Flavour Visions: 2011

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(Technical University Munich, TUM-IAS)

Beauty 2011
Amsterdam, Apr. 08th, 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**

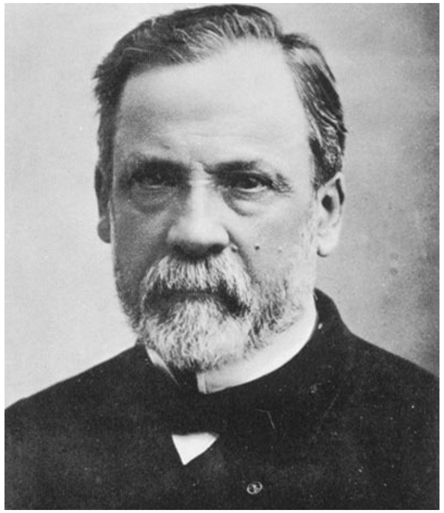
~500 Microscopes

(Magnification by ~300)

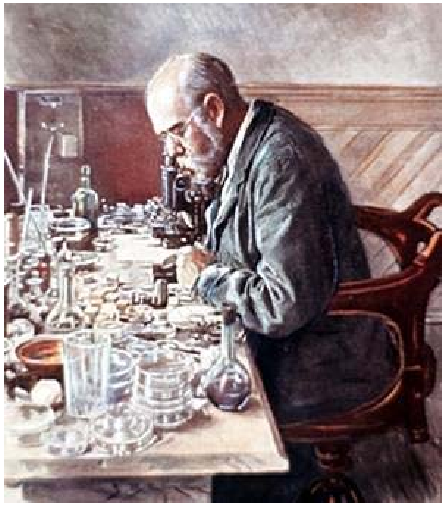
Animalcula Hunters

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**



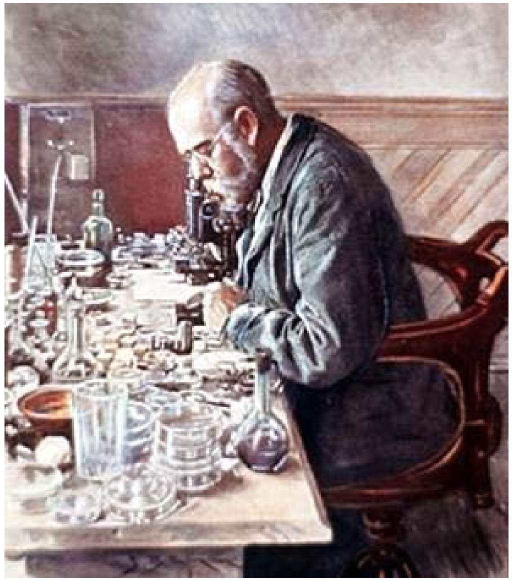
Robert Koch
***11.12.1843 ✝27.05.1910**

An Excursion towards the Very Short Distance Scales:

1676 - 2020

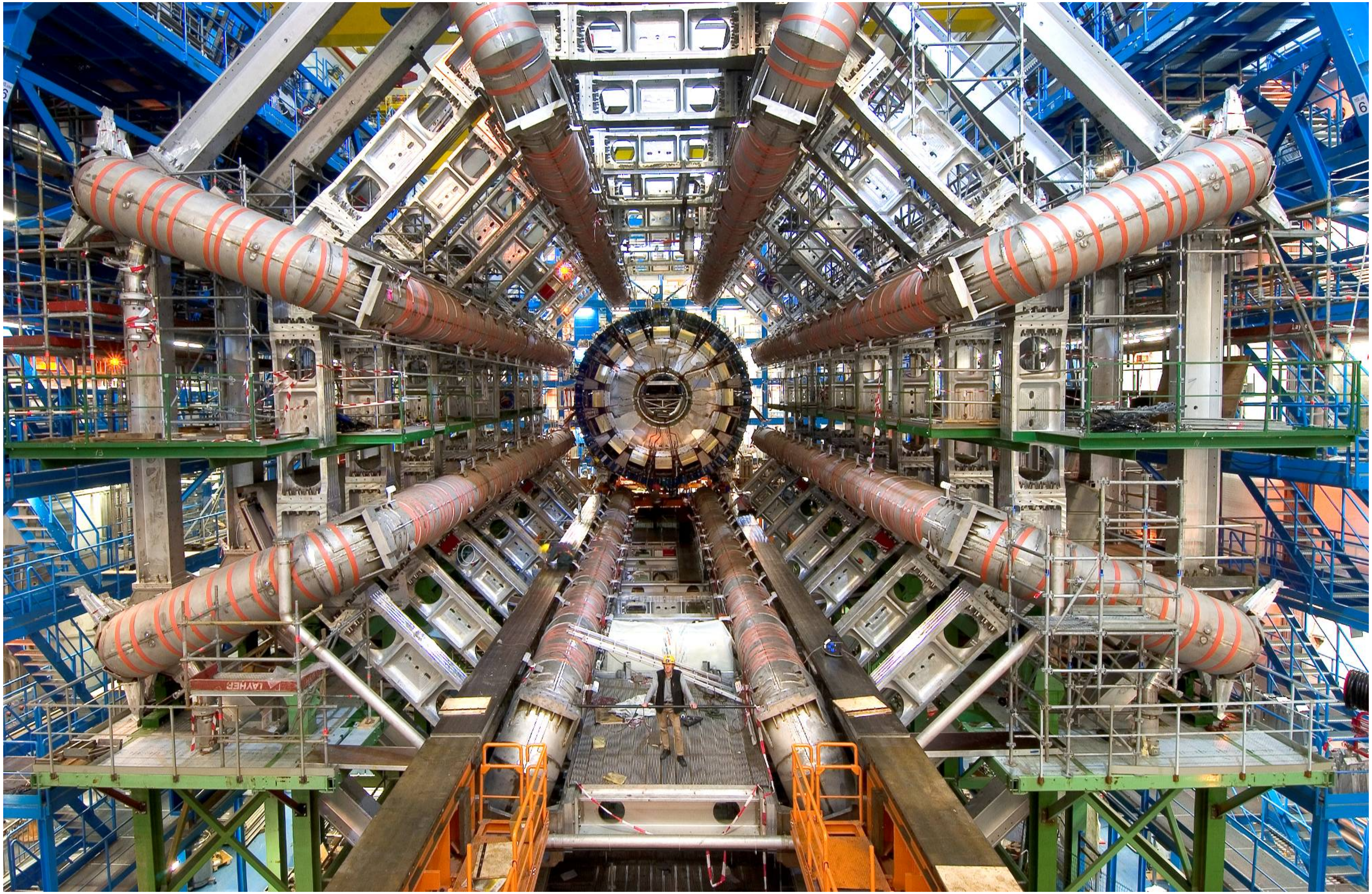
Microuniverse	**10^{-6}m**	**Bacteriology Microbiology**
Nanouniverse	**10^{-9}m**	**Nanoscience**
Femtouniverse	**10^{-15}m**	**Nuclear Physics Low Energy Elementary Particle Physics**
Attouniverse	**10^{-18}m**	**High Energy Particle Physics (present)**
High Energy Proton-Proton Collisions at the LHC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

The Technology for the Microuniverse

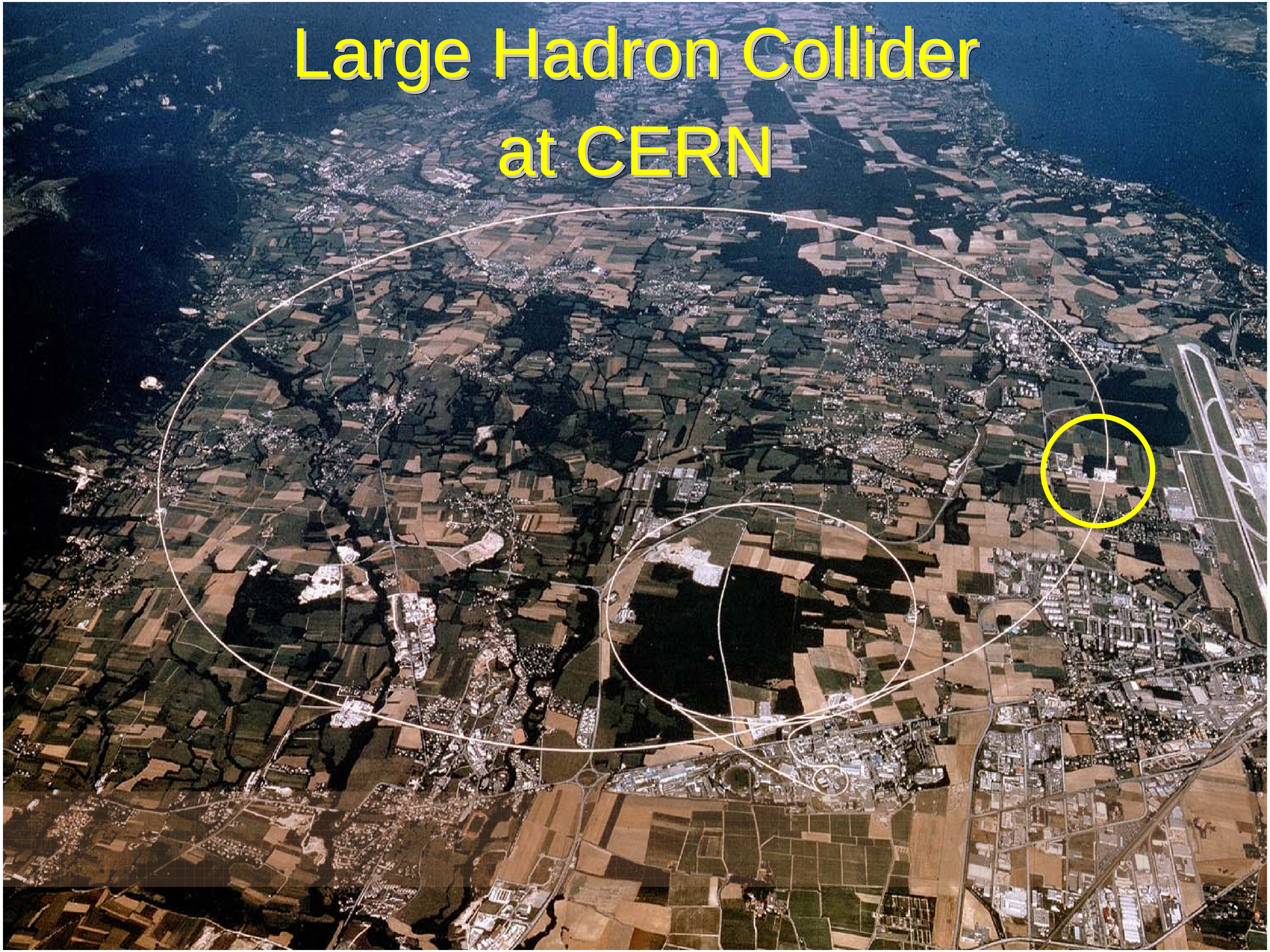


Robert Koch
***11.12.1843 ✝27.05.1910**

Technology to go beyond the Attouniverse



Large Hadron Collider at CERN



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!

Amsterdam Symphony No. 2

Amsterdam Symphony No. 2

1st Movement ： **Beyond the SM (13 min)**

Amsterdam Symphony No. 2

1st Movement : **Beyond the SM (13 min)**

2nd Movement : **Expectations and first Messages from New Animalcula (18 min)**

Amsterdam Symphony No. 2

1st Movement	:	**Beyond the SM (13 min)**
2nd Movement	:	**Expectations and first Messages from New Animalcula (18 min)**
3rd Movement	:	**DNA Tests of Flavour Physics (2 min)**

Amsterdam Symphony No. 2

1st Movement	:	Beyond the SM (13 min)
2nd Movement	:	Expectations and first Messages from New Animalcula (18 min)
3rd Movement	:	DNA Tests of Flavour Physics (2 min)
4th Movement	:	Finale: Vivace ! (2 min)

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

1st Movement

Beyond the SM

Fundamental Lagrangian of the Standard Model

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

$$\begin{aligned}
L_{\text{gauge}} &= \underbrace{-\frac{1}{4}G^{a}_{\mu\nu}G^{a\,\mu\nu}}_{\text{(QCD)}} \underbrace{-\frac{1}{4}W^{b}_{\mu\nu}W^{b\,\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}}_{\text{(Electroweak)}} \\
L_{\text{fermion}} &= \sum_{f} \bar{\psi}_{fL}\left(i\gamma^{\mu}D^{fL}_{\mu}\right)\psi_{fL} + \bar{\psi}_{fR}\left(i\gamma^{\mu}D^{fR}_{\mu}\right)\psi_{fR} \\
L_{\text{Higgs}} &= \left(D_{\mu}\varphi\right)^{\dagger}\left(D^{\mu}\varphi\right) - \left[\mu^{2}\varphi^{\dagger}\varphi + \frac{\lambda}{4}(\varphi^{\dagger}\varphi)^{2}\right] \\
L_{\text{Yukawa}} &= -\sum_{f} Y^{ij}\bar{\psi}^{i}_{fL}\,\varphi\,\psi^{j}_{fR} \;+\text{h.c.} \quad f = q, l
\end{aligned}$$

Standard Model of Strong and Electroweak Interactions

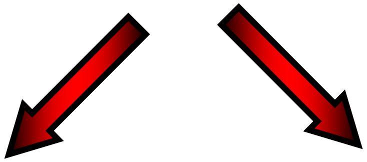
Low Energy Effective Quantum Field Theory based on (< 200 GeV)

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \xrightarrow[\text{broken}]{\text{spontaneously}} SU(3)_C \otimes U(1)_{QED}$$

which describes low energy phenomena in terms of 28 Parameters that have to be determined from experiment.

22 among these parameters are in the Flavour Sector !

CKM (Nobel Prize 2008)



Dirac Medal
(2010)

N. Cabibbo
(1935-2010)

M. Kobayashi

T. Maskawa

In our search for a more fundamental theory we need to improve our understanding of Flavour

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 (hierachy 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 ?

We need

New Physics

(new particles and forces)

in order to answer
all these questions and
solve all existing problems !

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New Animalcula !!!

Complementary Methods to Search for New Physics

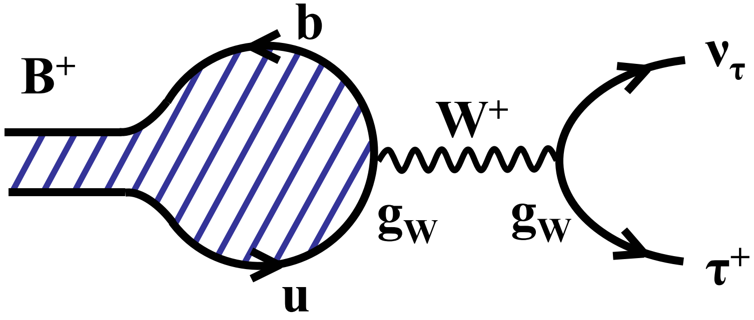
Direct Searches : Limited by the available Energy

Indirect Searches : Quantum Fluctuations

(Limited by precision)

Indirect Search: Precision Measurement of Decays of Mesons and Leptons

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

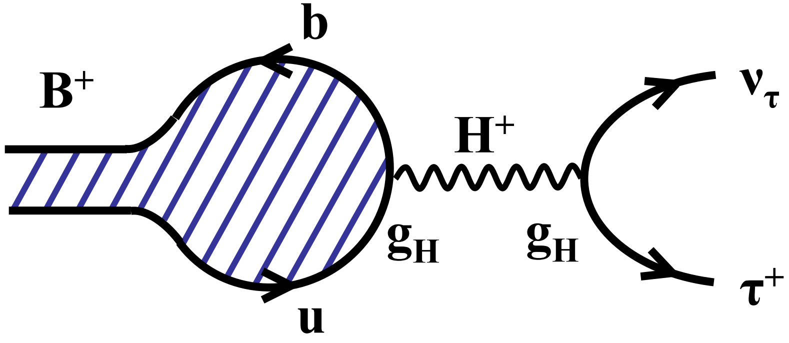


Standard Model

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

$m_B \approx 5$ GeV

A, B – parameters of a given theory



Contribution of a new charged Heavy Particle

$$Br\left(B^+ \to \tau^+ \nu_\tau\right) = \left| A \frac{g_W^2}{M_W^2} + B \frac{g_H^2}{M_H^2} \right|^2$$

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

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.

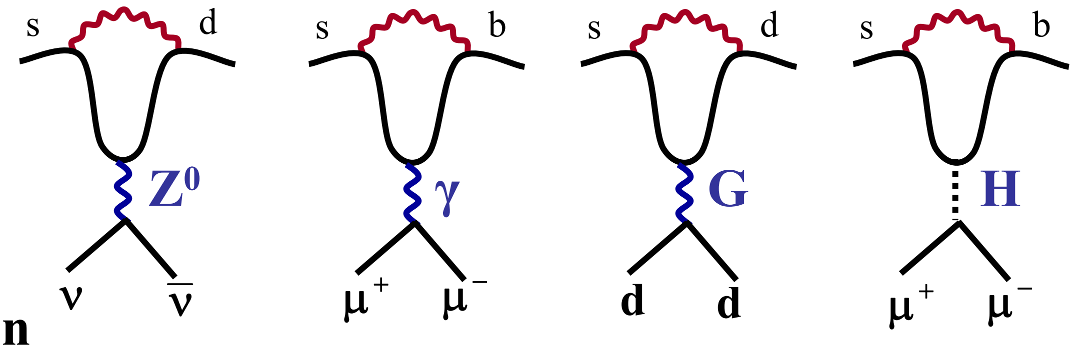
2. Study Patterns on Flavour Violation in various New Physics models (correlations between many flavour observables).

…and

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

Basic Diagrams in FCNC Processes

Penguin Family :

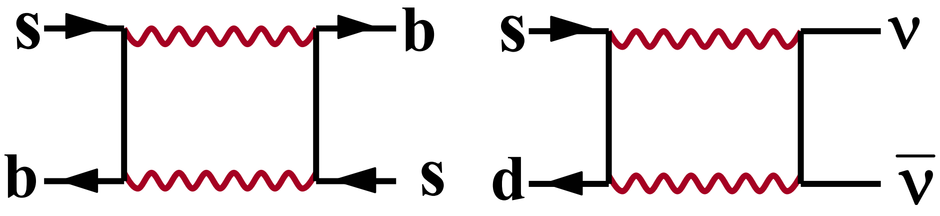


New Physics enters here

Similar diagrams in LFV and EDM´s

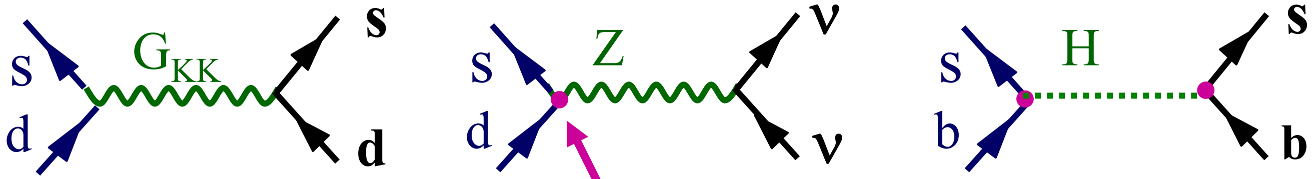
(GIM broken at one loop)

Box Diagrams

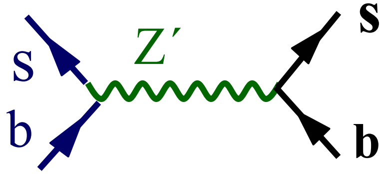


\+ other box diagrams

Tree Diagrams



(GIM broken at tree level)

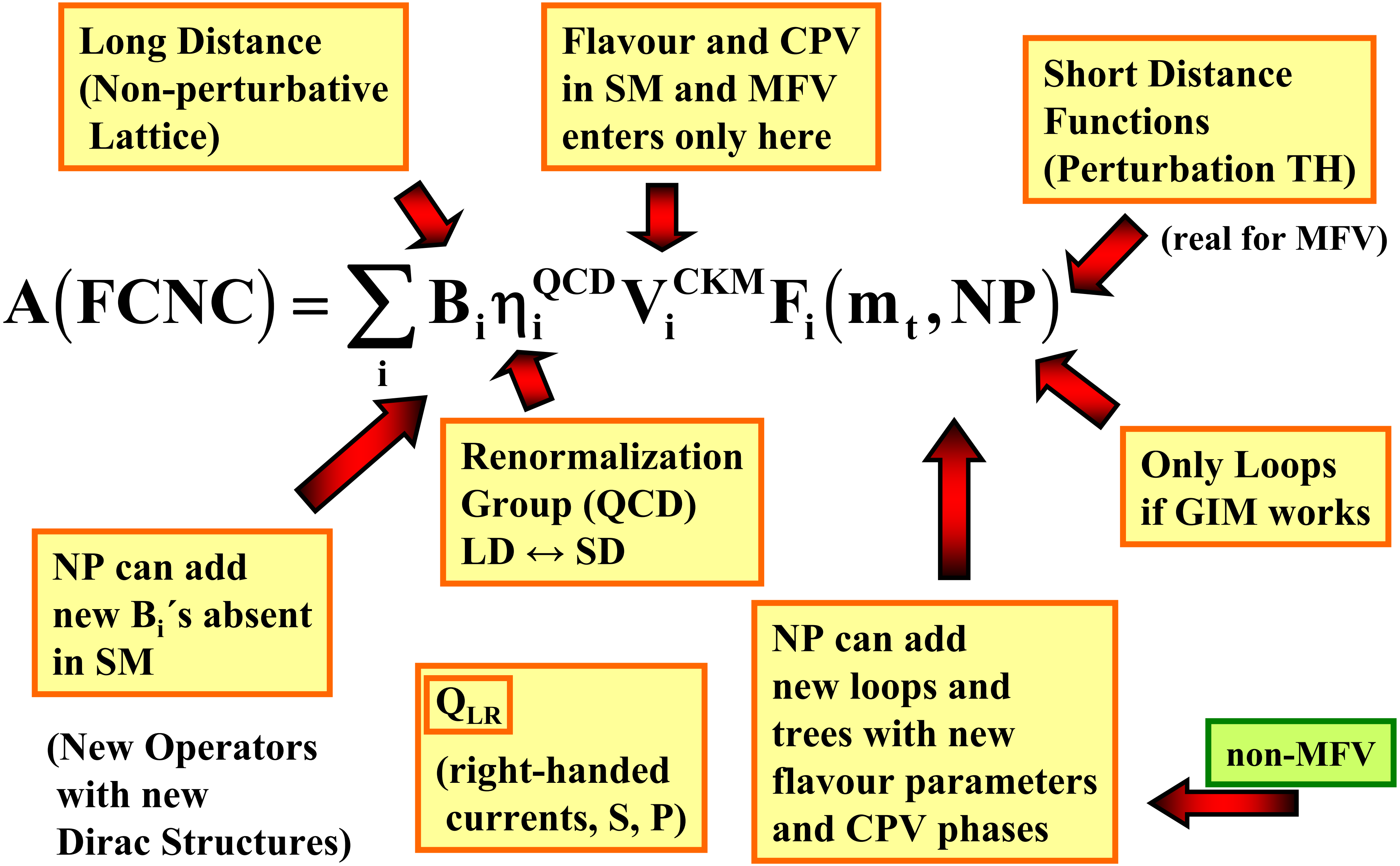


RS

Generated through mixing with New Gauge Bosons

Double Higgs Penguin in SUSY

Master Formula for FCNC Amplitudes



Long Distance
(Non-perturbative
Lattice)

Flavour and CPV
in SM and MFV
enters only here

Short Distance
Functions
(Perturbation TH)

(real for MFV)

$$A\left(FCNC\right) = \sum_i B_i \eta_i^{QCD} V_i^{CKM} F_i\left(m_t, NP\right)$$

Renormalization
Group (QCD)
LD ↔ SD

Only Loops
if GIM works

NP can add
new B_i´s absent
in SM

(New Operators
with new
Dirac Structures)

Q_{LR}

(right-handed
currents, S, P)

NP can add
new loops and
trees with new
flavour parameters
and CPV phases

non-MFV

Most popular BSM Directions

CMFV
(constrained MFV)

NEW **MFV** (NMFV) (GMFV)

NEW **2HDM**

NEW **RHMFV**

LHT
(Littlest Higgs with T-parity)

SUSY
(flavour models)

Z´
(Langacker…)

RS
(Randall-Sundrum)
(Warped Extra Dimensions)

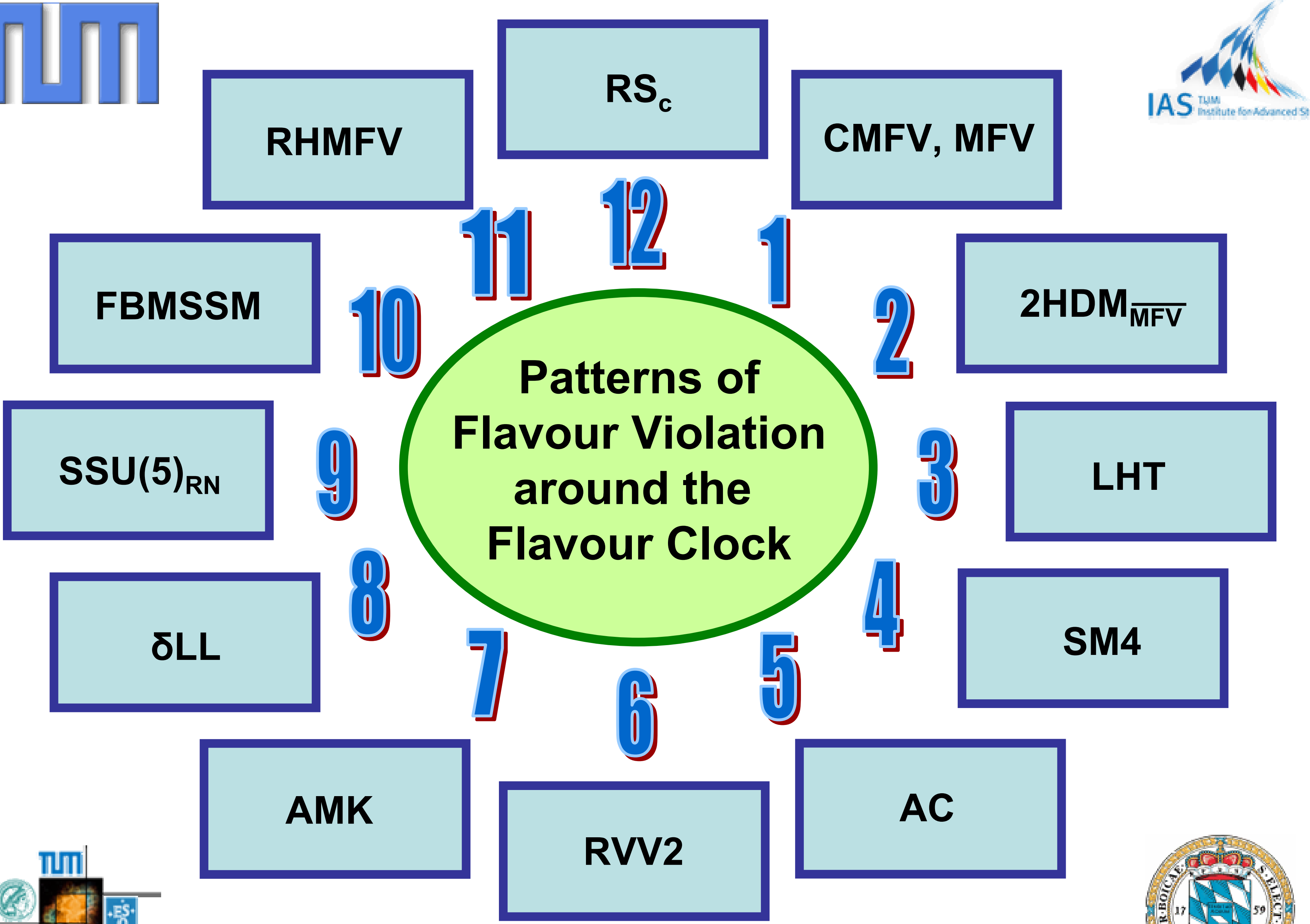
NEW **4th G**
(Hou.., Soni.., Lenz.., Melic)
Munich

Vector-Like Quarks
(Branco…, del Aguila)

⬇

Non-Decoupling

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



Patterns of Flavour Violation around the Flavour Clock

12 RS_c

1 CMFV, MFV

2 $2HDM_{\overline{MFV}}$

3 LHT

4 SM4

5 AC

6 RVV2

7 AMK

8 δLL

9 $SSU(5)_{RN}$

10 FBMSSM

11 RHMFV

hep-ph/1012.1447

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 ?

Superstars of 2011 – 2015 (Flavour Physics)

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

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

$\left(B_s \to \varphi\varphi\right)$

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

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

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

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

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

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

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
$K_L \to \pi\pi$

Dynamics of Two-Body Non-Leptonic B_s Decays in Correlation with B_d Decays

Dynamics of Two-Body Non-Leptonic B_s Decays in Correlation with B_d Decays

Magnificent Seven

M. Beneke

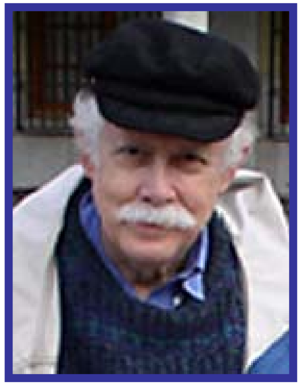
G. Buchalla

M. Neubert

C. Sachrajda

R. Fleischer

M. Gronau



J. Rosner

Charm, Charm, Charm …

Charm, Charm, Charm …

… and more Charm

Charm, Charm, Charm …

… and more Charm

Ikaros Bigi

Charm, Charm, Charm …

… and more Charm

Ikaros Bigi

(Rothschild / Mondavi Opus One Napa Valley 2005))

Big Superstars for 2011-2013

$S_{\psi\varphi}$

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

$\mu \to e\gamma$

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

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

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

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

CP-conserving Quark-Flavour Violating

Lepton Flavour Violation

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

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

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

and

Precise measurement of CKM phase = γ

2nd Movement

Expectations and First Messages from New Animalcula

Departures from Standard Model Expectations

$$\cancel{CP}\begin{cases} K^0-\overline{K}^0 & (\varepsilon_K) & \dfrac{|\varepsilon_K|_{\text{SM}}}{|\varepsilon_K|_{\text{exp}}}\approx 0.83\pm 0.10 \\ B_d^0-\overline{B}_d^0 & (S_{\psi K_s}) & (S_{\psi K_s})\cong \begin{matrix} 0.80\pm 0.04 & (\text{SM}) & (\text{UTfit}) \\ 0.672\pm 0.022 & (\text{exp}) & \end{matrix} \\ B_s^0-\overline{B}_s^0 & (S_{\psi\varphi}) & \dfrac{(S_{\psi\varphi})_{\text{exp}}}{(S_{\psi\varphi})_{\text{SM}}}\approx 10-20 \end{cases}$$

(AJB, Guadagnoli)

LHCb ?

(CDF, DØ, Lenz+Nierste)

0.04

$$\boxed{(S_{\psi\varphi})_{\text{exp}}\approx 0.8^{+0.1}_{-0.2}}$$

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

$$|V_{ub}|=\begin{cases} 4.5\cdot 10^{-3} & \text{Inclusive Decays} \quad (B\to X_u l\nu) \\ 3.5\cdot 10^{-3} & \text{Exclusive Decays} \quad (B\to \rho l\nu) \\ & \text{and SM-CKM fit} \end{cases}$$

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

Alexander Lenz & Ulrich Nierste
Masters of $B_s^0 - \overline{B}_s^0$ Mixing

Alexander Lenz & Ulrich Nierste
Masters of $B_s^0 - \overline{B}_s^0$ Mixing

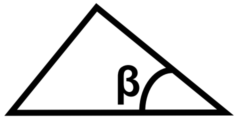
Possible Simplest Solutions

Soni, Lunghi

AJB, Guadagnoli
UTfitters
Lenz, Nierste +
CKMfitters
Laiho, Lunghi, van der Water
Fleicher et al
Blanke et al
Gronau+Rosner
....

A

$|V_{ub}|$ from inclusive decays is correct
New <u>negative</u> $\cancel{CP}$ phase φ_{new} in $B_d^0 - \bar{B}_d^0$ Mixing



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

0.80 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)

Correlated Implications:

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

(non-SUSY)

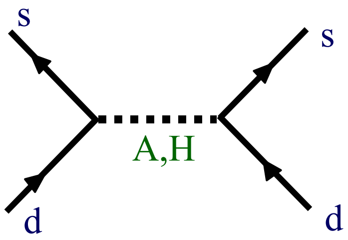
General 2HDM with MFV and Flavour Blind CPV Phases (in Yukawa Couplings)

(1005.5310)

(AJB, Carlucci, Gori, Isidori)

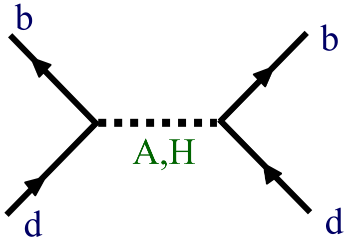
Provides correct pattern

ε_K :



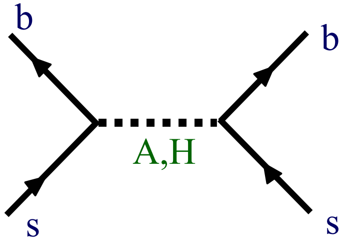
$$\approx \left[\frac{m_d m_s}{M_H^2}\right] m_t^4 (\tan\beta)^2 \left(V_{ts}^* V_{td}\right)^2$$ (tiny)

$S_{\psi K_s}$:



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

$S_{\psi\varphi}$:



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

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

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

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

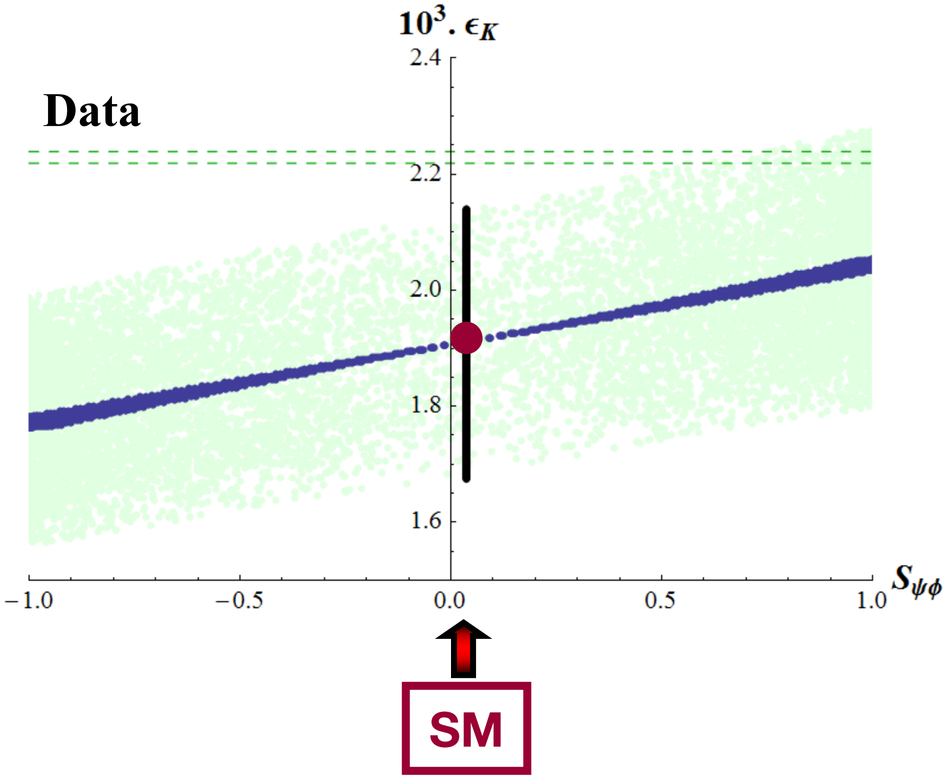
(AJB, Carlucci, Gori, Isidori)

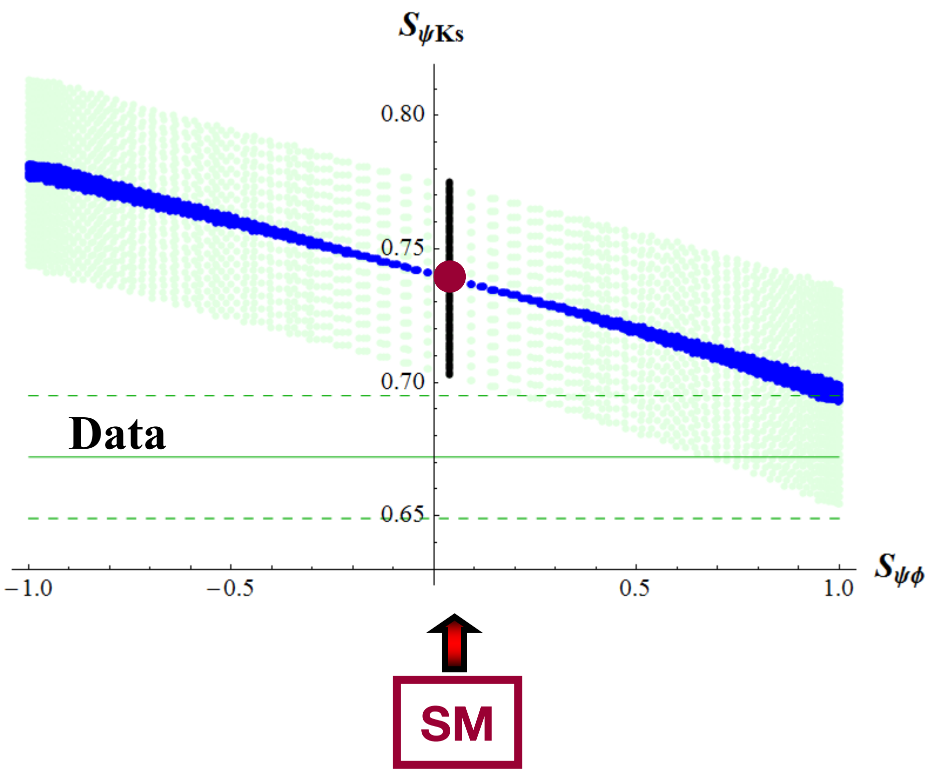
Correct pattern of NP effecs

Correlation between various $\not{CP}$ Effects

(But the effects appear a bit too weak)

$2HDM_{\overline{MFV}}$

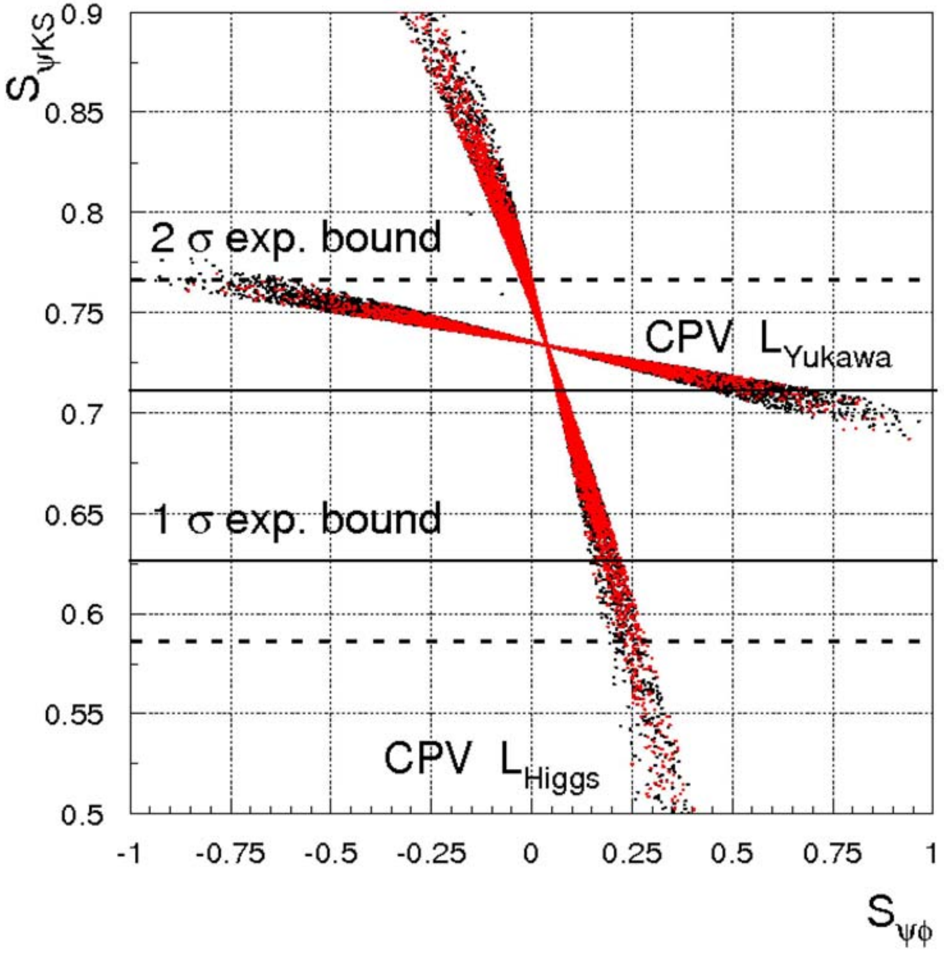




1005.5310

More on 2HDM with MFV and Flavour Blind Phases

Correlation between ~~CP~~ Effects



AJB, Isidori, Paradisi 1007.5291

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

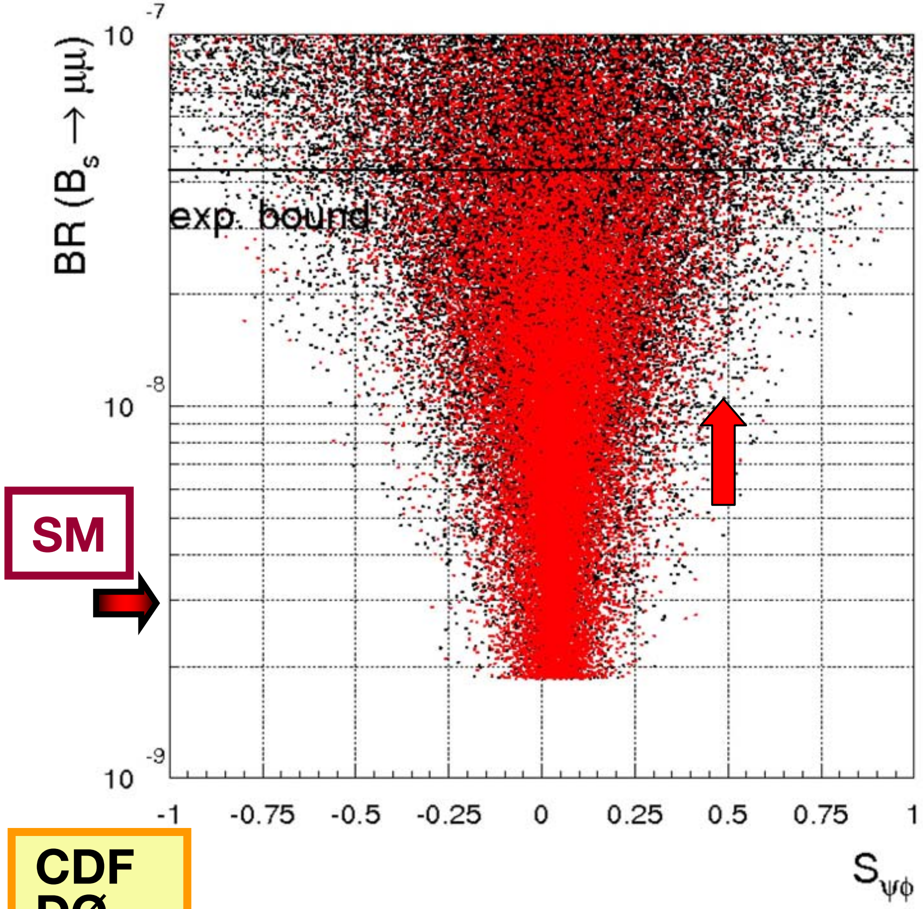
L_{Yukawa} : $$\frac{\theta_d^H}{\theta_s^H} \approx \frac{m_d}{m_s} \approx \frac{1}{17}$$ **BCGI**

L_{Higgs} : $$\frac{\theta_d^H}{\theta_s^H} = 1$$

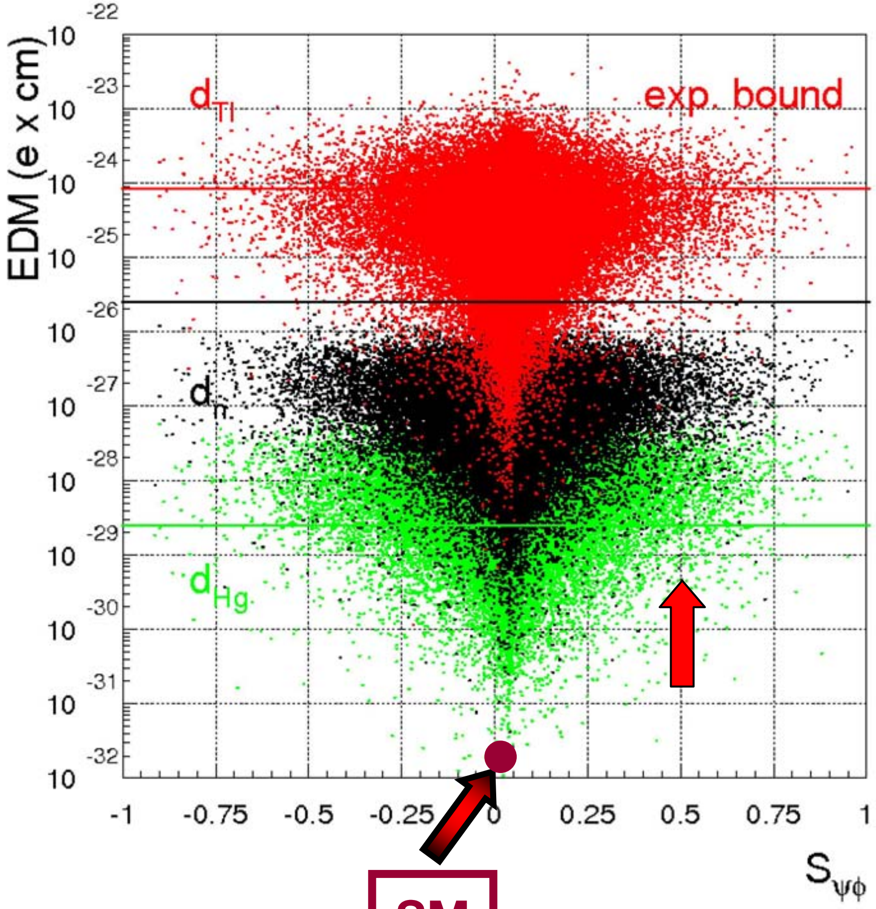
Kagan, Perez, Volansky, Zupan
Paradisi, Straub
Dobrescu, Fox, Martin
Blum, Hochberg, Nir
Ligeti, Papucci, Perez, Zupan

More on 2HDM with MFV and Flavour Blind Phases

$2HDM_{\overline{MFV}}$



SM



SM

CDF
DØ
LHCb

AJB, Isidori, Paradisi 1007.5291

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

Model Expectations

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

ABGPS

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

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

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

1. Enhanced $\mathrm{Br}\left(B_s \to \mu^+\mu^-\right)$
   (SUSY flavour models, $2\mathrm{HDM}_{\overline{\mathrm{MFV}}}$, 4G)
2. Enhanced $\mathrm{Br}\left(B_d \to \mu^+\mu^-\right)$
   ($2\mathrm{HDM}_{\overline{\mathrm{MFV}}}$, also in some SUSY flavour models)
3. $\mathrm{Br}\left(B_d \to \mu^+\mu^-\right)$ 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:
   $\mathrm{Br}(\mu \to e\gamma)$, $\mathrm{Br}(\tau \to \mu\gamma)$, $(g-2)_\mu$, d_e, d_n

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

Z-Penguin (SM
+ Boxes CMFV)

SM

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

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

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

AJB (03)

CMFV "Golden Relation"

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

$(\Delta B = 1)$

(0.95±0.03) Lattice

$(\Delta B = 2)$

Valid in all CMFV models

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

95% CL

LHCb

$$Br\left(B_s \to \mu^+\mu^-\right) \le \begin{cases} 3.3\cdot 10^{-8} & \text{(CDF)} \\ 5.3\cdot 10^{-8} & \text{(D0)} \end{cases}$$

$$Br\left(B_d \to \mu^+\mu^-\right) \le 1\cdot 10^{-8} \quad \text{(CDF)}$$

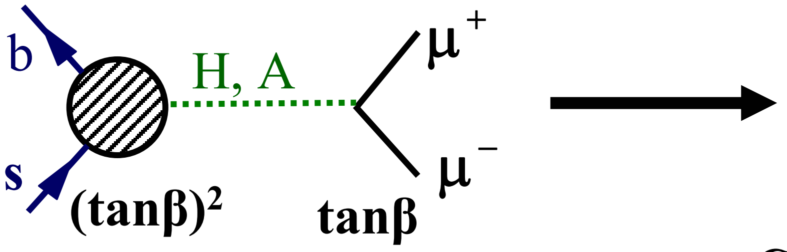
LHC should be able to discover $B_s \to \mu^+\mu^-$ even at the SM level

Fleischer et al

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

Babu, Kolda (99),…+100

SUSY :



$$\mathrm{Br}\left(B_{s,d} \to \mu^+\mu^-\right) \sim \frac{(\tan\beta)^6}{M_A^4}$$

Can reach CDF, DØ and LHCb bounds

$$\frac{\mathrm{Br}\left(B_{s,d} \to \mu^+\mu^-\right)_{4G}}{\mathrm{Br}\left(B_{s,d} \to \mu^+\mu^-\right)_{SM}} \leq 4$$

$$\frac{\mathrm{Br}\left(B_{s,d} \to \mu^+\mu^-\right)_{SUSY}}{\mathrm{Br}\left(B_{s,d} \to \mu^+\mu^-\right)_{SM}} \leq 20$$

$$\frac{\mathrm{Br}\left(B_{s,d} \to \mu^+\mu^-\right)_{LHT}}{\mathrm{Br}\left(B_{s,d} \to \mu^+\mu^-\right)_{SM}} \leq 1.3$$

(Z-penguin)
(Blanke et al) (09)
Larger effects without
custodial protection (Haisch et al.)

$$\frac{\mathrm{Br}\left(B_{s,d} \to \mu^+\mu^-\right)_{RS}}{\mathrm{Br}\left(B_{s,d} \to \mu^+\mu^-\right)_{SM}} \leq 1.1$$

(Z-penguin + Z-tree with
r.h. couplings)
(Custodial protection at work)
(Gori et al) (08)

Muon Anomalous Magnetic Moment

$$\begin{aligned} g_\mu^{\text{exp}} &= 2,002\,331\,841\,8 \\ g_\mu^{\text{theory}} &= 2,002\,331\,836\,7 \\ g_\mu^{\text{exp}} - g_\mu^{\text{theory}} &= (51 \pm 16) \times 10^{-10} \end{aligned}$$

$$\frac{\text{width of a hair}}{\text{Munich–Salzburg}} = \frac{0.1\,mm}{100\,km} = \frac{10^{-4}\,m}{10^{5}\,m} = 10 \times 10^{-10}$$

Disagreement by 3σ

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

Need $\left(\Delta a_\mu\right)_{\substack{\text{New}\\\text{Physics}}} \approx (2-3) \cdot 10^{-9}$

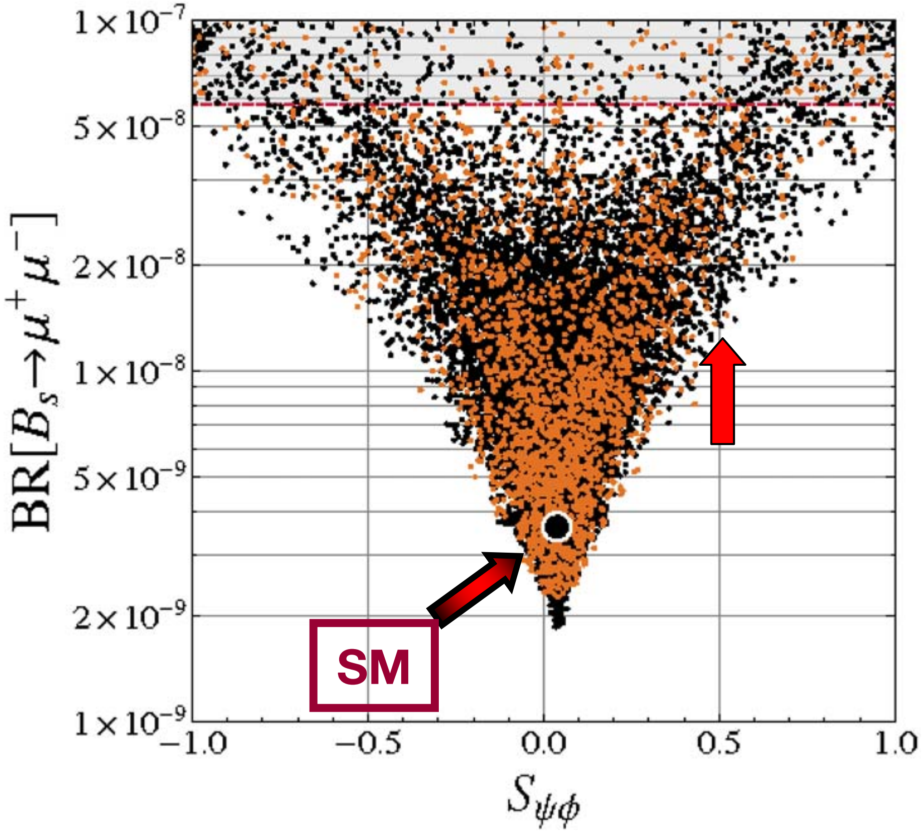
CDF, D0
LHCb

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

SUSY

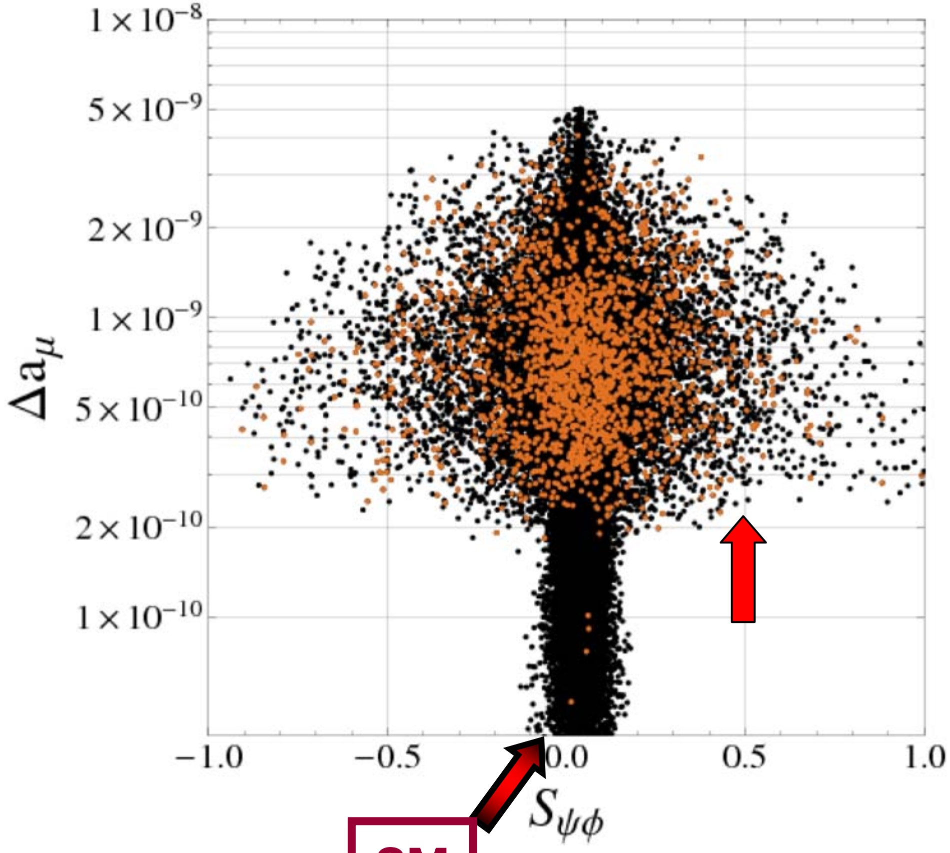
ABGPS

(0909.1333)



SM

Δa_μ vs $S_{\psi\varphi}$



SM

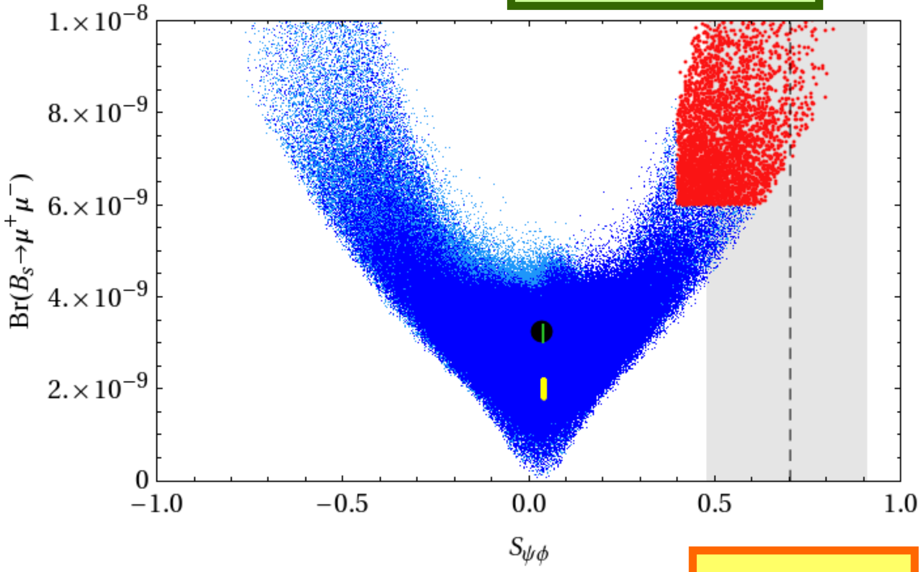
$\mathrm{Br}\left(B_s \to \mu^+\mu^-\right)$ vs $S_{\psi\varphi}$

4G

BDFHPR (1002.2126)

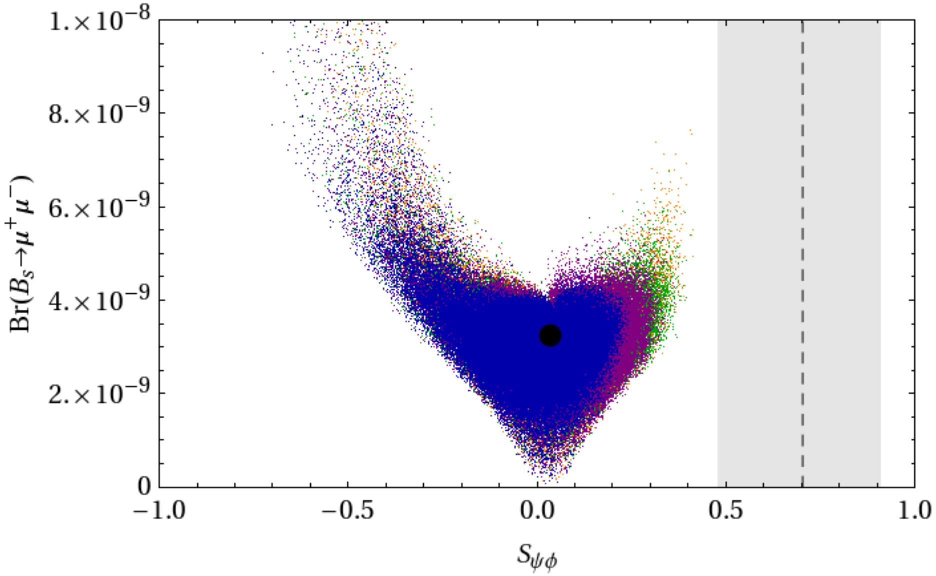
Similar Result by Soni et al.

See also Hou et al. and Lenz et al.



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

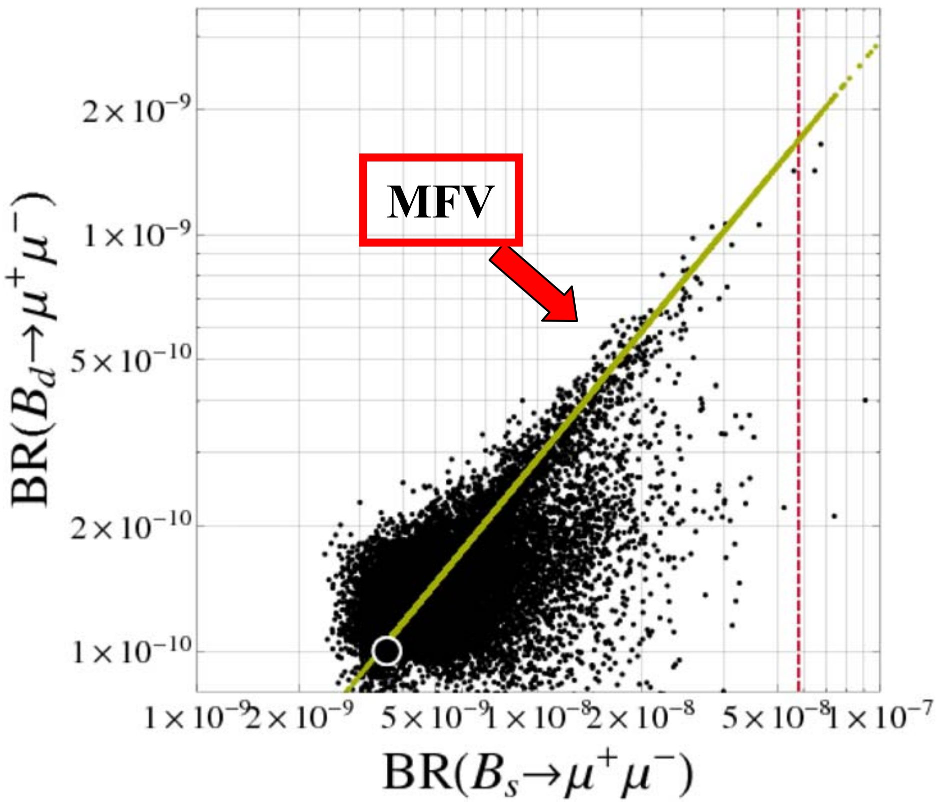
ABGPS

(0909.1333)

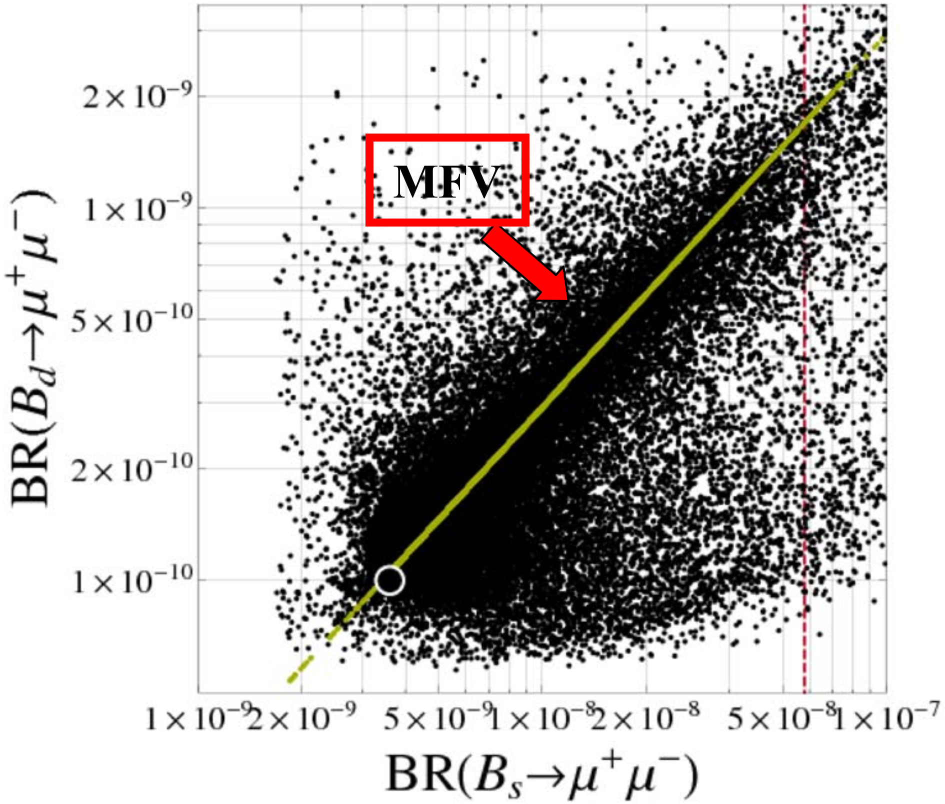
$\mathrm{Br}\left(B_d \to \mu^+\mu^-\right)$ vs $\mathrm{Br}\left(B_s \to \mu^+\mu^-\right)$

SUSY

MFV AJB; Hurth, Isidori, Kamenik, Mescia



RVV2 (RH currents)

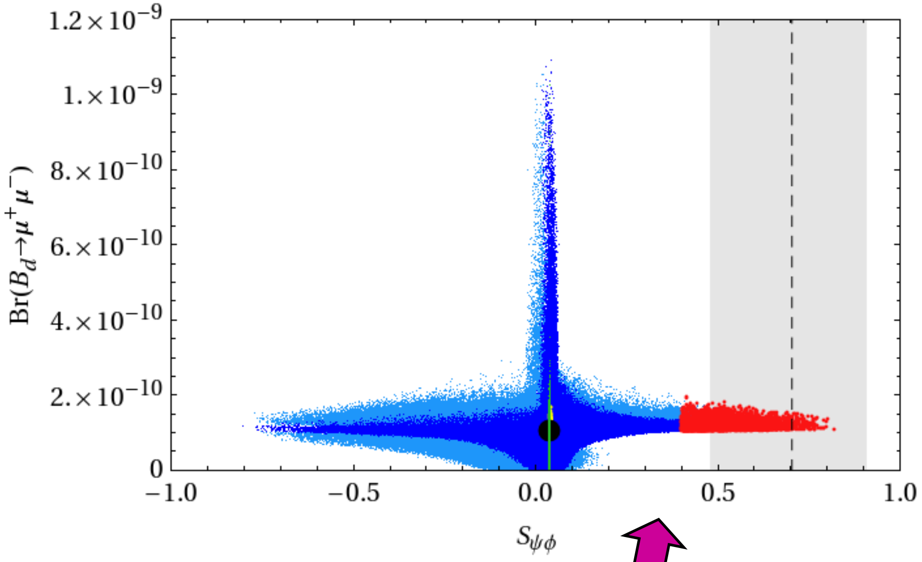


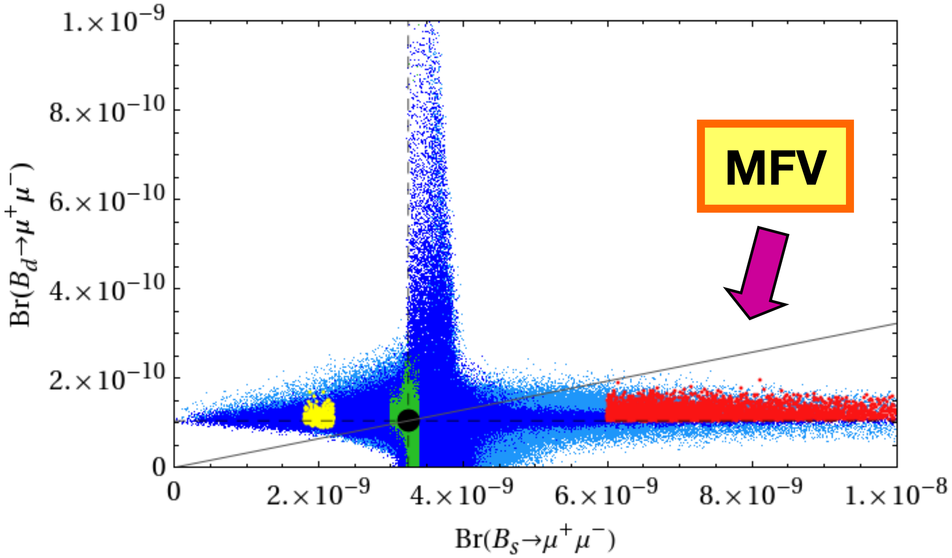
LH currents

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

4G

BDFHPR





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

Very different patterns compared with SUSY, 2HDM, MFV

Important Messages for $K \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ Funs

Ⓐ **These decays are very sensitive to New Animalcula !   (NP)**

Ⓑ **Absence of New Animalcula Effects in B-Physics will not preclude their discovery through $K \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$.**

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} $(d_e)_{SM} \approx 10^{-38}$

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

[e cm]

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)

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

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

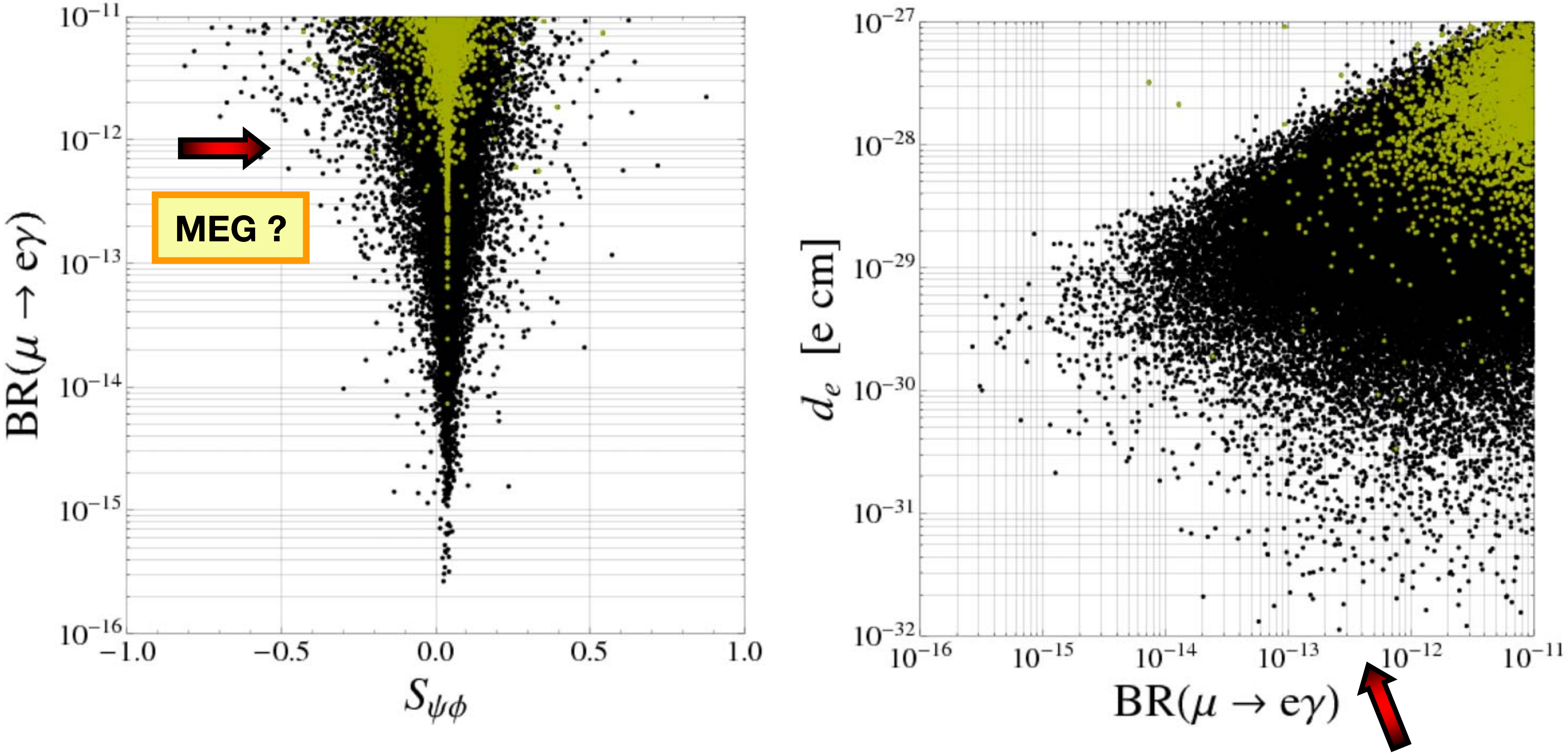
[e cm]

★ **MEG:** $\mathrm{Br}(\mu \to e\gamma) = O(10^{-12})$ **Rumours**

ABGPS

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

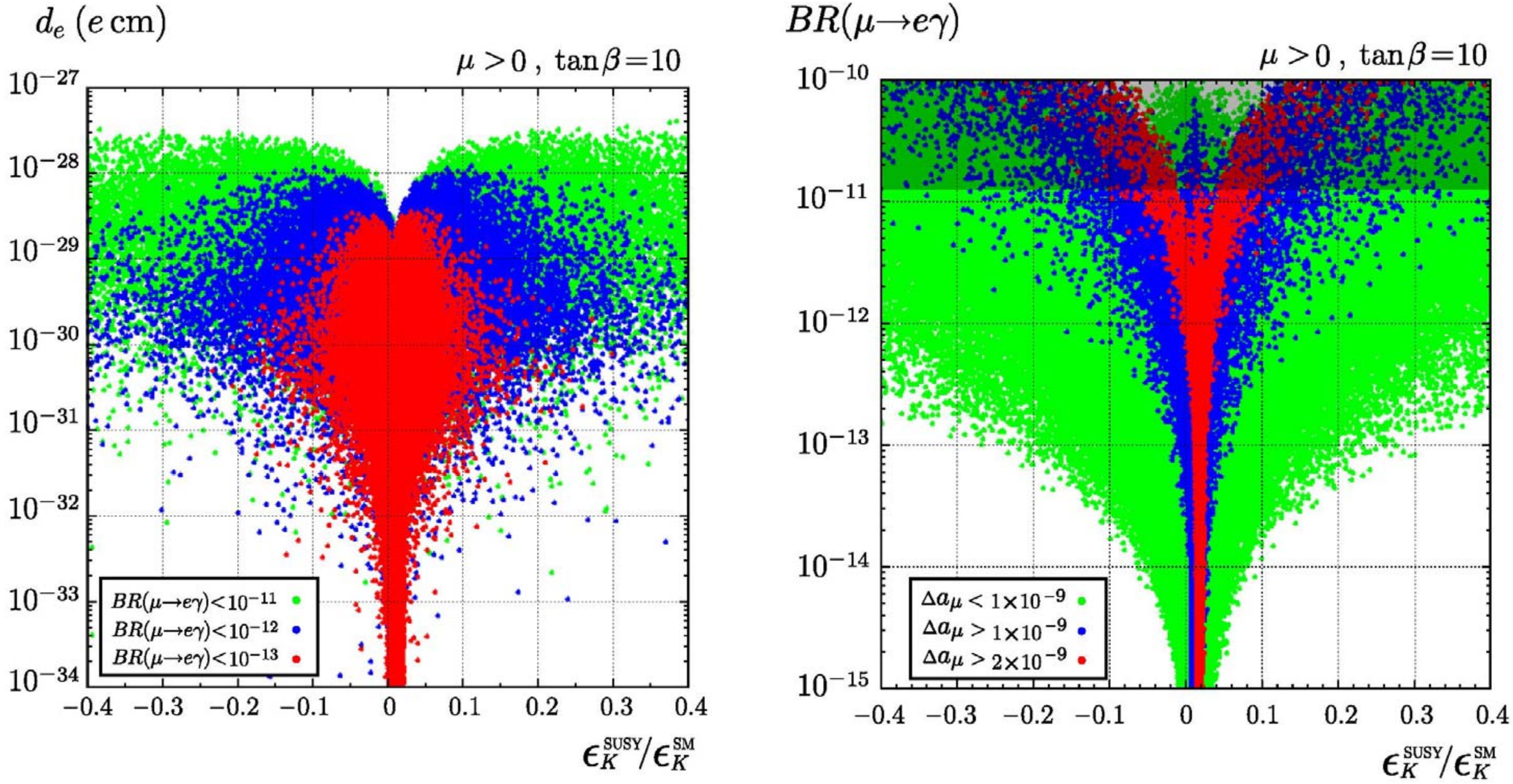
🟩 **Solution to (g-2)$_\mu$ anomaly**



MEG ?

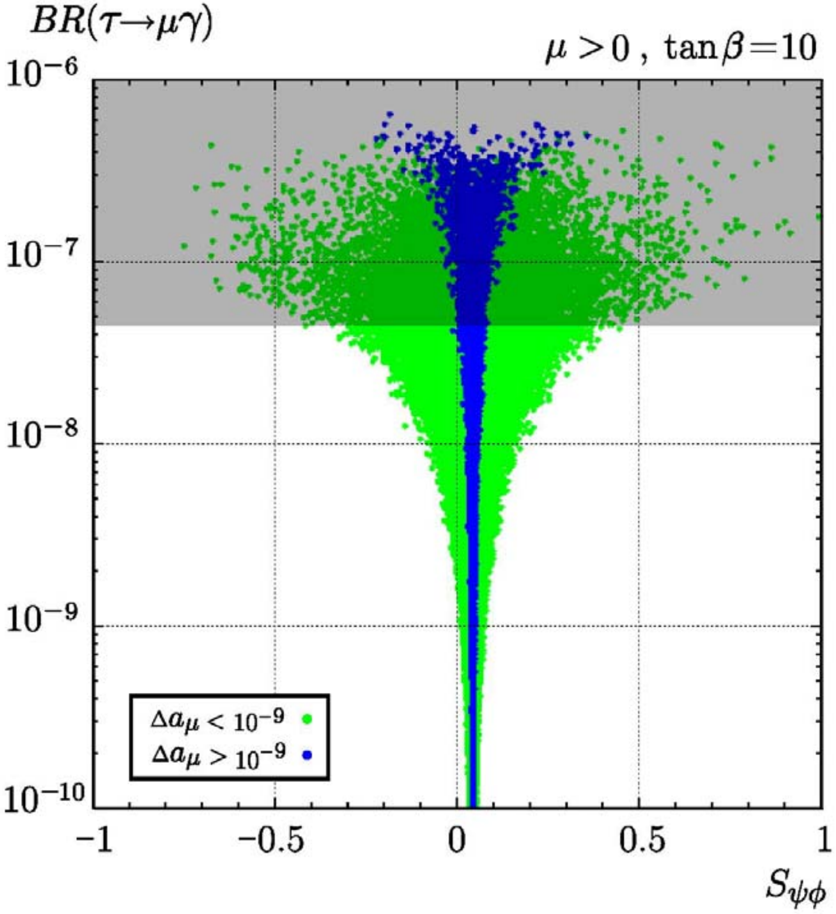
MEG ?

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



AJB, Nagai, Paradisi, 1011.1993

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



AJB, Nagai, Paradisi, 1011.1993

3rd Movement

DNA Tests of Flavour Physics

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

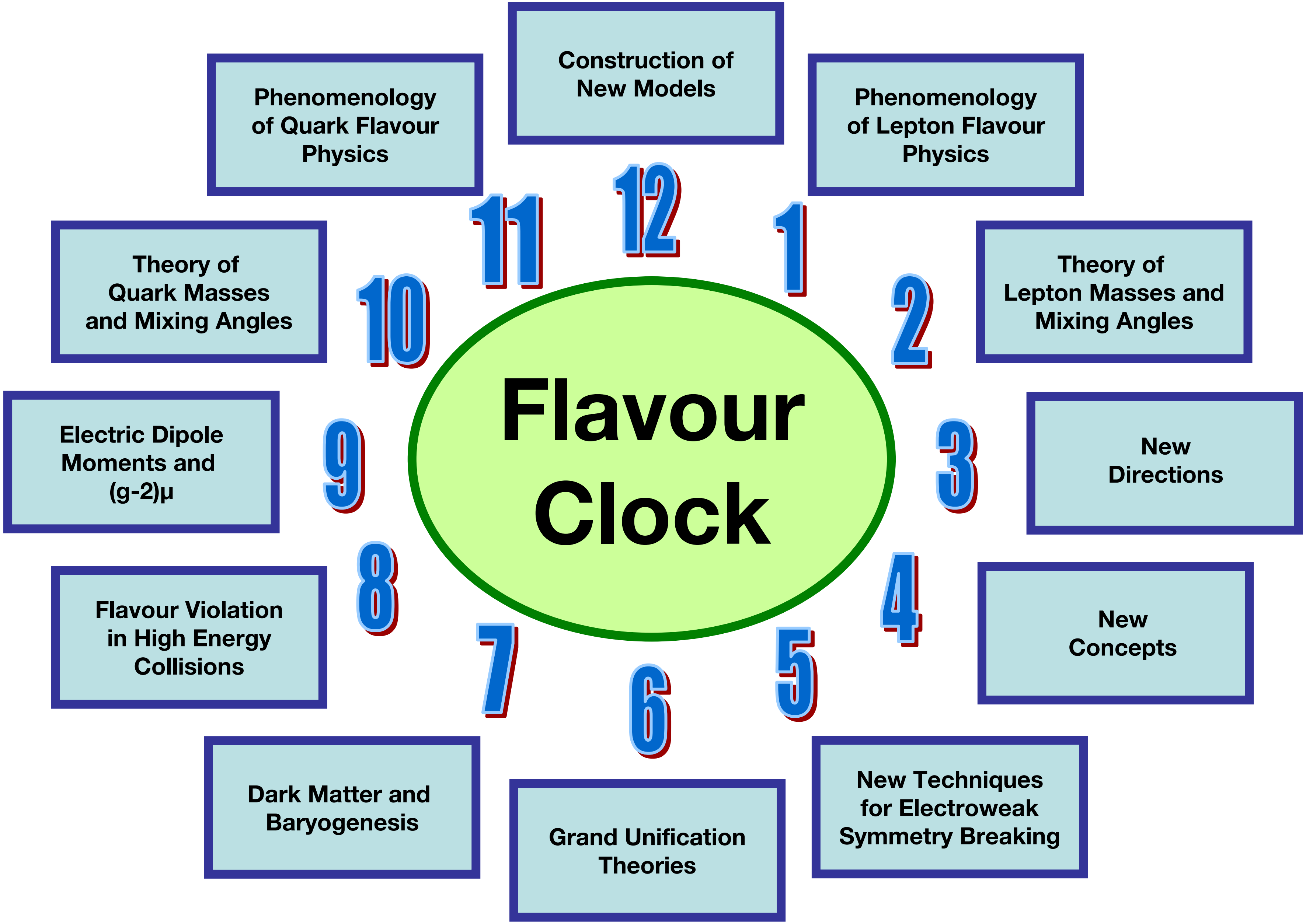
	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS	4G
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?	★★
ϵ_K	★	★★★	★★★	★	★	★★	★★★	★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?	★★
$A_{\rm CP}\,(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?	★
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?	★★
$A_9(B \to K^*\mu^+\mu^-)$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

2020 Vision

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

4th Movement

Finale: Vivace !



Flavour Clock

12 Construction of New Models

1 Phenomenology of Lepton Flavour Physics

2 Theory of Lepton Masses and Mixing Angles

3 New Directions

4 New Concepts

5 New Techniques for Electroweak Symmetry Breaking

6 Grand Unification Theories

7 Dark Matter and Baryogenesis

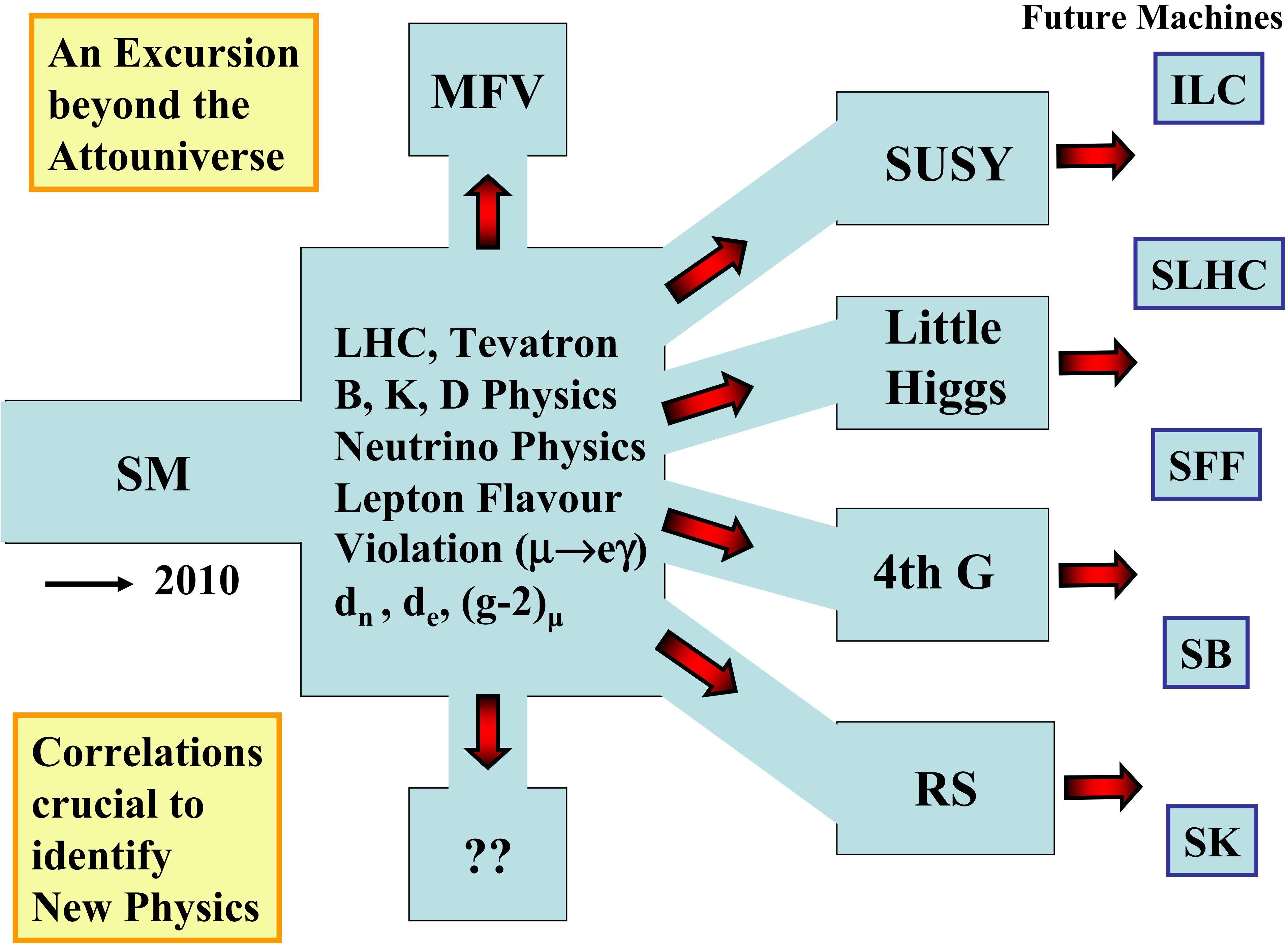
8 Flavour Violation in High Energy Collisions

9 Electric Dipole Moments and (g-2)μ

10 Theory of Quark Masses and Mixing Angles

11 Phenomenology of Quark Flavour Physics

An Excursion beyond the Attouniverse



Future Machines

MFV

SM

→ 2010

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

??

SUSY

Little Higgs

4th G

RS

ILC

SLHC

SFF

SB

SK

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
$K_L \to \pi\pi$

Many Thanks to my Collaborators

SUSY


W. Altmannshofer

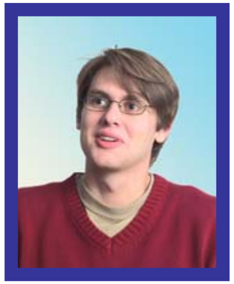

S. Gori


P. Paradisi


D. Straub

LHT


M. Blanke


B. Duling


A. Poschenrieder


S. Recksiegel


C. Tarantino

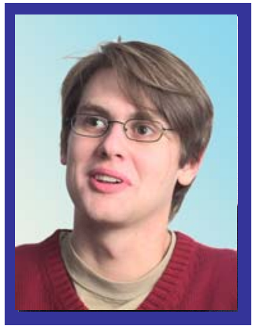

S. Uhlig


A. Weiler

RS


M. Albrecht


M. Blanke


B. Duling


K. Gemmler


S. Gori


A. Weiler

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

More Collaborators

I.Bigi

P. Ball

A. Bharucha

M. Wick

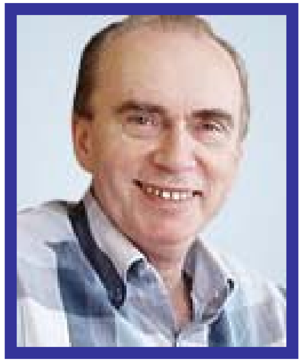
L. Calibbi

M. Nagai

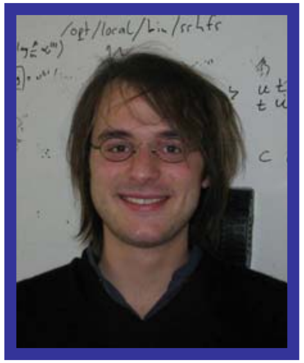
L. Merlo

C. Grojean

A. Lenz



S. Pokorski



E. Stamou

R. Ziegler

New Animalcula in Sight !

Thank You!

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Backup

Unitarity Triangle

(R_b, γ)
Reference UT
(Goto et al)

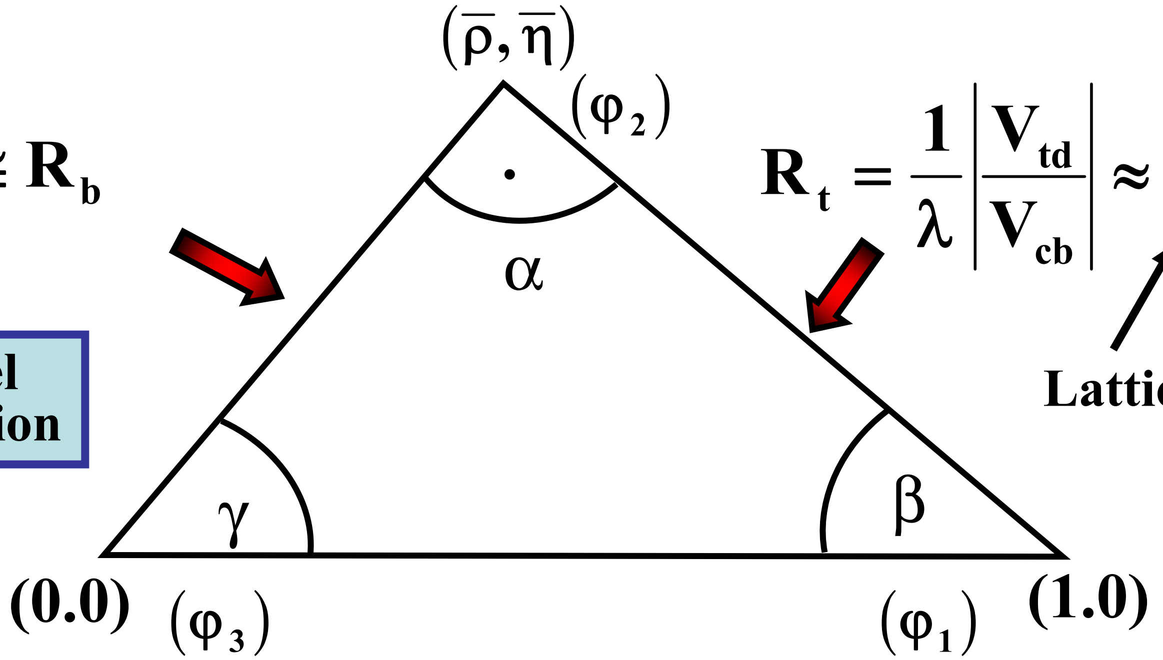
(coming decade)

$$\alpha \overset{?}{=} 90°$$

(this decade)

R_t, β
Universal UT of CMFV
(BGGJS, BBGT)

$(\varphi_{NP}=0,\ r_{NP}=1)$



$$\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right| \cong R_b$$

Tree Level Determination

(NP free)

$$R_t = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{cb}}\right| \approx \xi\sqrt{\frac{\Delta M_d}{\Delta M_s}}\, r_{NP}$$

Lattice

$$\xi = 1.21 \pm 0.04$$

Loop Determination

(Not NP free)

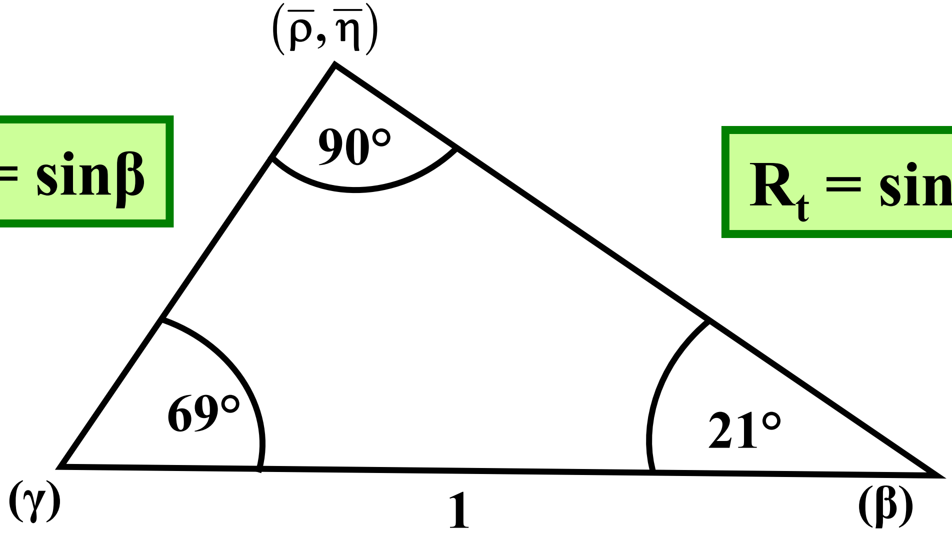
Flavour Matrix

$\varphi_{NP} = 0$ $r_{NP} = 1$	$\varphi_{NP} = 0$ $r_{NP} \neq 1$
$\varphi_{NP} \neq 0$ $r_{NP} \neq 1$	$\varphi_{NP} \neq 0$ $r_{NP} \neq 1$

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

Unitarity Triangle in LO Approximation

$\alpha = 90°$ $\sin 2\beta = 2/3$



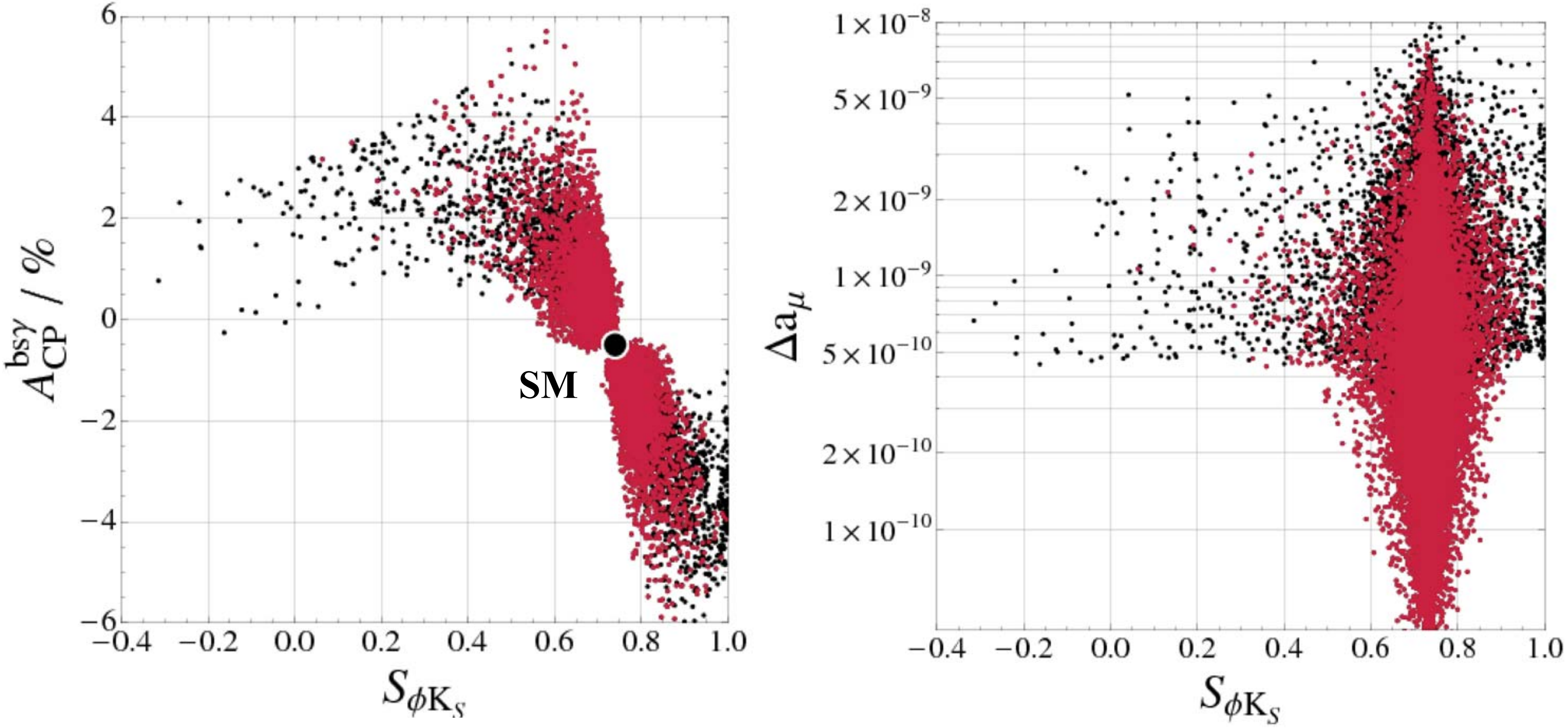
$R_b = \sin\beta$

$R_t = \sin(\alpha+\beta)$

$\bar{\rho} = \sin\beta \cos\gamma$ $\bar{\eta} = \sin\beta \sin\gamma$

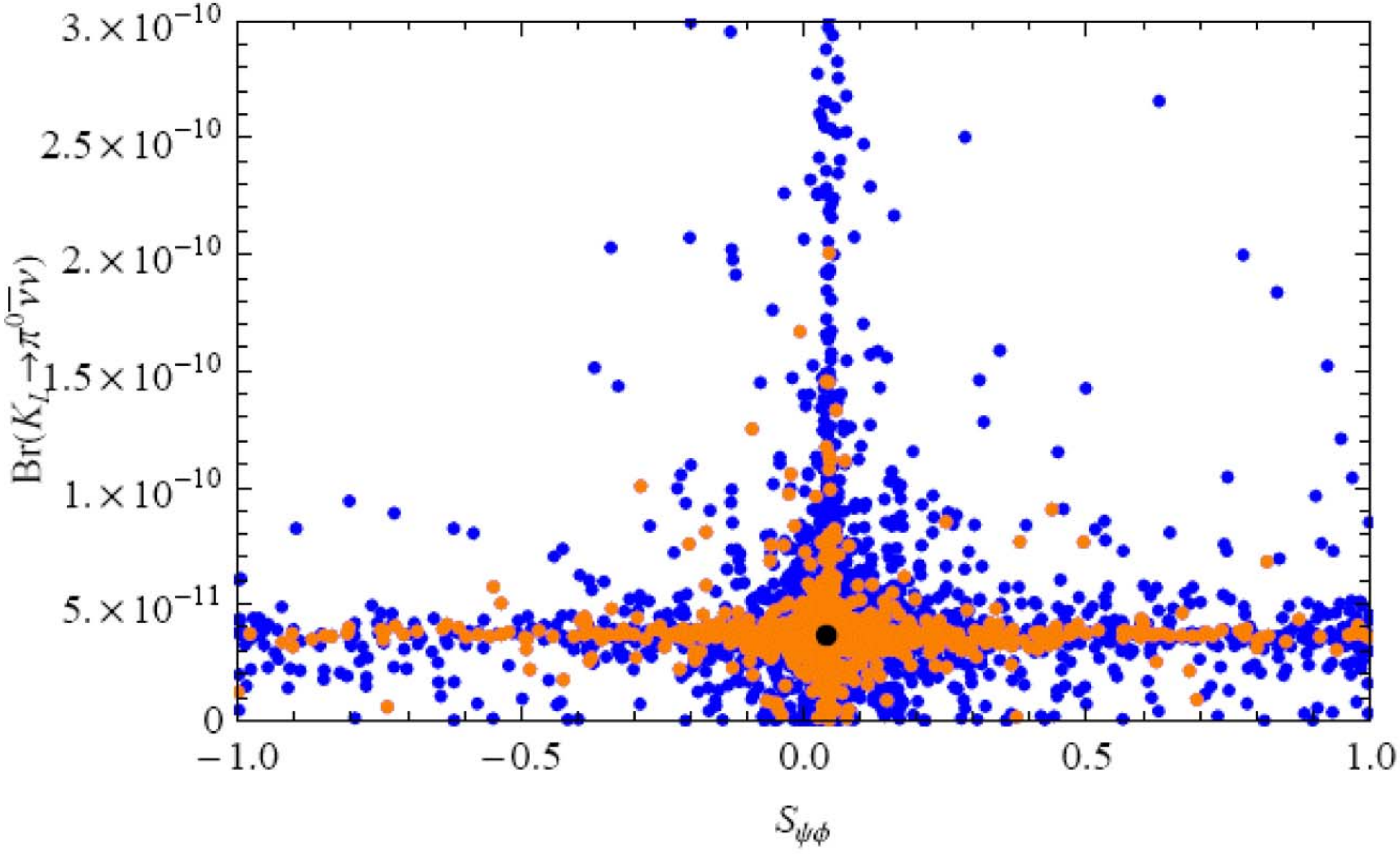
Correlations in a Flavour Model with LH Currents

🟥 $\mathrm{Br}\left(B_s \to \mu^+\mu^-\right) < 6\cdot 10^{-9}$



$K_L \to \pi^0 \nu\bar{\nu}$ vs. $S_{\psi\varphi}$ (RS)

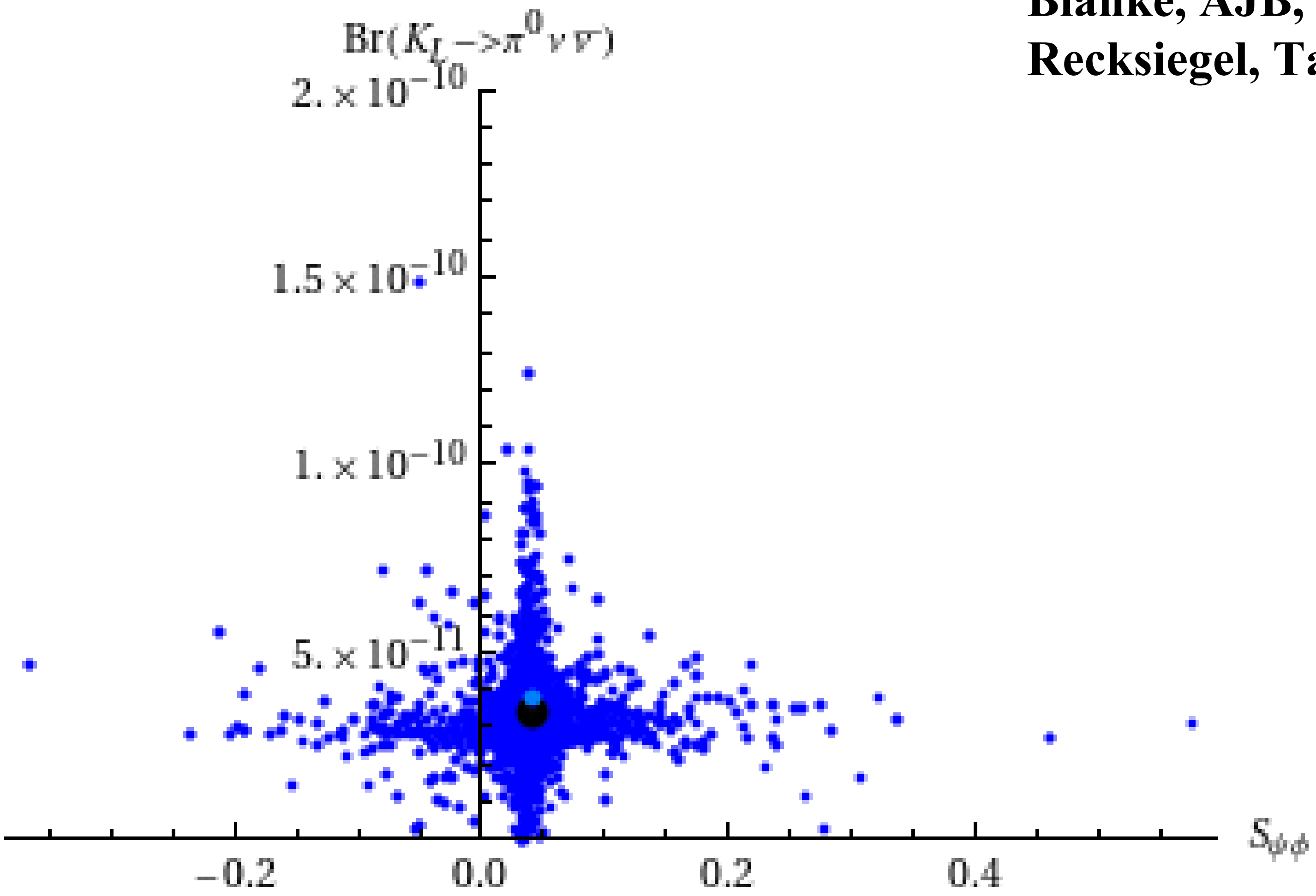
(Simultaneous Large Enhancements unlikely)



$K_L \rightarrow \pi^0 \nu\bar{\nu}$ vs. $S_{\psi\varphi}$ (LHT)

(Simultaneous Large Enhancements unlikely)

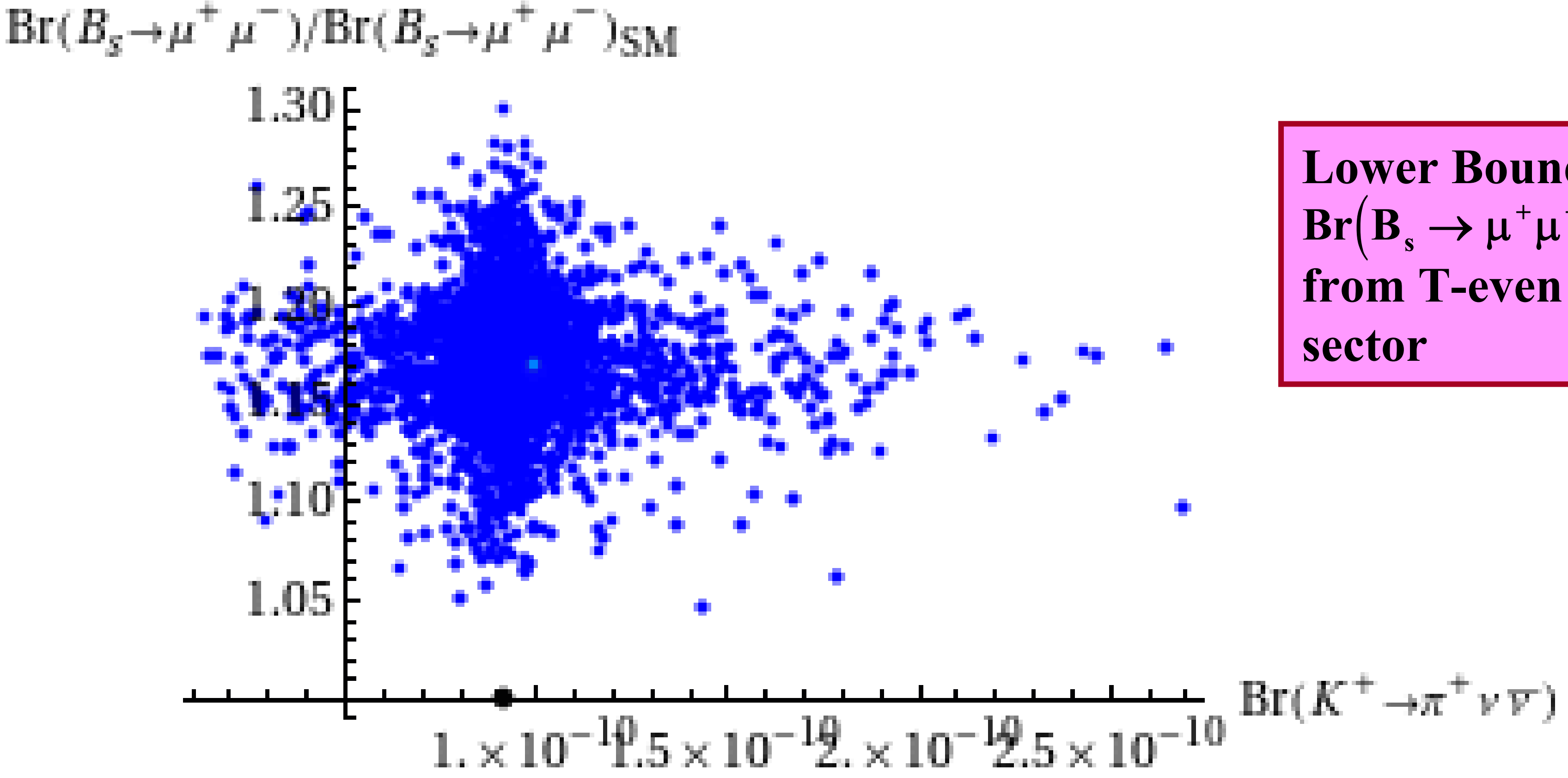
Blanke, AJB, Duling, Recksiegel, Tarantino



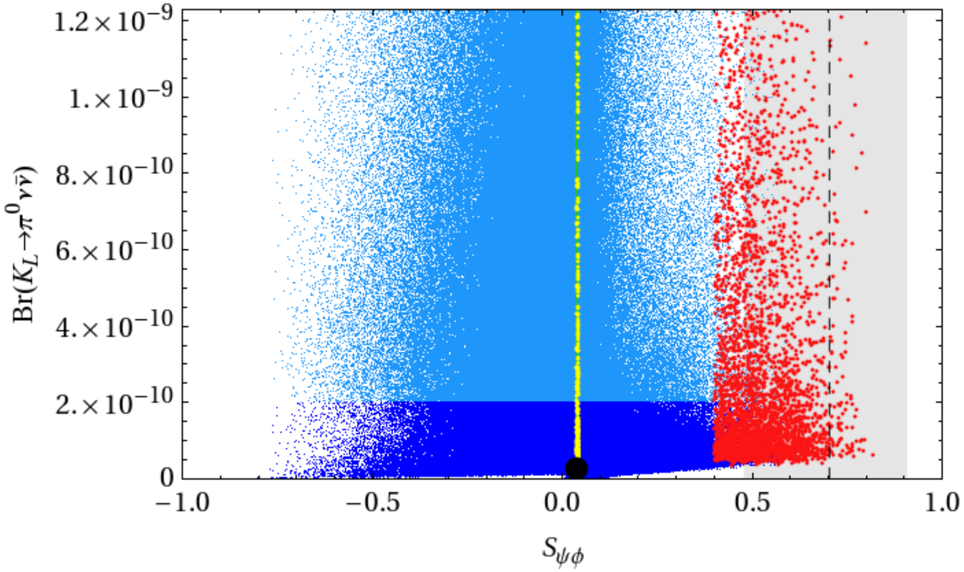
$B_s \to \mu^+\mu^-$ vs. $K^+ \to \pi^+\nu\bar{\nu}$

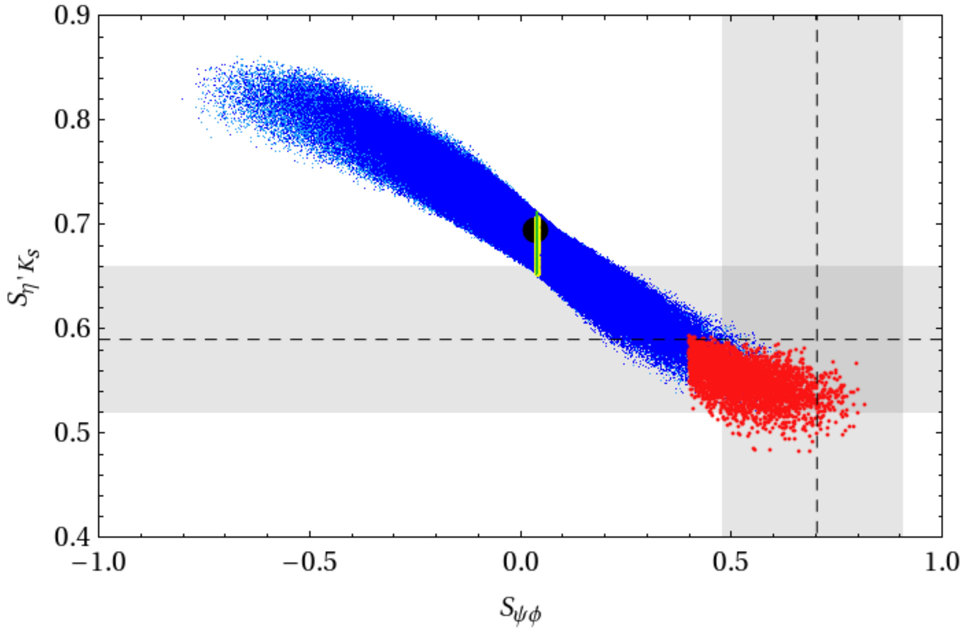
(LHT)

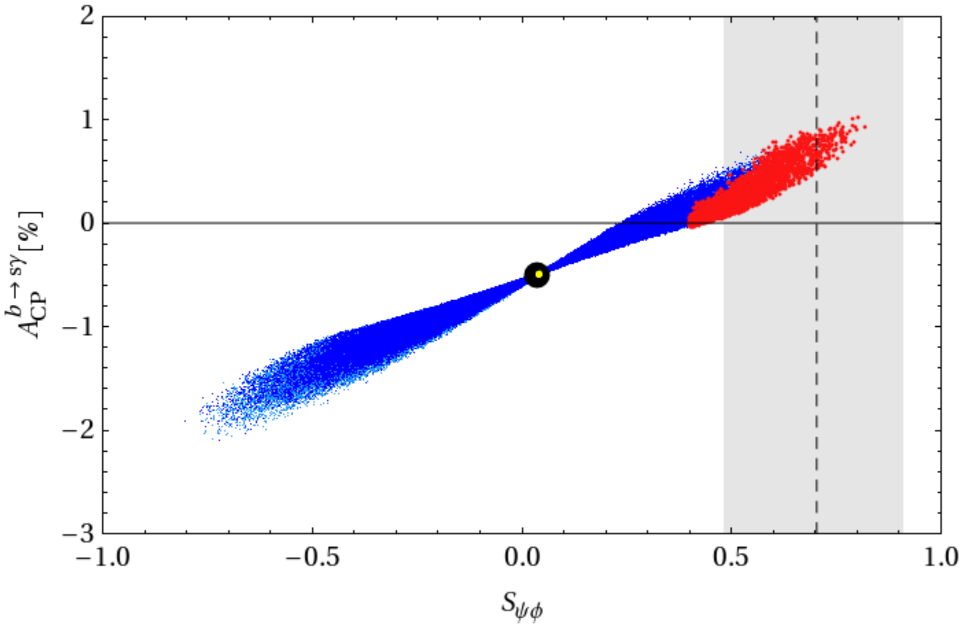
Blanke, AJB, Duling, Recksiegel, Tarantino



Lower Bound on $Br\left(B_s \to \mu^+\mu^-\right)$ from T-even sector


1.2×10^{-9}
$1.\times10^{-9}$
$8.\times10^{-10}$
$6.\times10^{-10}$
$4.\times10^{-10}$
$2.\times10^{-10}$
0
$\mathrm{Br}(K_L\to\pi^0\nu\bar{\nu})$
−1.0
−0.5
0.0
0.5
1.0
$S_{\psi\phi}$


0.9
0.8
0.7
0.6
0.5
0.4
$S_{\eta' K_S}$
−1.0
−0.5
0.0
0.5
1.0
$S_{\psi\phi}$


2
1
0
−1
−2
−3
$A_{\mathrm{CP}}^{b\to s\gamma}\,[\%]$
−1.0
−0.5
0.0
0.5
1.0
$S_{\psi\phi}$

Clear Distinction between MSSM and LHT

MSSM

LHT

Both can reach MEGA´s μ→eγ bound

$$\frac{\mathrm{Br}\left(\mu^- \to e^- e^+ e^-\right)}{\mathrm{Br}\left(\mu^- \to e^- \gamma\right)} \approx \frac{1}{161}$$

0.02 – 1

$$\frac{\mathrm{Br}\left(\tau^- \to \mu^- \mu^+ \mu^-\right)}{\mathrm{Br}\left(\tau^- \to \mu^- \gamma\right)} \approx \frac{1}{435}$$

0.04 – 0.4

MSSM : (Ellis, Hisano, Raidal, Shimizu; Arganda, Herrero; Paradisi)
(Brignole, Rossi)

LHT : (Blanke, AJB, Duling, Poschenrieder, Tarantino) (2007)
del Aguila, Illana, Jenkins (2008), Goto, Okada, Yamamoto (2009)

Impressive Success of the CKM Picture of Flavour Changing Interactions

(GIM)
(NFC)

(Once quark masses determined : only 4 parameters)

1. All leading decays of K, D, B_s^0, B_d^0 mesons correctly described

2. Suppressed transitions : $K^0 - \overline{K}^0$, $B_d^0 - \overline{B}_d^0$, $B_s^0 - \overline{B}_s^0$ mixings found at suppressed level

3. CP-violating Data (K, B_d) correctly described

4. $B \to X_s \gamma, \quad B \to X_s l^+ l^-$ OK

~~CP~~ in B_s?

$(g-2)_\mu$?

5. Very very highly suppressed transitions in the SM consistent with experiment: (not seen)

Standard Model	Exp Upper Bound
$\mathrm{Br}\left(B_s \to \mu^+\mu^-\right) \cong 3 \cdot 10^{-9}$	$\sim 4{\cdot}10^{-8}$
$\mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right) \cong 3 \cdot 10^{-11}$	$\sim 6{\cdot}10^{-8}$
$\mathrm{Br}\left(K_L \to \mu e\right) \cong \quad 10^{-40}$	$\sim 10^{-12}$
$\mathrm{Br}\left(\mu \to e\gamma\right) \quad \approx \quad 10^{-54}$	$\sim 10^{-11}$
$d_n \quad \approx \quad 10^{-32}\,\mathrm{ecm}$	$\sim 10^{-26}\mathrm{ecm}$

Number of new Flavour Parameters

(Quark Sector) (physical)

	Real	**~~CP~~ Phases**	
SUSY	36	27	(R-parity)
4G	5	2	
LHT	7	3	some sensitivity to UV
RS	18	9	
SM	9	1	

Standard Model Predictions for Superstars

$$S_{\psi\varphi} = 0.035 \pm 0.005$$

$$\left(S_{\psi\varphi}\right)_{\exp} = 0.52 \pm 0.20$$

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

$$Br\left(B_s \to \mu^+\mu^-\right)_{\exp} \le 4.2 \cdot 10^{-8}$$

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

$$Br\left(B_d \to \mu^+\mu^-\right)_{\exp} \le 1.0 \cdot 10^{-8}$$

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

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

$$\gamma = \left(64.2 \pm 3.1\right)^{o}$$

$$\gamma_{\exp} = \left(75 \pm 15\right)^{o}$$

(tree)

$$Br\left(K_L \to \pi^0\nu\bar{\nu}\right) = \left(2.8 \pm 0.6\right) \cdot 10^{-11}$$

$$Br\left(K_L \to \pi^0\nu\bar{\nu}\right)_{\exp} \le 6 \cdot 10^{-8}$$

Maximal Enhancements of $S_{\psi\varphi}$, $Br\left(B_s \to \mu^+\mu^-\right)$ and $K^+ \to \pi^+\nu\bar{\nu}$

(without taking correlation between them)

Model	Upper Bound on ($S_{\psi\varphi}$)	Enhancement of $Br\left(B_s \to \mu^+\mu^-\right)$	Enhancement of $Br\left(K^+ \to \pi^+\nu\bar{\nu}\right)$
CMFV	0.04	20%	20%
MFV	0.04	1000%	30%
LHT	0.30	30%	150%
RS	0.75	10%	60%
4G	0.80	400%	300%
AC	0.75	1000%	2%
RVV	0.50	1000%	10%

Large RH Currents

RS = RS with custodial protections

AC = Agashe, Carone $U(1)_F$

RVV = Ross, Velaso-Sevilla, Vives (04) $SU(3)_F$

Dominant New Flavour and CP Violating Interactions at 0(μ_{NP})

SUSY:

GIM

a) Misalignment of quark- and squark mass matrices, similarly for lepton sector

b) Effects enhanced at large tanβ : δ_{ij}^{AB}

Typical scales(200-1000 GeV)

LHT:

New flavour and CP violating mixing matrices in the interactions of SM fermions with mirror fermions mediated by W_H, Z_H, A_H

Typical scales (500-1000 GeV)

RS:

RS-GIM

New Heavy Gauge Bosons (KK)
New Heavy Vector-like Fermions (KK)

Tree Level FCNC´s mediated by KK Gluon ($\Delta F=2$) and Z($\Delta F=1$)
(Typical scales M_{KK} ≈2-3 TeV)

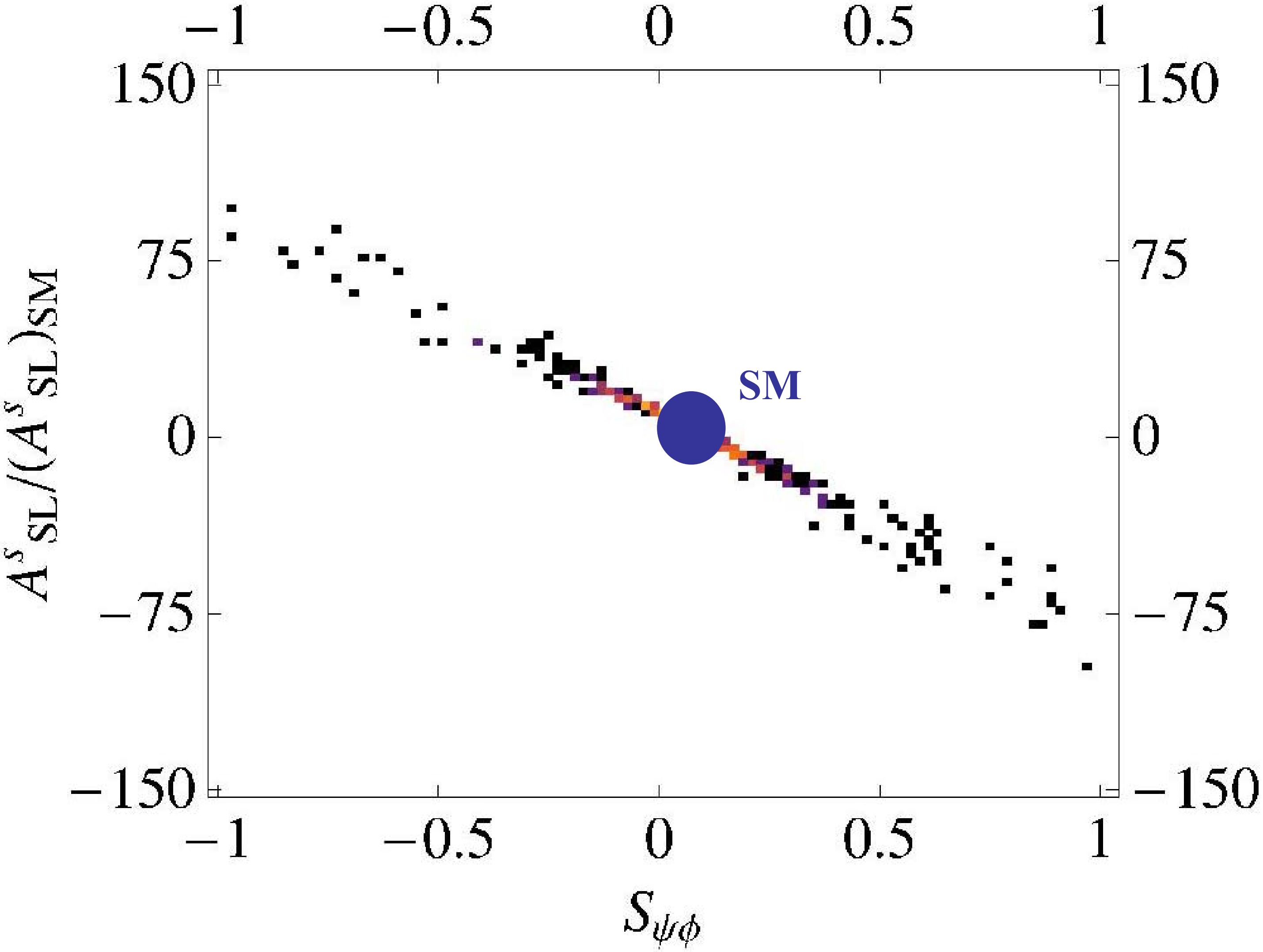
Related to the explanation of hierarchies in masses and mixings

2 x 2 Flavour Matrix of Basic NP Scenarios

(AJB, hep-ph/0101336, Erice)

	SM Operators	+ Additional Operators
CKM	**A** **CMFV** (Y_t) SM, 2 HDM at low tanβ LH without T-parity Universal flat ED	**B** **MFV** (Y_t,Y_b) MSSM with MFV 2 HDM at large tanβ
New Flavour (CP) Violating Interactions	**C** **beyond CMFV** LH with T-parity Some Z´-models 4th generation	**D** **beyond MFV** MSSM with $(\delta_{ij})_{AB}\neq 0$ RS, Other Z´models, LR Models, NMFV

Correlation in Warped Extra Dimensions (RS)



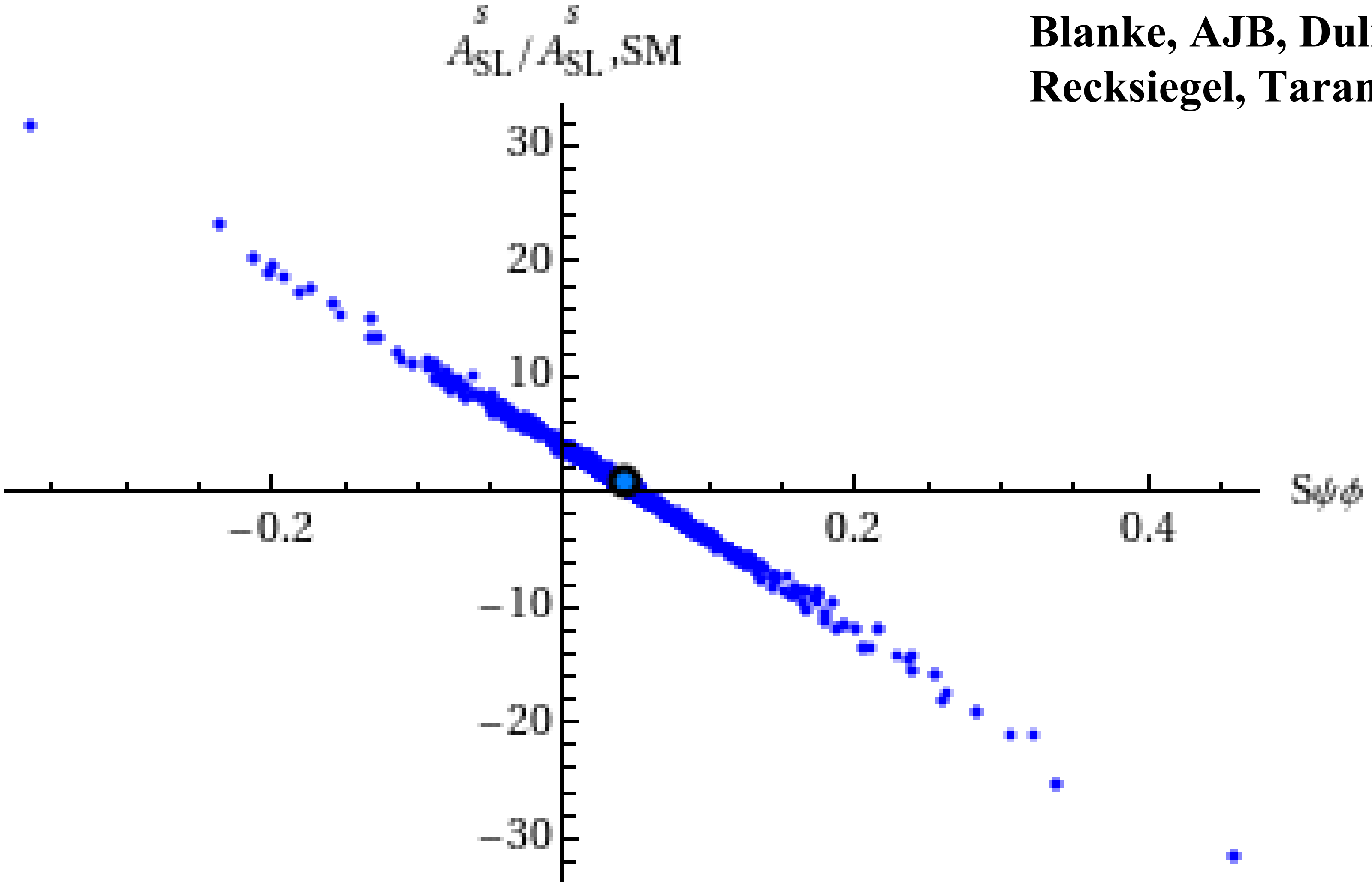
M.Blanke, AJB,
B.Duling, S.Gori,
A.Weiler (2008)

Model Independent Correlation

(Ligeti, Perez,…)

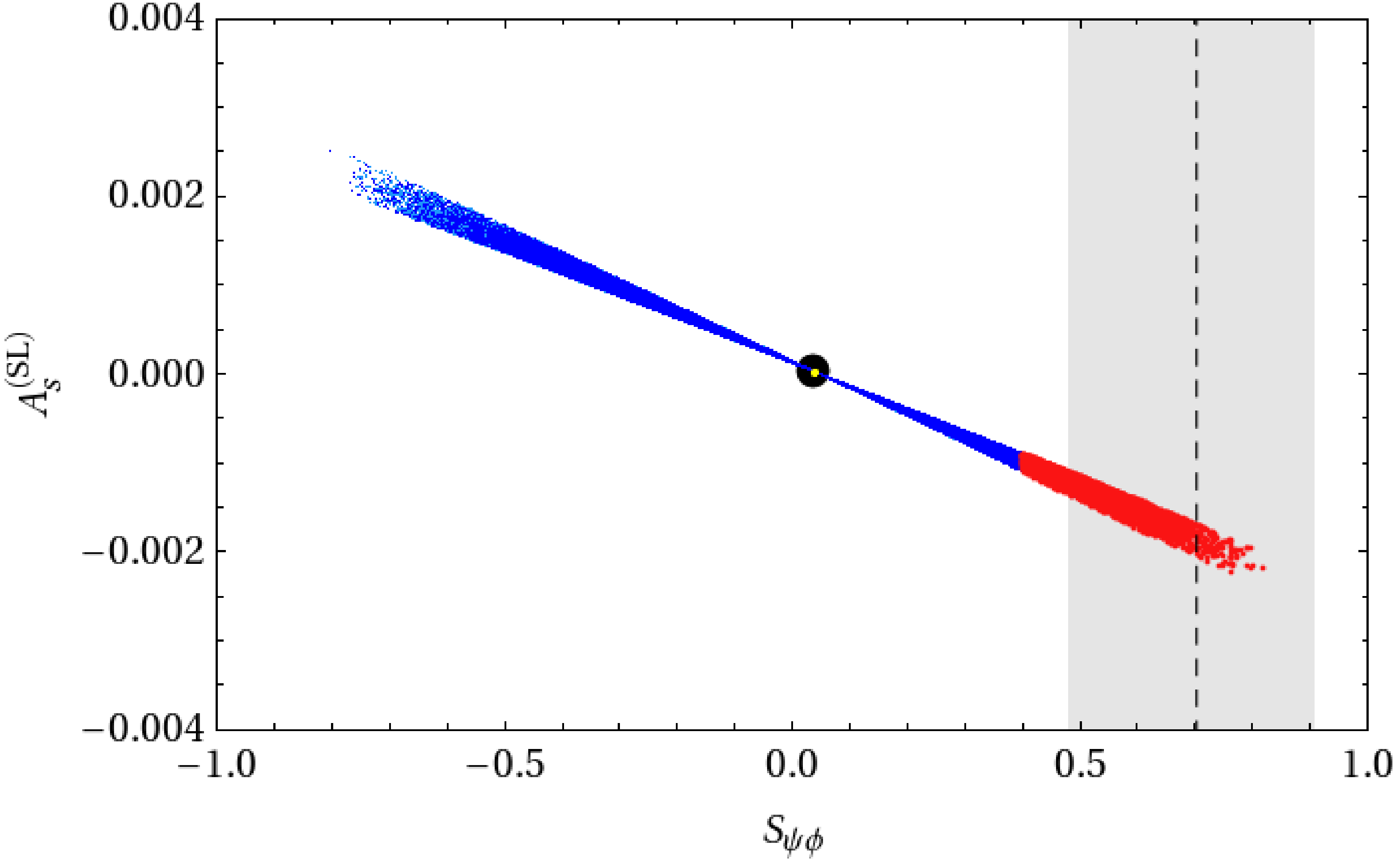
Correlation in LHT

Blanke, AJB, Duling, Recksiegel, Tarantino



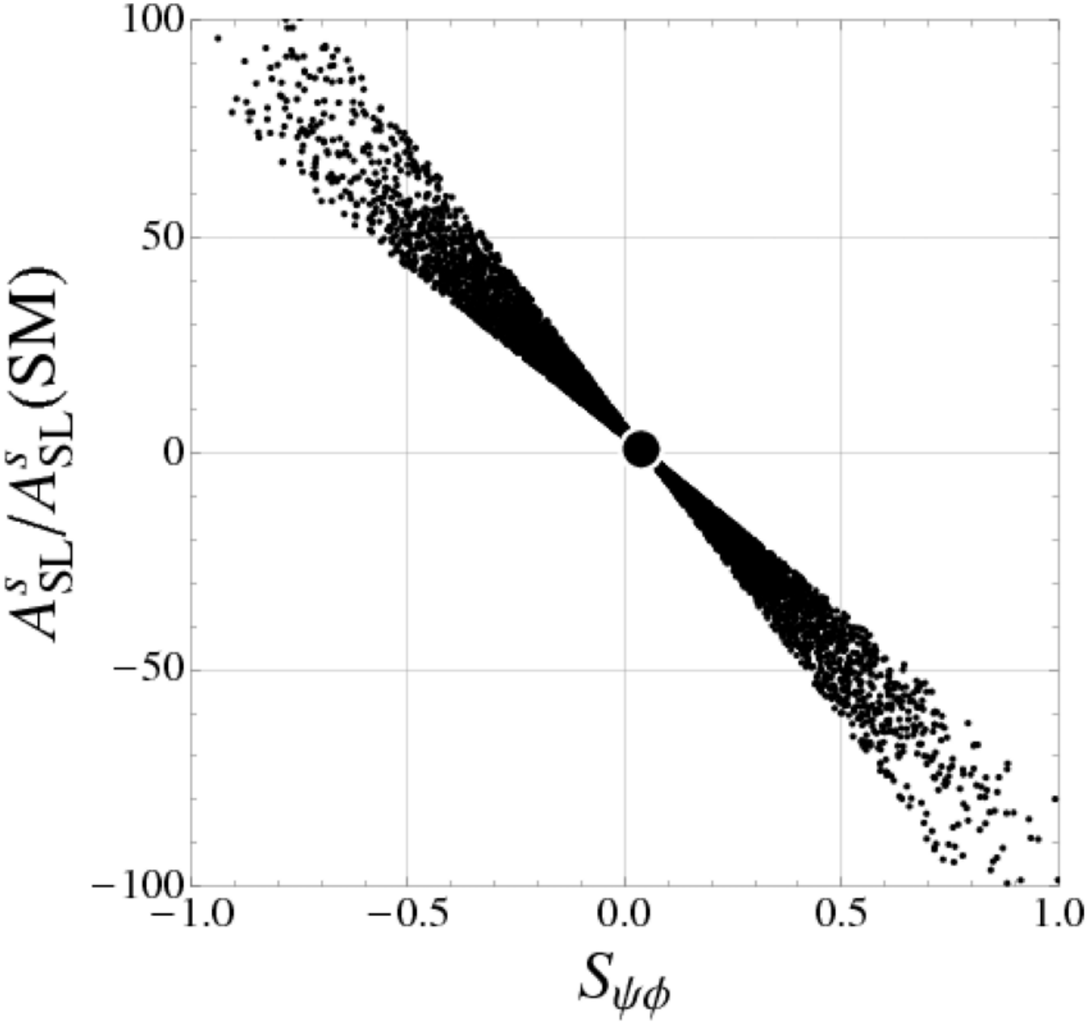
Correlation in 4G Model

AJB, Duling, Feldmann, Heidsieck, Promberger, Recksiegel (BDFHPR)



Correlation in Flavour SUSY Models

ABGPS



Minimal Flavour Violation (MFV)

MFV

SM Yukawa Couplings are the only breaking sources of the $SU(3)^5$ flavour symmetry of the low-energy effective theory

(Y_t, Y_b)

D´Ambrosio, Guidice, Isidori, Strumia (02) Chivukula, Georgi (87)

CKM the only source of Flavour Violation but for $Y_t \approx Y_b$ new operators could enter

CMFV

Operator structure of SM remains

VERY STRONG RELATIONS BETWEEN K and B Physics and generally $\Delta F=2$ and $\Delta F=1$ FCNC Processes

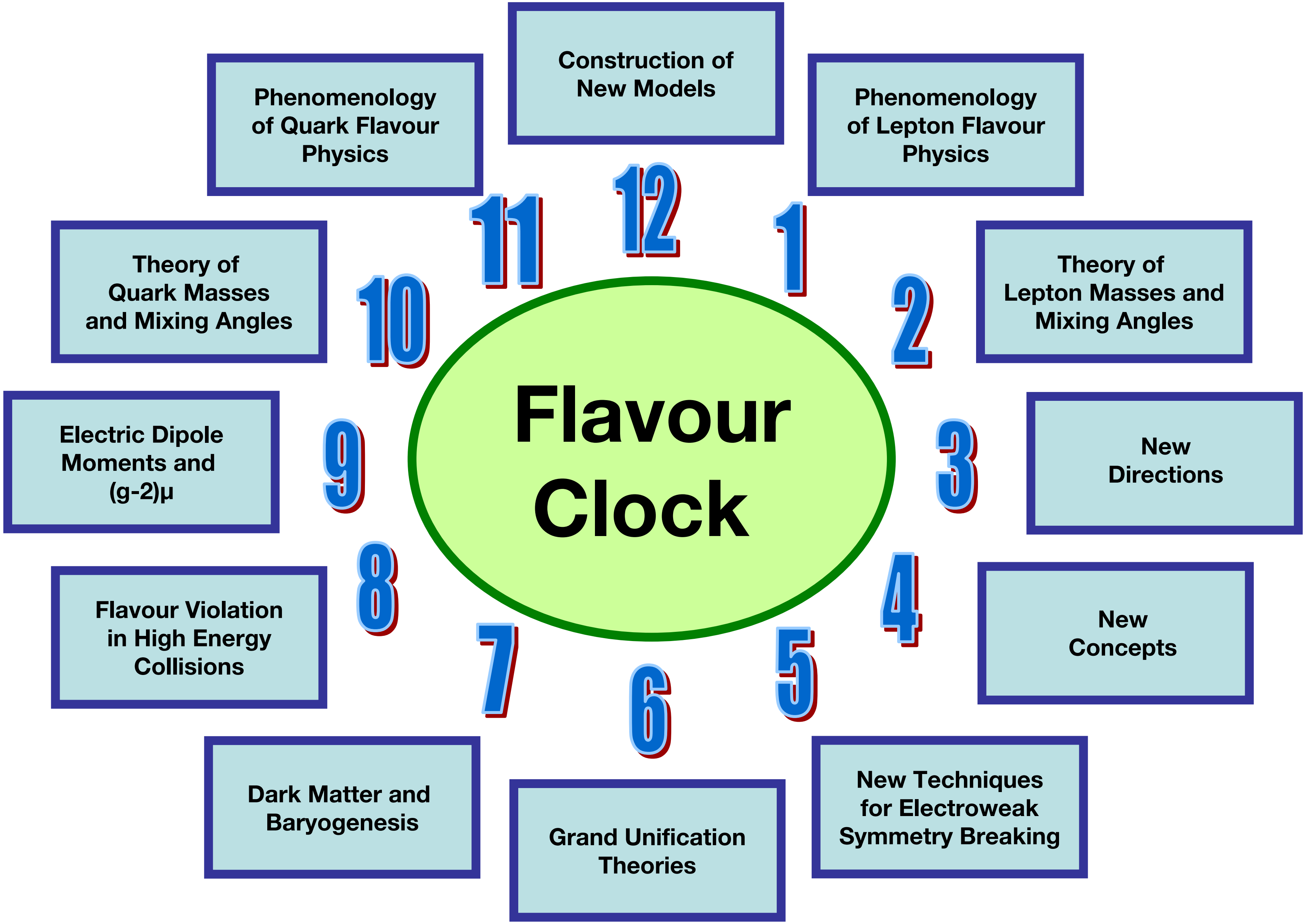
AJB, Gambino, Gorbahn, Jäger, Silvestrini (00)
Ali, London

Related Studies :
- Ratz et al (08)
- Smith et al (08)
- Zupan et al (09)
- Kagan et al (09)

Spurion Technology

Nir et al.
AGIS
Feldmann, Mannel

← also beyond MFV



Flavour Clock

- 12 Construction of New Models
- 1 Phenomenology of Lepton Flavour Physics
- 2 Theory of Lepton Masses and Mixing Angles
- 3 New Directions
- 4 New Concepts
- 5 New Techniques for Electroweak Symmetry Breaking
- 6 Grand Unification Theories
- 7 Dark Matter and Baryogenesis
- 8 Flavour Violation in High Energy Collisions
- 9 Electric Dipole Moments and (g-2)μ
- 10 Theory of Quark Masses and Mixing Angles
- 11 Phenomenology of Quark Flavour Physics

Prima Donna of 2010 – Flavour Physics

Mixing Induced CP Asymmetry in $B_s \to \psi\varphi$ $\left(S_{\psi\varphi}\right)$ (A^s_{SL})

(TH very clean;*) Analog of $S_{\psi K_s}$)

$$S_{\psi\varphi} = \sin\left(2|\beta_s| - 2\varphi_s^{new}\right) \overset{SM}{\cong} 0.035$$

$$V_{ts} = -|V_{ts}|e^{-\beta_s}$$
$$\left(\beta_s = -1°\right)$$

New Phase in $B_s^0 - \overline{B}_s^0$ mixing

CDF
D0 : Hints for a much larger value

Lenz, Nierste
+ CKM fitters

1008.1593

$S_{\psi\varphi} \approx 0.50 \pm 0.30$

(Personal estimate)

$$\begin{pmatrix} \text{CDF}: & (0.8\ \sigma) \\ \text{D0}\ \ : & (1.2\ \sigma) \end{pmatrix}$$ From SM

Still unclear situation

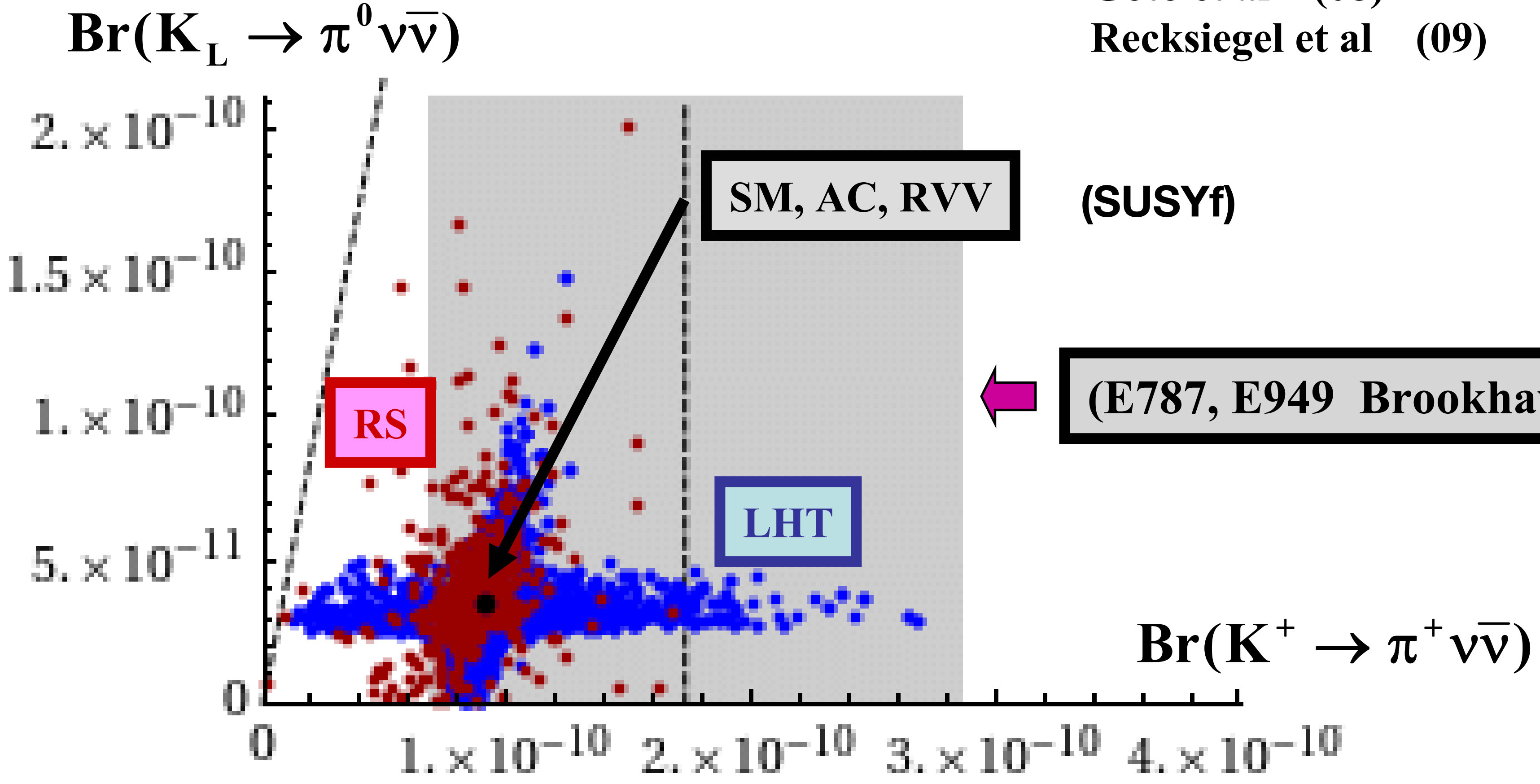
But both cannot exclude values above 0.5 !

---

*) See however Faller, Fleischer, Mannel (08)

★ $K_L \to \pi^0 \nu\bar{\nu}$ vs. $K^+ \to \pi^+ \nu\bar{\nu}$

Blanke et al (08)
Goto et al (08)
Recksiegel et al (09)



(SUSYf)

(E787, E949 Brookhaven)

2 x 2 Flavour Matrix of Basic NP Scenarios

(AJB, hep-ph/0101336, Erice)

	SM Operators	+ Additional Operators
CKM	**A** **CMFV** (Y_t) SM, 2 HDM at low tanβ LH without T-parity Universal flat ED	**B** **MFV** (Y_t, Y_b) MSSM with MFV 2 HDM at large tanβ
New Flavour (CP) Violating Interactions	**C** **beyond CMFV** LH with T-parity Some Z´-models 4th generation	**D** **beyond MFV** MSSM with $(\delta_{ij})_{AB} \neq 0$ RS, Other Z´models, LR Models, NMFV

3 x 3 Flavour Code Matrix

(hep-ph/1012.1447): “MFV and Beyond”

		Left	**Right**	**Scalar**	**Currents**
	Model	**LH**	**RH**	**SH**	
	MFV				
(Beyond MFV)	**BMFV**				
(Flavour Blind Phases)	**FBPs**				

Flavour Code Matrices

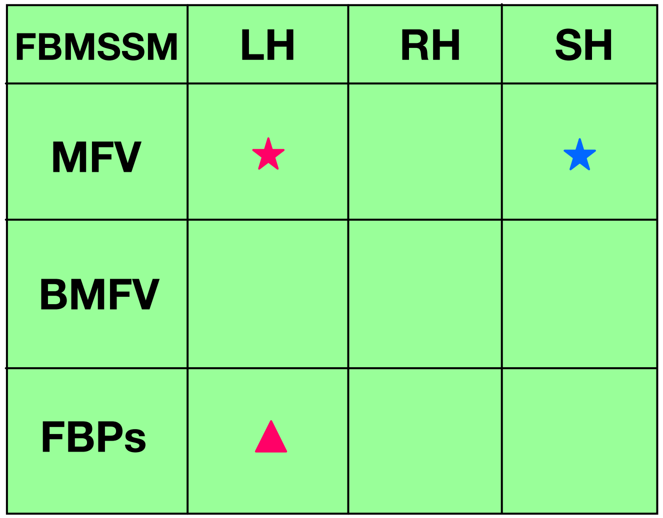
CMFV	LH	RH	SH
MFV	★		
BMFV			
FBPs			

$\text{2HDM}_{\overline{\text{MFV}}}$	LH	RH	SH
MFV	★		★
BMFV			
FBPs	▲		▲

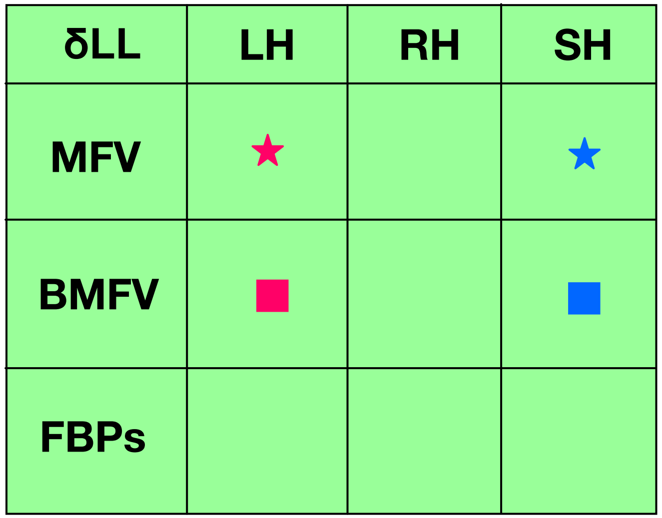
LHT	LH	RH	SH
MFV	★		
BMFV	■		
FBPs			

SM4	LH	RH	SH
MFV	★		
BMFV	■		
FBPs			

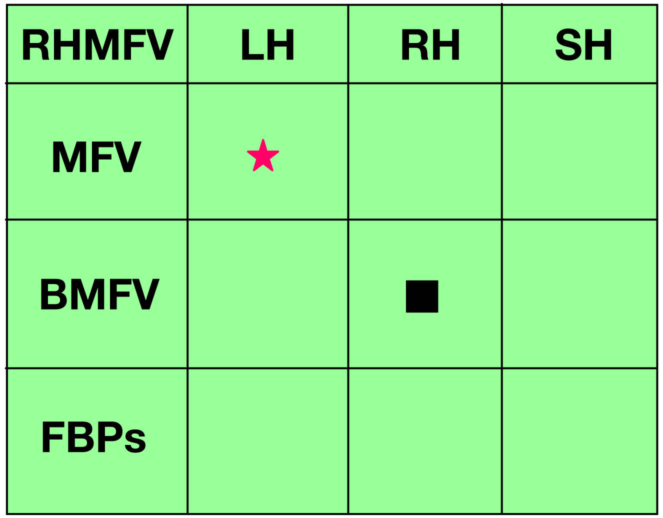
Flavour Code Matrices



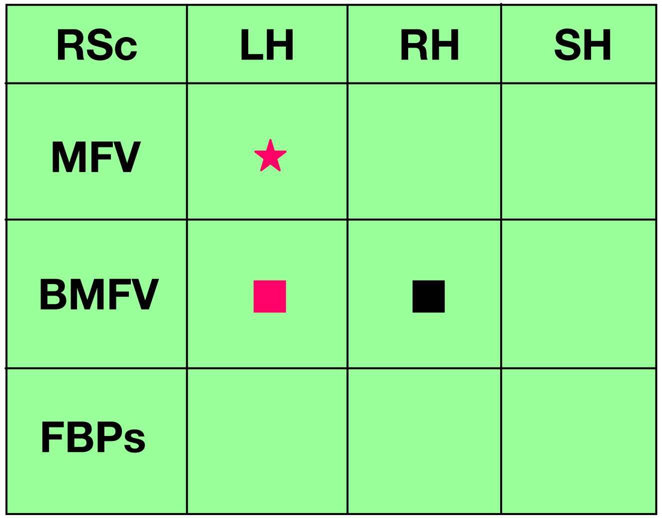
FBMSSM	LH	RH	SH
MFV	★		★
BMFV			
FBPs	🔺		



δLL	LH	RH	SH
MFV	★		★
BMFV	🟥		🟦
FBPs			



RHMFV	LH	RH	SH
MFV	★		
BMFV		⬛	
FBPs			



RSc	LH	RH	SH
MFV	★		
BMFV	🟥	⬛	
FBPs			

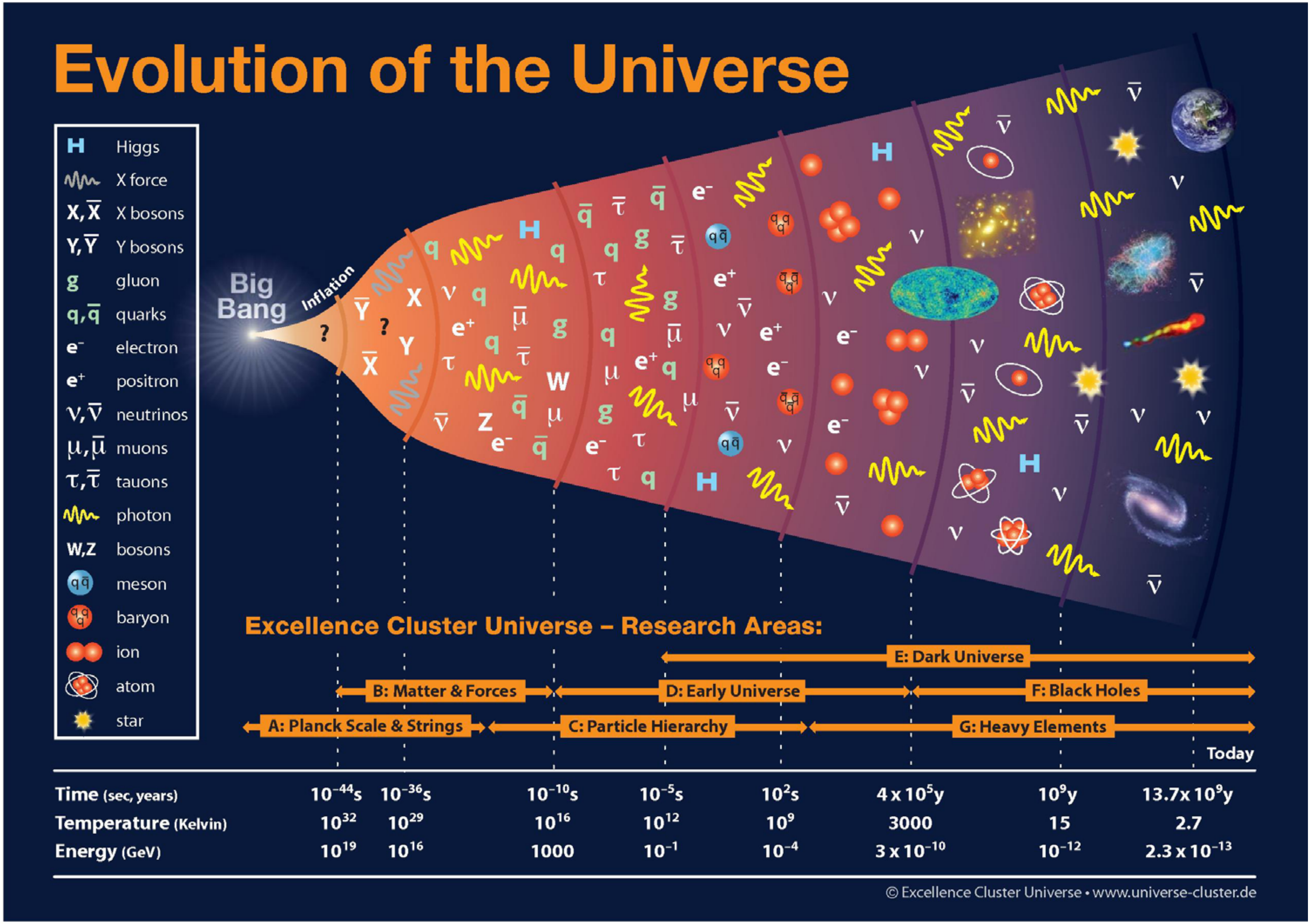
Flavour Code Matrices

AMK	LH	RH	SH
MFV	★		★
BMFV	🟥	⬛	🟦
FBPs			

AC	LH	RH	SH
MFV	★		★
BMFV		⬛	🟦
FBPs			

RVV2	LH	RH	SH
MFV	★		★
BMFV	🟥	⬛	🟦
FBPs			

$SSU(5)_{RN}$	LH	RH	SH
MFV	★		★
BMFV	🟥	⬛	🟦
FBPs			



Evolution of the Universe

H	Higgs
〰	X force
$X,\bar{X}$	X bosons
$Y,\bar{Y}$	Y bosons
g	gluon
$q,\bar{q}$	quarks
e^-	electron
e^+	positron
$\nu,\bar{\nu}$	neutrinos
$\mu,\bar{\mu}$	muons
$\tau,\bar{\tau}$	tauons
〰	photon
W,Z	bosons
$q\bar{q}$	meson
qqq	baryon
●	ion
⚛	atom
✸	star

Excellence Cluster Universe – Research Areas:

E: Dark Universe

B: Matter & Forces

D: Early Universe

F: Black Holes

A: Planck Scale & Strings

C: Particle Hierarchy

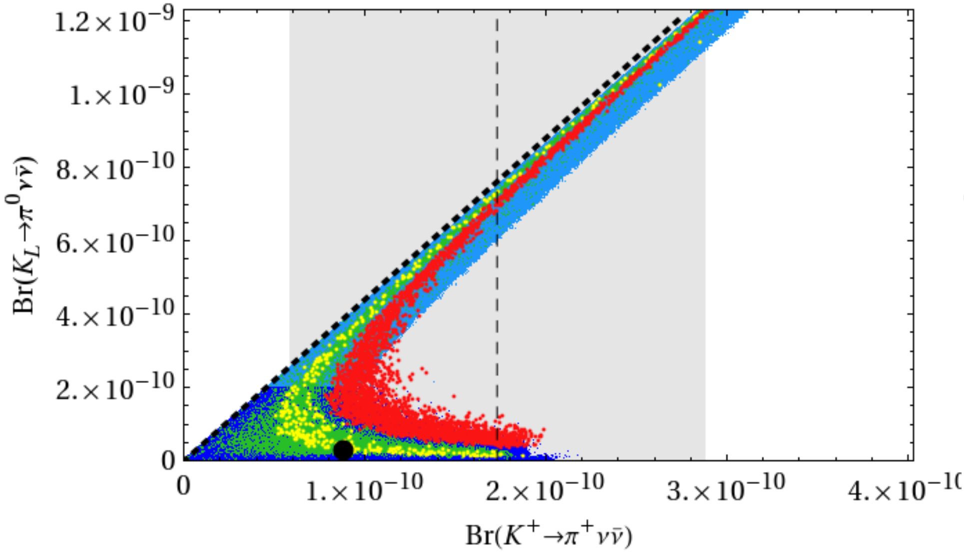
G: Heavy Elements

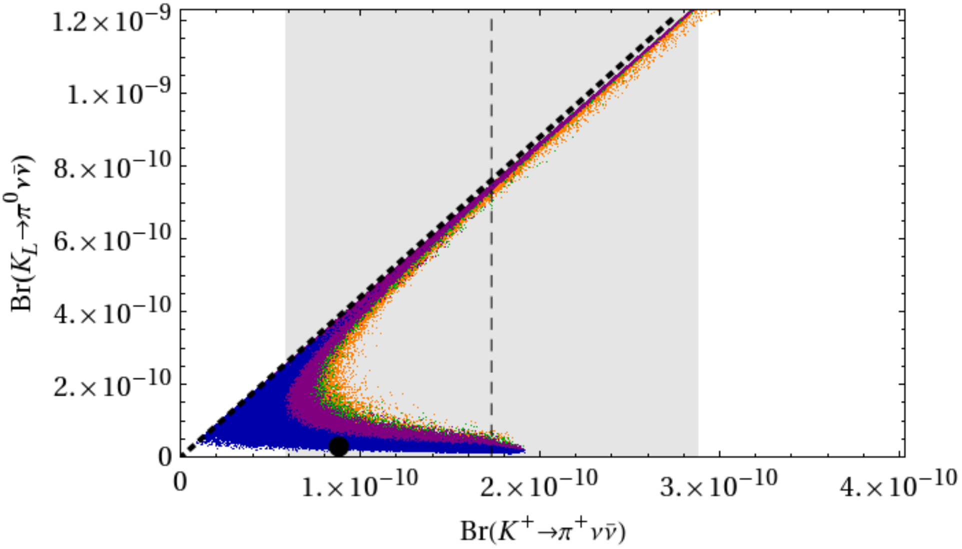
Today

Time (sec, years)	10^{-44}s	10^{-36}s	10^{-10}s	10^{-5}s	10^{2}s	4×10^{5}y	10^{9}y	13.7×10^{9}y
Temperature (Kelvin)	10^{32}	10^{29}	10^{16}	10^{12}	10^{9}	3000	15	2.7
Energy (GeV)	10^{19}	10^{16}	1000	10^{-1}	10^{-4}	3×10^{-10}	10^{-12}	2.3×10^{-13}

$K_L \to \pi^0 \nu\bar{\nu}$ vs. $K^+ \to \pi^+ \nu\bar{\nu}$ in 4G

see also
BDFHPR (1002.2126)
Soni et al.
Hou et al.





With ε'/ε Constraint

Much larger enhancements than in LHT, RS, SUSYf possible

$K^+ \to \pi^+ \nu\bar{\nu}$ 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 (QED, EW two loop)
Isidori, Mescia, Smith (several LD analyses)
Buchalla, Isidori (LD in $K_L \to \pi^0 \nu\bar{\nu}$)

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

SM : $Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(8.4 \pm 0.7\right) \cdot 10^{-11}$ $Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) = \left(2.6 \pm 0.4\right) \cdot 10^{-11}$

Exp : $Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(17 \begin{array}{c} +11 \\ -10 \end{array}\right) \cdot 10^{-11}$ $Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) \leq 6.8 \cdot 10^{-8}$

(E787, E949 Brookhaven) (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%

Can SM describe simultaneously $\not{CP}$ in K and B_d Systems?

$$R_t^2 \approx \xi \frac{\Delta M_d}{\Delta M_s}$$

Can SM describe simultaneously ~~CP~~ in K and B_d Systems?

$$|\varepsilon_K|^{SM} \sim \kappa_\varepsilon \hat{B}_K |V_{cb}|^2 \left(\frac{1}{2}|V_{cb}|^2 R_t^2 \sin 2\beta \underbrace{\overset{\text{(NLO)}}{\eta_{tt}^{QCD}}}_{\text{BJW (90)}} S_0(x_t) + F\Big(\underbrace{\overset{\text{(NLO)}}{\eta_{ct}^{QCD}, \eta_{cc}^{QCD}}}_{\text{HN (94)}}, m_c, ..\Big)\right)$$

2009
2010
News

★ $\hat{B}_K \cong 0.72 \pm 0.03$ (precise and lower by ~ 10% vs 2007)

RBC-UKQCD
Aubin et al.
ETMC

(Nierste; Vysotsky)

★ $\kappa_\varepsilon \cong 0.94 \pm 0.02$ AJB + Guadagnoli (08) + Isidori (10)

(LD Effects)

Large N
$\hat{B}_K = 0.70$

BBG (87)

★ **NNLO QCD calculation** of $\eta_{cc}^{QCD}, \eta_{ct}^{QCD}$ Brod + Gorbahn (10)

(BG) $|\varepsilon_K^{SM}| = (1.92 \pm 0.22) \cdot 10^{-3}$ $|\varepsilon_{exp}| = (2.229 \pm 0.012) \cdot 10^{-3}$

(BaBar
Belle)

using $(\sin 2\beta)_{\psi K_s} = 0.672 \pm 0.023$ (NA48, KLOE, KTeV)

Possible Solutions to ε_K - Anomaly

$$|\varepsilon_K|^{SM} \sim \kappa_\varepsilon \hat{B}_K |V_{cb}|^2 \left(\frac{1}{2} |V_{cb}|^2 R_t^2 \sin 2\beta \eta_{tt}^{QCD} S_0(x_t) + F\left(\eta_{ct}^{QCD}, \eta_{cc}^{QCD}, m_c, ..\right) \right)$$

1. Add New Physics to ε_K

CMFV $\boxed{S_0(x_t) \rightarrow S_0(x_t) + \Delta S_0^{NP}}$ or simply $\Delta\varepsilon_k$ (Non-MFV)

AJB
Guadagnoli

2. Increase $\boxed{\sin 2\beta \cong 0.67 \Rightarrow 0.85}$

$\boxed{\varphi_{NP} \cong -8.1^o}$

↓

$\boxed{\text{Large } |V_{ub}|}$ ↔ Super-B

Lunghi
Soni

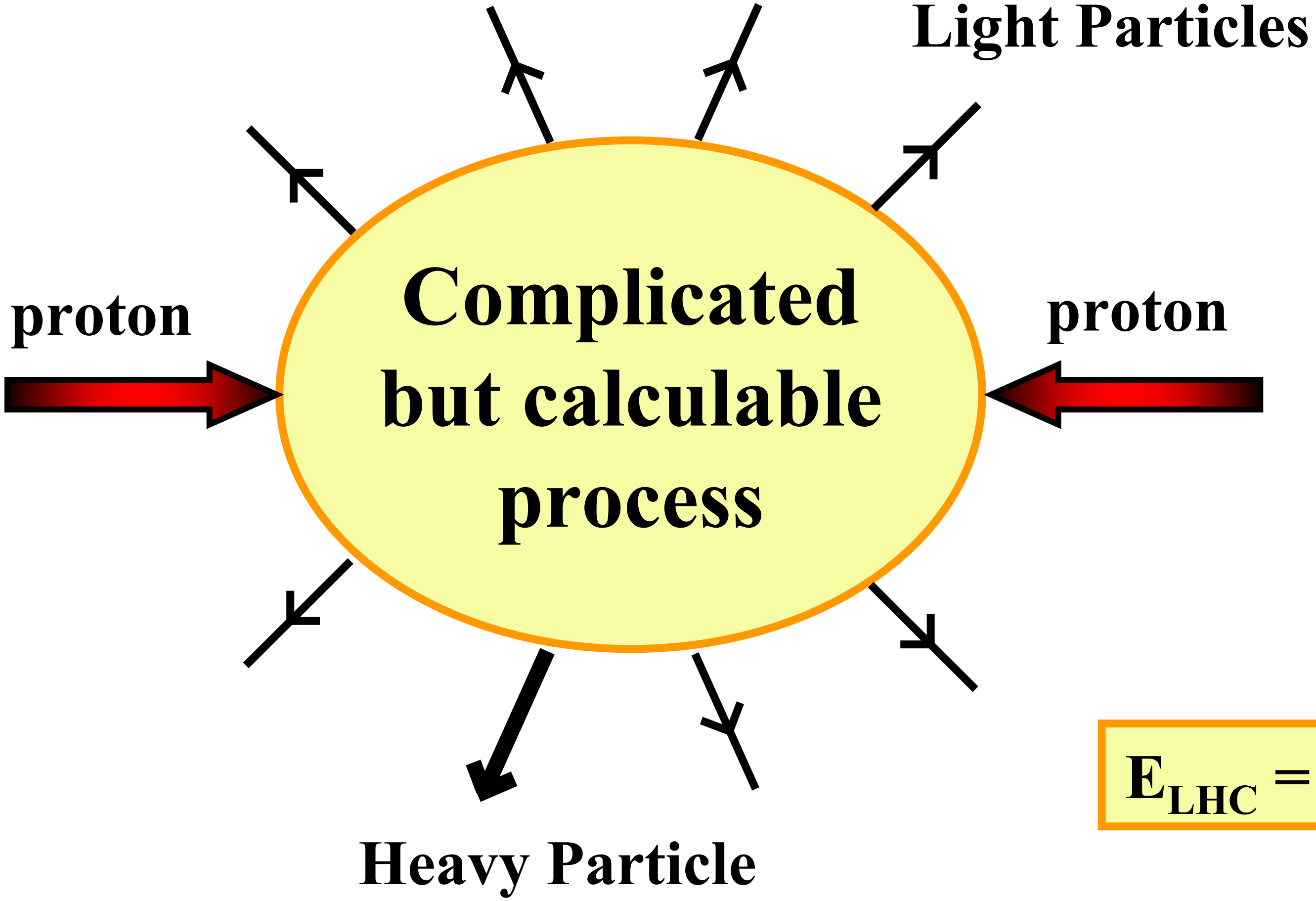
$$S_{\psi K_s} = \sin(2\beta + 2\varphi_{NP})$$

(Utfit; BBGT; Ball, Fleischer;
Branco et al)

3. Increase R_t → $\boxed{\gamma = \delta_{CKM} \approx 67^o \Rightarrow 82^o}$ ↔ LHC ★

4. Increase $\boxed{|V_{cb}| \approx (41.2 \cdot 10^{-3}) \Rightarrow (43.5 \cdot 10^{-3})}$ ↔ Super-B

Direct Search: Production of New Heavy Particles



$E_{LHC} = 14$ TeV

c = 1

For a Heavy Particle with mass M we need
at least $E_{pp} = M$ if single produced (t)
$E_{pp} = 2M$ if pair produced ($t\bar{t}$)

Search for New Physics in 2010´s through Flavour Physics

To search for NP in
rare K, B_d, B_s, D decays,
$\cancel{CP}$ in B_s, D decays,
Lepton Flavour Violations

Specific Plots (Correlations)

$\mathrm{Br}(K_L \to \pi^0 \nu\bar{\nu})$ vs $\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu})$
$\mathrm{Br}(B_s \to \mu^+\mu^-)$ vs $S_{\psi\varphi}$
$\mathrm{Br}(B_s \to \mu^+\mu^-)$ vs $\mathrm{Br}(B_d \to \mu^+\mu^-)$
$\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu})$ vs $S_{\psi\varphi}$
d_n vs $S_{\varphi K_s}$
$A_{CP}(B \to X_S\gamma)$ vs $S_{\varphi K_s}$
$\mathrm{Br}(\tau \to \mu\gamma)$ vs $\Delta(g-2)_\mu$
$\mathrm{Br}(\tau \to \mu\mu\mu)$ vs $\mathrm{Br}(\tau \to \mu\gamma)$
$\mathrm{Br}(\mu \to 3e)$ vs $\mathrm{Br}(\mu \to e\gamma)$

Correlations will be crucial to distinguish various NP scenarios

Patterns of Flavour Violations in specific NP Models