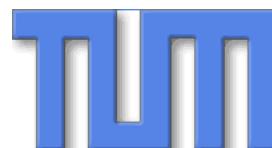


BSM Models Facing LHCb Data



Andrzej J. Buras
(Technical University Munich, TUM-IAS)



**Mass 2012
Stockholm, Nordita**

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

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

Frontiers of Elementary
Particle Physics in 2010's

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

10^{-21}m

Zeptouniverse

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

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

B

$B_s \rightarrow \mu^+ \mu^-$

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

$\text{Br}(B_s \rightarrow \mu^+ \mu^-) \simeq 0(10^{-8} - 10^{-7}) \quad (\text{SUSY, 2HDM, ...})$

A

March 2012 LHCb News

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

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



2σ
Range

: $-0.18 \lesssim S_{\psi\phi} \leq 0.18$

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

$S_{\psi K_s} = 0.68 \pm 0.02$

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

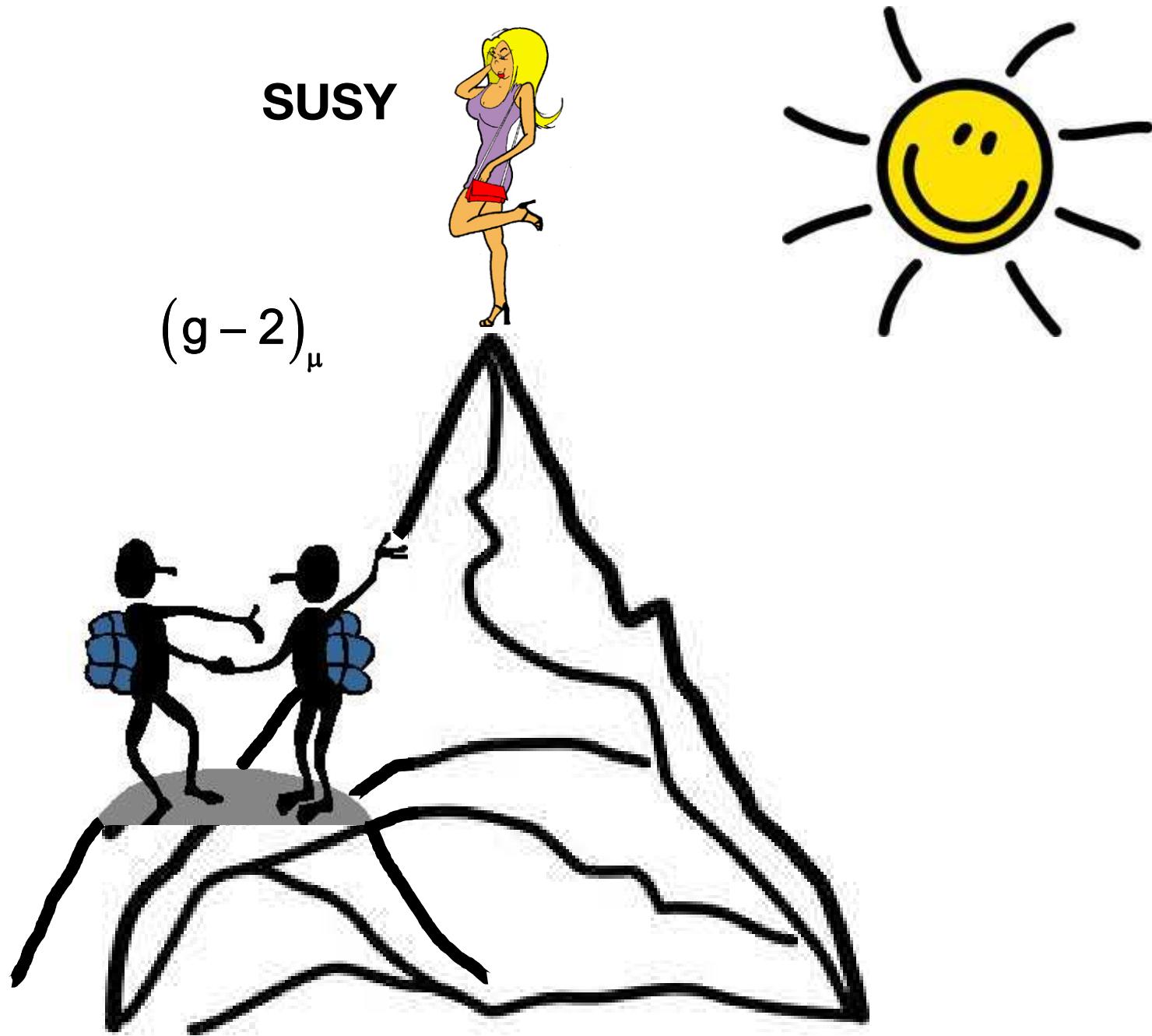
March 2012 LHCb News

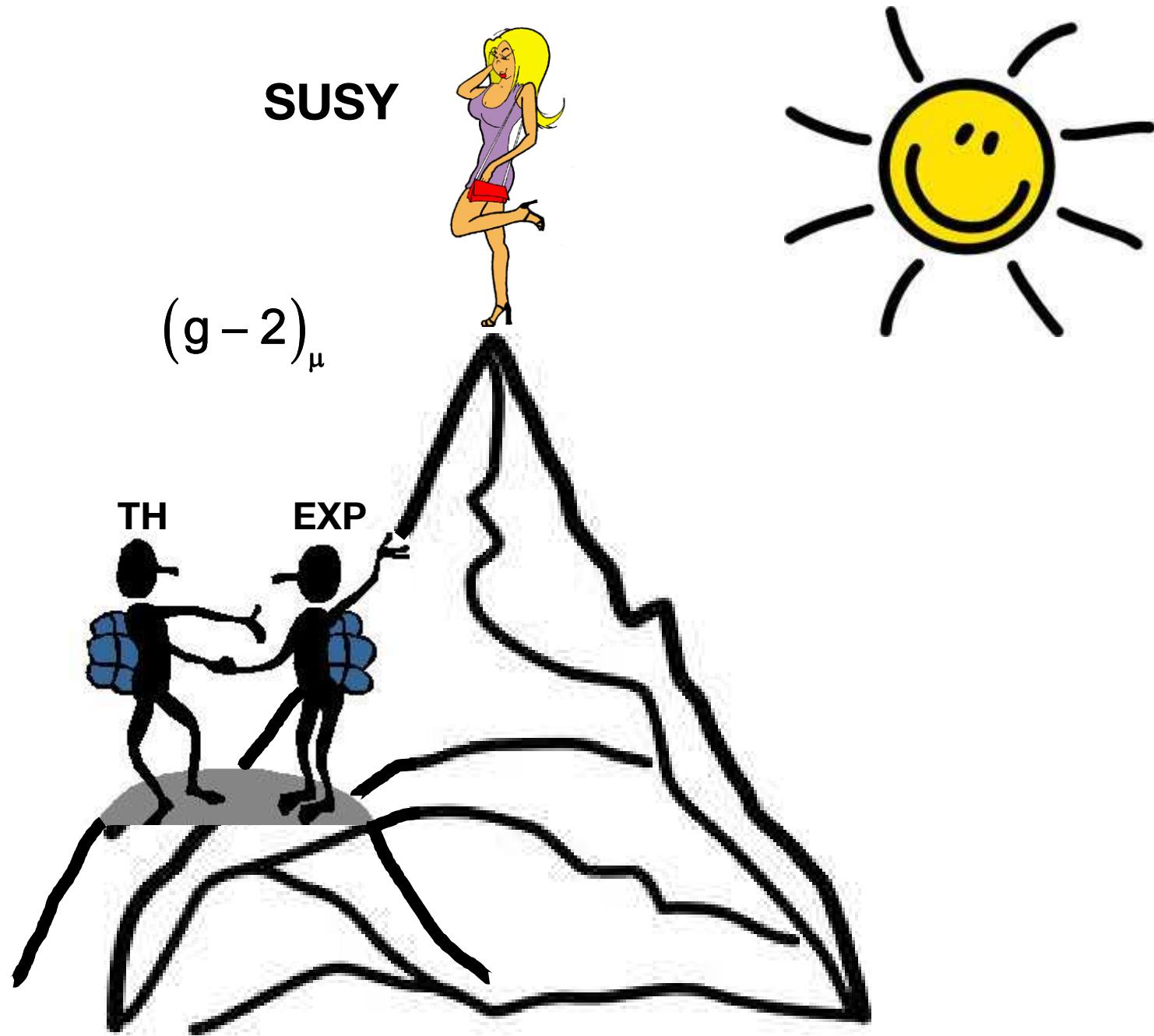
LHCb : $\text{Br}(B_s \rightarrow \mu^+ \mu^-) \leq 4.5 \cdot 10^{-9}$ 95% C.L.

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

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

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





May 2012



Strategy for the Next 36 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)

Strategy for the Next 36 min

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3.

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Finale Vivace !

AJB

hep-ph/0910.1032
hep-ph/1012.1447

hep-ph/1204.5064
(AJB + J. Girrbach)



1.

Searching for New Physics (Rare Decays and CP Violation)

Fundamental Lagrangian of the Standard Model

$$L = L_{\text{gauge}} + L_{\text{fermion}}$$

$$L_{\text{gauge}} = \underbrace{-\frac{1}{4}G_{\mu\nu}^a G^{a\mu\nu}}_{(\text{QCD})} - \underbrace{\frac{1}{4}W_{\mu\nu}^b W^{b\mu\nu} - \frac{1}{4}B_{\mu\nu} B^{\mu\nu}}_{(\text{Electroweak})}$$

$$L_{\text{fermion}} = \sum_f \bar{\psi}_{fL} \left(i\gamma^\mu D_\mu^{fL} \right) \psi_{fL} + \bar{\psi}_{fR} \left(i\gamma^\mu D_\mu^{fR} \right) \psi_{fR}$$

**Exact $\text{SU}(3)_c \otimes \text{SU}(2)_L \otimes \text{U}(1)_Y$ gives
the correct description of
Gauge boson-Fermion Couplings**

Fundamental Lagrangian of the Standard Model

$$L = L_{\text{gauge}} + L_{\text{fermion}} + L_{\text{Higgs}} + L_{\text{Yukawa}}$$

$$L_{\text{gauge}} = \underbrace{-\frac{1}{4}G_{\mu\nu}^a G^{a\mu\nu}}_{(\text{QCD})} - \underbrace{\frac{1}{4}W_{\mu\nu}^b W^{b\mu\nu} - \frac{1}{4}B_{\mu\nu} B^{\mu\nu}}_{(\text{Electroweak})}$$

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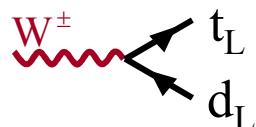
$$L_{\text{Higgs}} = (D_\mu \varphi)^\dagger (D^\mu \varphi) - \left[\mu^2 \varphi^\dagger \varphi + \frac{\lambda}{4} (\varphi^\dagger \varphi)^2 \right]$$

$$L_{\text{Yukawa}} = - \sum_f Y^{ij} \bar{\psi}_{fL}^i \varphi \psi_{fR}^j + \text{h.c.} \quad f = q, l$$

“Landau-Ginzburg”

Pillars in Flavour Physics

1. Charged Current Interactions only between left-handed Quarks



$$\frac{g_2}{2\sqrt{2}} \gamma_\mu (1 - \gamma_5) \cdot V_{td}$$

2. Quark Mixing

$$\{ \text{Weak Eigenstates} \} \neq \{ \text{Mass Eigenstates} \}$$

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

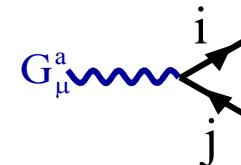
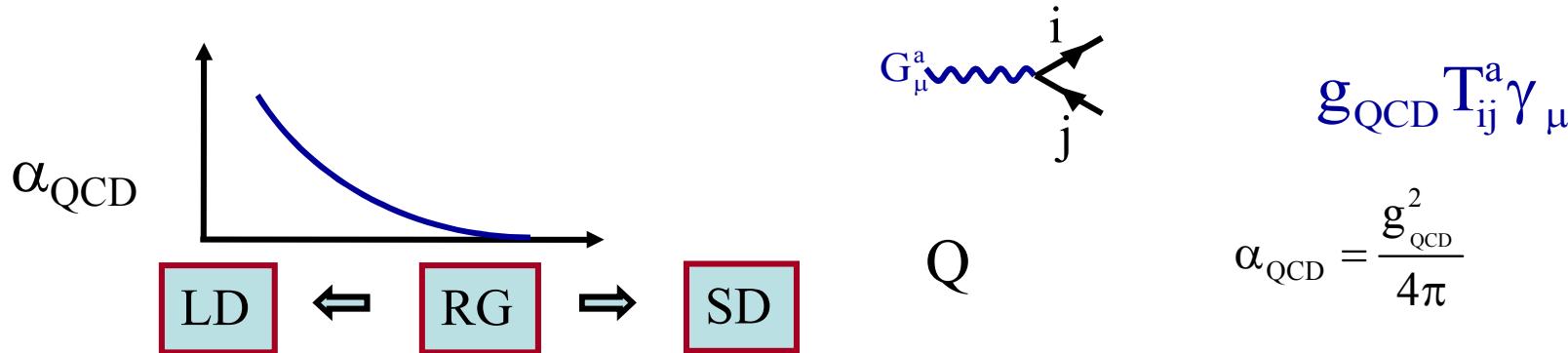
$$\begin{bmatrix} \text{Weak} \\ \text{Eigenstates} \end{bmatrix} \begin{bmatrix} \text{Unitarity} \\ \text{CKM-Matrix} \end{bmatrix} \begin{bmatrix} \text{Mass} \\ \text{Eigenstates} \end{bmatrix}$$

3. GIM Mechanism

Natural suppression of FCNC

$$\left\{ \gamma, G, Z^0, H^0 \right. \begin{array}{c} \nearrow i \\ \searrow j \end{array} = 0 \left. \right\} \rightarrow \left\{ \text{Loop Induced Decays, sensitive to} \right. \\ \left. \text{short distance flavour dynamics} \right\}$$

4. Asymptotic Freedom



Q

$$g_{\text{QCD}} T_{ij}^a \gamma_\mu$$

$$\alpha_{\text{QCD}} = \frac{g_{\text{QCD}}^2}{4\pi}$$

$$\alpha_{\text{QCD}}(Q) = \frac{4\pi}{\beta_0 \ln(Q^2 / \Lambda_{\overline{\text{MS}}}^2)} \left[1 - \frac{\beta_1}{\beta_0^2} \frac{\ln \ln(Q^2 / \Lambda_{\overline{\text{MS}}}^2)}{\ln(Q^2 / \Lambda_{\overline{\text{MS}}}^2)} + \dots \right]$$

$$\Lambda_{\overline{\text{MS}}}^{(5)} = 240 \pm 15 \text{ MeV} \quad \alpha_{\overline{\text{MS}}}^{(5)}(M_Z) = 0.1187 \pm 0.0009$$

SD = Short Distances (Perturbation Theory)

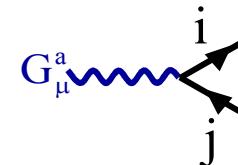
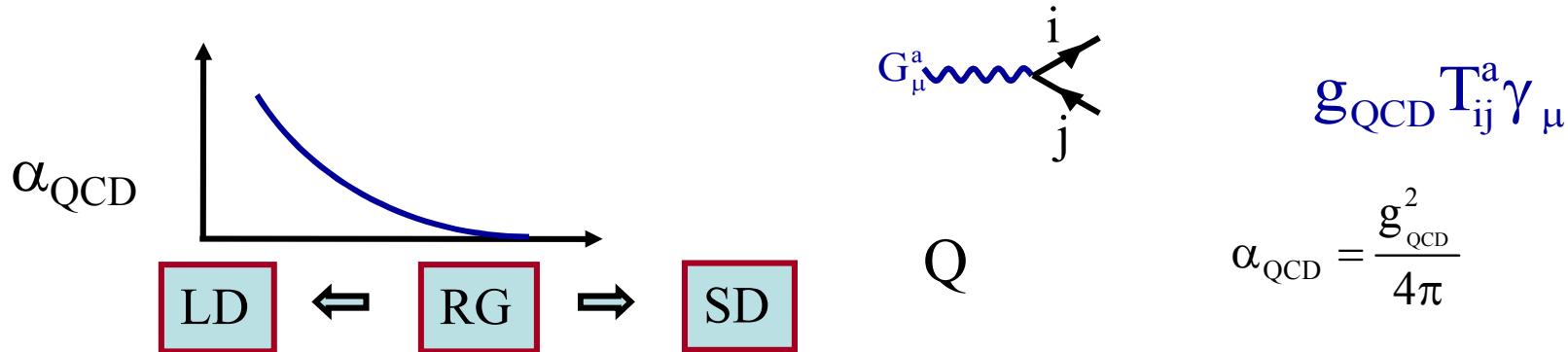


RG = Renormalization Group Effects



LD = Long Distances (Non-Perturbative Physics)

4. Asymptotic Freedom



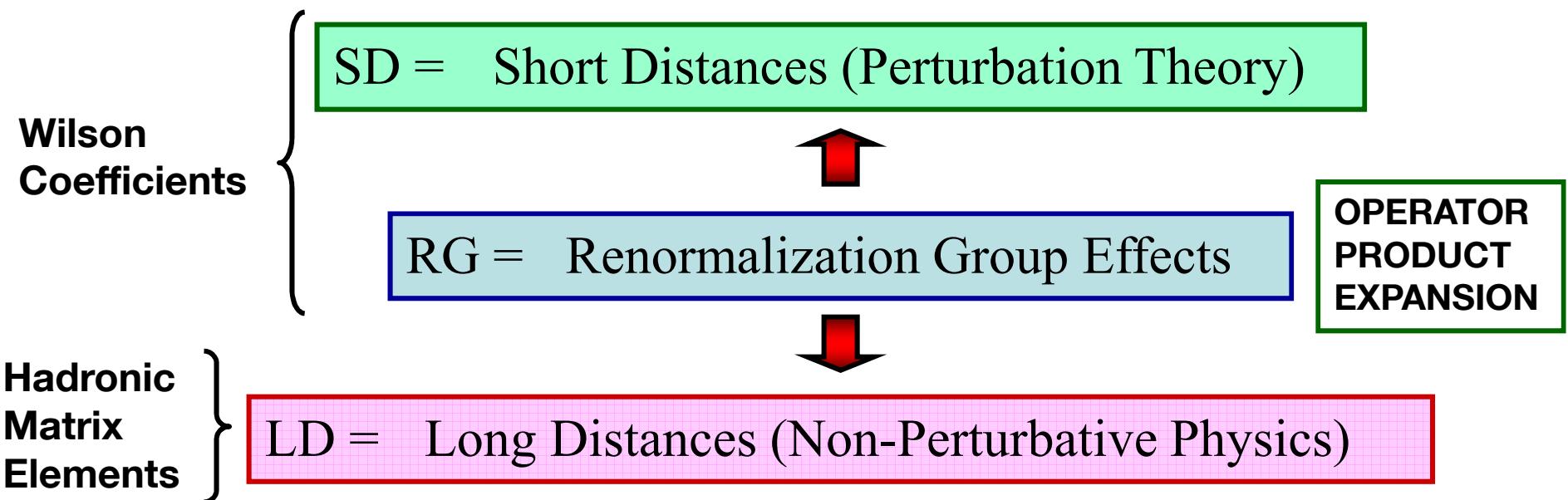
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$$\Lambda_{\overline{\text{MS}}}^{(5)} = 240 \pm 15 \text{ MeV} \quad \alpha_{\overline{\text{MS}}}^{(5)}(M_Z) = 0.1187 \pm 0.0009$$



CKM

(Nobel Prize 2008)

**Dirac Medal
(2010)**



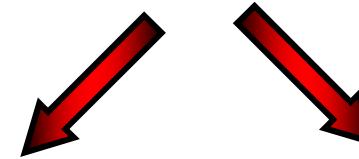
**N. Cabibbo
(1935-2010)**



M. Kobayashi



T. Maskawa

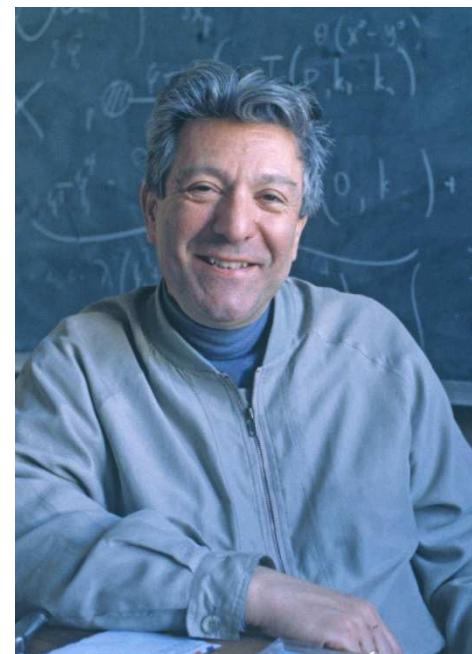


EPS

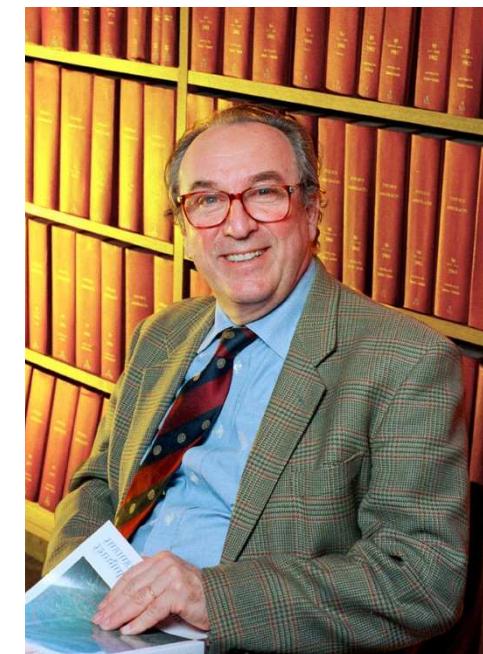
(High Energy Prize 2011)



Sheldon Glashow



John Iliopoulos

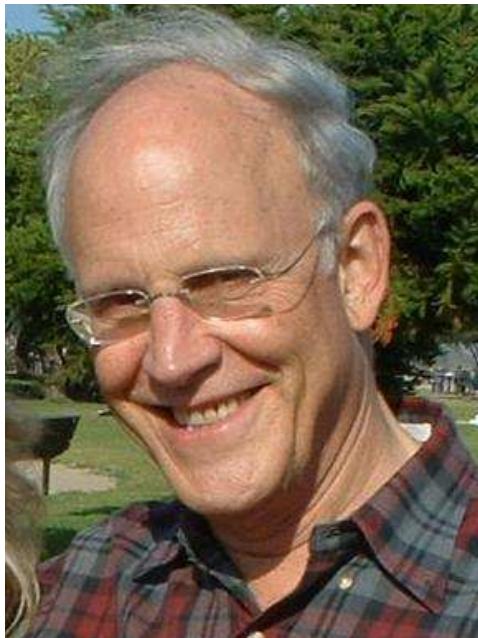


Luciano Maiani

GIM

Asymptotic Freedom

(Nobel Prize 2004)
(EPS High Energy
Prize 2003)



David Gross

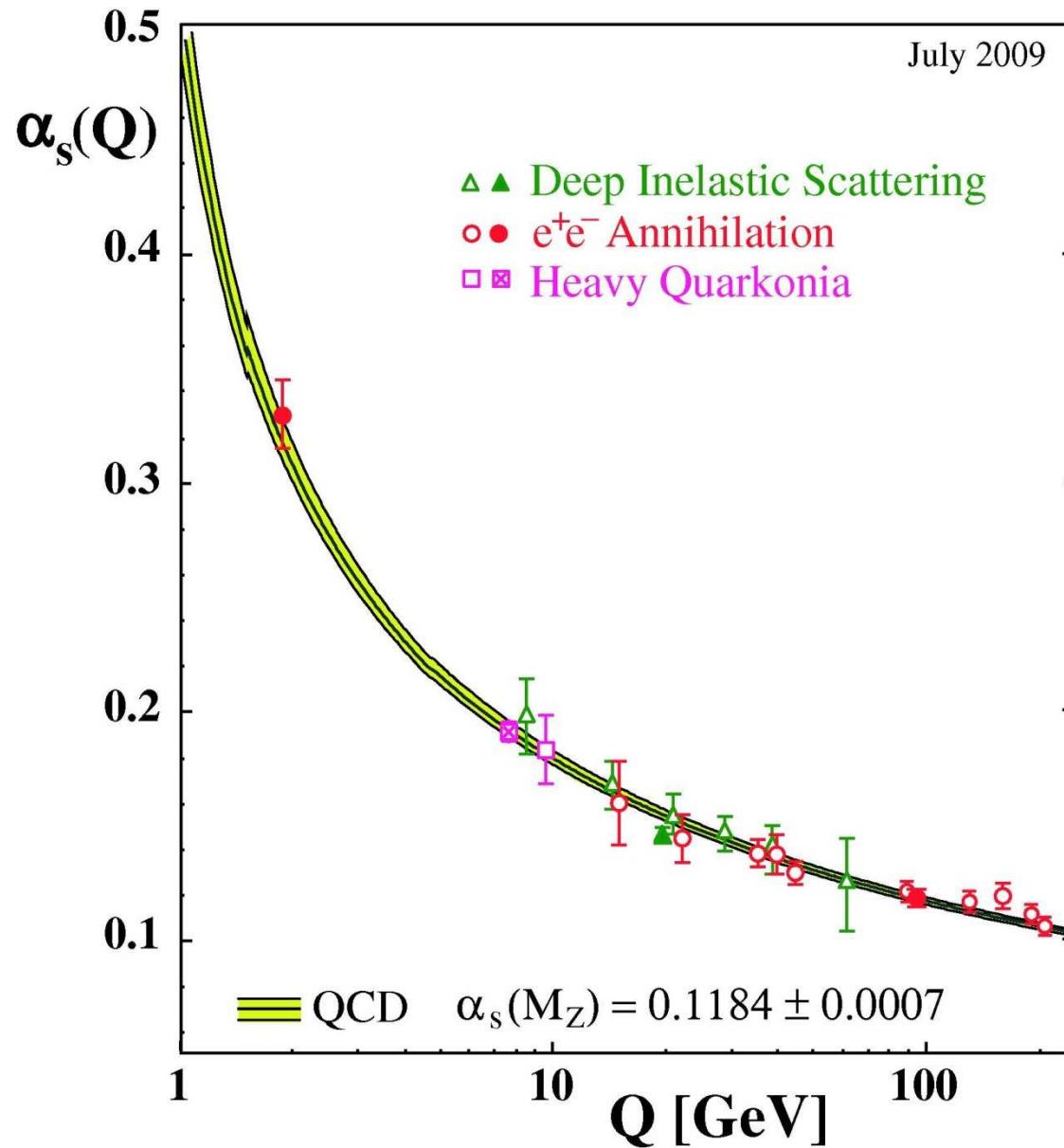


Frank Wilczek



David Politzer

Asymptotic Freedom in QCD



Bethke
hep-ex/0908.1135

Gross
Politzer
Wilczek
(1973)

Nobel Prize
2004

Hierarchical Structure of the CKM Matrix

$$\begin{pmatrix} 0.97 & s_{12} & s_{13} e^{-iy} \\ -s_{12} & 0.97 & s_{23} \\ s_{12}s_{23} - s_{13}e^{iy} & -s_{23} & 1 \end{pmatrix}$$

$$s_{13} \ll s_{23} \ll s_{12}$$

$$(4 \cdot 10^{-3}) \quad (4 \cdot 10^{-2}) \quad (0.2)$$



GIM Structure of FCNC's

Large \mathcal{CP} effects in B_d
 Small \mathcal{CP} effects in B_s
 Tiny \mathcal{CP} effects in K_L

$$A_{\mathcal{CP}}(B_d \rightarrow \psi K_s) \approx 0(1) \quad S_{\psi K_s} \approx \frac{2}{3}$$

$$A_{\mathcal{CP}}(B_s \rightarrow \psi \phi) \approx 0(10^{-2}) \quad S_{\psi \phi} \approx \frac{1}{25}$$

$$\varepsilon \approx 0(10^{-3}) \quad \varepsilon' \approx 0(10^{-6})$$

$$Br(K_L \rightarrow \pi^0 \bar{v} v) \approx 0(10^{-11})$$

PMNS: Negligible LFV
 (tiny v masses)

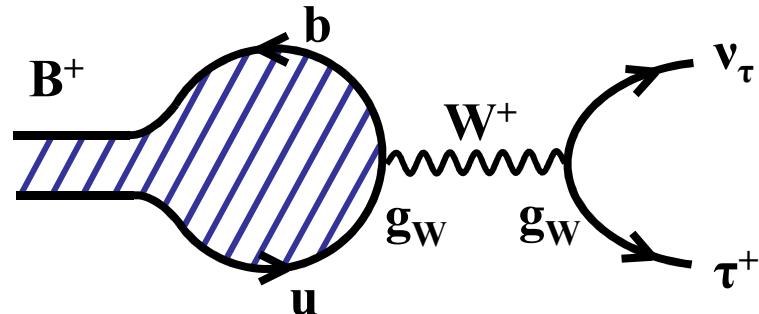
Crucial Question

**What is the Origin of
Particle Masses and the Reason
for their Hierarchy and
Hierarchy of their
Flavour-Changing Interactions ?**

**Which Dynamics could be responsible for the observed
structure of Electroweak Symmetry Breaking and of
Patterns seen in Flavour Physics ?**

- 1.** Could it be an elementary SM Higgs system with all problems of instability under radiative corrections (hierarchy problems) ?
Crucial questions in Particle Physics
- 2.** Could it be a new strong dynamics with a composite Higgs or without Higgs at all ?
- 3.** Could this dynamics help us understanding matter-antimatter asymmetry and the amount of dark matter in the universe ?
- 4.** Would these dynamics explain anomalies in flavour physics ?

Indirect Search: Precision Measurements of Decays of Mesons and Leptons



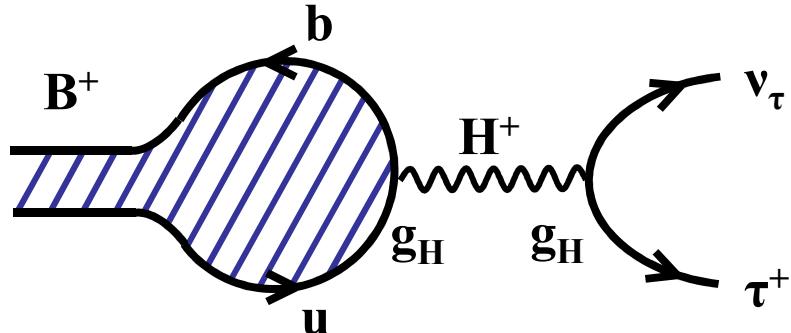
$$B^+ \rightarrow \tau^+ \nu_\tau$$

Standard Model

$$Br(B^+ \rightarrow \tau^+ \nu_\tau)_{SM} = \left| A \frac{g_w^2}{M_w^2} \right|^2$$

$m_B \approx 5 \text{ GeV}$

A, B – parameters of a given theory



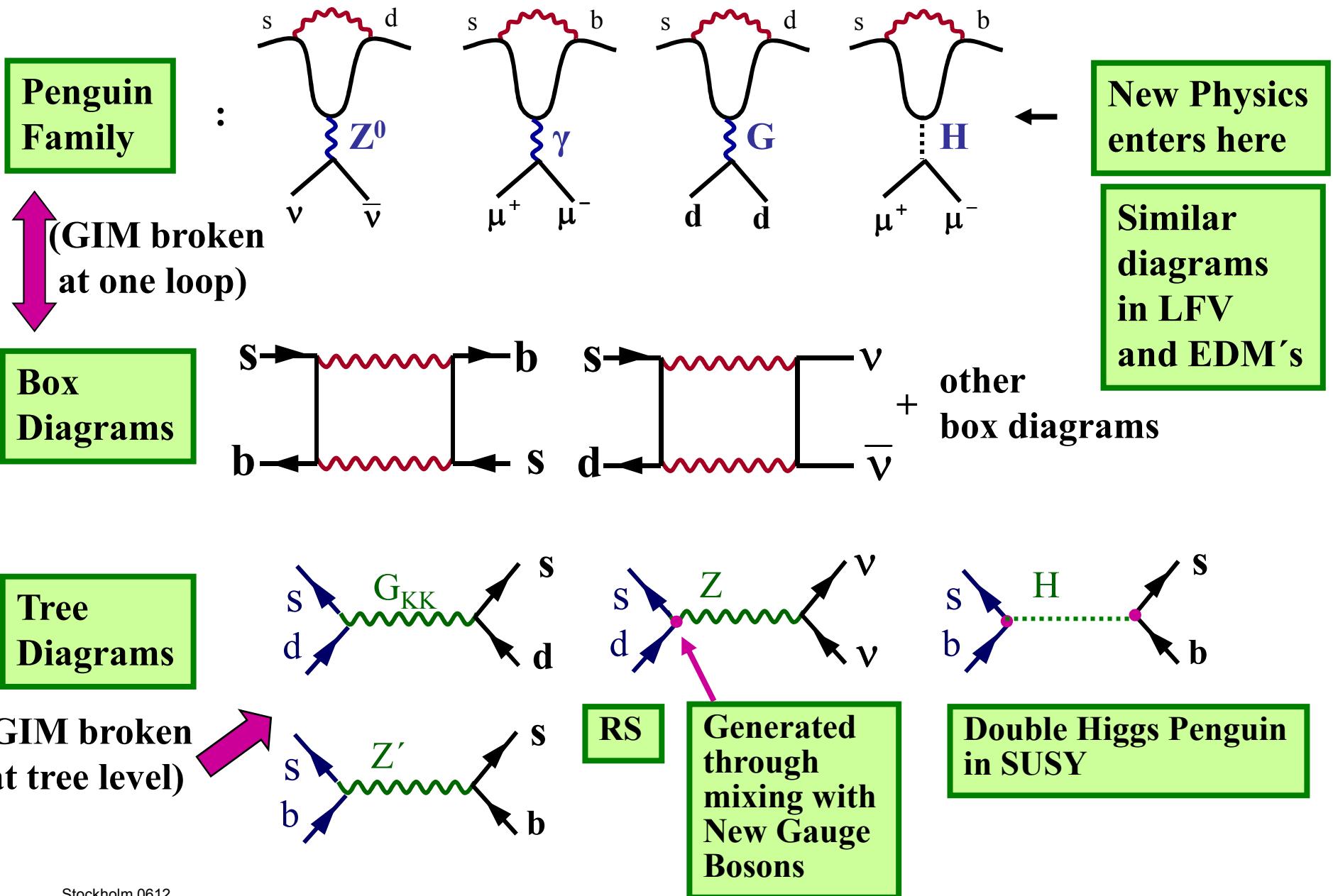
Contribution
of a new
charged Heavy
Particle

$$Br(B^+ \rightarrow \tau^+ \nu_\tau) = \left| A \frac{g_w^2}{M_w^2} + B \frac{g_H^2}{M_H^2} \right|^2$$

$$\Delta = Br(B^+ \rightarrow \tau^+ \nu_\tau) - Br(B^+ \rightarrow \tau^+ \nu_\tau)_{SM} \neq 0$$

Signal of a
new particle

Arena of FCNC Processes



In Order to identify New Physics through Flavour Physics

We need

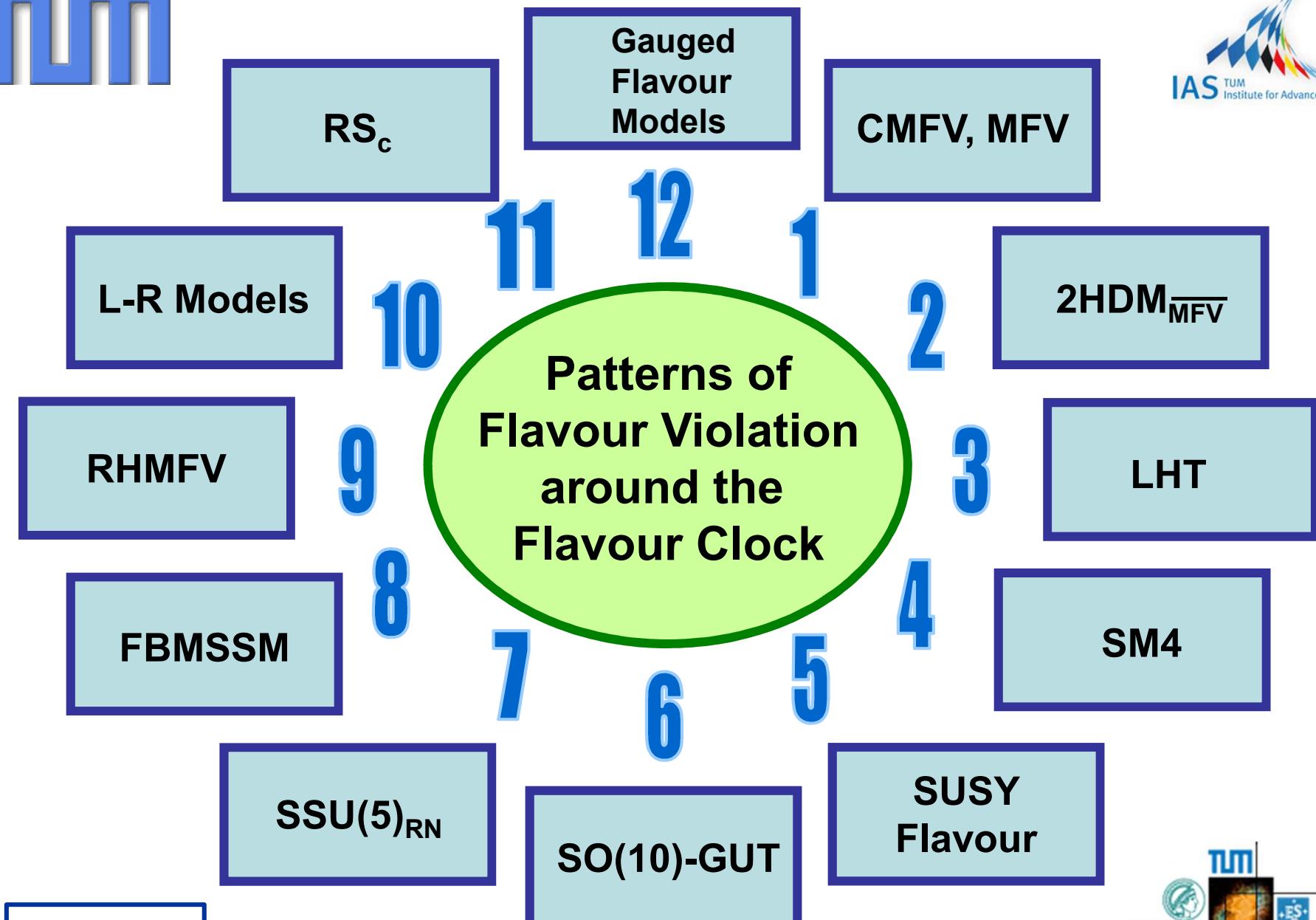
- 1.** Many precision measurements of many observables and precise theory.
- 2.** Study Patterns on Flavour Violation in various New Physics models (correlations between many flavour observables).

...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 ($1/\Lambda^2, \dots$)**



Expedition

Attouniverse → Zeptouniverse

Junior BSM Collaborators M



W.Altmannshofer



P.Paradisi



D.Straub



B.Duling



A.Poschenrieder



S.Recksiegel



T.Heidsieck



C.Promberger



T.Feldmann



D.Guadagnoli



L.Merlo



R.Ziegler



A.Weiler



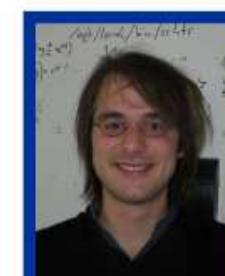
O.Cata



M.Wick



L.Calibbi



E.Stamou



M.Nagai

Senior BSM Collaborators M



W.Bardeen



I.Bigi



G.Branco



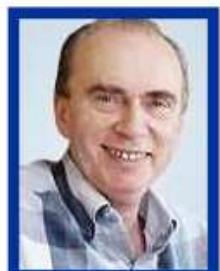
G.Buchalla



R.Fleischer



C.Grojean



S.Pokorski



G.Isidori



P.Q.Hung



U.Nierste



M.Gorbahn



S.Jäger



L.Silvestrini



P.Gambino



A.Romanino



G.Colangelo



C.Bobeth



J.Rosiek

BSM Collaborators F



M.V.Carlucci



S.Gori



C.Tarantino



F. de Fazio



M.Blanke



K.Gemmler



J.Girrbach



S.Uhlig



M.Albrecht



P.Ball



A.Bharucha

Present ERC Collaborators



M.Blanke



G.Buchalla



M.V.Carlucci



O.Cata



F. de Fazio



J.Drobnak



K.Gemmler



J.Girrbach



T.Heidsieck



A.Ibarra



G.Isidori



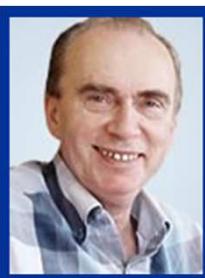
L.Merlo



M.Nagai



P.Paradisi



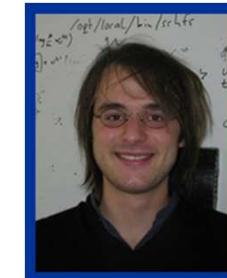
S.Pokorski



M.Ratz



Y.Omura



E.Stamou



R.Ziegler

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



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



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

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

CMFV Candles of Flavour Physics

1.

$$S_{\psi K_s} = \left(S_{\psi K_s} \right)^{\text{SM}}$$

$$S_{\psi \phi} = \left(S_{\psi \phi} \right)^{\text{SM}}$$

2.

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

3.

$$\frac{\text{Br}(B_d \rightarrow \mu^+ \mu^-)}{\text{Br}(B_s \rightarrow \mu^+ \mu^-)} = \frac{\tau(B_d)}{\tau(B_s)} \frac{m_{B_d}}{m_{B_s}} \frac{F_{B_d}^2}{F_{B_s}^2} \left| \frac{V_{td}}{V_{ts}} \right|^2 \quad (\text{MFV, CMFV})$$

4.

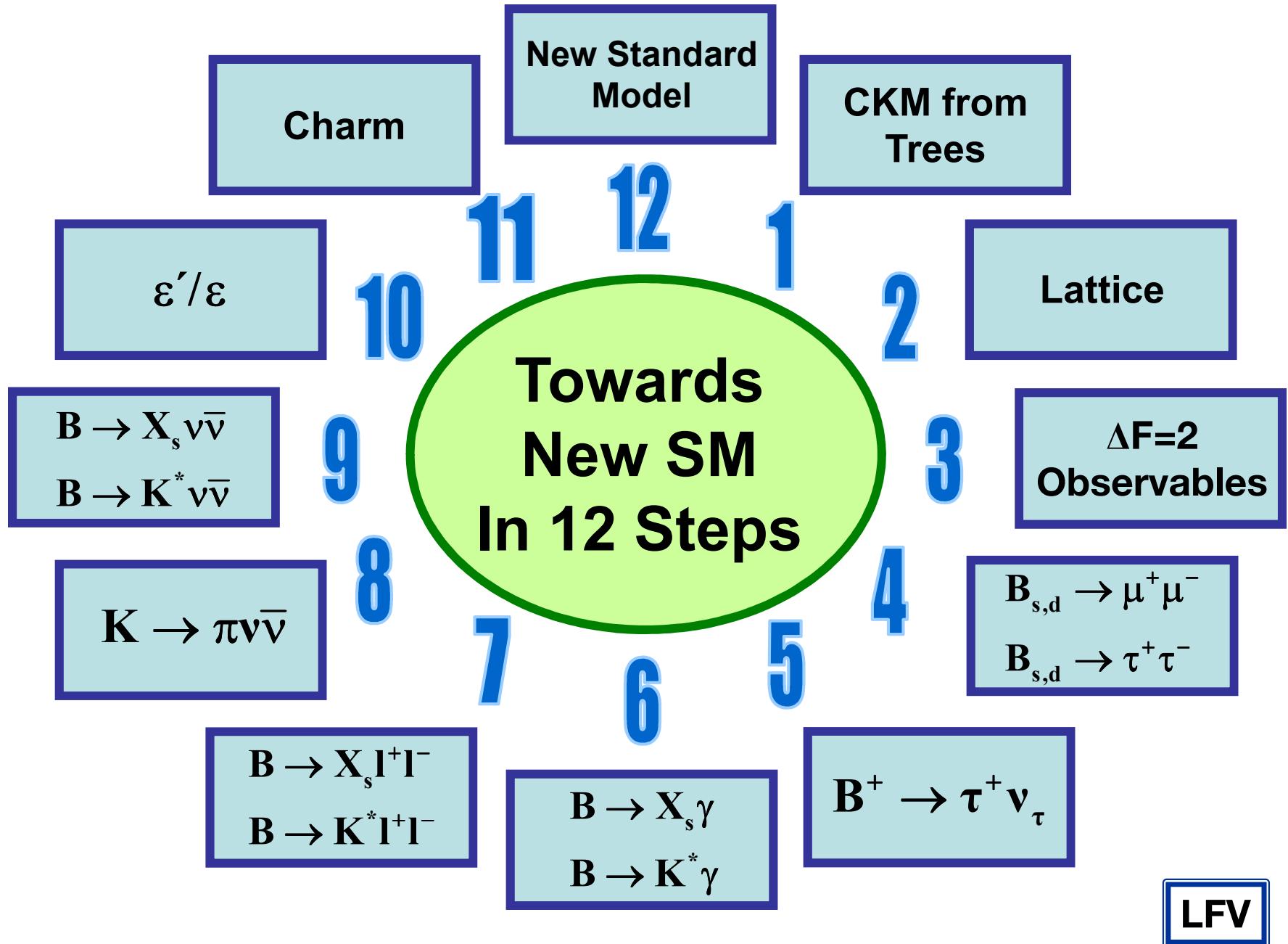
$$\frac{\text{Br}(B_s \rightarrow \mu^+ \mu^-)}{\text{Br}(B_d \rightarrow \mu^+ \mu^-)} = \frac{\hat{B}_d}{\hat{B}_s} \frac{\tau(B_s)}{\tau(B_d)} \frac{\Delta M_s}{\Delta M_d} \quad (\text{CMFV})$$

5.

All FCNC Processes can be described by 7 real and flavour universal gauge independent master functions.

S, X, Y, Z, E, D', E' 

Stringent Correlations
between CPV and Rare Decays
in K , B_d and B_s systems



2.

Anomalies in Flavour Data

Departures from Standard Model Expectations

CP	$K^0 - \bar{K}^0$	(ε_K)	$\frac{ \varepsilon_K _{\text{SM}}}{ \varepsilon_K _{\text{exp}}} \approx 0.80 \pm 0.10$	(AJB, Guadagnoli) (Brod, Gorbahn)
	$B_d^0 - \bar{B}_d^0$	$(S_{\psi K_s})$	$S_{\psi K_s} \approx 0.82 \pm 0.04$ (SM) (UTfit)	
	$B_s^0 - \bar{B}_s^0$	$(S_{\psi\phi})$	$S_{\psi\phi} = 0.678 \pm 0.022$ (exp)	

$$S_{\psi\phi} = \begin{cases} 0.035 \pm 0.002 & (\text{SM}) \\ 0.002 \pm 0.087 & (\text{LHCb}) \end{cases}$$

Ok
now

$$\frac{\text{Br}(B^+ \rightarrow \tau^+ \nu)_\text{exp}}{\text{Br}(B^+ \rightarrow \tau^+ \nu)_\text{SM}} \approx 2.2 \pm 0.5$$

$$|V_{ub}| = \begin{cases} 4.3 \cdot 10^{-3} & \text{Inclusive Decays } (B \rightarrow X_u l \nu) \text{ (Right-handed currents? Crivellin; Mannel et al.)} \\ 3.4 \cdot 10^{-3} & \text{Exclusive Decays } (B \rightarrow \rho l \nu) \text{ (AJB, Gemmeler, Isidori)} \end{cases}$$

Inclusive Decays $(B \rightarrow X_u l \nu)$ (Right-handed currents?
Crivellin;
Mannel et al.
AJB, Gemmeler,
Isidori)

Exclusive Decays $(B \rightarrow \rho l \nu)$ (AJB, Gemmeler,
Isidori)

and SM-CKM fit

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)

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

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

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

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

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

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

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

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

$$S_{\psi K_s}, S_{\psi \phi}$$

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 $|\epsilon_K|$ implies automatically enhancements
Of ΔM_s and ΔM_d spoiling the agreement with data

$Br(B^+ \rightarrow \tau^+ \nu_\tau)$ factor 2 below the data

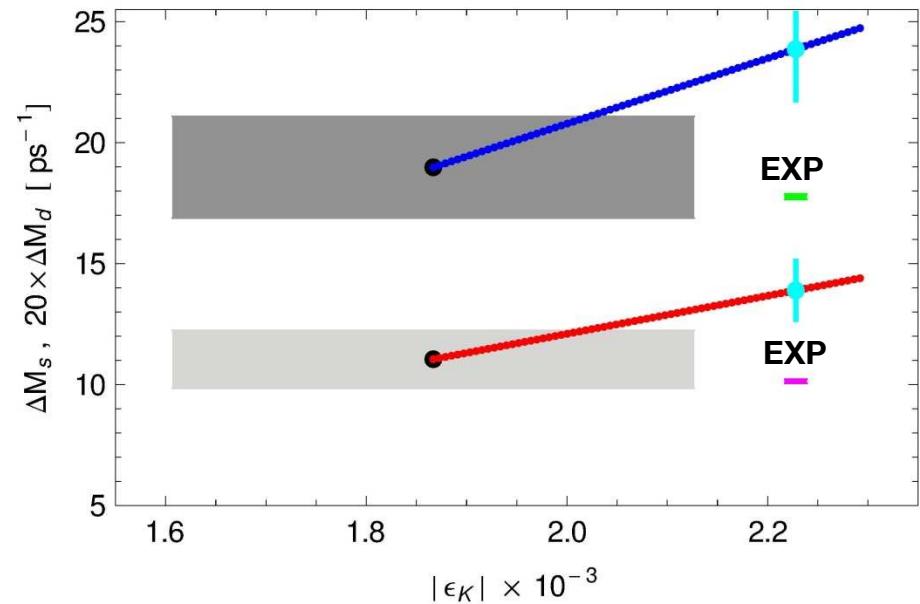
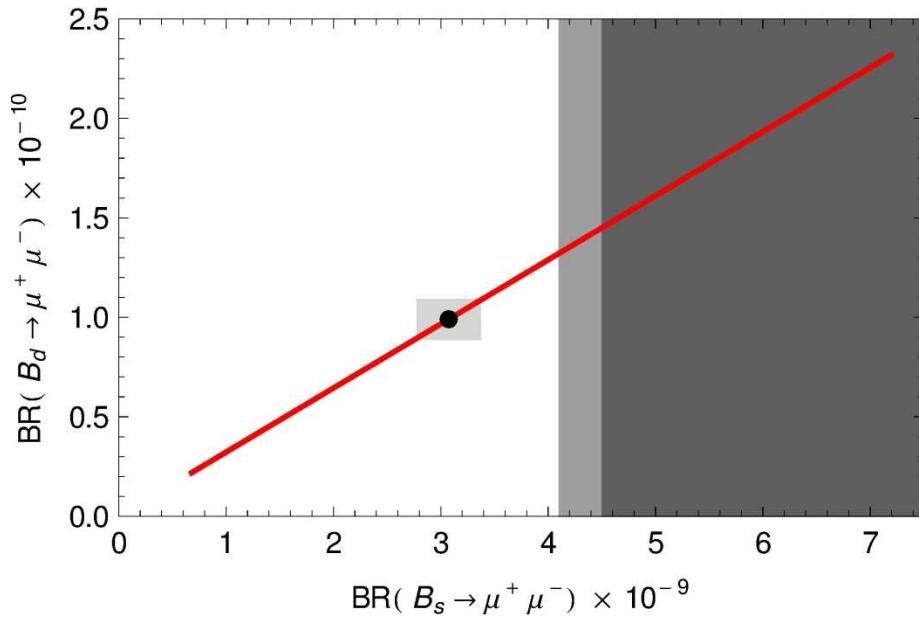
Conclusion:

CMFV under pressure

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

Constrained Minimal Flavour Violation

AJB + J. Girrbach (2012)



$$\text{Br}(B_d \rightarrow \mu^+ \mu^-) \leq 1.3 \cdot 10^{-10}$$

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

Tension within CMFV

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

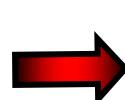
Non-Supersymmetric 2HDM And Flavour Blind Phases

With MFV

2HDM_{MFV}

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

{Tree-Level Higgs Exchanges}



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

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

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

Unambiguous Implications of 2HDM_{MFV}

(Stringent Correlations)

Step 1

: Need $|V_{ub}| \approx 4.4 \cdot 10^{-3}$ to get $\varepsilon_K^{\text{exp}}$



(Exp : $1.7 \pm 0.3 \cdot 10^{-4}$)

Step 2

: $\text{Br}(B^+ \rightarrow \tau^+ \nu_\tau) \Rightarrow 1.3 \cdot 10^{-4}$ (Enhancement by 1.7 over SM value)

$S_{\psi K_s} = \sin 2\beta \approx 0.82$ compared to $S_{\psi K_s}^{\text{exp}} \approx 0.68 \pm 0.02$

Step 3

: $S_{\psi K} = \sin(2\beta - \theta_H^d) \rightarrow S_{\psi K_s} \approx 0.68$ θ_H^d = new phase from Higgs sector

Step 4

: $S_{\psi \varphi} = \sin(\underbrace{2\beta_s}_{\text{small}} + \theta_H^s)$ $\begin{cases} \theta_H^s \approx \frac{m_s}{m_d} \theta_H^d \approx 17 \theta_H^d & (\text{Yukawa's}) \\ \theta_H^s \approx \theta_H^d & (\text{Higgs Potential}) \end{cases}$ ★

Step 5

: With enhanced $S_{\psi \varphi}$: $\left. \begin{array}{l} \text{Br}(B_s \rightarrow \mu^+ \mu^-) \\ \text{Br}(B_d \rightarrow \mu^+ \mu^-) \end{array} \right\}$ still enhanced for small $S_{\psi \varphi}$?

Basic Questions

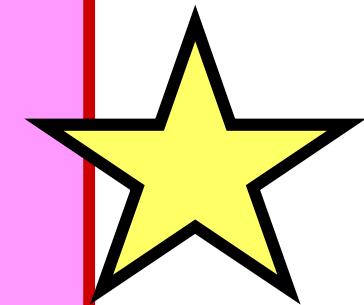
Can 2HDM_{MFV} bring down

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

without violating the data

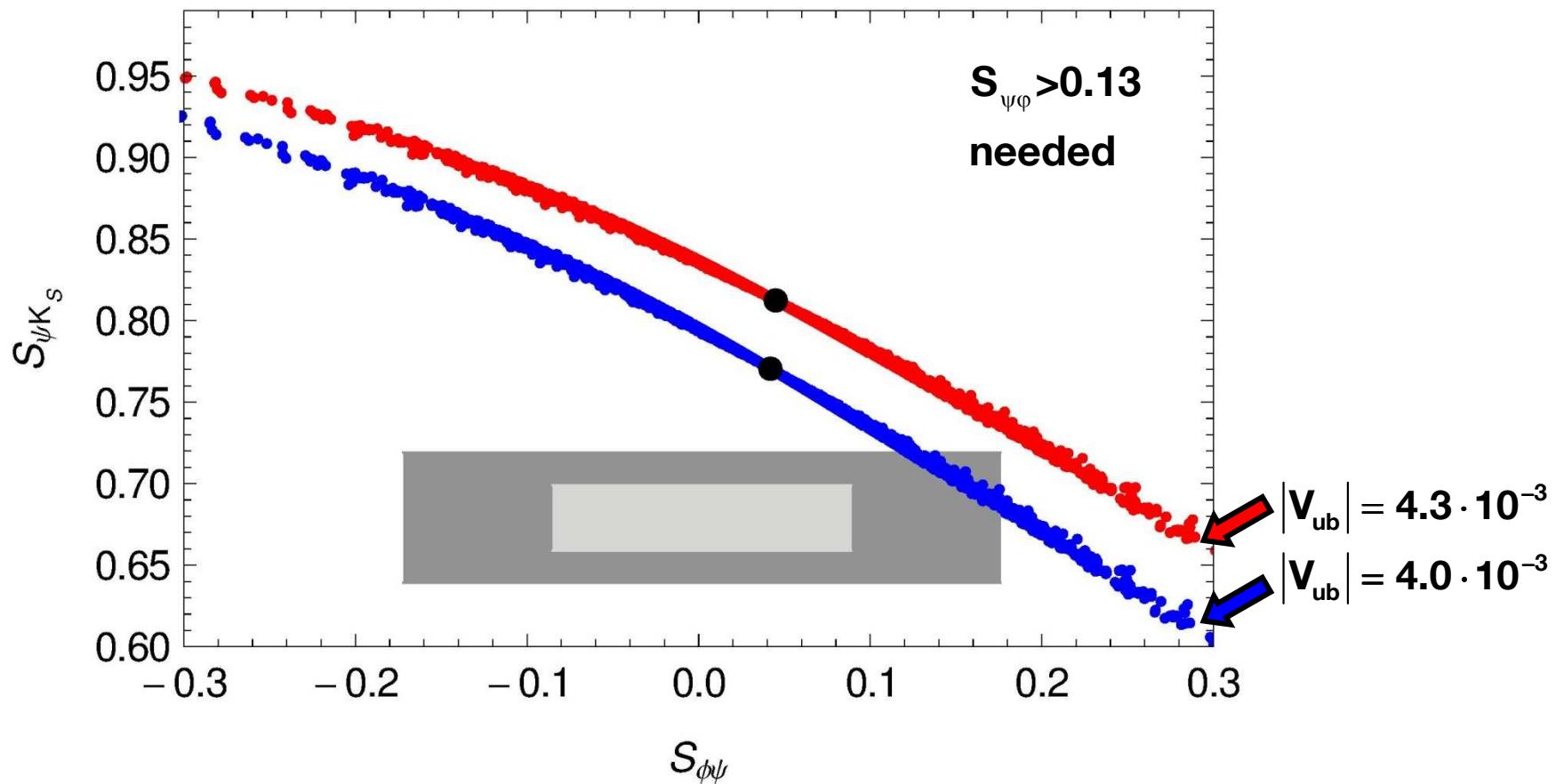
on $S_{\psi\varphi}$ and $\text{Br}(B_{s,d} \rightarrow \mu^+\mu^-)$

from LHCb ?



2HDM_{MFV} Facing LHCb Data

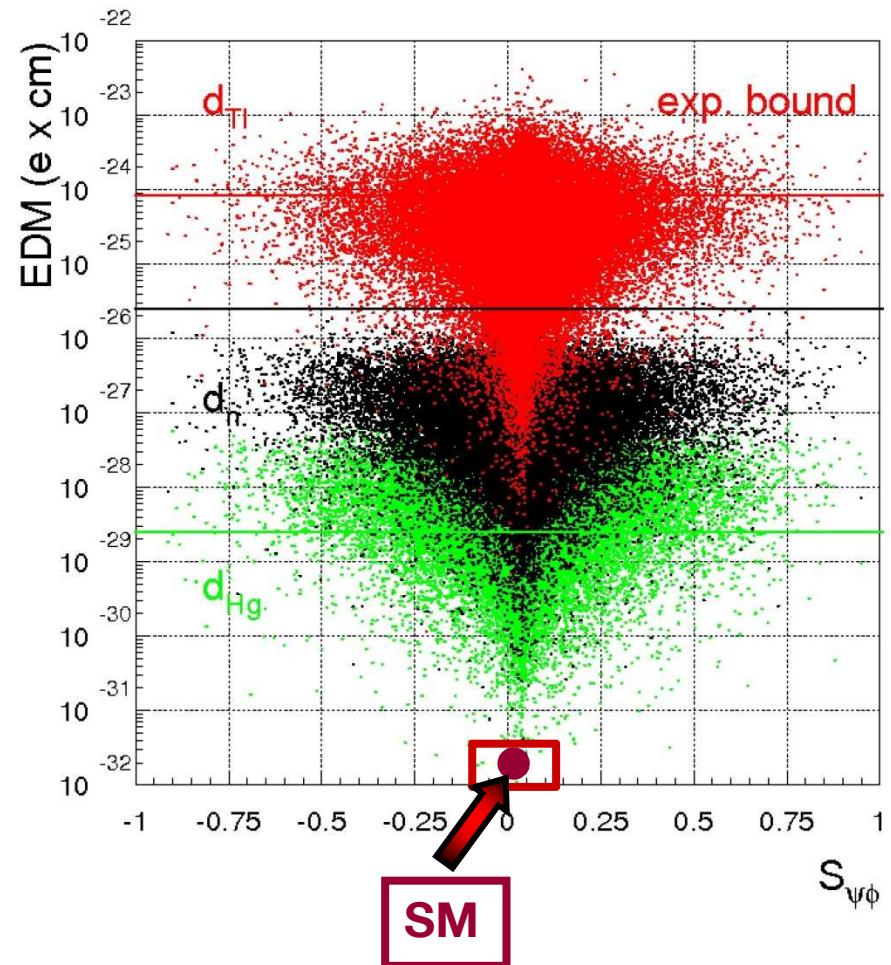
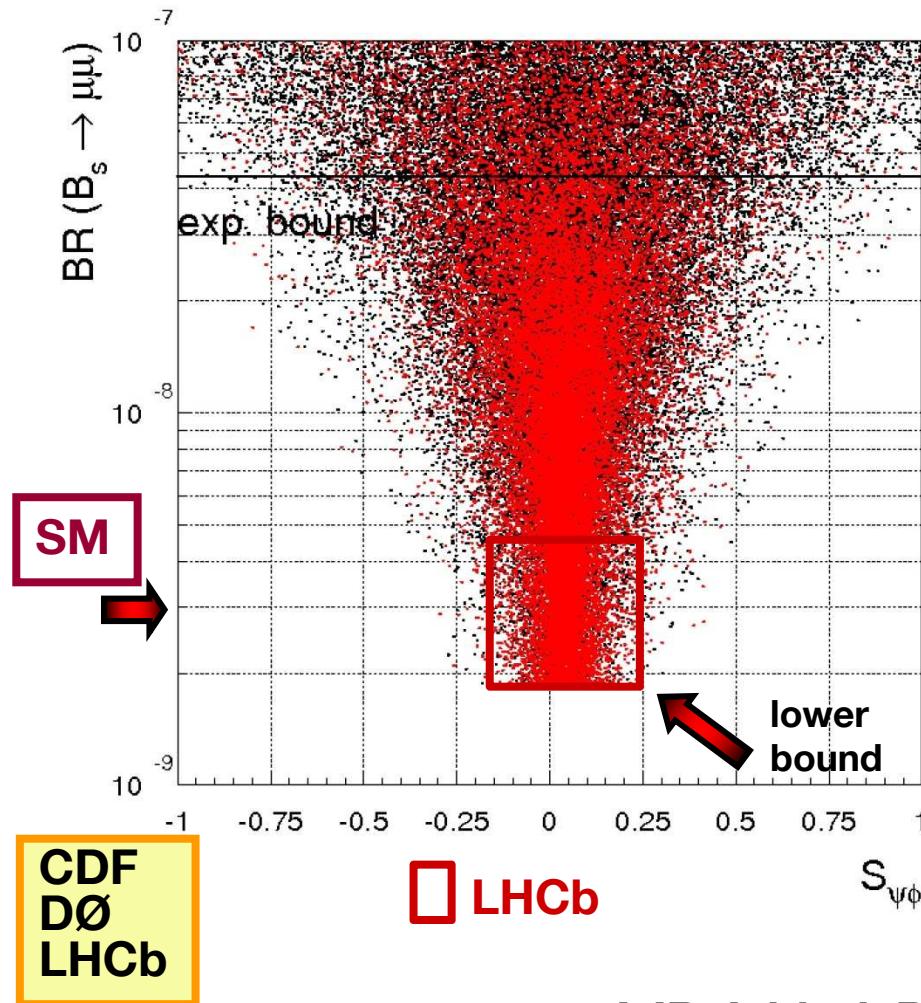
AJB, Girrbach, Nagai, Paradisi (2012)



More on 2HDM with MFV and Flavour Blind Phases

2HDM_{MFV}

2012: no problems with both observables



AJB, Isidori, Paradisi 1007.5291

Conclusion on 2HDM_{MFV}

Still alive but finding

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

will rule it out.



Littlest Higgs Model with T-Parity

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

**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
 $|S_{\psi\phi}| \leq 0.25$
 $\{S_{\psi\phi} > 0.20\} \Rightarrow \begin{cases} \text{No New Physics Effects} \\ \text{in } K^+ \rightarrow \pi^+ v\bar{v}, K_L \rightarrow \pi^0 v\bar{v} \end{cases}$

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
(0909.1333)

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

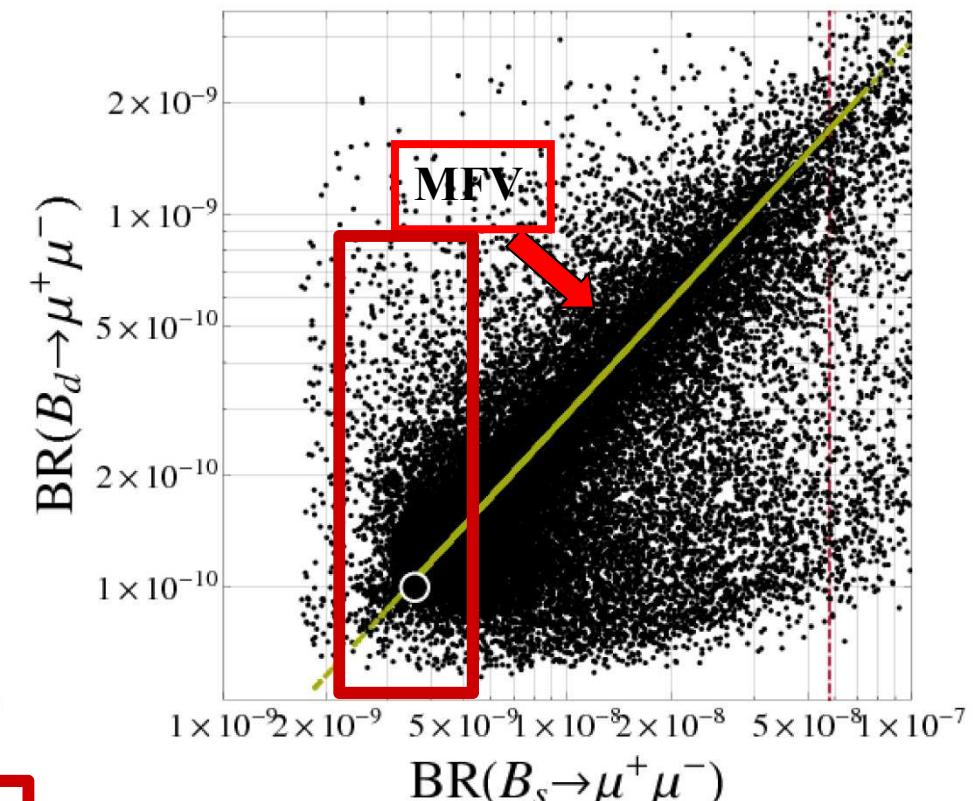
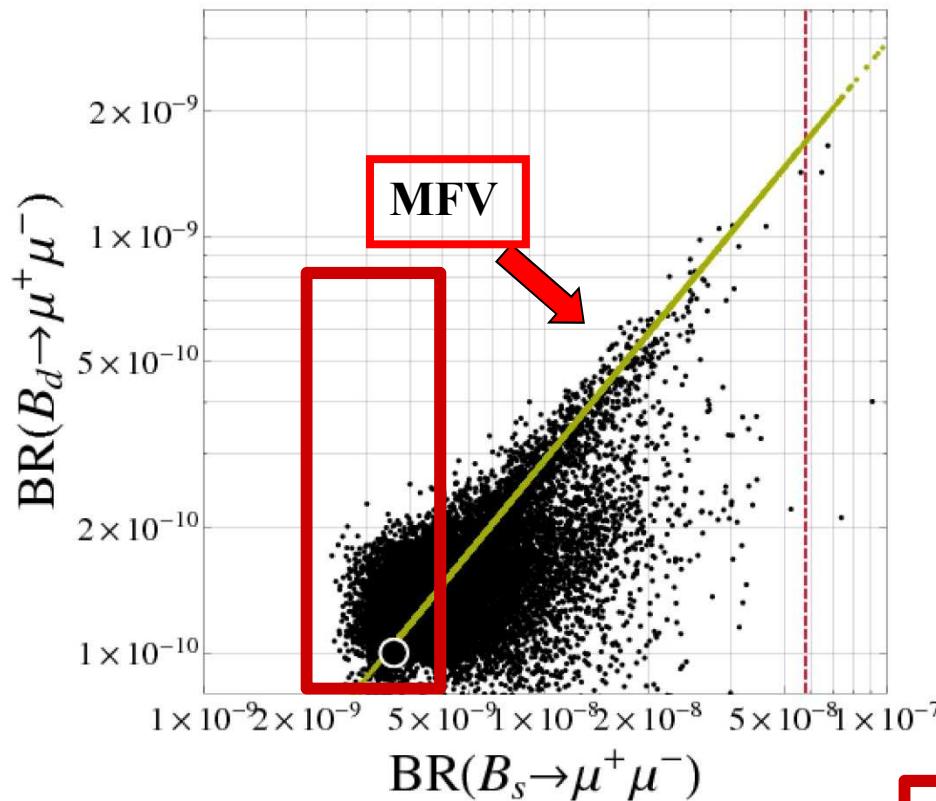
**SUSY
(Flavour)**

Altmannshofer, AJB, Gori, Paradisi, Straub

● = SM

MFV

AJB; Hurth, Isidori, Kamenik, Mescia



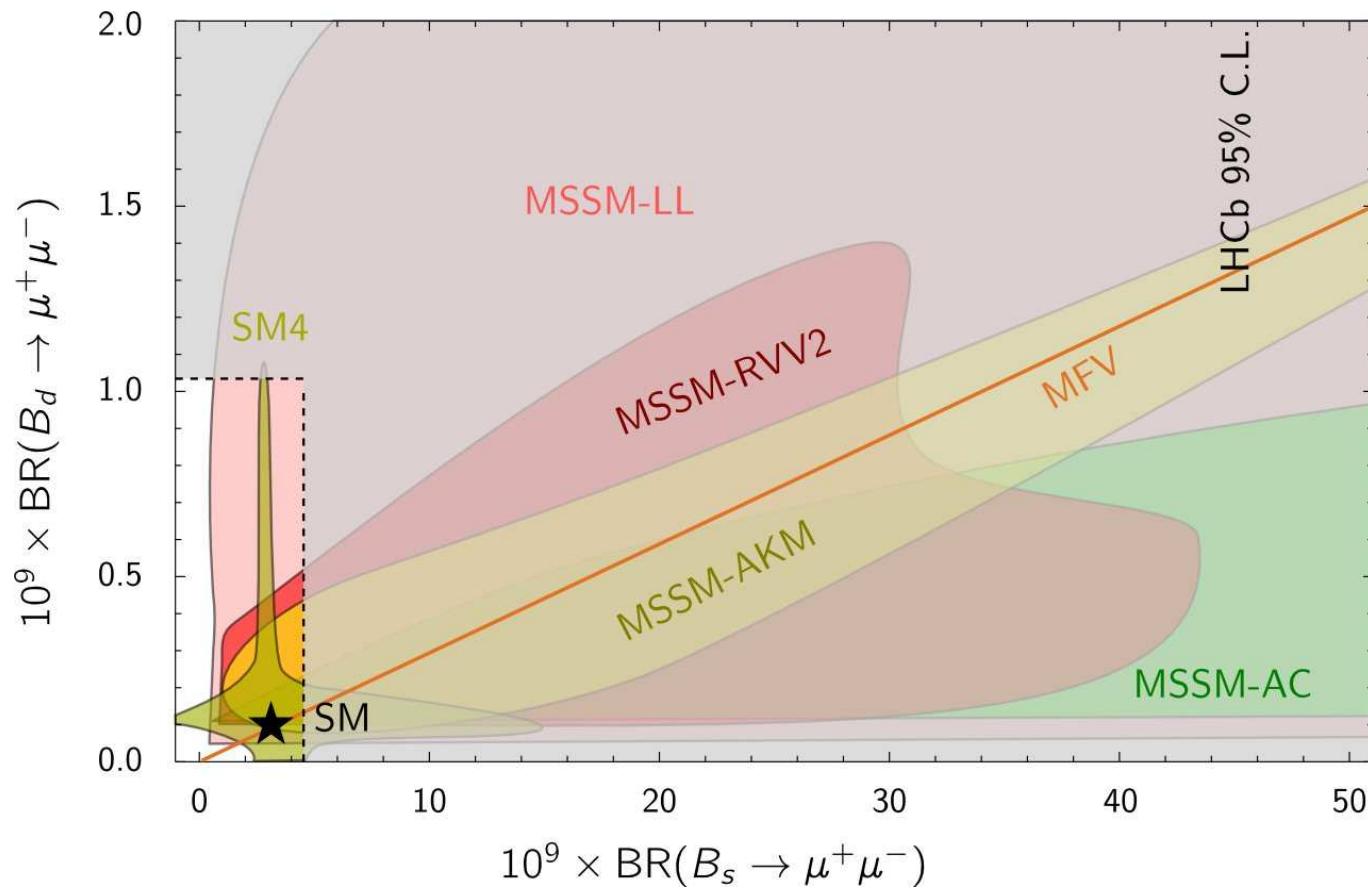
RVV2 (RH currents)

LHCb

LH currents

Supersymmetric Models Facing LHCb Data

ABGPS
Straub 1012.3893



Models with new left-handed currents favoured

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

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

RHMFV

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

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

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

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

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

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

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
Gemmeler
Heidsieck
(1111.5014)

Minimal Effective Model with Right-Handed Currents

AJB, Gemmeler, 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 $S_{\psi\varphi}$ 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 $S_{\psi\varphi}$ 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

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

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

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

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

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

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

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

(E787, E949 Brookhaven)

(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%

Important Messages

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.

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
 $|V_{ub}|$**

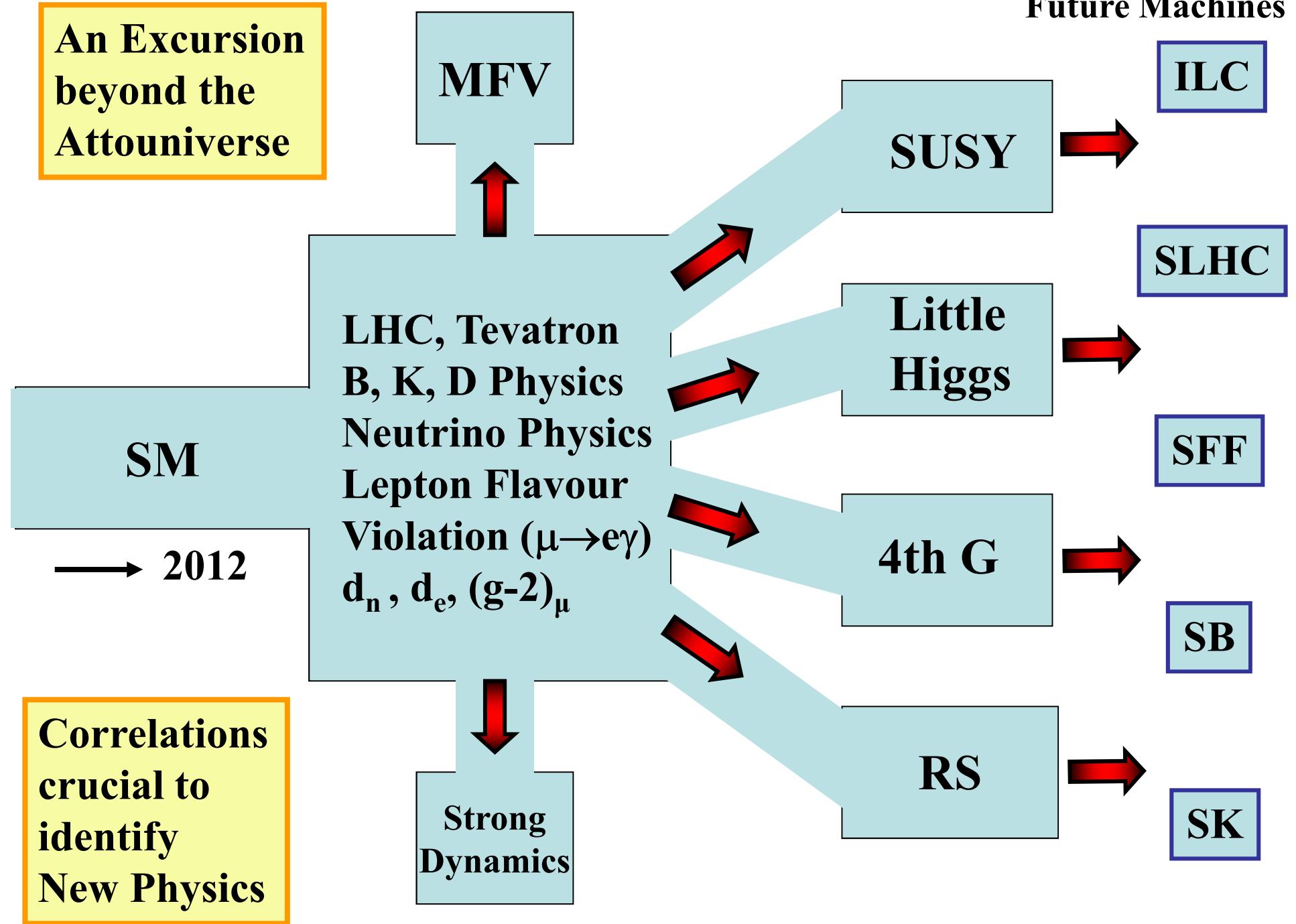
:

**CMFV,
Gauged Flavour
Models**

**Large
 $|V_{ub}|$**

:

**2HDM_{MFV}
RHMFV**



New Standard Model

CKM from
Trees

Charm

ε'/ε

$B \rightarrow X_s v\bar{v}$
 $B \rightarrow K^* v\bar{v}$

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

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

Towards
New SM
In 12 Steps

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

$B^+ \rightarrow \tau^+ v_\tau$

$\Delta F=2$
Observables

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

Lattice

2

3

4

1

12

7

6

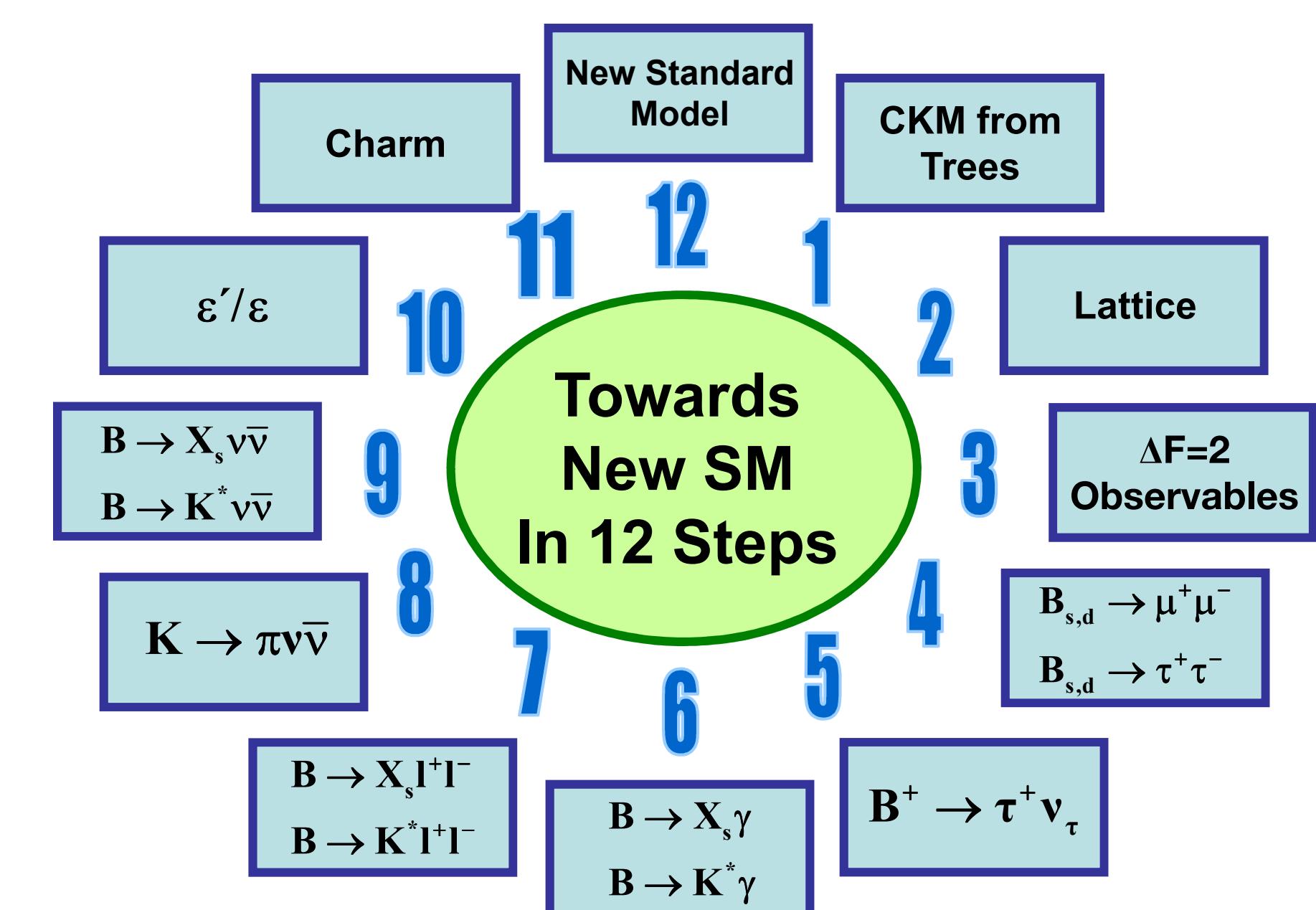
5

9

8

10

11



Final Messages

- 1.** SM does not offer a satisfactory description of present flavour data.
- 2.** CMFV does not improve on this.
- 3.** 2HDM $_{\overline{\text{MFV}}}$ under pressure because of $S_{\psi K_s} \leftrightarrow S_{\psi\varphi}$ correlation.
Prediction: $S_{\psi\varphi} > (S_{\psi\varphi})^{\text{SM}} > 0$
- 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



Sign of $S_{\psi\varphi}$



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



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



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



Lepton Flavour Violation

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

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

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



ε'/ε provided QCD Penguin hadronic matrix under control

Standard
Candles
of
Flavour
Physics

Should we be frustrated after LHC, LHCb Data?

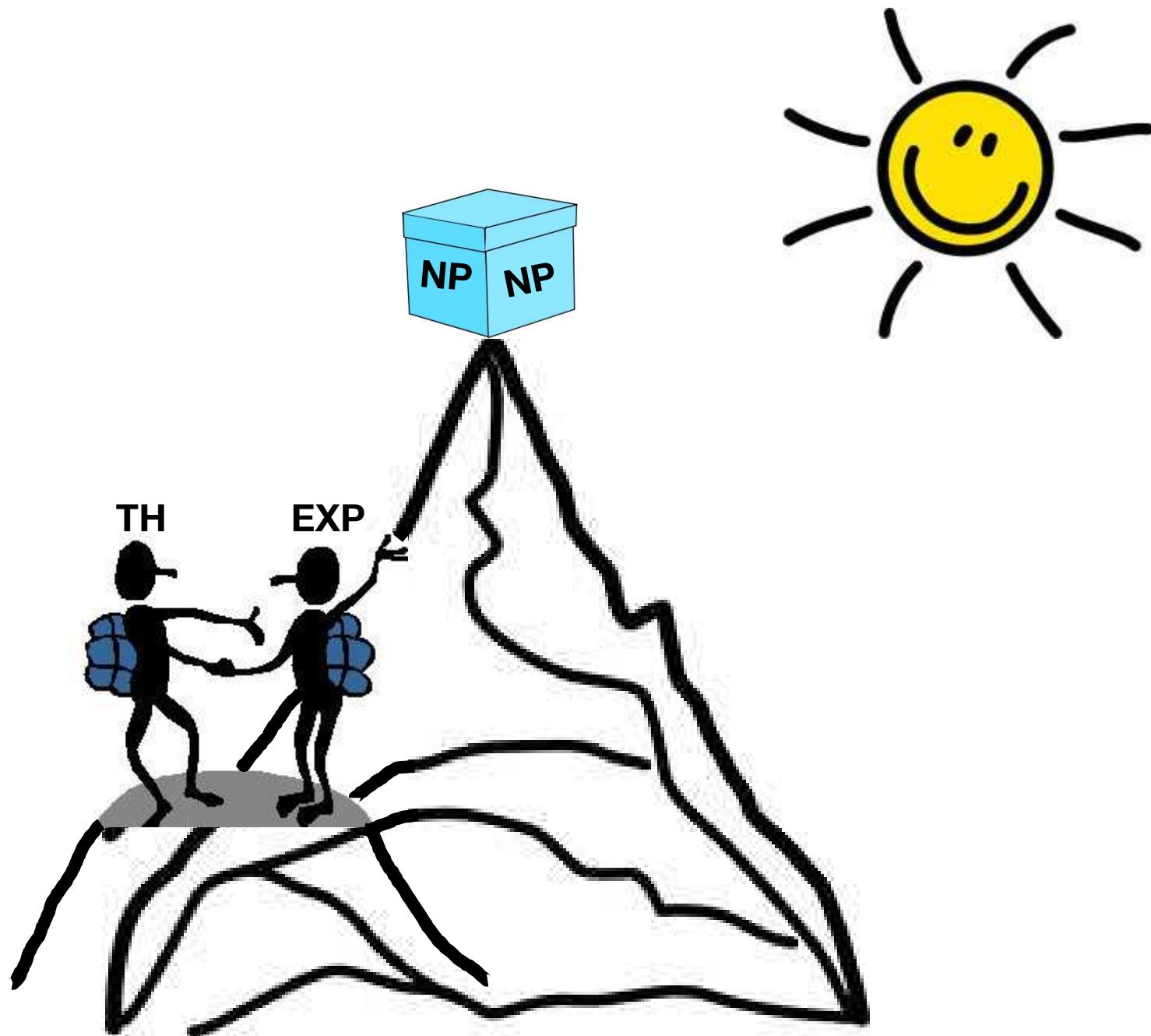
**Should we be frustrated
after LHC, LHCb Data?**

No, no, no !!!

**Should we be frustrated
after LHC, LHCb Data?**

No, no, no !!!

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

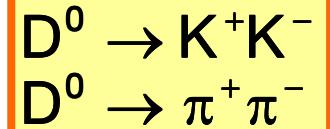


Backup

First Evidence for CP Violation in Charm

Difference
in time-
integrated
CP asymmetries

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



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

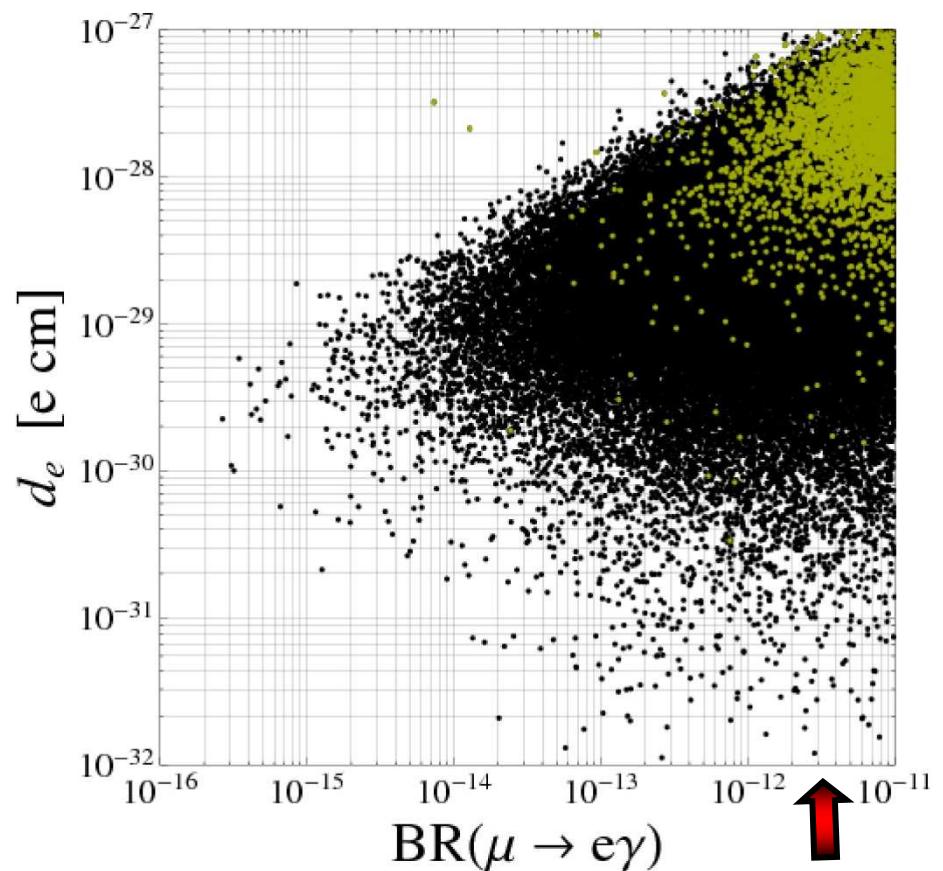
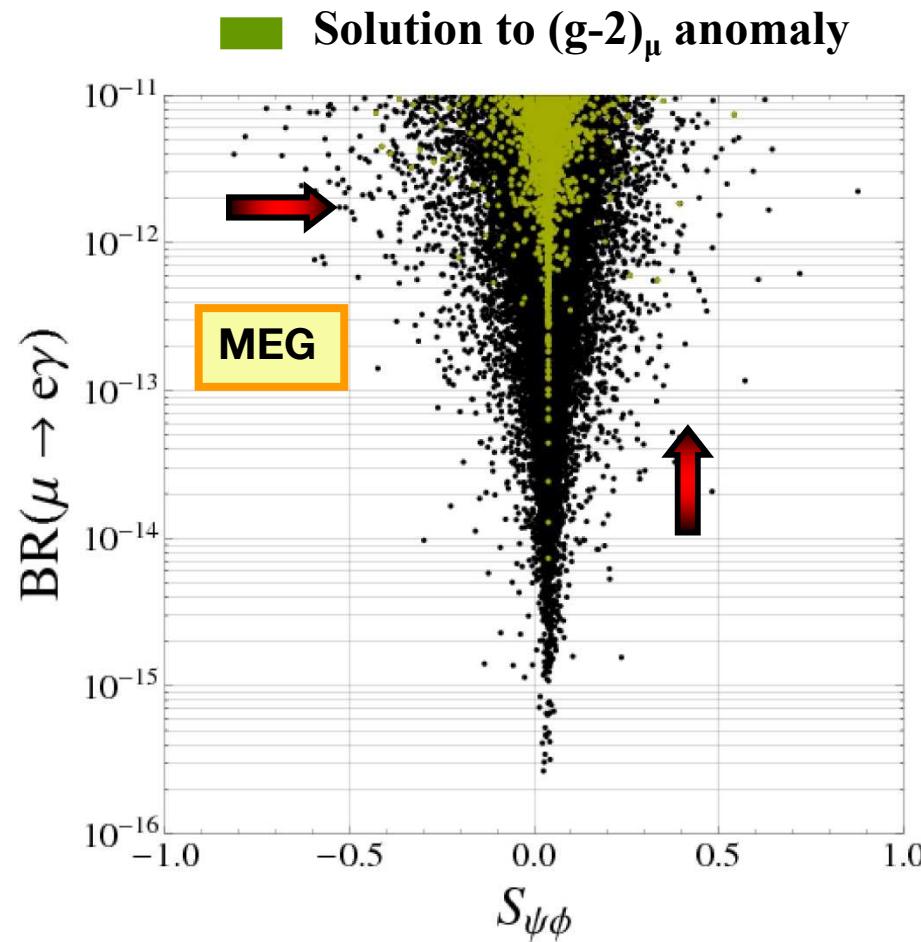
Significance 3.5σ ; Sensitive mainly to direct CPV

**VERY
PRELIMINARY**

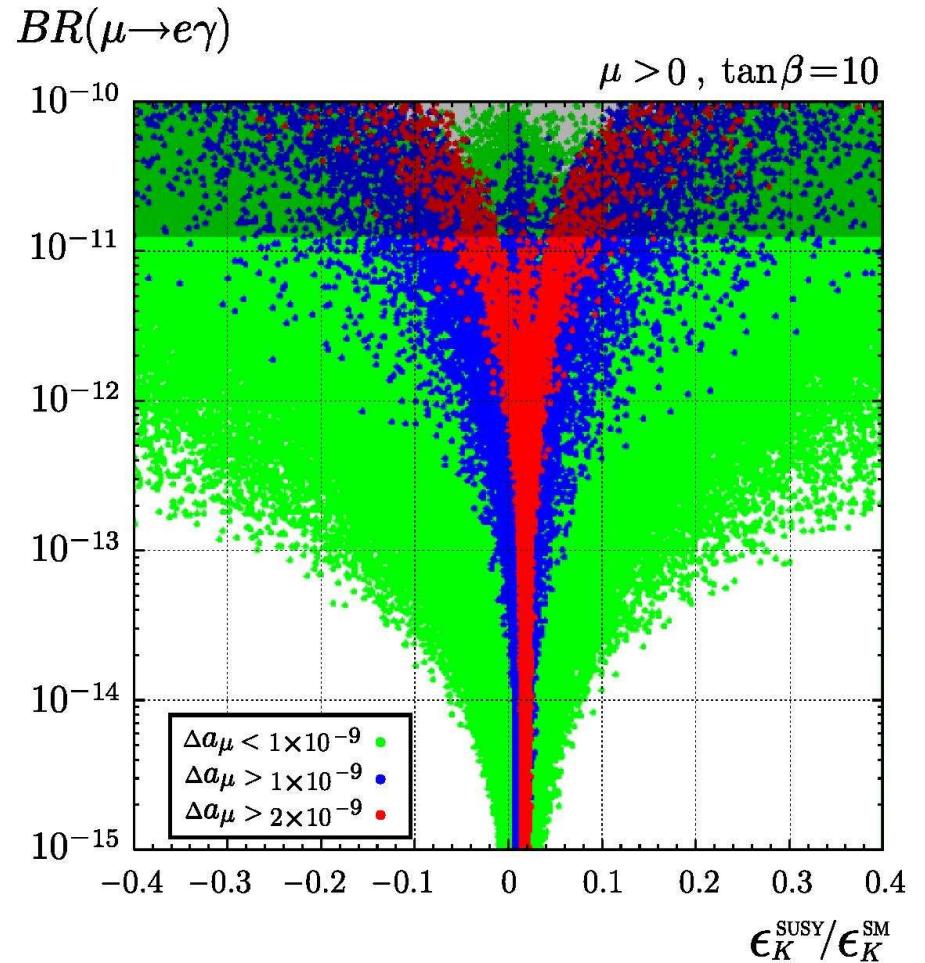
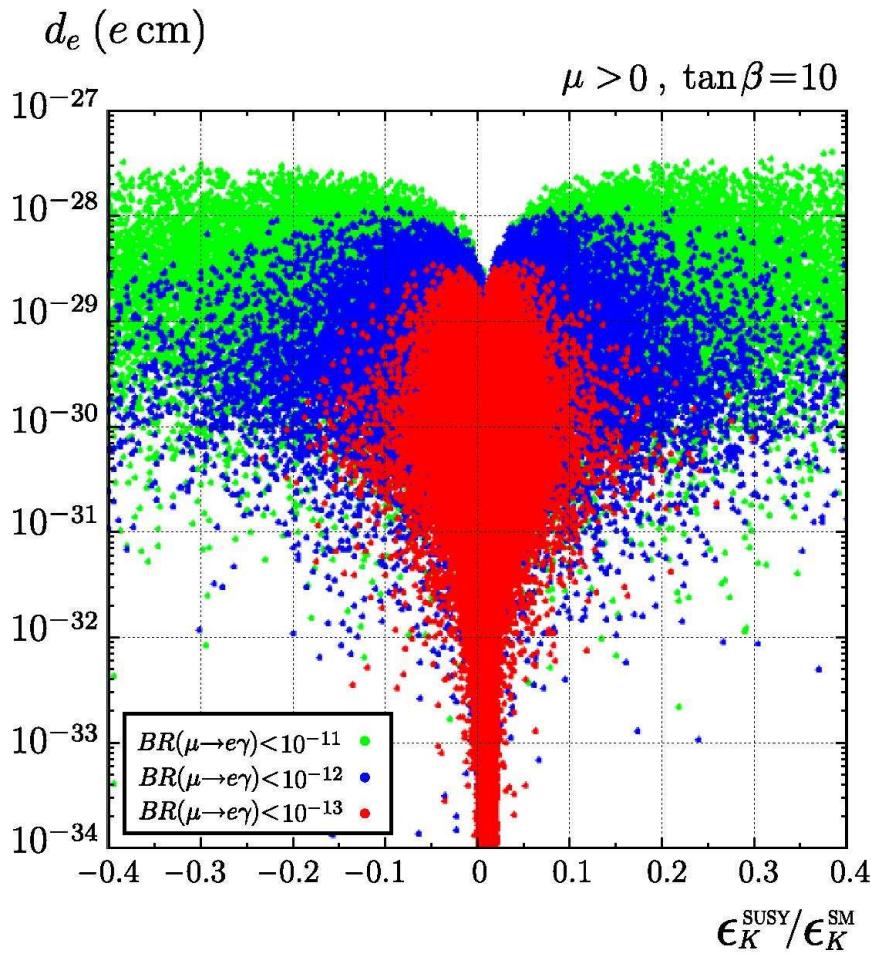
Central value larger than SM expectation
but theoretical uncertainties in direct CPV
are substantial.

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

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



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



AJB, Nagai, Paradisi, 1011.1993



$$B_s \rightarrow \mu^+ \mu^- \text{ and } B_d \rightarrow \mu^+ \mu^-$$

Z-Penguin (SM
+ Boxes CMFV)

SM

$$\begin{aligned} Br(B_s \rightarrow \mu^+ \mu^-) &= (3.1 \pm 0.2) \cdot 10^{-9} \\ Br(B_d \rightarrow \mu^+ \mu^-) &= (1.0 \pm 0.1) \cdot 10^{-10} \end{aligned}$$

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

AJB (03)

CMFV
“Golden Relation”

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

$(\Delta B = 1)$ (0.95 ± 0.03) $(\Delta B = 2)$
Lattice

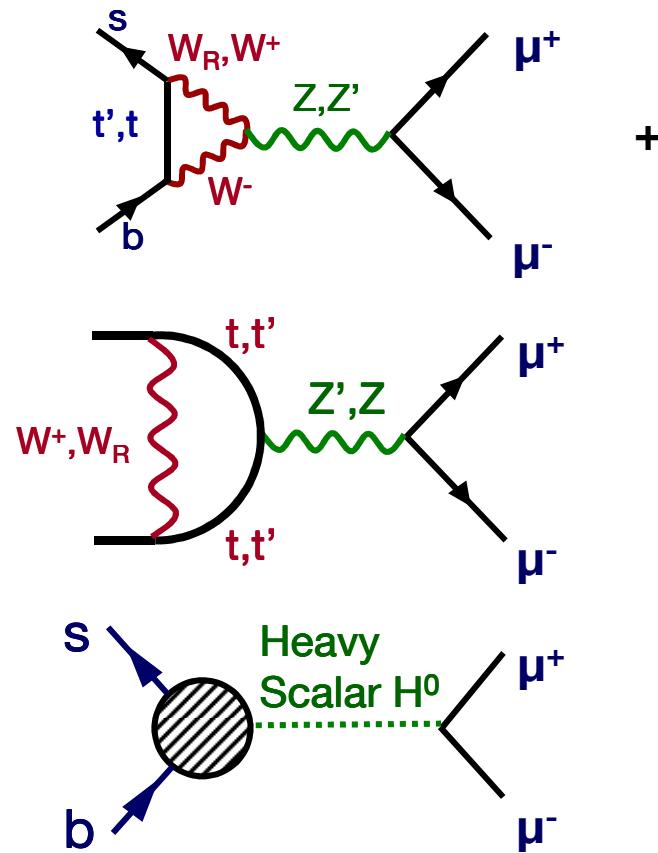
Valid in all CMFV models

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

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

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

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



Other Z-Penguins
and Boxes

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

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

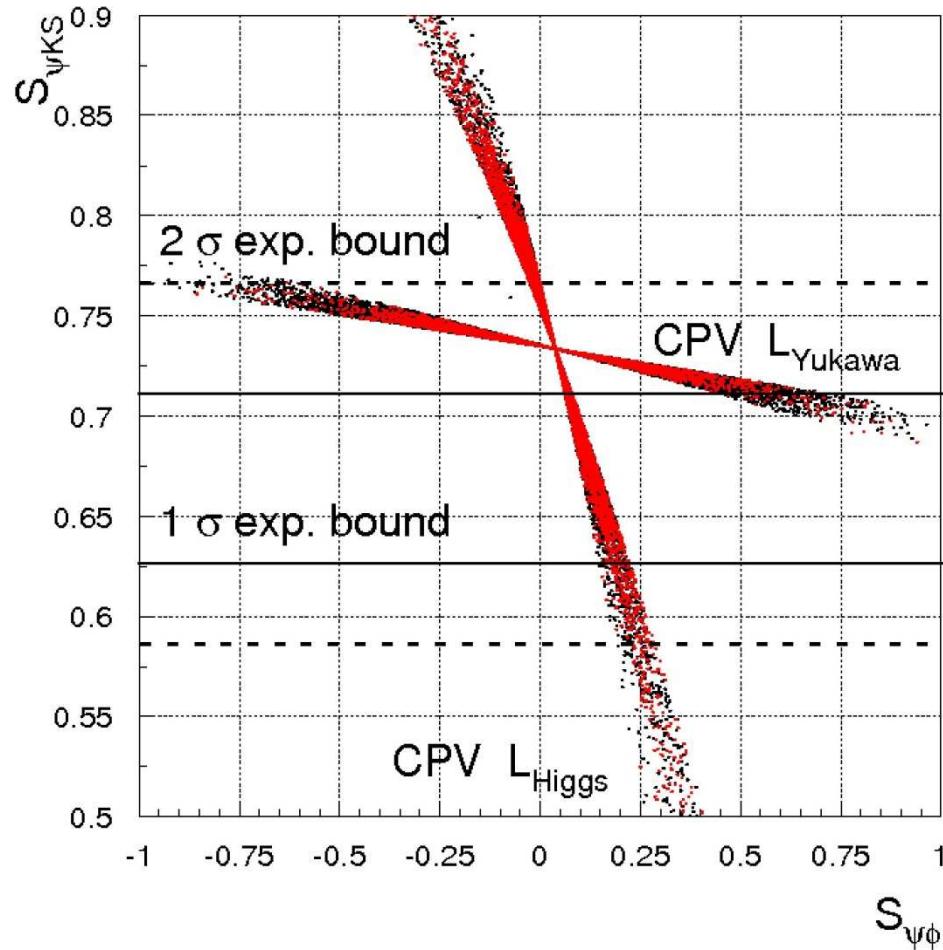
In the case of

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

distinction between Z, Z' and H^0
possible

More on 2HDM with MFV and Flavour Blind Phases

Correlation between CP Effects



AJB, Isidori, Paradisi 1007.5291

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

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



SM4 : Four Generations

New parameters in 4x4 mixing matrix

$s_{14}, s_{24}, s_{34}, m_t, m_b,$
 $\delta_{13}, \delta_{24}, \delta_{14}$

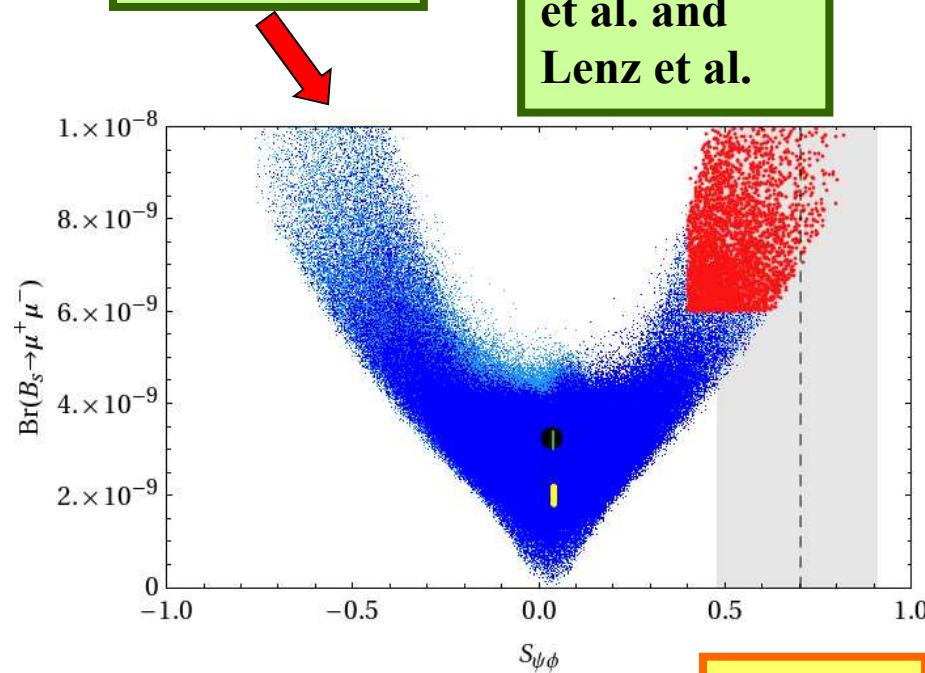
Can remove $\Delta F=2$ tensions and have
 $S_{\psi\phi} < 0$ but $B^+ \rightarrow \tau^+ \nu_\tau$ problem remains.

Similar
Result
by Soni et al.

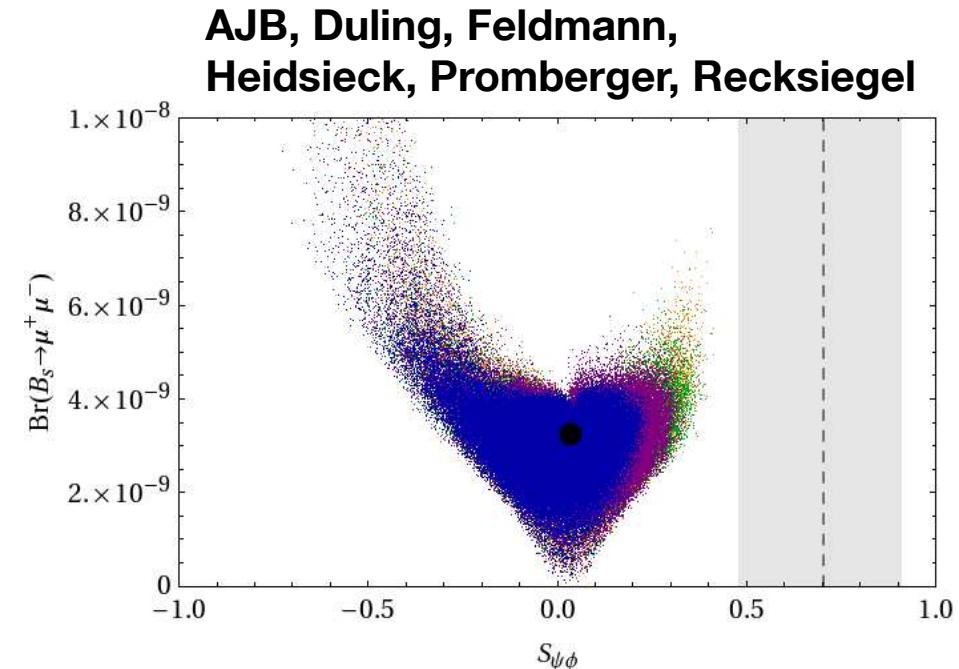
$\text{Br}(B_s \rightarrow \mu^+ \mu^-) \text{ vs } S_{\psi\phi}$

4G

BDFHPR
(1002.2126)



See also Hou
et al. and
Lenz et al.



No Impact
on Δa_μ

CDF D0

Adding ε'/ε Constraint

4G has hard time to describe simultaneously ε'/ε
and $S_{\psi\phi} > 0.2$ 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:

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

mixings

flavour-anarchial Yukawa in vectorial fermion sector

masses of vectorlike fermions

3.

Modification of W^\pm , Z , H couplings (FCNC's) but $M_Q, M_U \sim 0$ (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