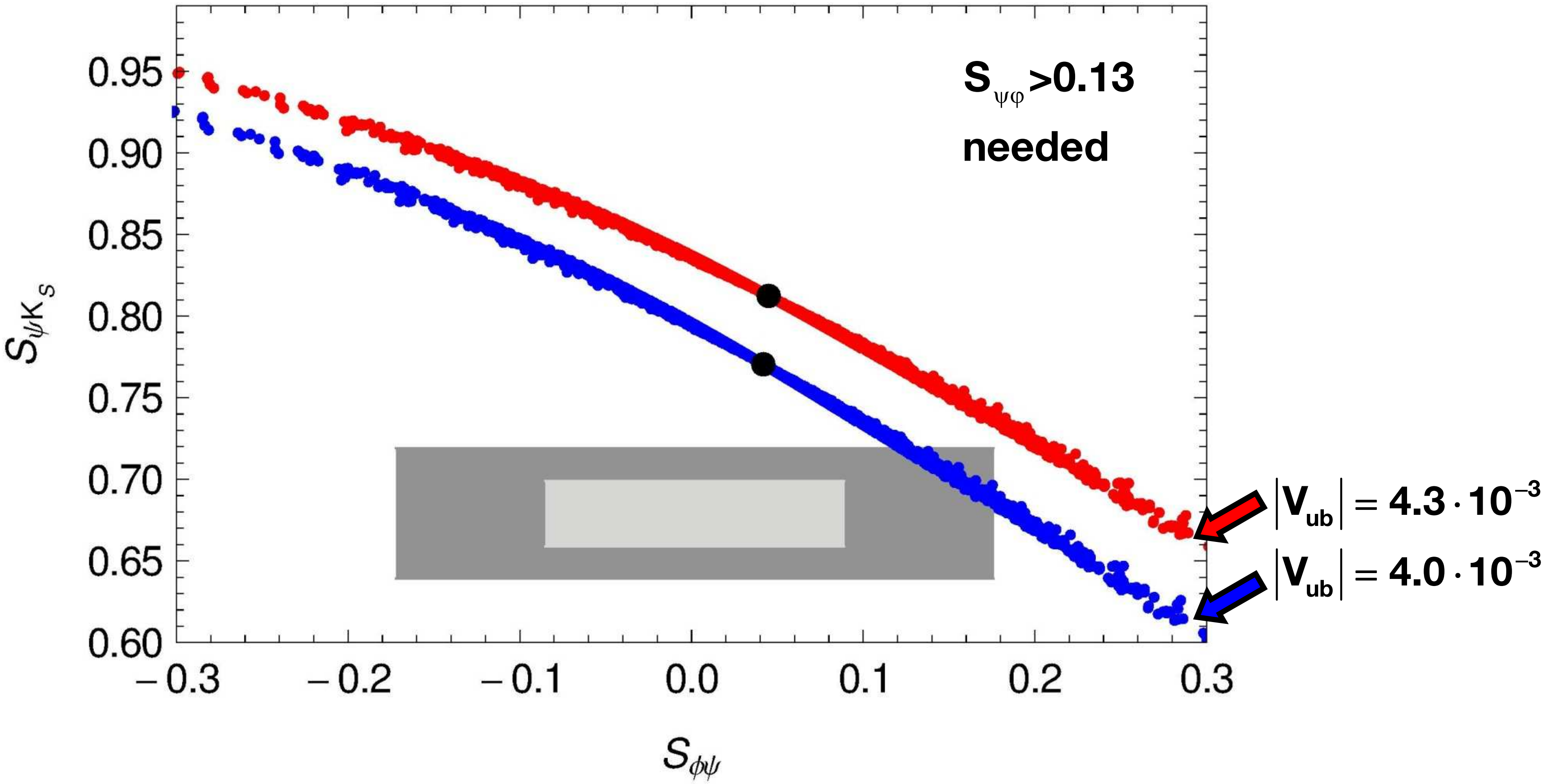
without violating the data

on $S_{\psi\varphi}$ and $Br\left(B_{s,d} \to \mu^+\mu^-\right)$

from LHCb ?

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

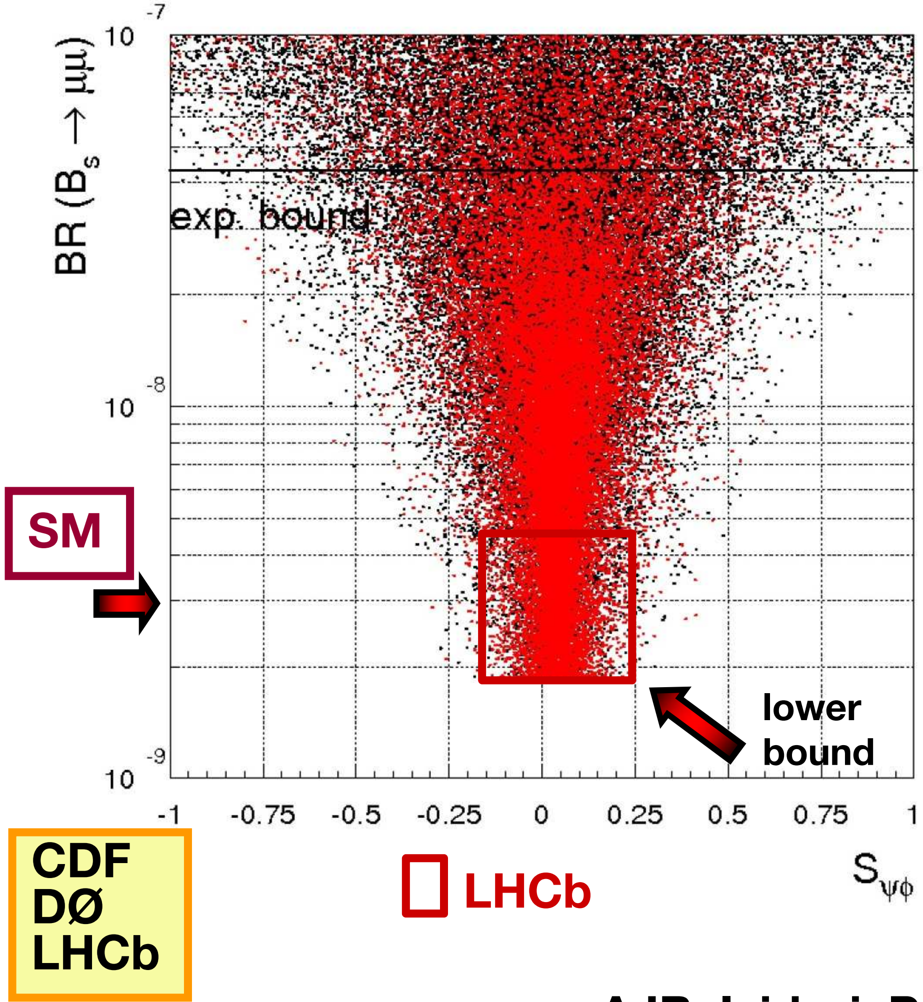
AJB, Girrbach, Nagai, Paradisi (2012)

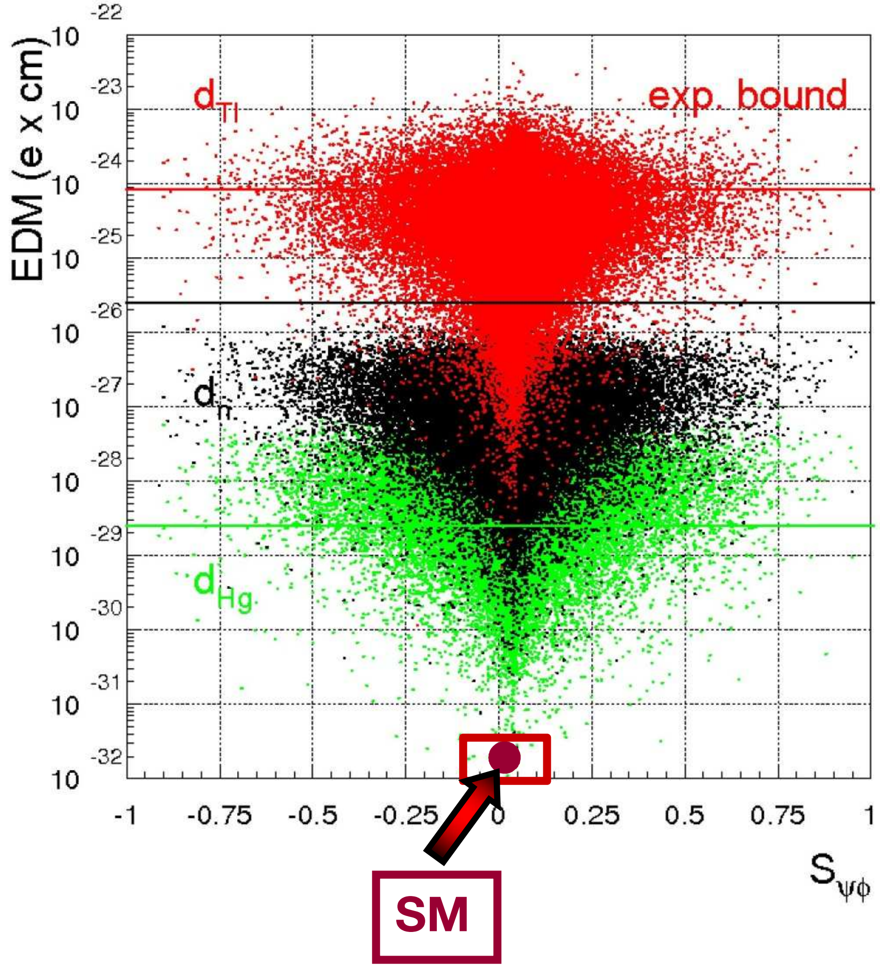


More on 2HDM with MFV and Flavour Blind Phases

$2HDM_{\overline{MFV}}$

2012: no problems with both observables





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.

LHT after LHCb Data

Our 2006 Predictions (Blanke et al.) :

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

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

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

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

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

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

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

ABGPS

(0909.1333)

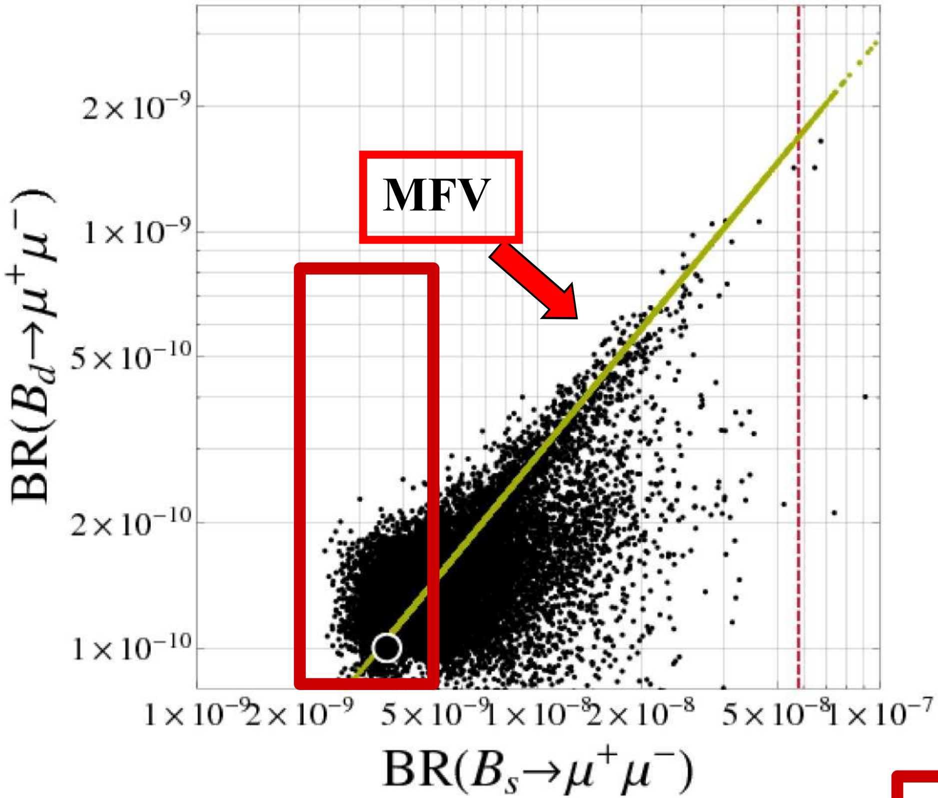
$Br(B_d \to \mu^+\mu^-)$ vs $Br(B_s \to \mu^+\mu^-)$

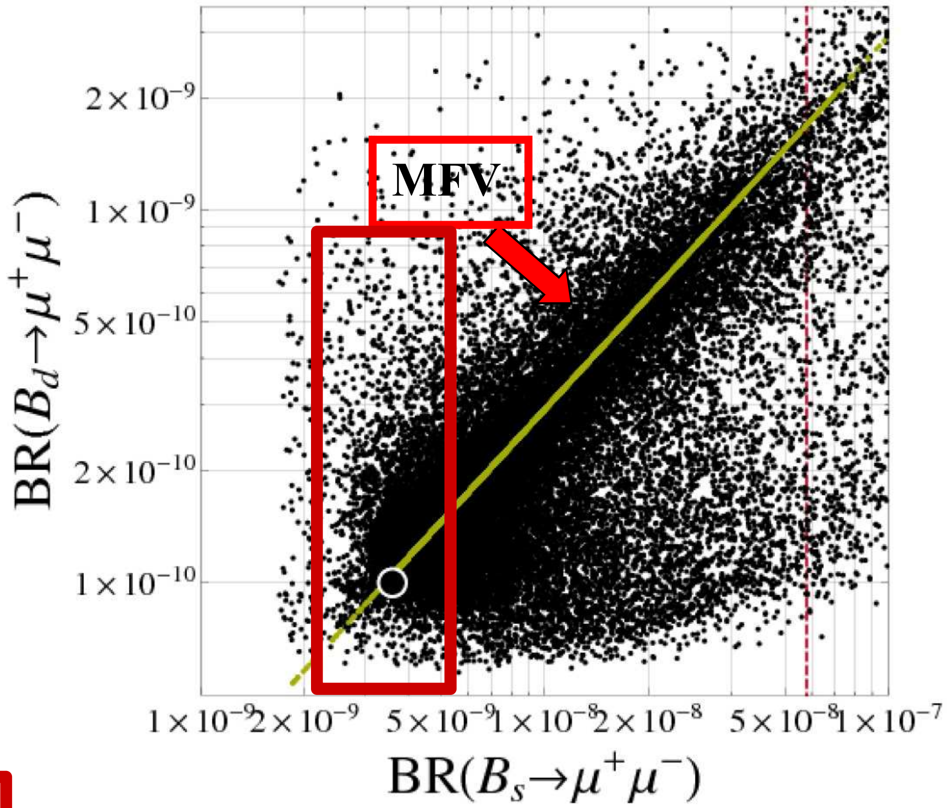
SUSY (Flavour)

Altmannshofer, AJB, Gori, Paradisi, Straub

● = SM

MFV AJB; Hurth, Isidori, Kamenik, Mescia





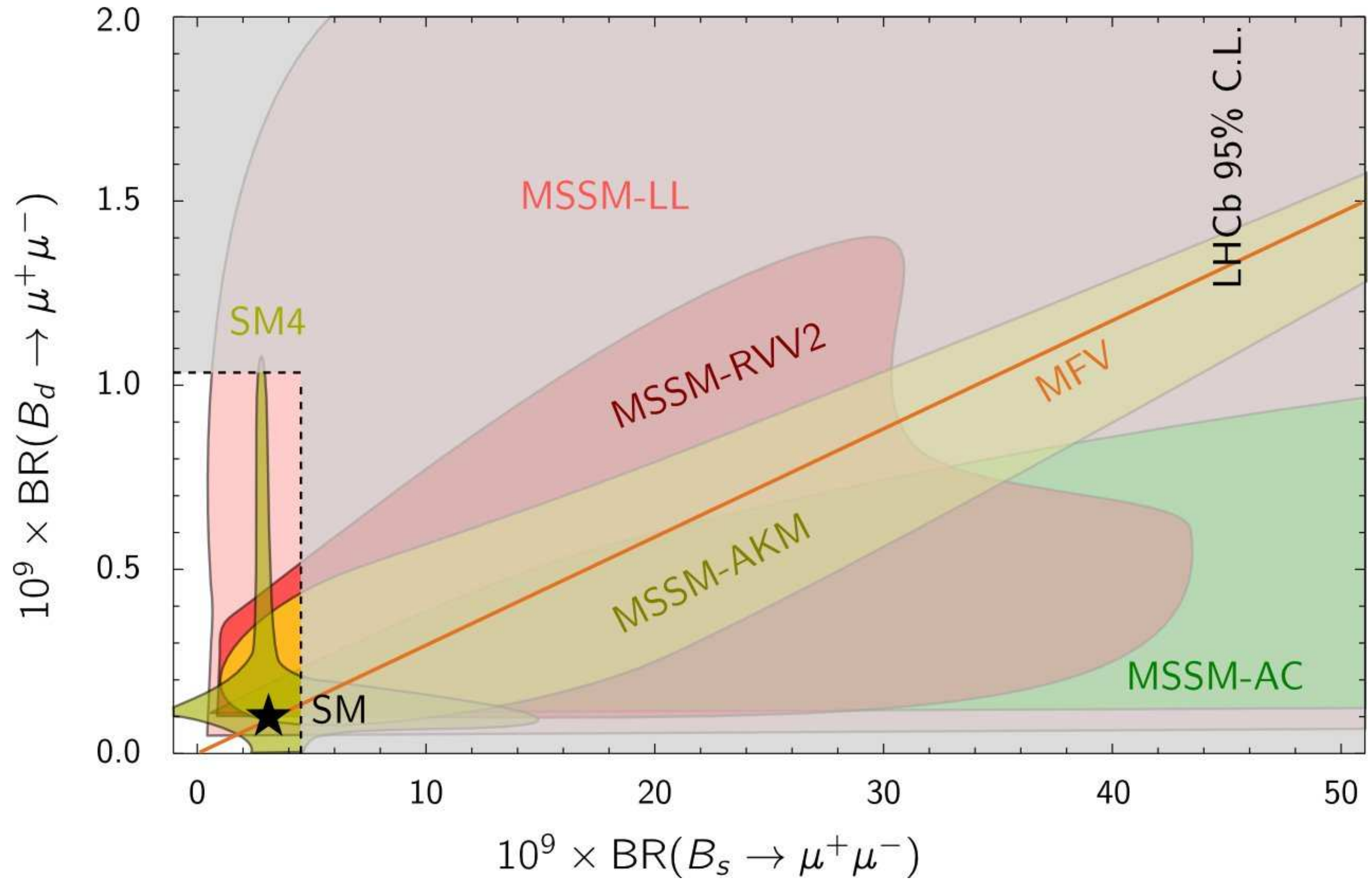
LHCb

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 $S_{\psi\varphi}$

$$|V_{ub}|_{excl} = 3.38\ (36) \cdot 10^{-3}$$

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

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

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

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

Generally: in principle yes

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

Blanke
AJB
Gemmler
Heidsieck
(1111.5014)

$K^+ \to \pi^+ \nu\bar{\nu}$ 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)

J-PARC KOTO

Both very sensitive to New Physics

CP-conserving
TH uncertainty 2-3%

CP-Violation in Decay
TH uncertainty 1-2%

Important Messages

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

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

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

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.

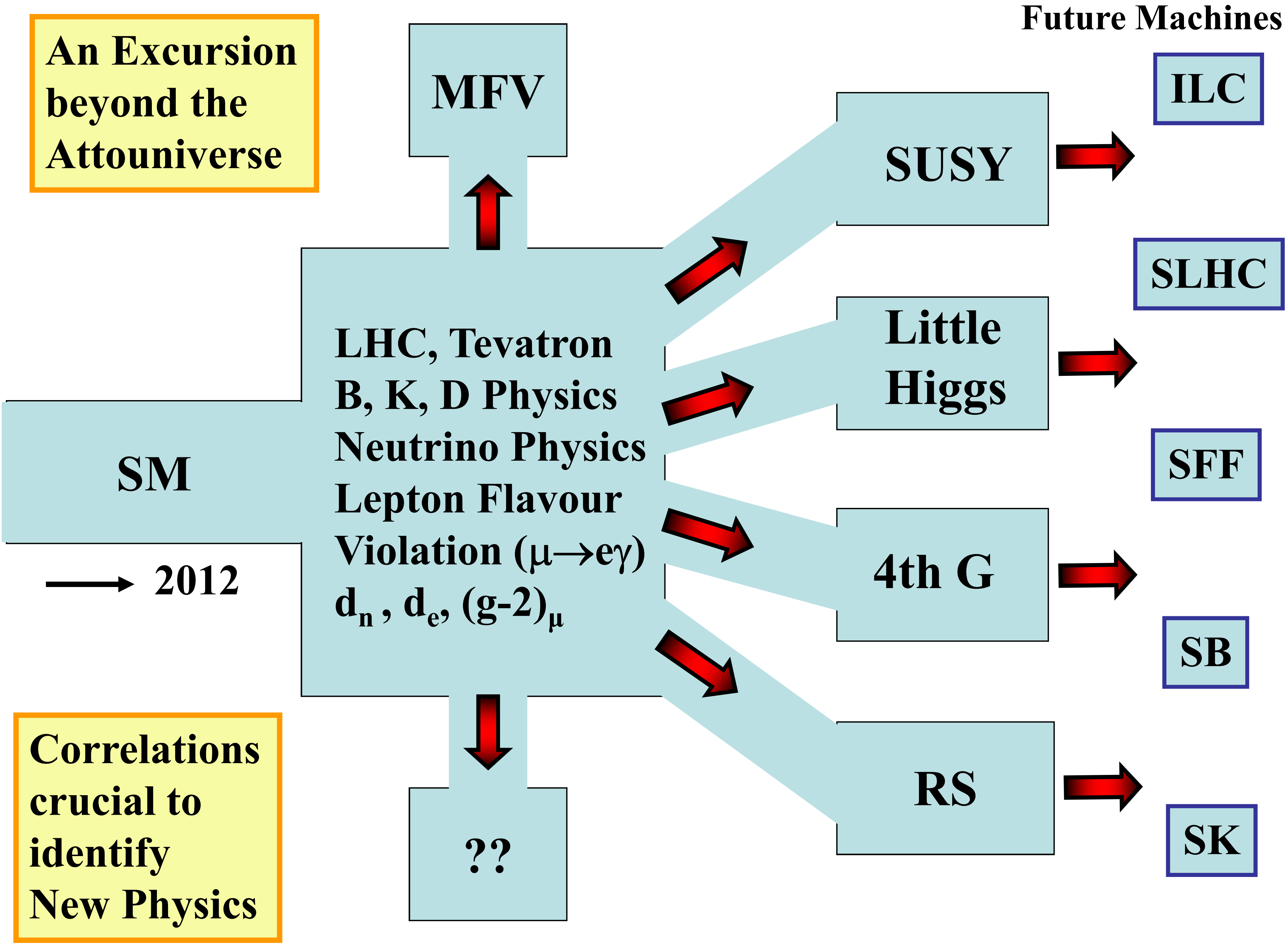
Finale: Vivace !

LHCb Data had profound impact on various BSM models with some relief for (LHT, RHMFV)

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 $|V_{ub}|$**	:	**$2HDM_{\overline{MFV}}$ RHMFV**



Future Machines
An Excursion beyond the Attouniverse
MFV
SUSY
ILC
SLHC
Little Higgs
SFF
SM
LHC, Tevatron
B, K, D Physics
Neutrino Physics
Lepton Flavour Violation (μ→eγ)
d_n , d_e, (g-2)_μ
2012
4th G
SB
RS
SK
??
Correlations crucial to identify New Physics

An Excursion beyond the Attouniverse

Future Machines

MFV

SM

→ 2012

LHC, Tevatron
B, K, D Physics
Neutrino Physics
Lepton Flavour Violation ($\mu \to e\gamma$)
d_n , d_e, $(g-2)_\mu$

SUSY

Little Higgs

4th G

RS

ILC

SLHC

SFF

SB

SK

Correlations crucial to identify New Physics

Final Messages

1. SM does not offer a satisfactory description of present flavour data, but LHCb brought definitely a relief.

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, …) can still remove all tensions in the data. In particular both $S_{\psi\varphi} > 0$ and $S_{\psi\varphi} < 0$ possible.

5. Models for fermion masses and mixing imply generally non-MFV interactions. (Lalak, Pokorski, Ross)

Simple Tests in the Coming Years

Standard Candles of Flavour Physics

- Sign of $S_{\psi\varphi}$

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

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

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

- **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

Should we be frustrated after LHC, LHCb Data?

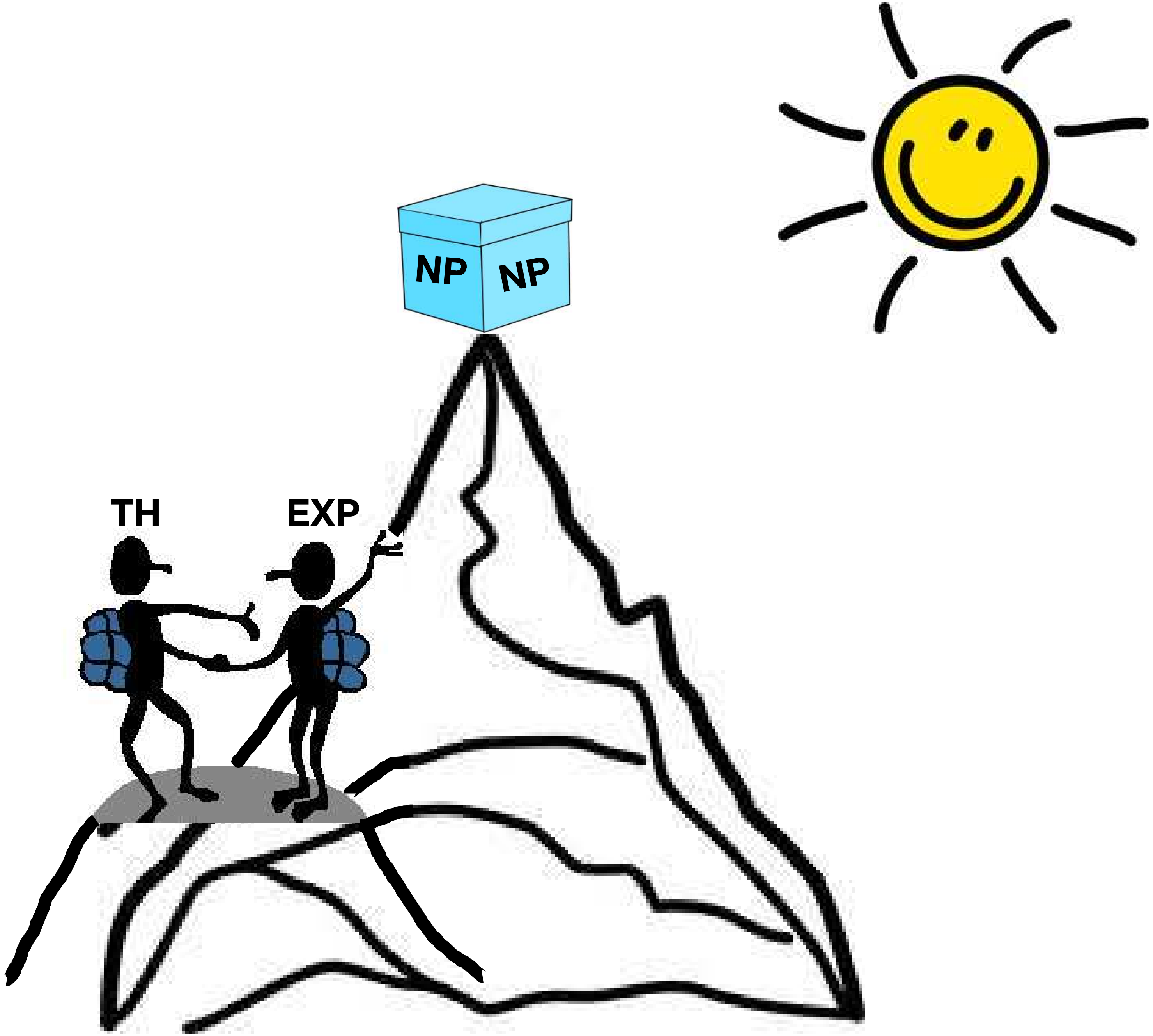
Should we be frustrated after LHC, LHCb Data?

No, no, no !!!

Should we be frustrated after LHC, LHCb Data?

No, no, no !!!

Exciting Times are just ahead of us !!!


NP
NP
TH
EXP

Most Exciting !!!

Most Exciting !!!

Planck 2022 (Warsaw)

Most Exciting !!!

Planck 2022 (Warsaw)

80th Birthday of Stefan Pokorski !!!

100 lat, 100 lat niech zyje zyje nam !

Backup

(LHCb)

First Evidence for CP Violation in Charm

$$\Delta A_{CP} \equiv A_{CP}\left(K^{-}K^{+}\right) - A_{CP}\left(\pi^{+}\pi^{-}\right)$$

$D^0 \rightarrow K^{+}K^{-}$
$D^0 \rightarrow \pi^{+}\pi^{-}$

Difference in time-integrated CP asymmetries

$$\Delta A_{CP} \equiv -0.82 \pm 0.21(\text{stat}) \pm 0.11(\text{sys})\%$$

Significance 3.5σ ; Sensitive mainly to direct CPV

VERY PRELIMINARY

Central value larger than SM expectation but theoretical uncertainties in direct CPV are substantial.

From
Mat Charles (Oxford)
LHCb-CONF-2011-061

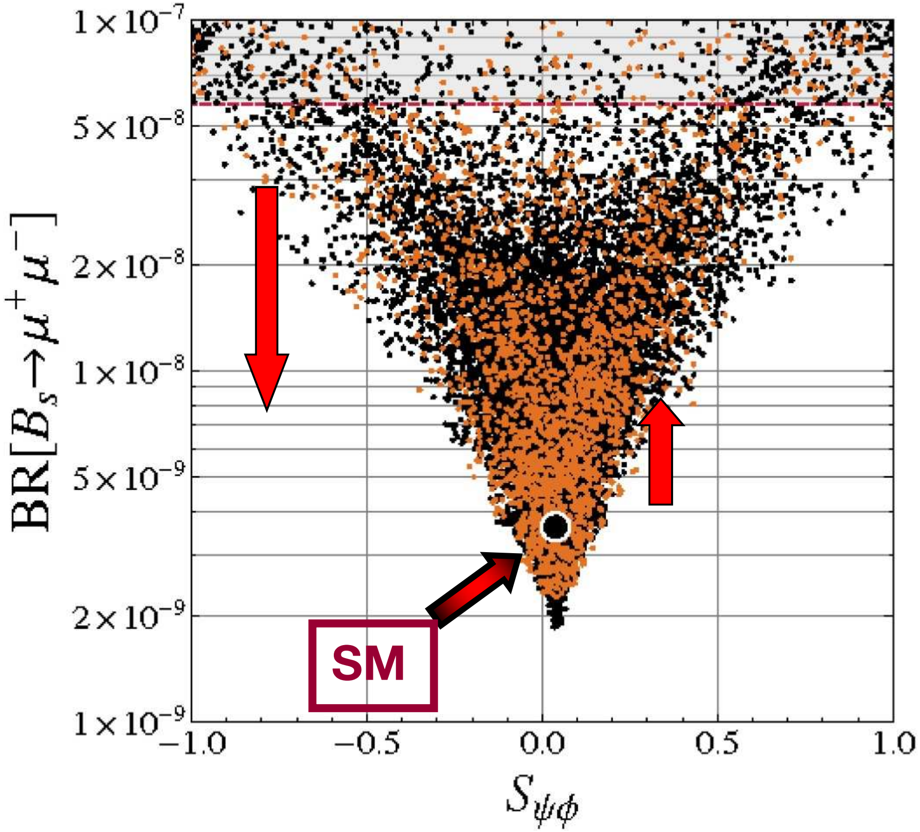
CDF, D0
LHCb

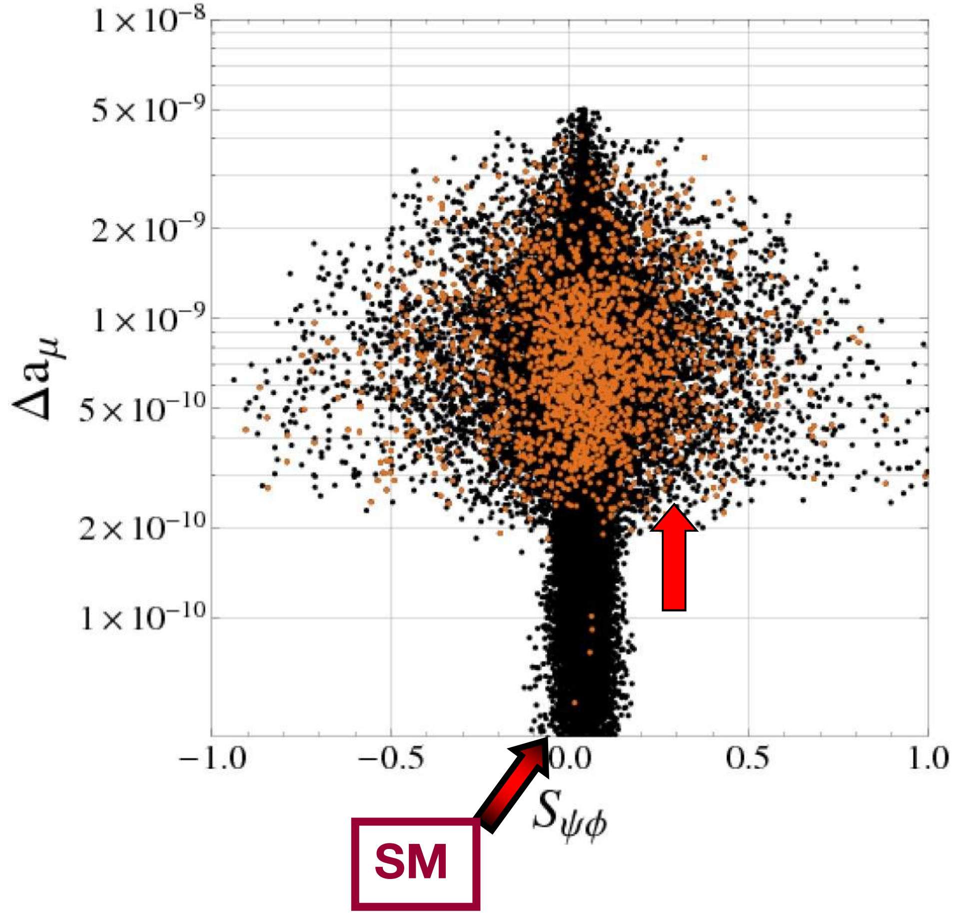
$Br(B_s \to \mu^+\mu^-)$ vs $S_{\psi\varphi}$

SUSY

ABGPS
(0909.1333)

$\Delta a_\mu \sim \Delta(g-2)_\mu$ vs $S_{\psi\varphi}$

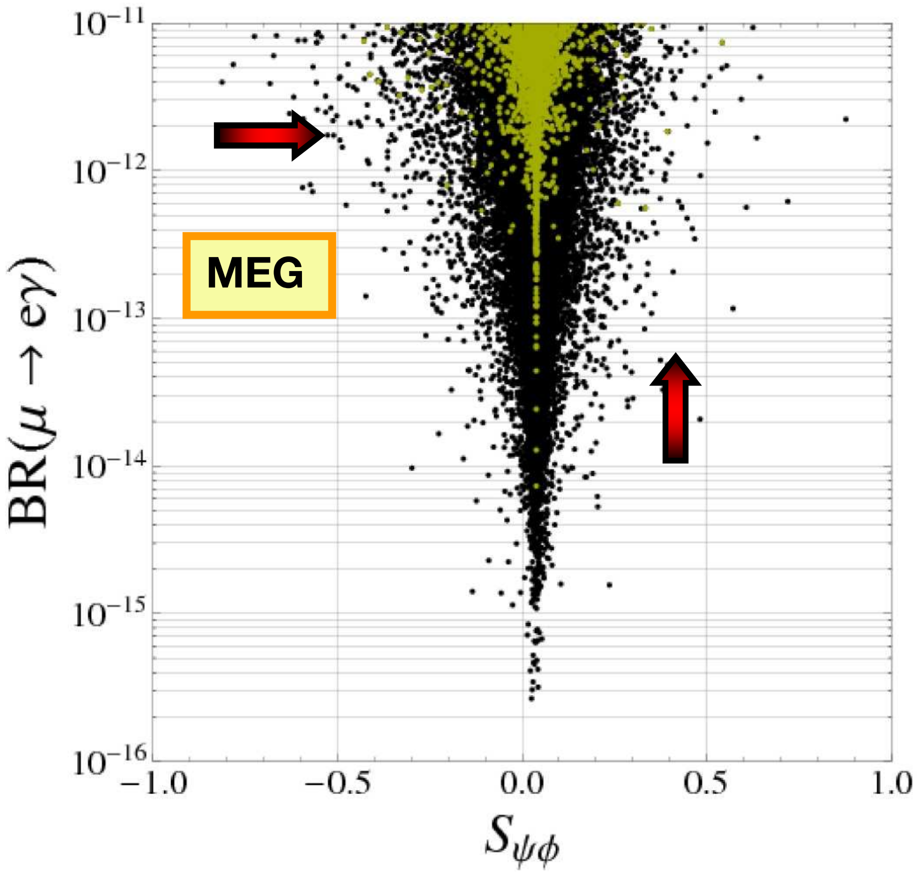


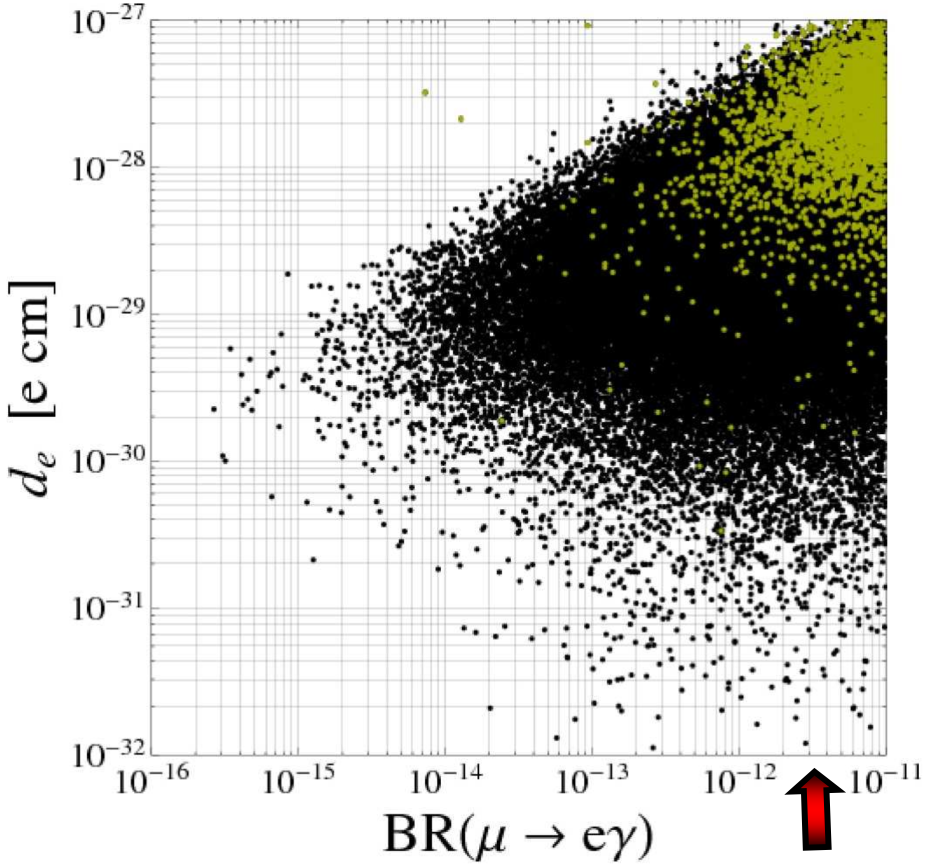


ABGPS

Correlations in the SU(3) Flavour SUSY Model (RVV)

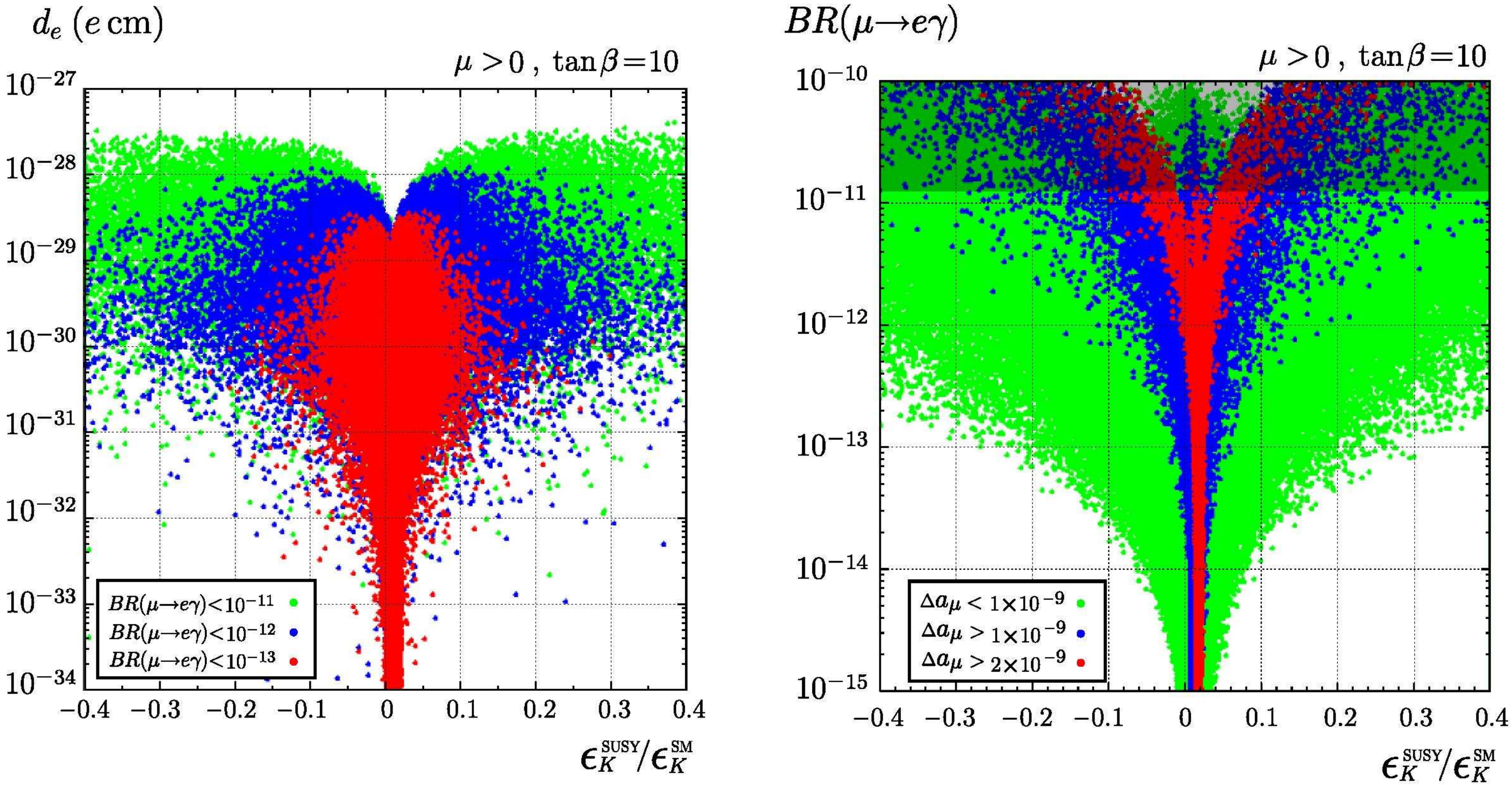
Solution to $(g\text{-}2)_\mu$ anomaly





MEG

Correlations within SUSY-SU(5)-GUT with RH Neutrinos



AJB, Nagai, Paradisi, 1011.1993

★ $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$

Z-Penguin + Boxes (SM CMFV)

SM

$$Br(B_s \to \mu^+\mu^-) = (3.1 \pm 0.2)\cdot 10^{-9}$$

$$Br(B_d \to \mu^+\mu^-) = (1.0 \pm 0.1)\cdot 10^{-10}$$

Error dominated by $\hat{B}_{d,s}$

AJB (03)

CMFV "Golden Relation"

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

$(\Delta B = 1)$ $(\Delta B = 2)$

(0.95±0.03) Lattice

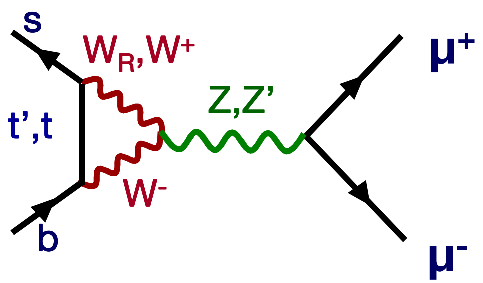
Valid in all CMFV models

Can be strongly violated in SUSY, LHT, RS, 4G

LHCb : $Br(B_s \to \mu^+\mu^-) \le 4.5 \cdot 10^{-9}$ 95% C.L.

LHCb : $Br(B_d \to \mu^+\mu^-) \le 8.2 \cdot 10^{-10}$ 95% C.L.

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



\+

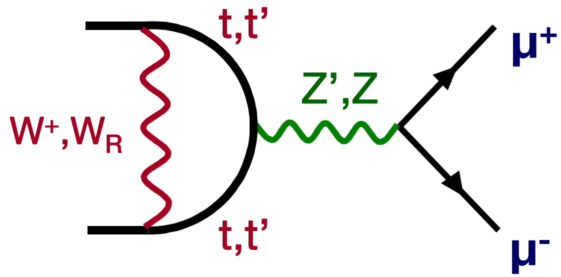
Other Z-Penguins and Boxes

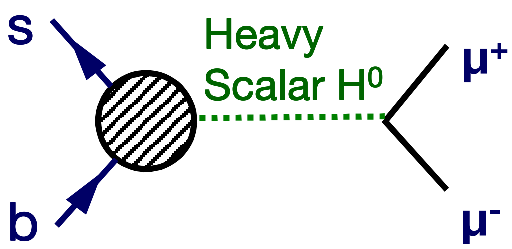
SM: (3.2 ± 0.2) · 10^{-9}

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

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

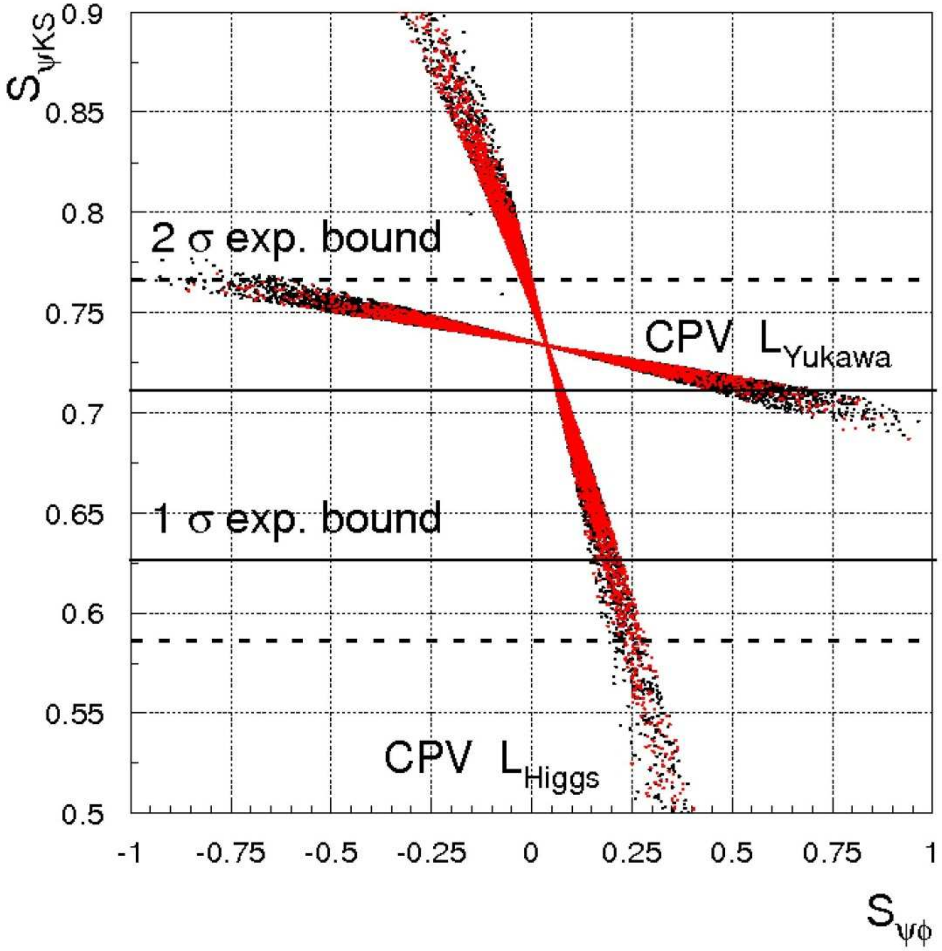
In the case of

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

distinction between Z,Z' and H^0 possible

More on 2HDM with MFV and Flavour Blind Phases

Correlation between CP Effects



AJB, Isidori, Paradisi 1007.5291

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

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

★

SM4 : Four Generations

New parameters in 4x4 mixing matrix

s_{14}, s_{24}, s_{34}, $m_{t'}$, $m_{b'}$,

δ_{13}, δ_{24}, δ_{14}

Can remove $\Delta F=2$ tensions and have $S_{\psi\phi} < 0$ but $B^+ \to \tau^+\nu_\tau$ problem remains.

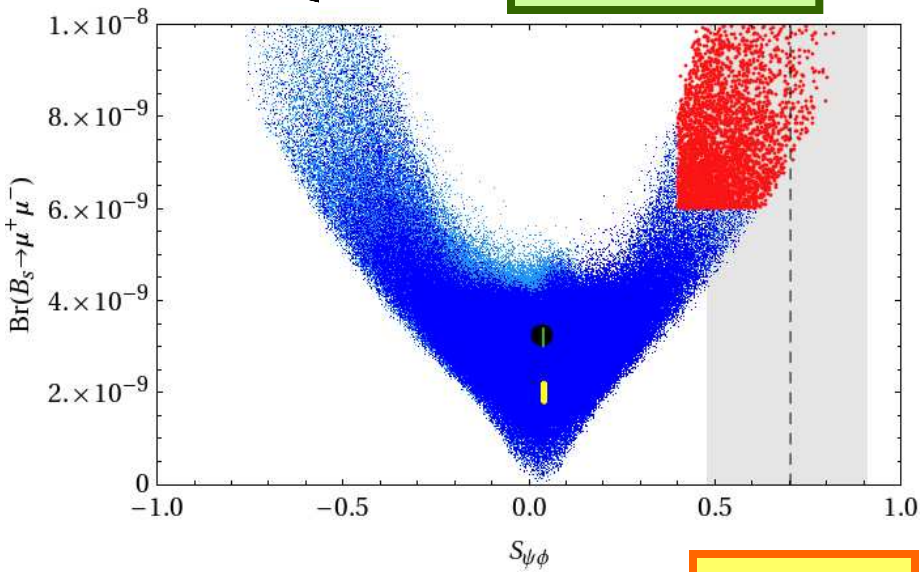
$Br(B_s \to \mu^+\mu^-)$ vs $S_{\psi\varphi}$

4G

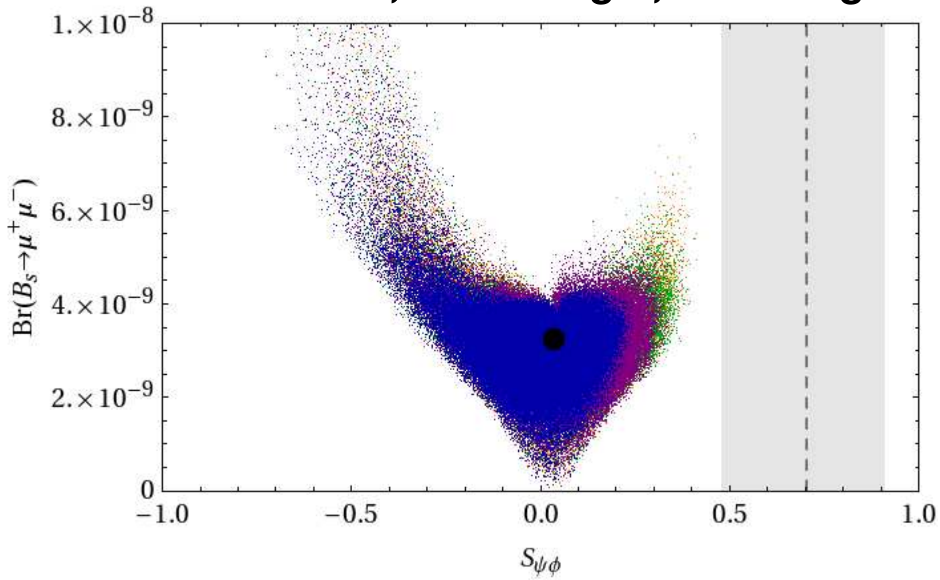
BDFHPR (1002.2126)

Similar Result by Soni et al.

See also Hou et al. and Lenz et al.



AJB, Duling, Feldmann, Heidsieck, Promberger, Recksiegel



No Impact on Δa_μ

CDF D0

Adding ε'/ε Constraint

4G has hard time to describe simultaneously ε'/ε and $S_{\psi\varphi} > 0.2$ if $B_{6,8}$ within 20% from large N values

FCNC Effects in a Minimal Theory of Fermion Masses

AJB, Grojean, Pokorski, Ziegler (1105.3725)
(describes heavy fermion effects in several models: FN, RS, ...)

1. No direct coupling of SM quarks to Higgs.

2. SM Yukawa couplings generated through mixing of heavy vectorial fermions with SM quarks:

$$Y^{SM} = \frac{m_Q m_U}{M_Q M_U} \lambda$$

mixings ($m_Q m_U$)

λ: flavour-anarchial Yukawa in vectorial fermion sector

masses of vectorlike fermions ($M_Q M_U$)

3. Modification of $W^{\pm}$, Z, H couplings (FCNC´s) but M_Q, M_U ~ 0 (few TeV) allowed while satisfying all constraints and fitting quark masses + CKM matrix.

Detailed analysis soon !

In BSM with the same Operator Structure but non-MFV the 7 master functions become non-universal (K, B_d, B_s) complex functions and CMFV relation are broken

Littlest Higgs with T-Parity, SM4

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

★ **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 $S_{\psi\phi} < 0$