Flavour
in the
LHC Era

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

“Particle Physics and the LHC”
Vienna, November 2011

Overture

1676

A very important year for the humanity !

1676 : The Discovery of the Microuniverse (Animalcula) (The Empire of Bacteria)

10^{-6}m

Antoni van Leeuwenhoek
***24.10.1632 ✝27.08.1723**

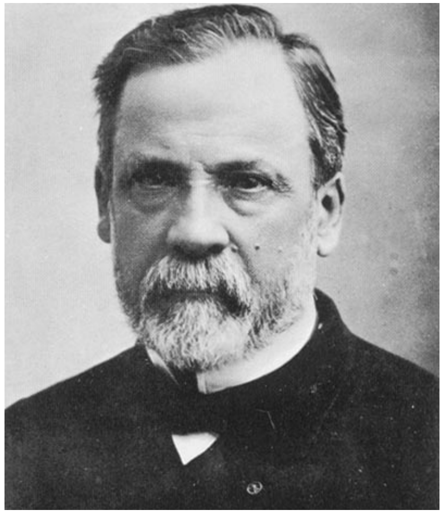
~500 Microscopes

(Magnification by ~300)

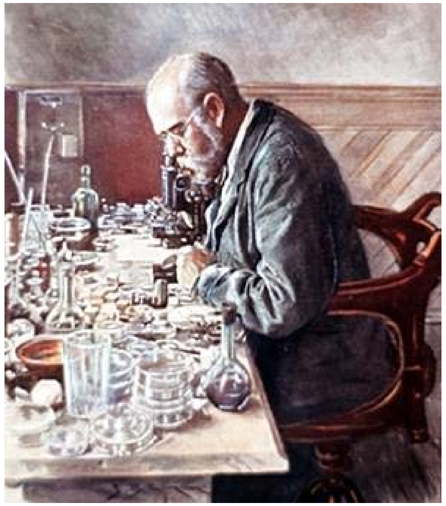
Animalcula Hunters

Antoni van Leeuwenhoek
***24.10.1632 ✝27.08.1723**

Lazzaro Spallanzani
***12.01.1729 ✝12.02.1799**



L. Pasteur
***27.12.1822 ✝28.09.1895**



Robert Koch
***11.12.1843 ✝27.05.1910**

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**

Most important Message from this Talk

Antoni van Leeuwenhook discovered in 1676

Animalcula

Most important Message from this Talk

Antoni van Leeuwenhook discovered in 1676

Animalcula

We all expect to discover **New Animalcula**

in the coming years with the help

of **LHC** and **High Precision Experiments**

But how will these New Animalcula look like ?

But how will these
New Animalcula look like ?

Overture Completed!

Vienna Symphony No. 6

Vienna Symphony No. 6

1st Movement ： **Introduction and Basic Strategy (17 min)**

Vienna Symphony No. 6

1st Movement	:	**Introduction and Basic Strategy (17 min)**
2nd Movement	:	**Expectations and first Messages from New Animalcula (10 min)**

Vienna Symphony No. 6

1st Movement	:	Introduction and Basic Strategy (17 min)
2nd Movement	:	Expectations and first Messages from New Animalcula (10 min)
3rd Movement	:	New Animalcula Fairytales (10 min)

Vienna Symphony No. 6

1st Movement	:	Introduction and Basic Strategy (17 min)
2nd Movement	:	Expectations and first Messages from New Animalcula (10 min)
3rd Movement	:	New Animalcula Fairytales (10 min)
4th Movement	:	Finale: Vivace ! (2 min)

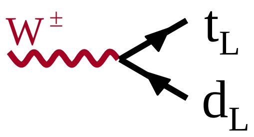
(hep-ph/0910.1032): "Flavour Theory : 2009"
(hep-ph/1012.1447): "MFV and Beyond"

1st Movement

Introduction and Basic Strategy

Pillars in Flavour Physics

1. Charged Current Interactions only between left-handed Quarks



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

2. Quark Mixing

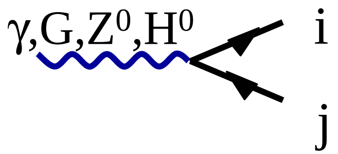
{ Weak Eigenstates } ≠ {Mass Eigenstates }

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

(Weak Eigenstates) (Unitarity CKM-Matrix) (Mass Eigenstates)

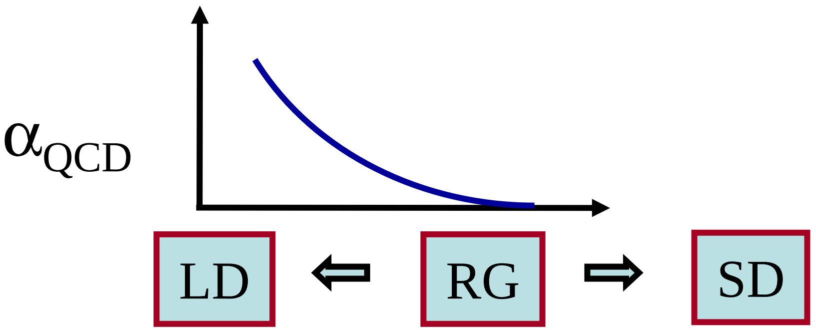
3. GIM Mechanism

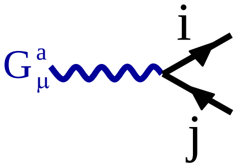
Natural suppression of FCNC



$$\left\{ \quad = 0 \right\} \Rightarrow \left\{ \begin{array}{c} \text{Loop Induced Decays, sensitive to} \\ \text{short distance flavour dynamics} \end{array} \right\}$$

4. Asymptotic Freedom





$$g_{QCD} T^a_{ij} \gamma_\mu$$

$$\alpha_{QCD} = \frac{g^2_{QCD}}{4\pi}$$

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

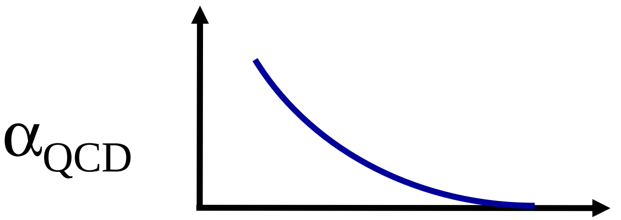
$\Lambda^{(5)}_{\overline{MS}} = 240 \pm 15$ MeV $\qquad \alpha^{(5)}_{\overline{MS}}(M_Z) = 0.1187 \pm 0.0009$

SD = Short Distances (Perturbation Theory)

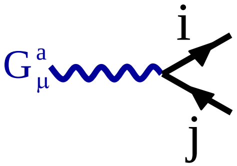
RG = Renormalization Group Effects

LD = Long Distances (Non-Perturbative Physics)

4. Asymptotic Freedom



LD ⇐ RG ⇒ SD



$$g_{QCD} T^a_{ij} \gamma_\mu$$

$$\alpha_{QCD} = \frac{g^2_{QCD}}{4\pi}$$

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

$\Lambda^{(5)}_{\overline{MS}} = 240 \pm 15\ \text{MeV}$ $\alpha^{(5)}_{\overline{MS}}(M_Z) = 0.1187 \pm 0.0009$

Wilson Coefficients

SD = Short Distances (Perturbation Theory)

⇑

RG = Renormalization Group Effects

⇓

Hadronic Matrix Elements

LD = Long Distances (Non-Perturbative Physics)

OPERATOR PRODUCT EXPANSION

CKM (Nobel Prize 2008)

Dirac Medal (2010)

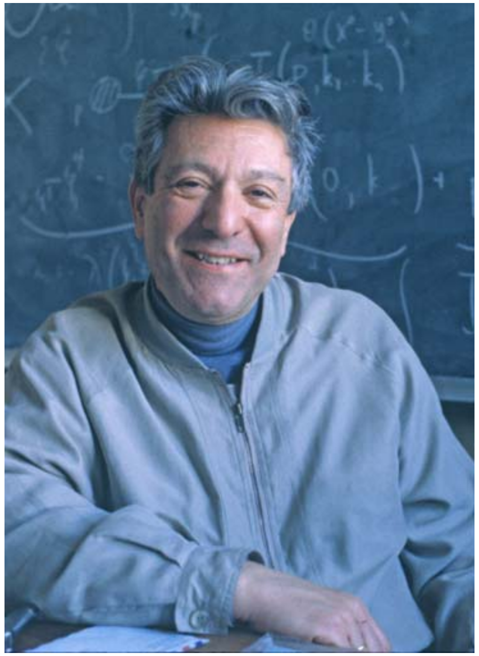
N. Cabibbo
(1935-2010)

M. Kobayashi

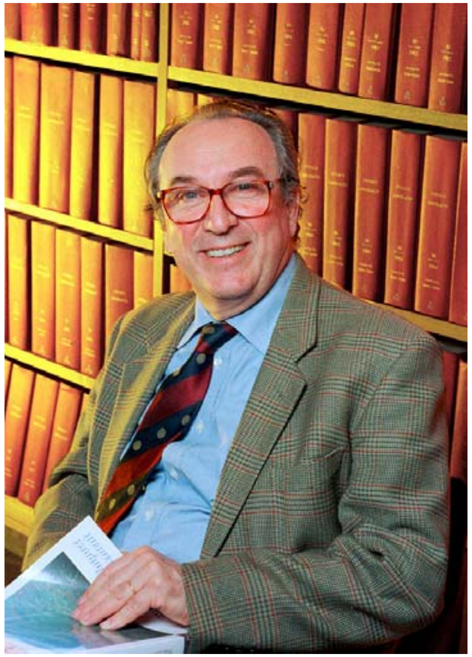
T. Maskawa

EPS (High Energy Prize 2011)

Sheldon Glashow



John Iliopoulos

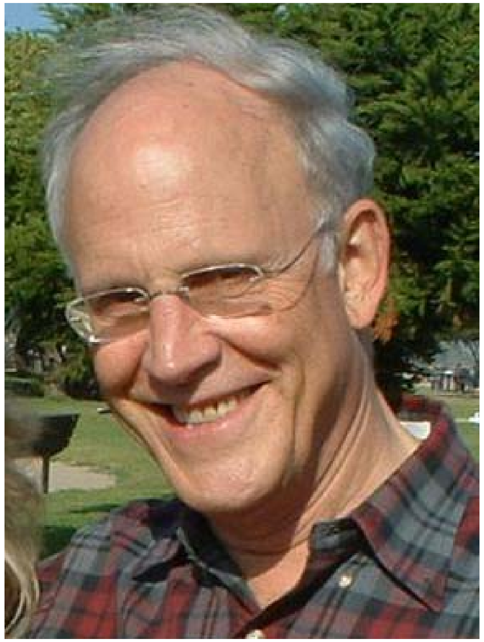


Luciano Maiani

GIM

Asymptotic Freedom

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

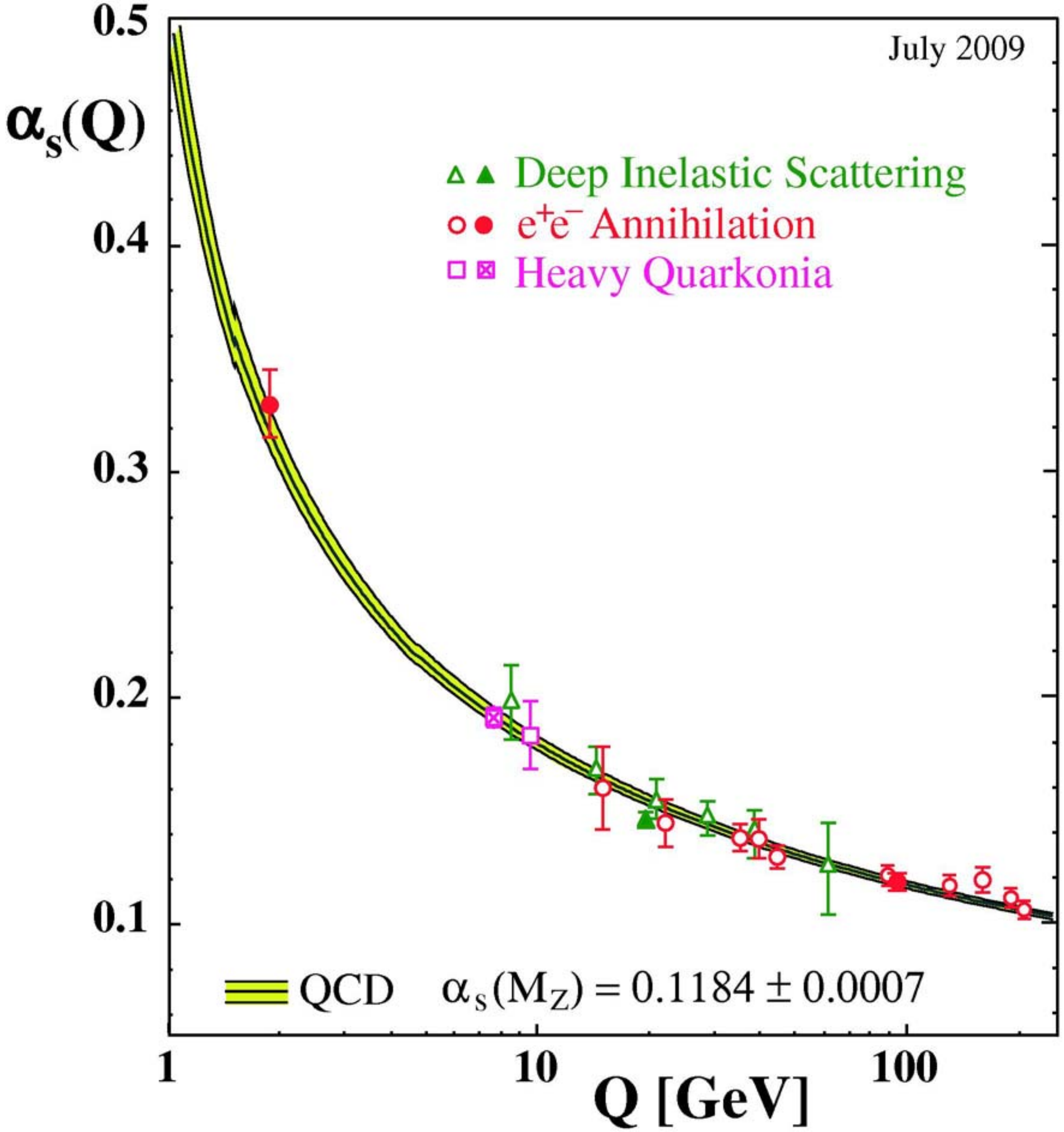


David Gross

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

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

$s_{13} << s_{23} << s_{12}$

$(4\cdot10^{-3})$ $(4\cdot10^{-2})$ (0.2)

GIM Structure of FCNC´s

Large $\not{CP}$ effects in B_d

Small $\not{CP}$ effects in B_s

Tiny $\not{CP}$ effects in K_L

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

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

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

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

PMNS: Negligible LFV

(tiny ν 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 ?

Crucial questions in Particle Physics

1. Could it be an elementary SM Higgs system with all problems of instability under radiative corrections (hierachy problems) ?

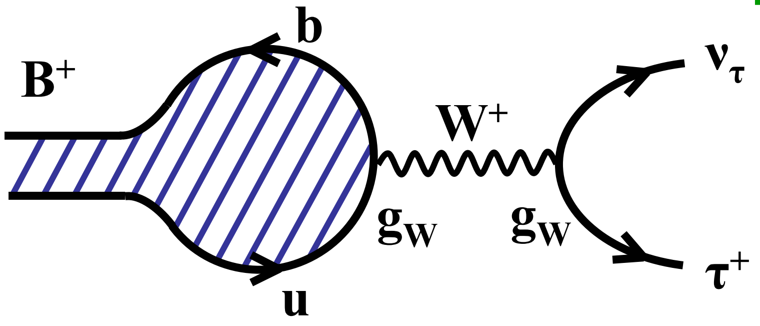
2. Could it be a new strong dynamics with a composite Higgs or without Higgs at all ?

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

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

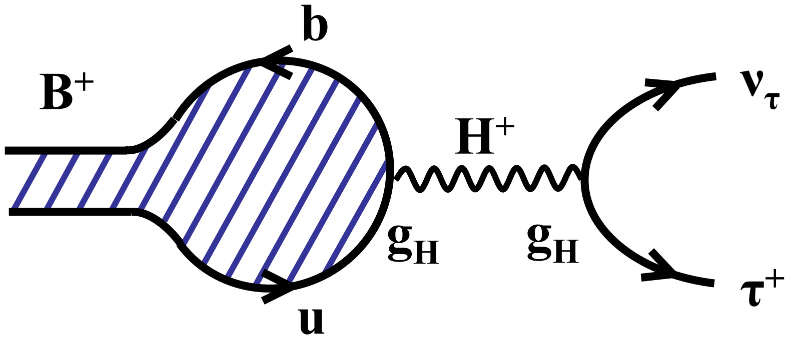


Standard Model

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

$m_B \approx 5$ GeV

A, B – parameters of a given theory



Contribution of a new charged Heavy Particle

$$Br\left(B^+ \rightarrow \tau^+ \nu_\tau\right)$$

$$= \left| A \frac{g_W^2}{M_W^2} + B \frac{g_H^2}{M_H^2} \right|^2$$

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

Signal of a new particle

In Order to identify New Animalcula 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

Basic Questions for Flavour Physics

New Flavour violating CPV phases?

Flavour Conserving CPV phases?

Non-MFV Interactions?

(Non-CKM)

Right-Handed Charged Currents?

Scalars H^0, $H^\pm$ and related FCNC´s?

New Fermions? New Gauge Bosons?

★ How to explain dynamically 22 free Parameters in the Flavour Sector ?

Most popular BSM Directions

CMFV

(constrained MFV)

MFV

(NMFV)
(GMFV)

2HDM

LHT

(Littlest Higgs
with T-parity)

SUSY

(flavour models)

Z´

(Langacker…)

RHMFV

RS

(Randall-Sundrum)
(Warped Extra
Dimensions)

4th G

(Hou.., Soni.., Lenz.., Melic)
Munich

Vector-Like Quarks

(Branco…,
del Aguila)

Gauge Flavour Models NEW

L-R Models NEW

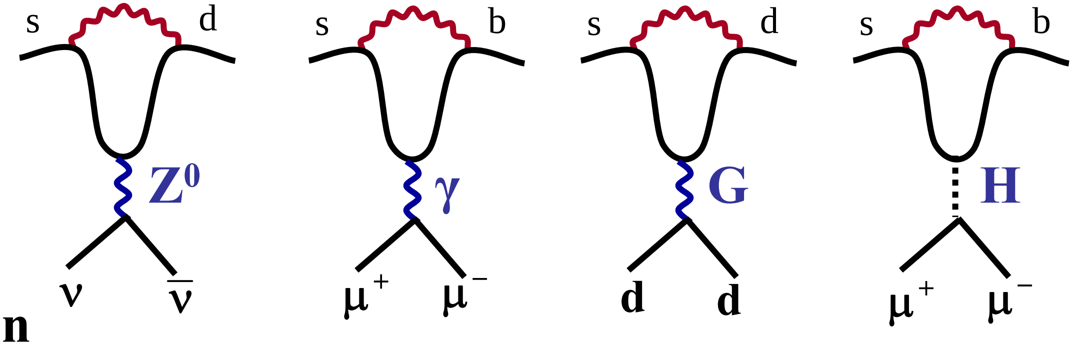
↓

Non-Decoupling

New gauge bosons, fermions, scalars in loops and even trees with often non-CKM interactions.

Basic Diagrams in FCNC Processes

Penguin Family :

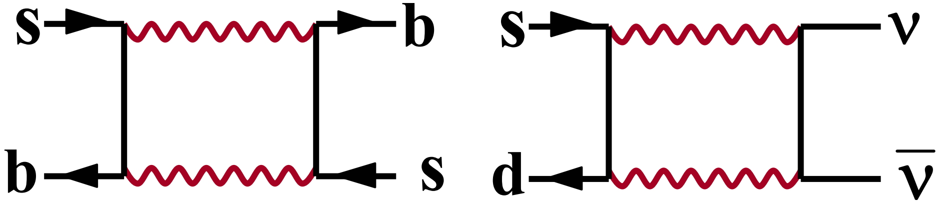


New Physics enters here

Similar diagrams in LFV and EDM´s

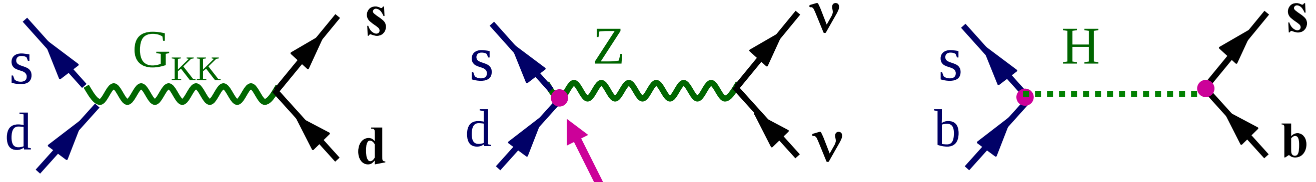
(GIM broken at one loop)

Box Diagrams

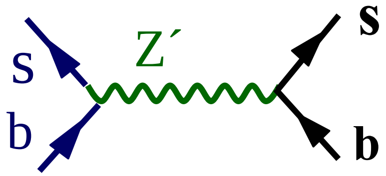


\+ other box diagrams

Tree Diagrams



(GIM broken at tree level)



RS

Generated through mixing with New Gauge Bosons

Double Higgs Penguin in SUSY

Patterns of Flavour Violation around the Flavour Clock

- 12 RS_c
- 1 CMFV, MFV
- 2 $\mathrm{2HDM}_{\overline{\mathrm{MFV}}}$ ★
- 3 LHT
- 4 SM4
- 5 L-R Models ★
- 6 General 2HDM
- 7 Gauge Flavour Models ★
- 8 SUSY
- 9 $\mathrm{SSU(5)}_{\mathrm{RN}}$
- 10 FBMSSM
- 11 RHMFV

hep-ph/1012.1447

Superstars of 2011 – 2015 (Flavour Physics)

$\boxed{S_{\psi\varphi}}$

$\cancel{CP}$ in $B_s^0 - \overline{B}_s^0$

$(B_s \to \varphi\varphi)$

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

$(B_d \to \mu^+\mu^-)$

$(B^+ \to \tau^+\nu_\tau)$

$K^+ \to \pi^+\nu\overline{\nu}$

$(K_L \to \pi^0\nu\overline{\nu})$

$(B_d \to K^*\mu^+\mu^-)$

γ, V_{ub} from Tree Level Decays

$\mu \to e\gamma$

$\tau \to \mu\gamma$

$\tau \to e\gamma$

$\mu \to 3e$

$\tau \to 3$ leptons

ε'/ε *)

(Lattice)

EDM´s

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

*) Direct $\cancel{CP}$ in $K_L \to \pi\pi$

2nd Movement

Expectations and First Messages from New Animalcula

(LHCb)

First Evidence for CP Violation in Charm

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

$D^0 \to K^+K^-$
$D^0 \to \pi^+\pi^-$

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

Departures from Standard Model Expectations

$$\cancel{CP}\begin{cases} K^0 - \bar{K}^0 \qquad (\varepsilon_K) \qquad \dfrac{|\varepsilon_K|_{SM}}{|\varepsilon_K|_{exp}} \approx 0.80 \pm 0.10 \\ B_d^0 - \bar{B}_d^0 \qquad (S_{\psi K_s}) \qquad (S_{\psi K_s}) \cong \begin{matrix} 0.82 \pm 0.04 & (SM) & (UTfit) \\ 0.678 \pm 0.022 & (exp) & \end{matrix} \\ B_s^0 - \bar{B}_s^0 \qquad (S_{\psi\varphi}) \qquad \dfrac{(S_{\psi\varphi})_{exp}}{(S_{\psi\varphi})_{SM}} \approx 10 - 20 \end{cases}$$

(AJB, Guadagnoli)
(Brod, Gorbahn)

(CDF, DØ,
Lenz+Nierste)

Spring 2011

0.04

$$(S_{\psi\varphi})_{exp} \approx 0.8 \begin{matrix} +0.1 \\ -0.2 \end{matrix}$$

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

$$|V_{ub}| = \begin{cases} 4.4 \cdot 10^{-3} & \text{Inclusive Decays} \quad (B \to X_u l\nu) \\ 3.4 \cdot 10^{-3} & \text{Exclusive Decays} \quad (B \to \rho l\nu) \\ & \text{and SM-CKM fit} \end{cases}$$

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

News about New Physics from Summer Conferences

DØ, CDF, LHCb

$$\boxed{-0.1 \leq S_{\psi\varphi} \leq 0.4} \quad {}^{*)}$$

?

***) Altmannshofer + Carena**
1110.0843

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

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

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

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

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

$$|V_{ub}|_{excl} = |V^L_{ub} + a\varepsilon^2 V^R_{ub}|$$

$$|V_{ub}|_{inc} \approx |V^L_{ub}|$$

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
November
2011

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

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

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 $|V_{ub}|$

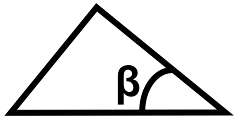
Possible Simplest Solutions

Soni, Lunghi

AJB, Guadagnoli
UTfitters
Lenz, Nierste +
CKMfitters
Laiho, Lunghi,
van der Water
Fleischer et al
Blanke et al
Branco et al
....

A New <u>negative</u> ~~CP~~ phase φ_{new} in $B_d^0 - \bar{B}_d^0$ Mixing

➡ $|V_{ub}|$ from inclusive decays is correct



$$\left(S_{\psi K_s}\right)_{SM} = \sin 2\beta \rightarrow S_{\psi K_s} = \sin\left(2\beta - \varphi_{new}\right)$$

0.82 0.68 for $\varphi_{new} = 10°$

➡ ε_K and $Br\left(B^+ \rightarrow \tau^+ \nu\right)$ much closer to experiment

B <u>Dynamical Model</u> : Non-Supersymmetric Two-Higgs Doublet Model with <u>Flavour Blind Phases</u> (AJB, Carlucci, Gori, Isidori AJB, Isidori, Paradisi)

$2HDM_{\overline{MFV}}$

Correlated Implications:

★ $\text{Enhanced } S_{\psi\varphi},\ Br\left(B_s \rightarrow \mu^+\mu^-\right),\ Br\left(B_d \rightarrow \mu^+\mu^-\right),\ \text{EDM's}$

(non-SUSY)

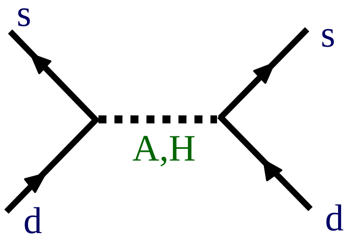
General 2HDM with MFV and Flavour Blind CPV Phases (in Yukawa Couplings)

(1005.5310)

(AJB, Carlucci, Gori, Isidori)

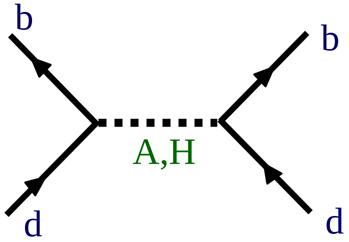
Provides correct pattern

ε_K :



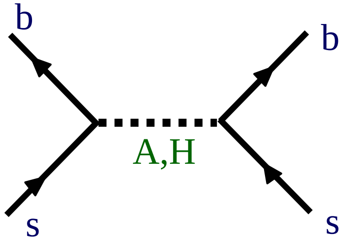
$$\approx \left[\frac{m_d m_s}{M_H^2}\right] m_t^4 (\tan\beta)^2 \left(V_{ts}^* V_{td}\right)^2$$ (tiny)

$S_{\psi K_s}$:



$$\approx \left[\frac{m_b m_d}{M_H^2}\right] m_t^4 (\tan\beta)^2 \left(V_{tb}^* V_{td}\right)^2 e^{i\varphi_{\text{new}}}$$

$S_{\psi\varphi}$:



$$\approx \left[\frac{m_b m_s}{M_H^2}\right] m_t^4 (\tan\beta)^2 \left(V_{tb}^* V_{ts}\right)^2 e^{i\varphi_{\text{new}}}$$

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

$$\frac{\theta_d^H}{\theta_s^H} \approx \frac{m_d}{m_s} \approx \frac{1}{17}$$

Large RG QCD effects Q_{LR}

$$\sin 2\beta > S_{\psi K_s}$$

$$\left(\left|\varepsilon_K\right| \text{ enhanced}\right)$$

$$\frac{\tan\beta \approx 10-20}{M_H \approx 250\text{GeV}}$$

$|\varepsilon_K|$ vs $S_{\psi\varphi}$ and $S_{\psi K_s}$ vs $S_{\psi\varphi}$ in a General 2HDM with MFV and Flavour Blind CPV

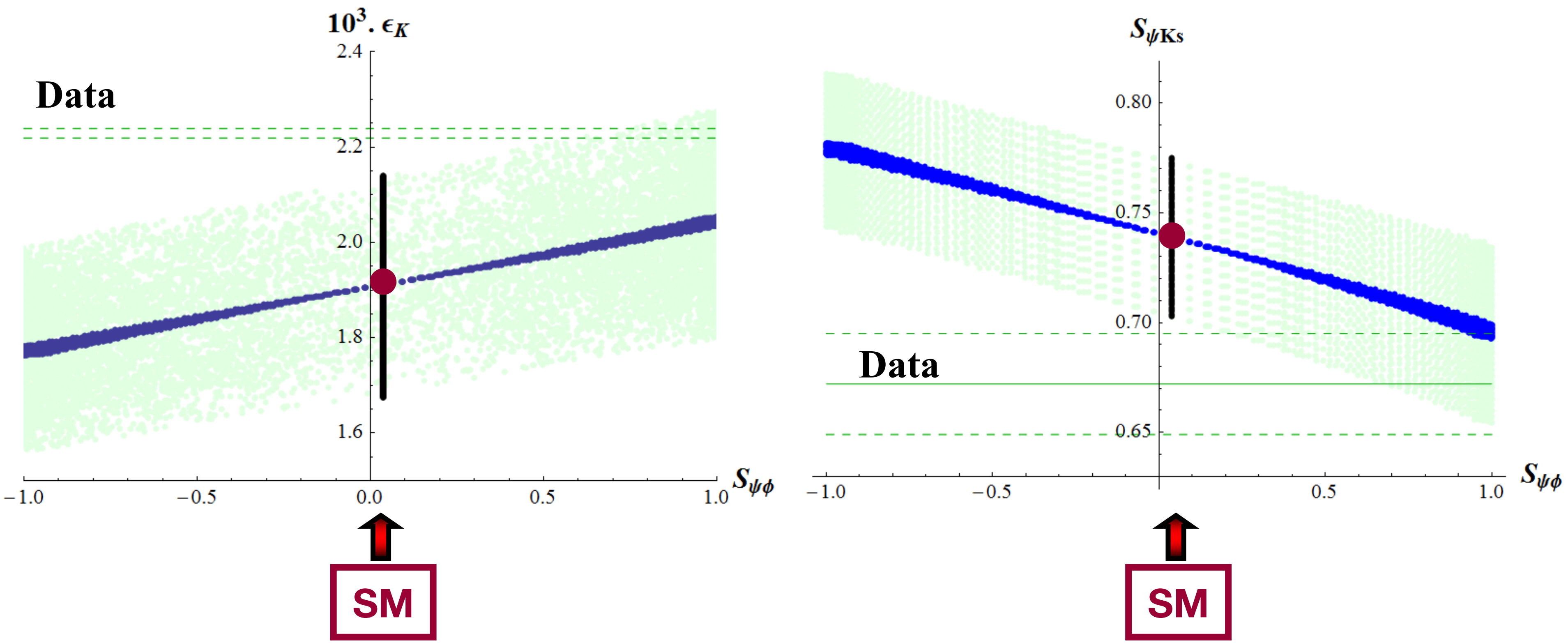
(AJB, Carlucci, Gori, Isidori)

Correct pattern of NP effecs

Correlation between various $\not{CP}$ Effects

(But the effects appear a bit too weak)

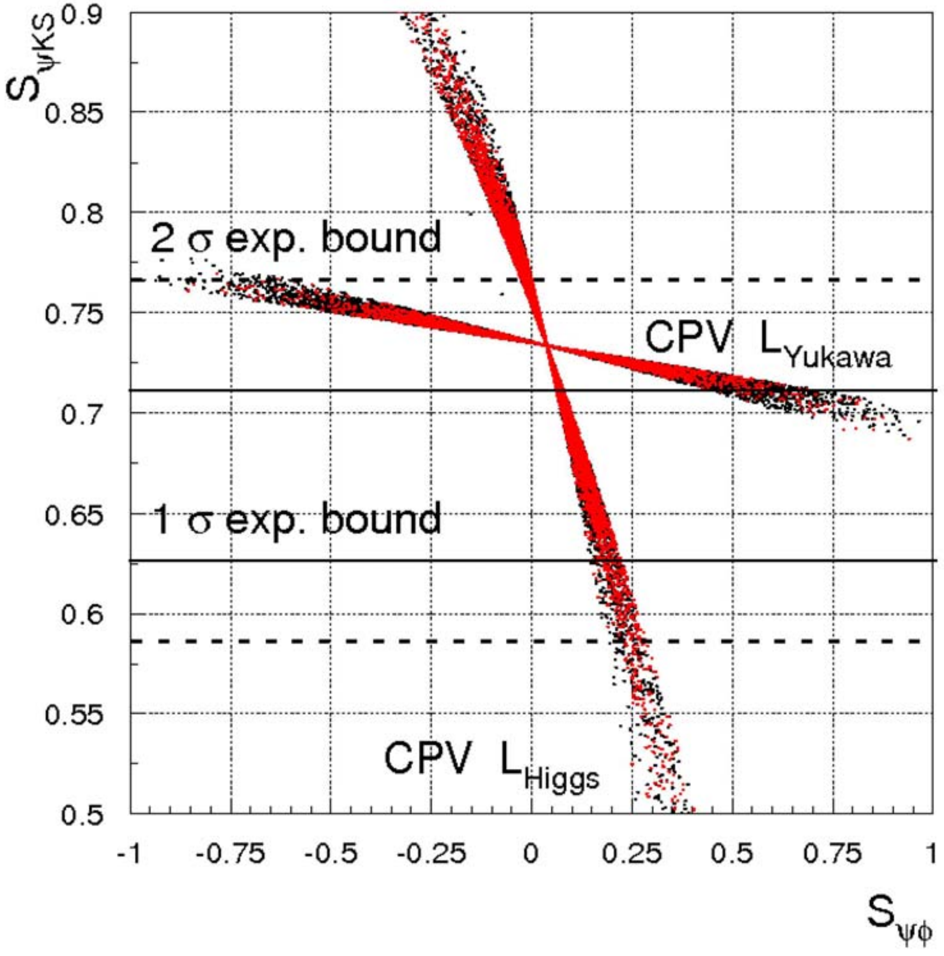
$2HDM_{\overline{MFV}}$



1005.5310

More on 2HDM with MFV and Flavour Blind Phases

Correlation between ~~C~~P 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)
$$\frac{\theta_d^H}{\theta_s^H} = 1$$

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

Insight after Summer Conferences

$$\left\{-0.1 \leq \mathrm{S}_{\psi\varphi} \leq 0.4\right\} \Rightarrow \left\{\begin{array}{l}\text{Phases in} \\ \text{Higgs Potential} \\ \text{favoured}\end{array}\right\}$$

LHCb, CDF, DØ

See also: Altmannshofer + Carena
1110.0843 (MFV-MSSM
+ higher-dimension
operators)

But $|V_{ub}|$ could turn out to be small !

$$|V_{ub}| \simeq |V_{ub}|_{exl} \approx 3.4 \cdot 10^{-3}$$

AJB, Guadagnoli (2008)

$$\text{Then } \left(S_{\psi K_s}\right)_{SM} \cong \left(S_{\psi K_s}\right)_{exp}$$

Solution

C

$$\text{But } \left(\varepsilon_K\right)_{SM} \cong 0.8\left(\varepsilon_K\right)_{exp}$$

Need new contributions to ε_K without new phases in $B_d^0 - \overline{B}_d^0$ mixing

AJB, Carlucci, Merlo, Stamou (2011)

Flavour Gauge Model of Grinstein et al provides an example

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

Z-Penguin (SM
+ Boxes CMFV)

SM

$$Br(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \cdot 10^{-9}$$

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

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

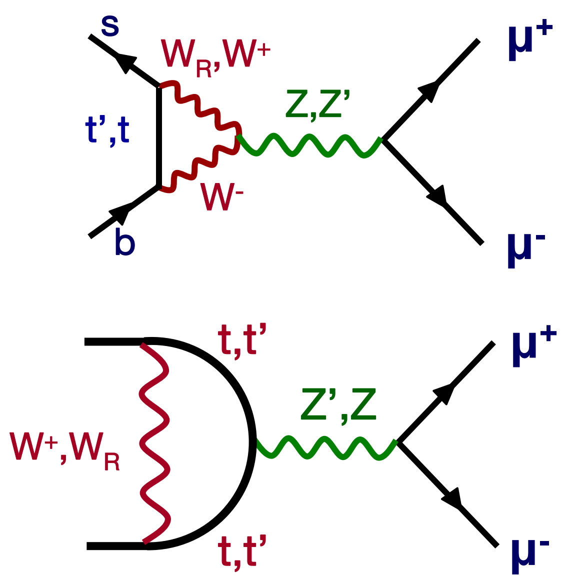
95% CL

$$Br(B_s \to \mu^+\mu^-) = \begin{cases} \left(18\begin{smallmatrix}+11\\-9\end{smallmatrix}\right) \cdot 10^{-9} & \text{(CDF)} \\ < 11 \cdot 10^{-9} & \text{(LHC)} \end{cases}$$

$$Br(B_d \to \mu^+\mu^-) \le 4 \cdot 10^{-9} \quad \text{(LHC)}$$

(CDF)

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



\+

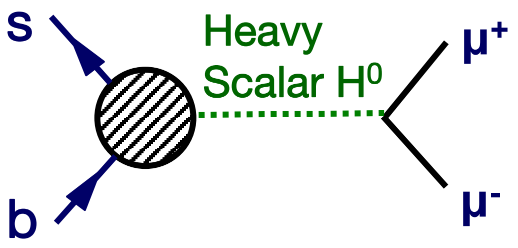
Other Z-Penguins and Boxes

SM: (3.2 ± 0.2) · 10^{-9}

Model Independent Limit (95% C.L.)

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

Altmannshofer, Paradisi, Straub 1111.1257



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

in SUSY

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

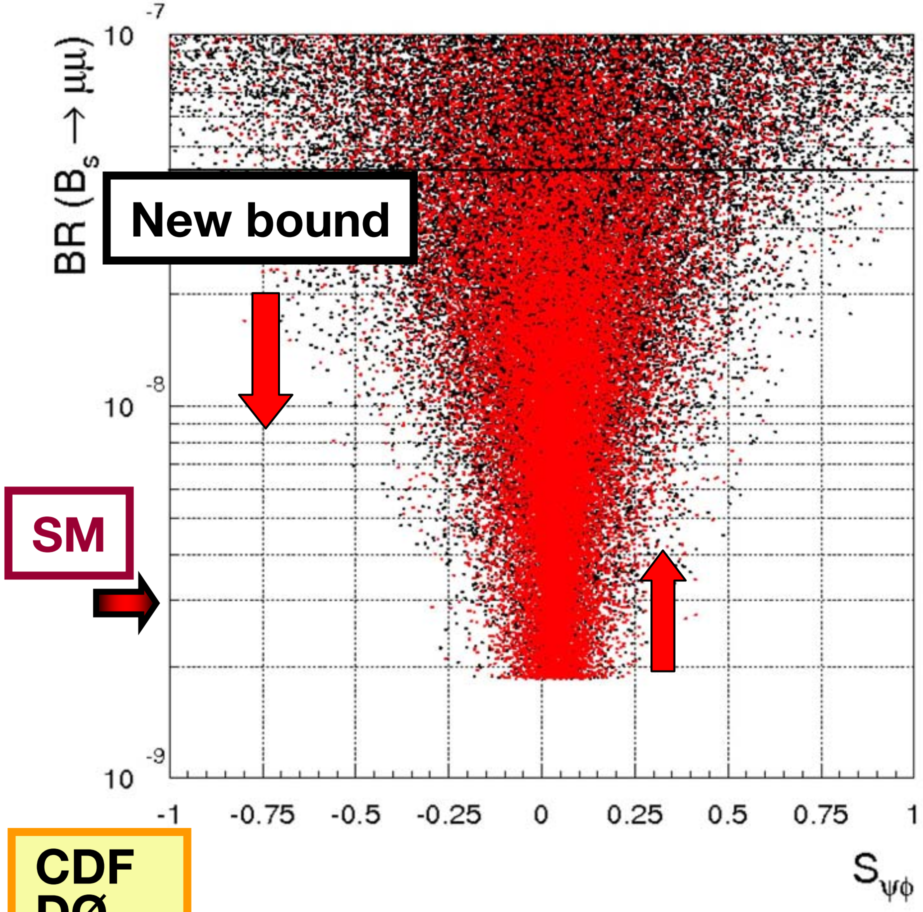
In the case of

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

distinction between Z,Z' and H^0 possible

More on 2HDM with MFV and Flavour Blind Phases

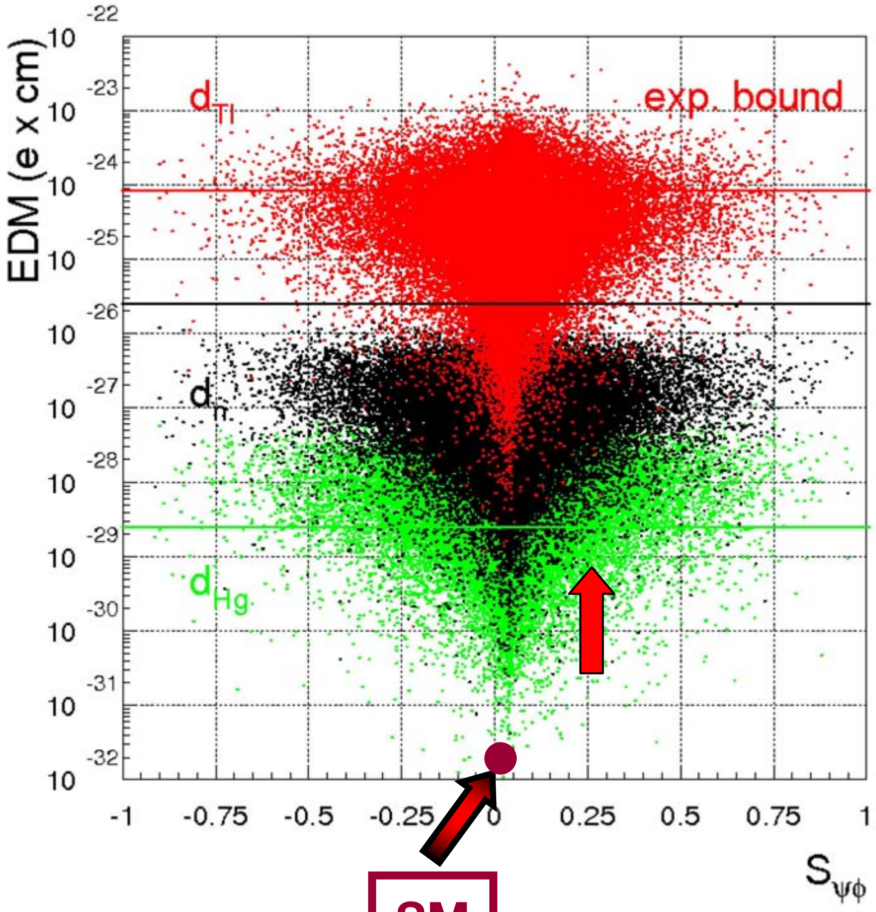
$2HDM_{\overline{MFV}}$



New bound

SM

CDF
DØ
LHCb



SM

AJB, Isidori, Paradisi 1007.5291

3rd Movement

New Animalcula
Fairytales

Most popular BSM Directions

CMFV

(constrained MFV)

MFV

(NMFV)
(GMFV)

2HDM

LHT

(Littlest Higgs
with T-parity)

SUSY

(flavour models)

Z′

(Langacker…)

RHMFV

RS

(Randall-Sundrum)
(Warped Extra
Dimensions)

4th G

(Hou.., Soni.., Lenz.., Melic)
Munich

Vector-Like Quarks

(Branco…,
del Aguila)

Gauge Flavour Models NEW

L-R Models NEW

Non-Decoupling

New gauge bosons, fermions, scalars in loops and even trees with often non-CKM interactions.

Models with non-MFV Interactions facing Large $S_{\psi\varphi}$

Model Expectations

$$S_{\psi\varphi} \leq \begin{cases} 0.80 \;\; \text{(4G) (Fourth Generation) (t') (Soni, Hou, Munich, Lenz)} \\ 0.75 \;\; \text{(AC) (abelian flavour, SUSY) (Higgs penguin)} \\ 0.50 \;\; \text{(RVV) (non - abelian flavour, SUSY) (Higgs penguin)} \\ 0.75 \;\; \text{(RS) (Heavy KK Gauge Bosons) (Duling et al (08))} \\ 0.30 \;\; \text{(LHT) (Mirror Fermions at work) (Tarantino et al (09))} \end{cases}$$

ABGPS

$$(S_{\psi\varphi})_{SM} \approx 0.04$$

ABGPS = Altmannshofer, AJB, Gori, Paradisi, Straub 0909.1333

Implications of an Enhanced $S_{\psi\varphi}$

1. $\text{Enhanced Br}\left(B_s \to \mu^+\mu^-\right)$
   (SUSY flavour models, $2\text{HDM}_{\overline{\text{MFV}}}$, 4G)
2. $\text{Enhanced Br}\left(B_d \to \mu^+\mu^-\right)$
   ($2\text{HDM}_{\overline{\text{MFV}}}$, also in some SUSY flavour models)
3. $\text{Br}\left(B_d \to \mu^+\mu^-\right)$ forced to be SM - like in 4G
4. $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ forced to be SM - like
   (LHT, Randall - Sundrum)
5. Automatic enhancements in SUSY - GUT models:
   $\text{Br}\left(\mu \to e\gamma\right),\ \text{Br}\left(\tau \to \mu\gamma\right),\ \left(g-2\right)_\mu,\ d_e,\ d_n$

ABGPS

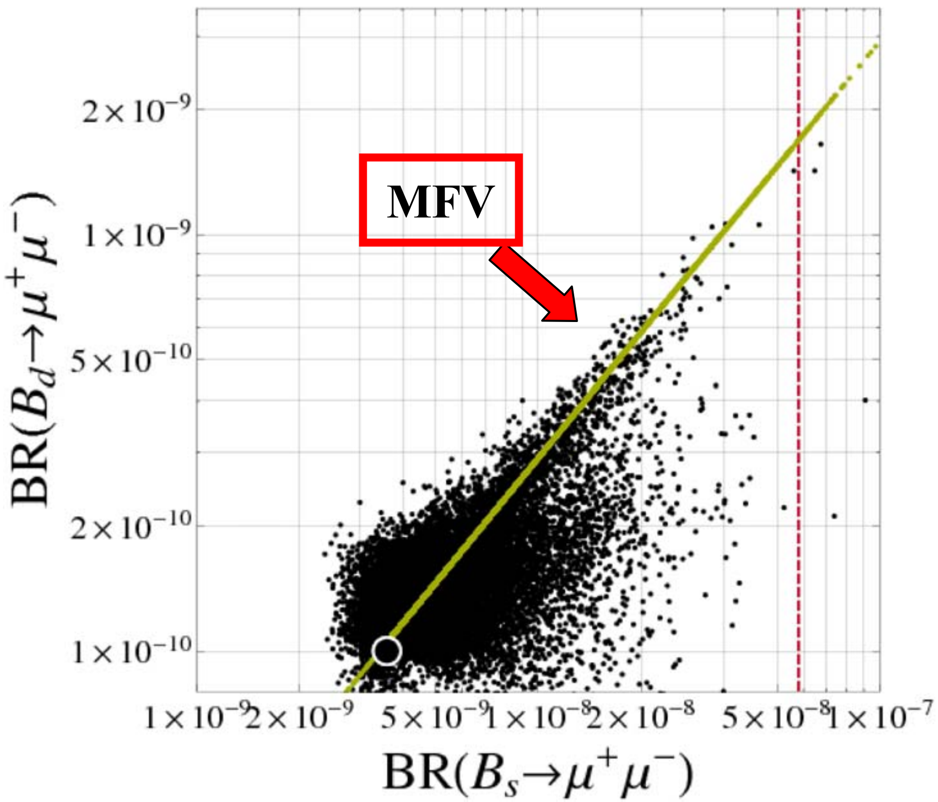
(0909.1333)

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

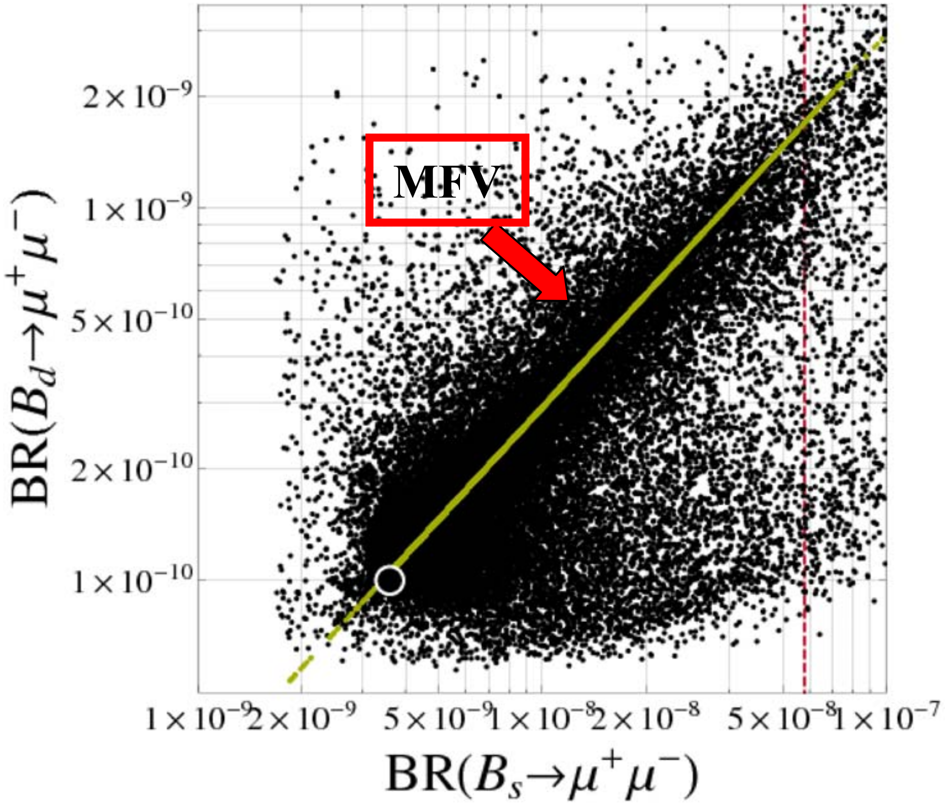
SUSY

● = SM

MFV AJB; Hurth, Isidori, Kamenik, Mescia



RVV2 (RH currents)



LH currents

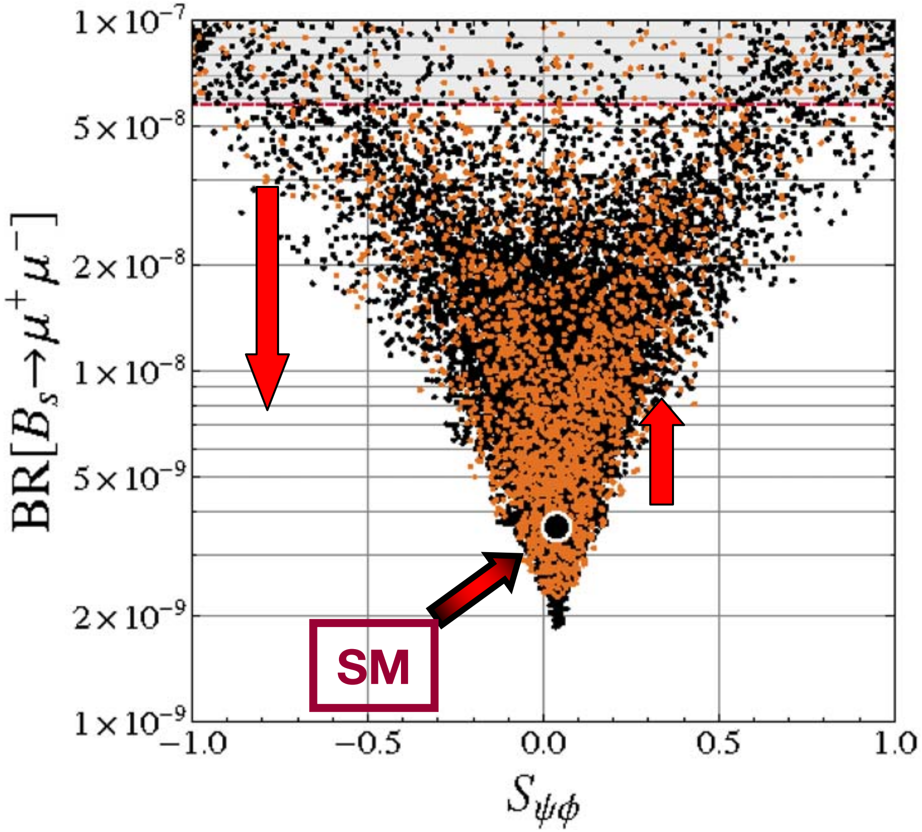
CDF, D0
LHCb

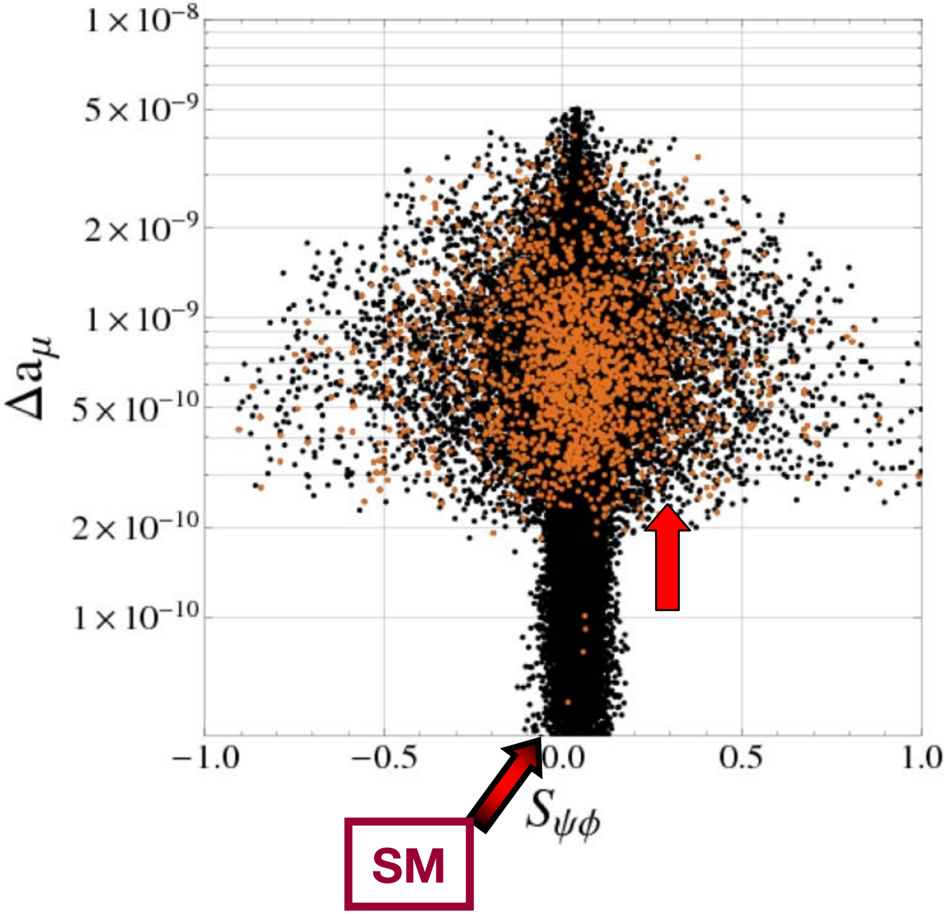
$Br\left(B_s \to \mu^+\mu^-\right)$ vs $S_{\psi\varphi}$

SUSY

ABGPS
(0909.1333)

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





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

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

SM :

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

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

Exp :

$$\mathrm{Br}\left(K^+ \to \pi^+\nu\bar{\nu}\right) = \left(17\,{}^{+11}_{-10}\right)\cdot 10^{-11}$$

(E787, E949 Brookhaven)

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

(E391a, KEK)

Future :

NA62
Project X (FNAL)

Both very sensitive to New Physics

J-PARC KOTO

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**

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

$$\mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right) \sim 10\mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right)_{\mathrm{SM}}$$

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

Lepton Flavour Violation, $\Delta(g-2)_{\mu}$ and EDM's

(MEGA) $\mathrm{Br}(\mu\to e\gamma) < 1.2\cdot 10^{-11}$ $\Rightarrow$ 10^{-13}(MEG) SM:10^{-54}

$\left(a_{\mu}\right)_{SM} < \left(a_{\mu}\right)_{exp} \quad (3.1\sigma)$

$a_{\mu} = \frac{1}{2}(g-2)_{\mu}$

(Regan et al) $d_e < 1.6\cdot 10^{-27}$ $\Rightarrow$ 10^{-31} $(d_e)_{SM} \approx 10^{-38}$

[e cm]

(Baker et al) $d_n < 2.9\cdot 10^{-26}$ $\Rightarrow$ 10^{-28} $(d_n)_{SM} \approx 10^{-32}$

Lepton Flavour Violation, $\Delta(g-2)_\mu$ and EDM's

(MEGA) $\mathrm{Br}(\mu\to e\gamma) < 1.2 \cdot 10^{-11}$ ➡ 10^{-13}(MEG) SM:10^{-54}

$(a_\mu)_{SM} < (a_\mu)_{exp}$ (3.1σ)

$$a_\mu = \frac{1}{2}(g-2)_\mu$$

(Regan et al) $d_e < 1.6 \cdot 10^{-27}$ ➡ 10^{-31} $(d_e)_{SM} \approx 10^{-38}$

[e cm]

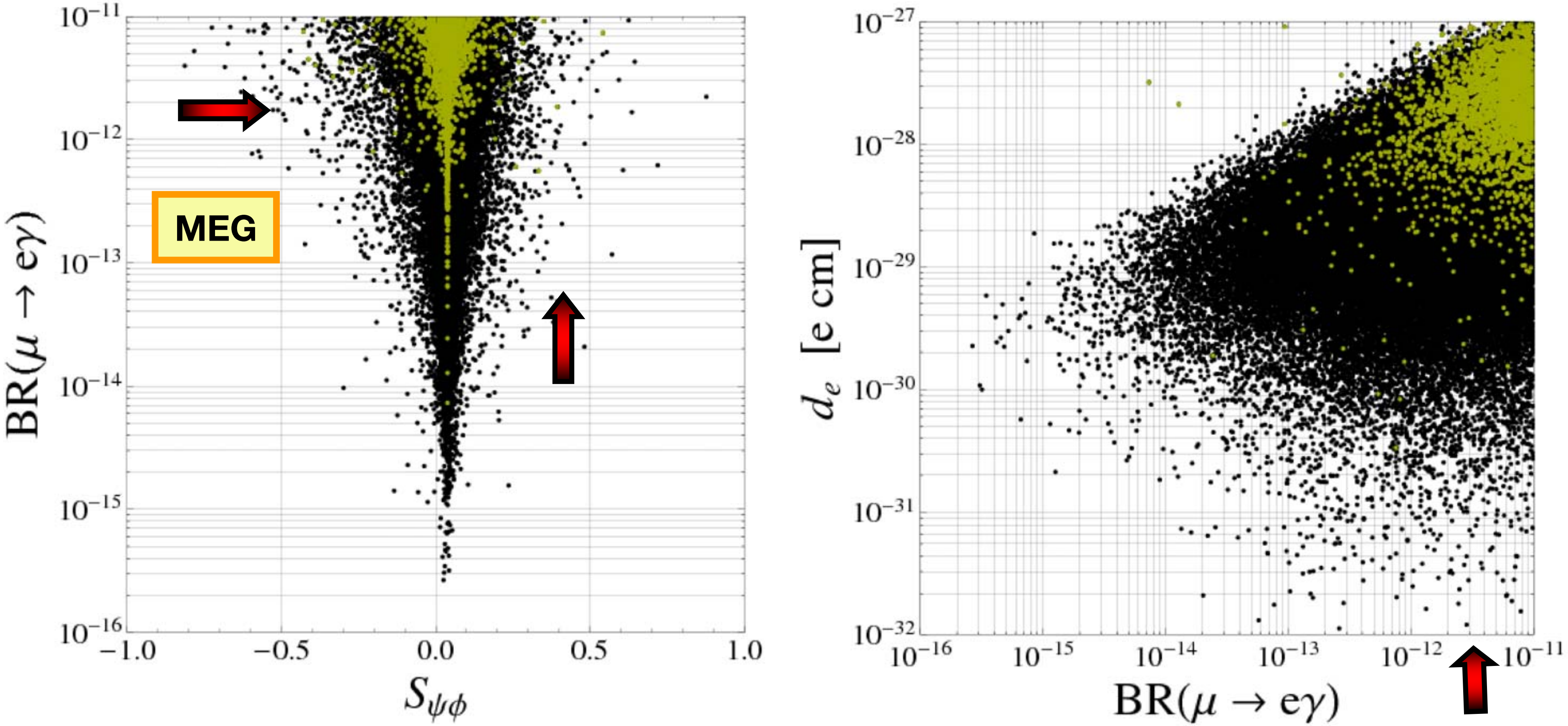
(Baker et al) $d_n < 2.9 \cdot 10^{-26}$ ➡ 10^{-28} $(d_n)_{SM} \approx 10^{-32}$

★ **MEG:** $\mathrm{Br}(\mu \to e\gamma) \le 2 \cdot 10^{-12}$

ABGPS

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

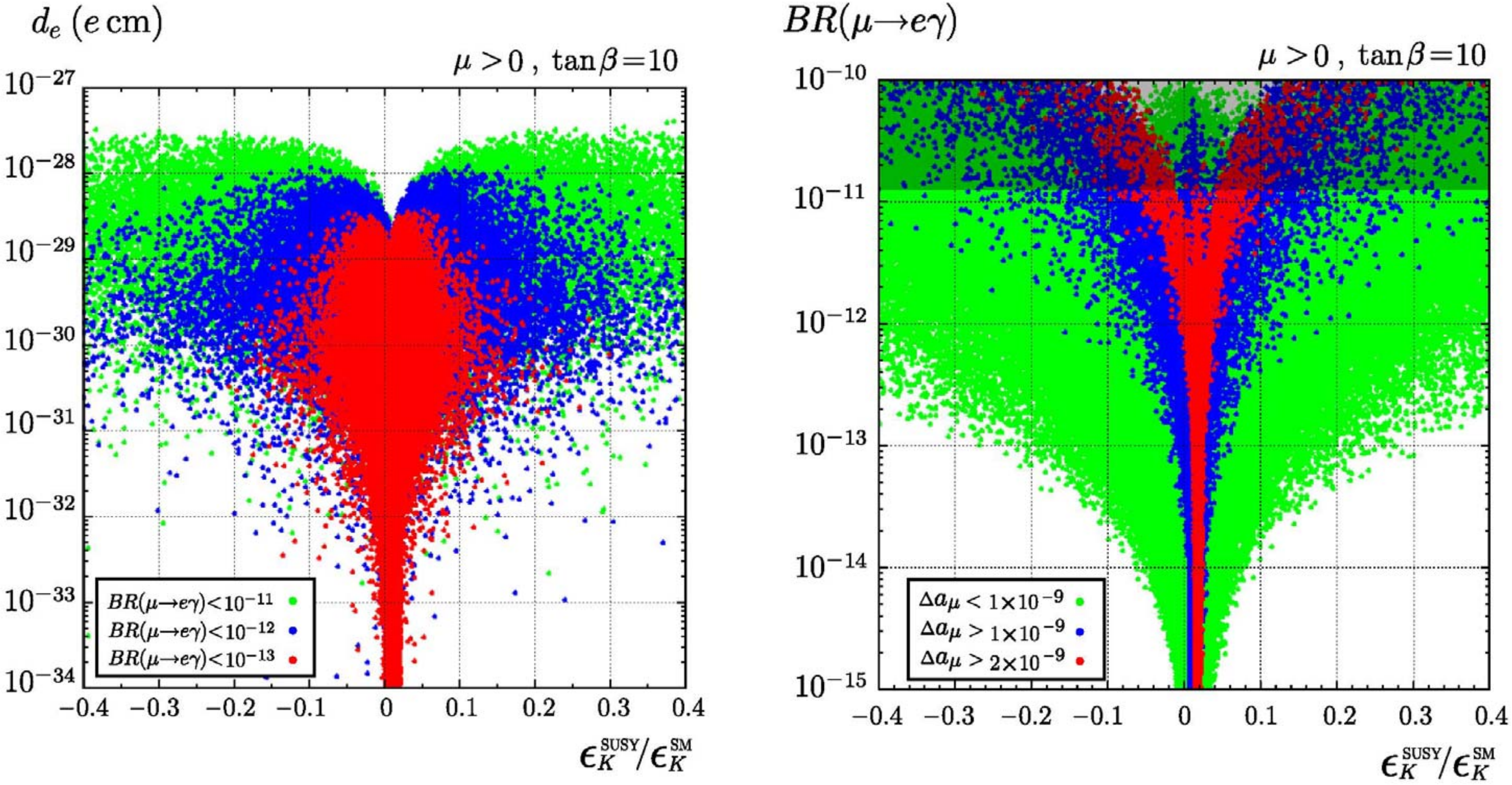
🟩 **Solution to $(g\text{-}2)_\mu$ anomaly**



MEG

MEG

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



AJB, Nagai, Paradisi, 1011.1993

DNA Tests of Flavour Models

O_i : Observables ***M_i : Models beyond SM***

	M_1	M_2	M_3	M_4	M_5
O_1	★★★	★	★	★	★★
O_2	★	★★	★★★	★★	★
O_3	★★	★★★	★★	★	★
O_4	★★★	★★	★	★★★	★★
O_5	★	★★★	★	★★	★★★

★★★ **Very large New Physics effect**

★★ **Moderate New Physics effect**

★ **Very small New Physics effect**

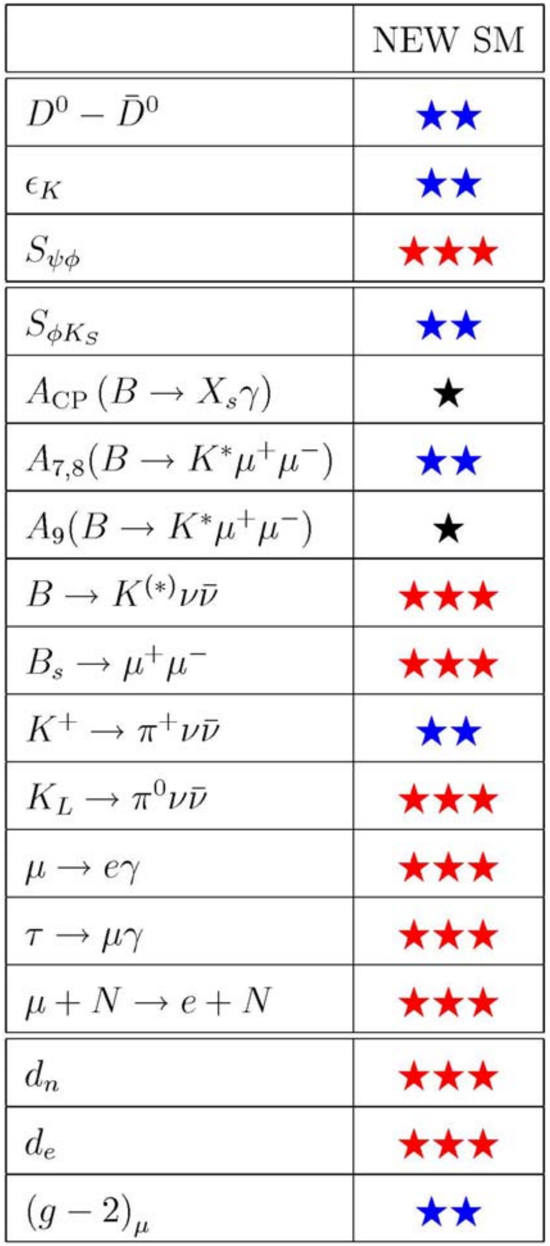
ABGPS

DNA Tests of Flavour Models

0909.1333

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS	4G
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?	★★
ϵ_K	★	★★★	★★★	★	★	★★	★★★	★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?	★★
$A_{\rm CP}\,(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?	★
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?	★★
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?	★★
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★	★★★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★	★
d_e	★★★	★★★	★★	★	★★★	★	★★★	★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?	★

Vienna 2020 Vision

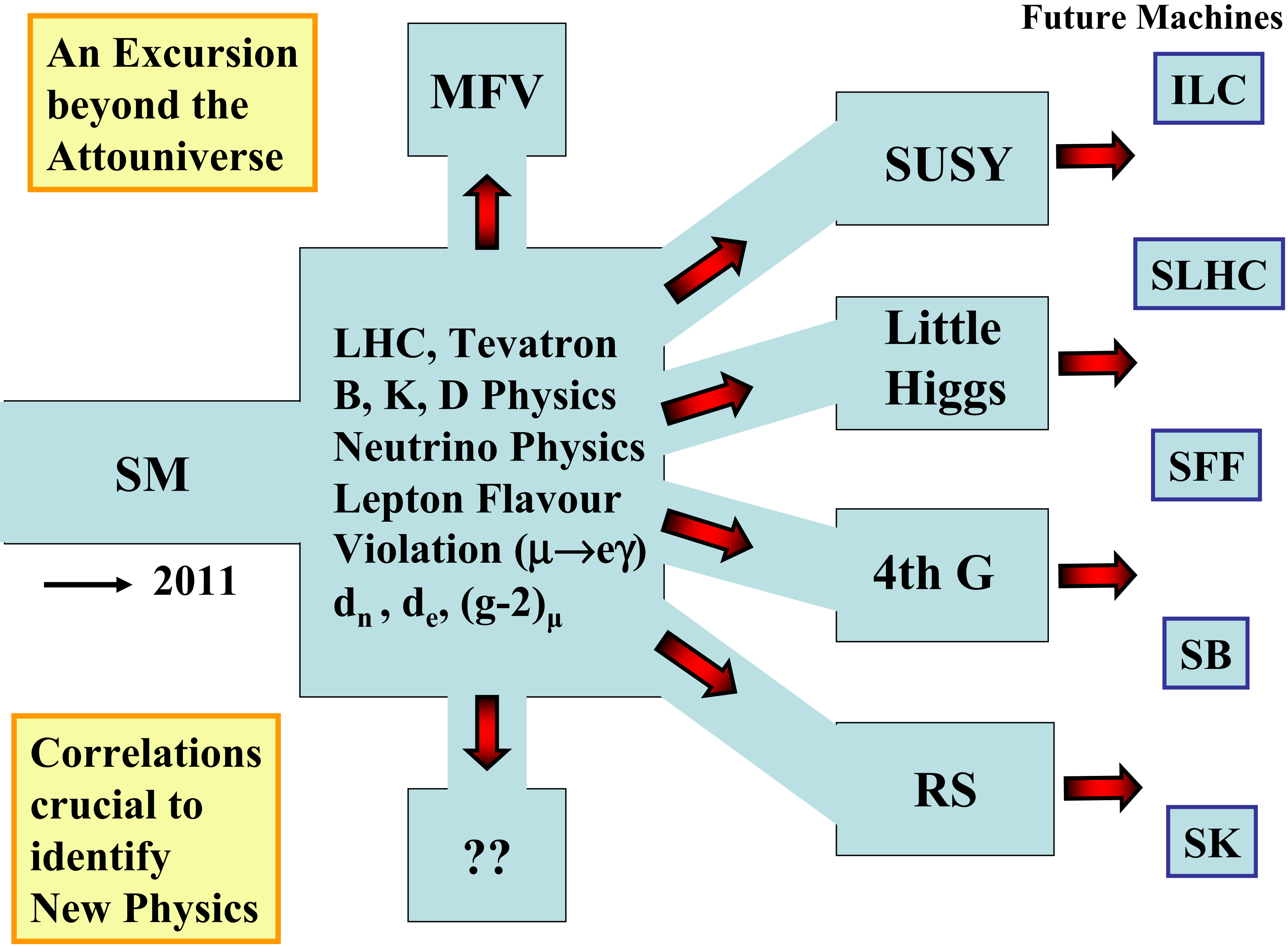


	NEW SM
$D^0 - \bar{D}^0$	★★
ϵ_K	★★
$S_{\psi\phi}$	★★★
$S_{\phi K_S}$	★★
$A_{\rm CP}\,(B \to X_s\gamma)$	★
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★★
$A_9(B \to K^*\mu^+\mu^-)$	★
$B \to K^{(*)}\nu\bar{\nu}$	★★★
$B_s \to \mu^+\mu^-$	★★★
$K^+ \to \pi^+\nu\bar{\nu}$	★★
$K_L \to \pi^0\nu\bar{\nu}$	★★★
$\mu \to e\gamma$	★★★
$\tau \to \mu\gamma$	★★★
$\mu + N \to e + N$	★★★
d_n	★★★
d_e	★★★
$(g-2)_\mu$	★★

4th Movement

Finale: Vivace !

An Excursion beyond the Attouniverse



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

Correlations crucial to identify New Physics

Superstars of 2011 – 2015 (Flavour Physics)

$\boxed{S_{\psi\varphi}}$

$\cancel{CP}$ in $B_s^0 - \bar{B}_s^0$

$(B_s \to \varphi\varphi)$

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

$(B_d \to \mu^+\mu^-)$

$(B^+ \to \tau^+\nu_\tau)$

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

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

$(B_d \to K^*\mu^+\mu^-)$

γ
from Tree
Level
Decays

$\mu \to e\gamma$

$\tau \to \mu\gamma$

$\tau \to e\gamma$

$\mu \to 3e$

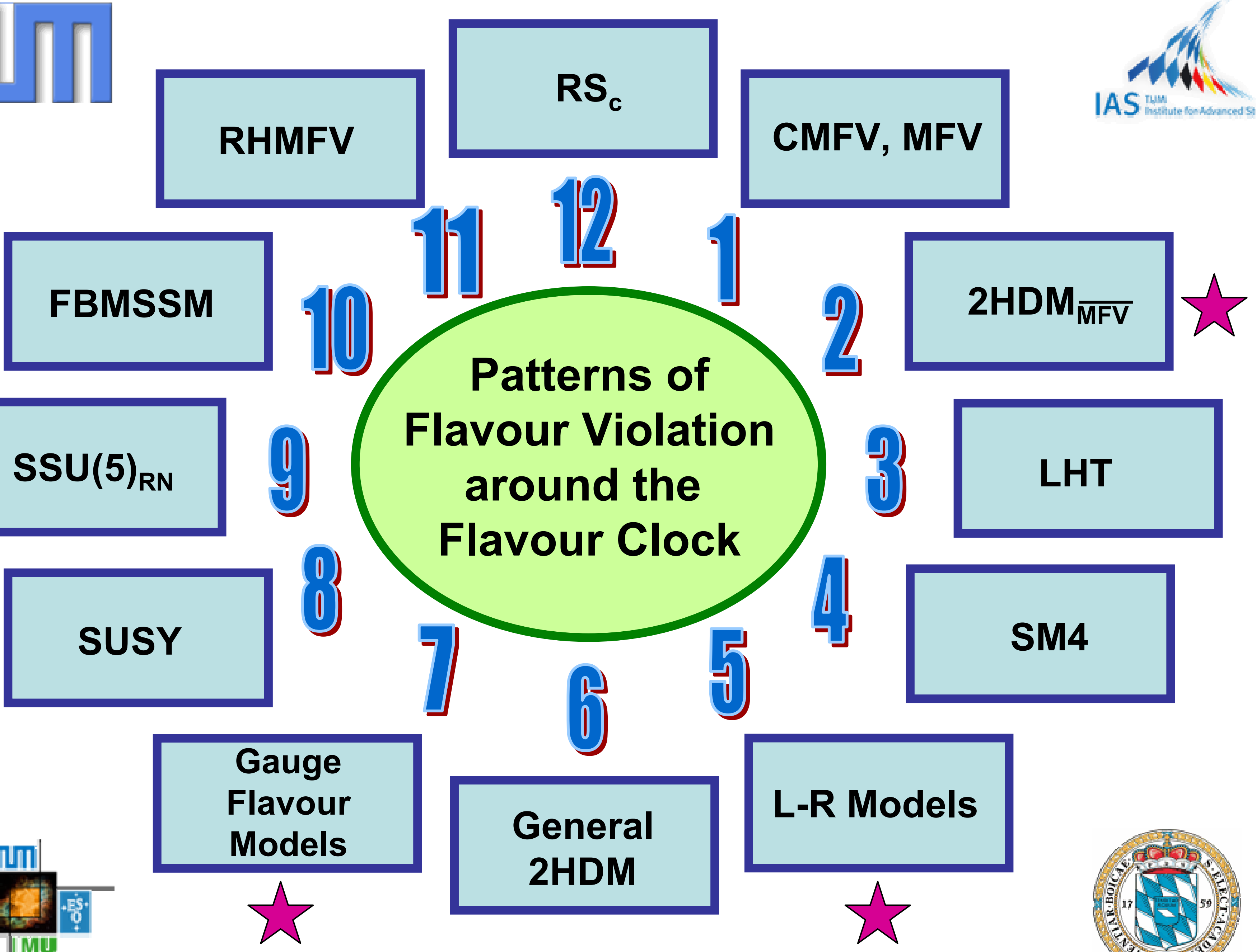
$\tau \to 3$ leptons

ε'/ε *)

(Lattice)

EDM´s
$(g\text{-}2)_\mu$

*) Direct $\cancel{CP}$ in
$K_L \to \pi\pi$



Patterns of Flavour Violation around the Flavour Clock

- 12 RS_c
- 1 CMFV, MFV
- 2 $\mathrm{2HDM}_{\overline{\mathrm{MFV}}}$ ★
- 3 LHT
- 4 SM4
- 5 L-R Models ★
- 6 General 2HDM
- 7 Gauge Flavour Models ★
- 8 SUSY
- 9 $\mathrm{SSU(5)}_{\mathrm{RN}}$
- 10 FBMSSM
- 11 RHMFV

hep-ph/1012.1447

Many Thanks to my Collaborators

SUSY


W. Altmannshofer

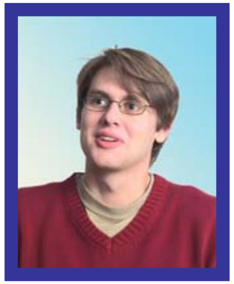

S. Gori


P. Paradisi


D. Straub

LHT


M. Blanke


B. Duling


A. Poschenrieder


S. Recksiegel


C. Tarantino

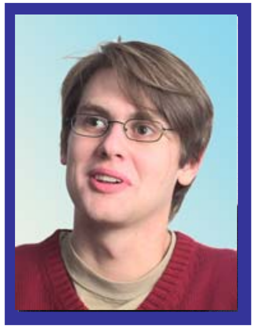

S. Uhlig


A. Weiler

RS


M. Albrecht


M. Blanke


B. Duling


K. Gemmler


S. Gori


A. Weiler

ALL WANTED !!

SUSY


W. Altmannshofer

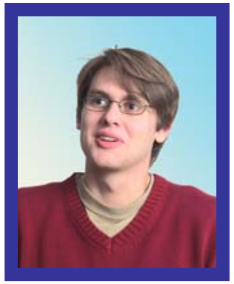

S. Gori


P. Paradisi


D. Straub

LHT


M. Blanke


B. Duling


A. Poschenrieder


S. Recksiegel


C. Tarantino

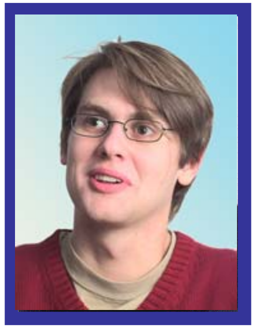

S. Uhlig


A. Weiler

RS


M. Albrecht


M. Blanke


B. Duling


K. Gemmler


S. Gori


A. Weiler

4 G


B. Duling


T. Heidsieck


C. Promberger


T. Feldmann


S. Recksiegel

2 HDM


M.V.Carlucci


S. Gori


G. Isidori

ε_K


D. Guadagnoli

RH Currents


K. Gemmler


G. Isidori

More Collaborators


I.Bigi


P. Ball


A. Bharucha


M. Wick

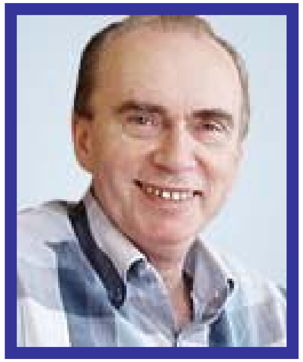

L. Calibbi

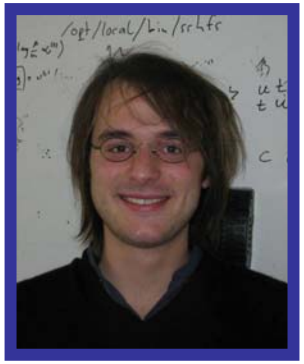

M. Nagai


L. Merlo


C. Grojean


A. Lenz


S. Pokorski


E. Stamou


R. Ziegler


J. Girrbach

←

Next Speaker

Should we be frustrated after Summer Conferences ?

Should we be frustrated after Summer Conferences ?

No, no, no !!!

Should we be frustrated after Summer Conferences ?

No, no, no !!!

Exciting Times are just ahead of us !!!

New Animalcula in Sight !

New Animalcula in Sight !

Hopefully we will soon know how they really look like !

Thank You !!

New Animalcula
in Sight !

Hopefully we will soon know
how they really look like !

Backup

Big Superstars for 2011-2013

$S_{\psi\varphi}$

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

$\mu \to e\gamma$

Mixing induced CP Violation
$(B_s^0 - \overline{B}_s^0)$

$$\left(S_{\psi\varphi}\right)_{SM} \cong 0.04$$

$$\left(S_{\psi K_S}\right)_{SM} \cong 0.80$$

Mixing induced CP Violation
$(B_d^0 - \overline{B}_d^0)$

$$Br\left(B_{s,d} \to \mu^+\mu^-\right)_{SM} \cong 3.2 \cdot 10^{-9}\left(1 \cdot 10^{-10}\right)$$

CP-conserving Quark-Flavour Violating

$$Br\left(\mu \to e\gamma\right)_{SM} \cong 0\left(10^{-54}\right)$$

Lepton Flavour Violation

Precise prediction for ε_K ($\cancel{CP}$ in $K_L \to \pi\pi$)

and

Precise measurement of CKM phase = γ

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

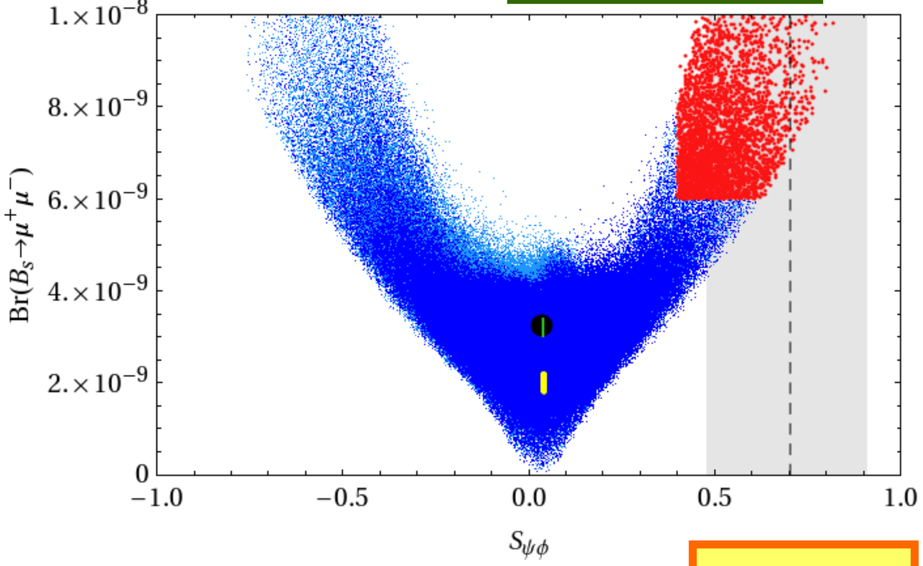
4G

BDFHPR
(1002.2126)

Similar Result by Soni et al.

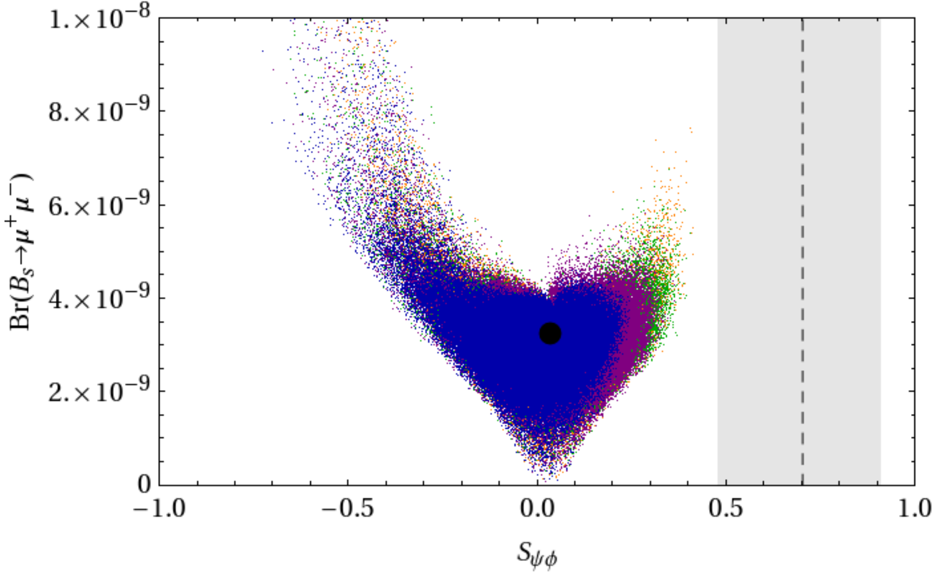
See also Hou et al. and Lenz et al.

AJB, Duling, Feldmann, Heidsieck, Promberger, Recksiegel



CDF D0

No Impact on Δa_μ



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

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

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

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

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

$\left|V_{ub}\right|_{A} = 4.70\ (56) \cdot 10^{-3}$

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

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

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

$\left|V_{ub}\right|_{A} = \left|V_{ub}^{L} - a\varepsilon^{2} V_{ub}^{R}\right|$

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
November
2011