Flavourful Ways to the Shortest Distance Scales Explored by Humans

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Flavourful Ways to New Physics, 28-31 October 2014, Black Forest

Overture

1676

A very important year for the humanity !

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

10^{-6}m

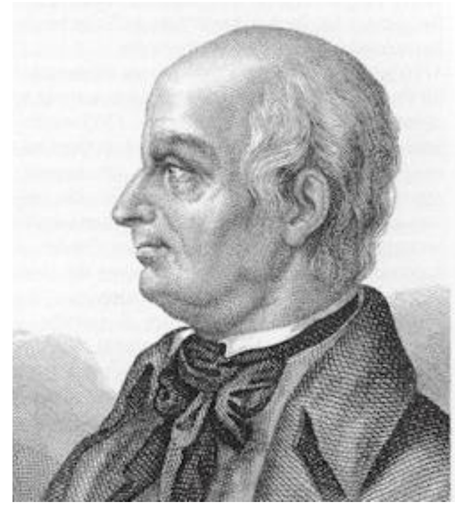
Antoni van Leeuwenhoek
***24.10.1632 ✞27.08.1723**

~500 Microscopes

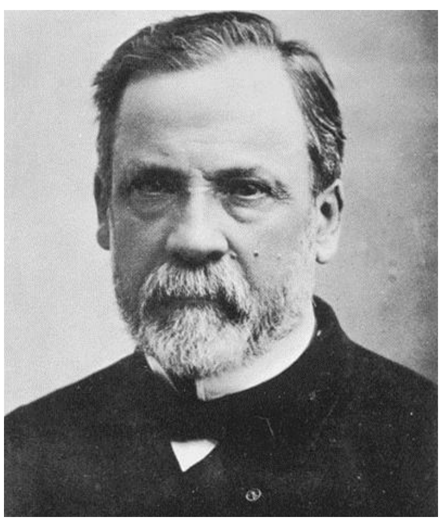
(Magnification by ~300)

Animalcula Hunters

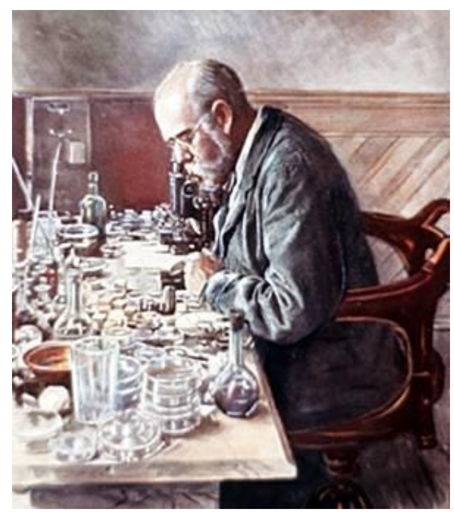
Antoni van Leeuwenhoek
***24.10.1632 ✞27.08.1723**



Lazzaro Spallanzani
***12.01.1729 ✞12.02.1799**



L. Pasteur
***27.12.1822 ✞28.09.1895**



Robert Koch
***11.12.1843 ✞27.05.1910**

A Journey to the Very Short Distance Scales:

1676 - 2046

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

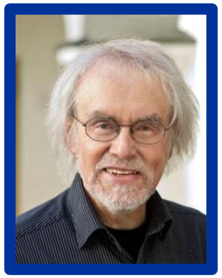
Expedition

Attouniverse → Zeptouniverse

10^{-18}m → 10^{-21}m

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

Present ERC Flavour Team


AJB


J.Girrbach-Noe


G.Isidori


S.Pokorski


F. De Fazio


D.Buttazzo


G.Buchalla


A.Ibarra


C.Bobeth


R.Knegjens


M.Ratz


O.Cata

Overture Finished

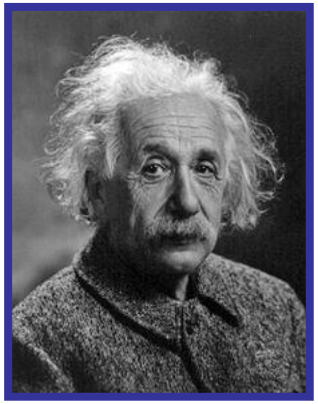
Black Forest Symphony No. 13

1st Movement	:	An Excursion into the Attouniverse: Standard Model and Open Questions
2nd Movement	:	Flavour Physics
3rd Movement	:	Rare Processes: Technology to reach Zeptouniverse
4th Movement	:	Finale: Vivace !

1st Movement:

An Excursion into the Attouniverse: Standard Model and Open Questions

The Pillars of our Field



$E = mc^2$

Proton mass: 1 GeV

$\Delta p \cdot \Delta x \geq \frac{\hbar}{2}$

(c = 1)

Relativistic Quantum Field Theories with local gauge symmetries

(Feynman, Schwinger, Tomonaga, Weinberg, Salam, Glashow…)

Language and Technology to study phenomena at

$L = 10^{-16} - 10^{-21} m$ | $E \approx 1 - 10^5 GeV$ | $\Delta t \simeq 10^{-24} - 10^{-29} sec$

Dictionary

(Using Heisenberg´s Uncertainty Principle)

Energy		Length	
20 GeV	$\Longleftrightarrow$	10^{-17} m	(Attouniverse)
200 GeV	$\Longleftrightarrow$	10^{-18} m	
2 TeV	$\Longleftrightarrow$	10^{-19} m	
20 TeV	$\Longleftrightarrow$	10^{-20} m	(Zeptouniverse)
200 TeV	$\Longleftrightarrow$	10^{-21} m	
2000 TeV	$\Longleftrightarrow$	10^{-22} m	

Elementary Particles and Forces

The Standard Model

	Matter			Forces
QUARKS	**u** up	**c** charm	**t** top	**γ** photon
QUARKS	**d** down	**s** strange	**b** bottom	**g** gluons
LEPTONS	ν_e	ν_μ	ν_τ	**Z** Z-boson
LEPTONS	**e** electron	**μ** muon	**τ** tau	**W** W-boson

Electromagnetic Force

Strong Force

Weak Force

γ, Gluons massless

★ **Higgs** provides masses to **Quarks Leptons W, Z**

Proton = u u d
Neutron = d d u

Masses of Proton and Neutron come from Strong Force, not Higgs !!

Periodic Table of Elementary Particles

(Fermions : Spin ½)

Families				Charge	
1	ν_e	ν_μ	ν_τ	0	Neutrinos
2	e^-	μ^-	τ^-	-1	Charged Leptons
3	u u u	c c c	t t t	2/3	Quarks
4	d d d	s s s	b b b	-1/3	
Generations	1	2	3	6 Flavours	

u = up
d = down
c = charm
s = strange
t = top
b = bottom

Masses of Elementary Particles

$\begin{pmatrix} m_\nu, \\ m_u, \\ \vdots \end{pmatrix}$

in units of **GeV = 10^9eV**

Families ⬇

1	ν_e (≈0)	ν_μ (≈0)	ν_τ (≈0)	< 10^{-9}
2	e^- ($5\cdot10^{-4}$)	μ^- (0.105)	τ^- (1.78)	
3	u ($3\cdot10^{-3}$)	c (1.3)	t (170)	
4	d ($6\cdot10^{-3}$)	s (0.100)	b (4.5)	

Very hierarchical structure

Particles in a given family distinguished only by the mass!

Basic Framework

Gauge Theories:
Relativistic Quantum Field Theories with elementary Forces following from Gauge Symmetries

Quantum Electrodynamics (QED)	Quantum Flavourdynamics (QFD)	Quantum Chromodynamics (QCD)
Symmetry: $U(1)_Q$	Symmetry: $SU(2)_L \otimes U(1)_Y$	Symmetry: $SU(3)_c$
Theory of electromagnetic interactions	Unified theory of weak and electromagnetic interactions	Theory of strong interactions (also basic for Nuclear Physics)
Mediated by Photon (γ) ($m_\gamma = 0$)	Mediated by weak gauge bosons Photon (γ), $\boxed{W^\pm \quad Z^0}$ ($m_\gamma = 0$) (80 GeV) (91 GeV)	Mediated by 8 Gluons ($m_G = 0$)

Fundamental Lagrangian of the Standard Model

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

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

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

"Landau-Ginzburg"

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

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

Standard model of particle physics (SM)

$$
\begin{aligned}
\mathcal{L}_{SM} = & \\
& -\tfrac{1}{4} W^a_{\mu\nu} W^{\mu\nu a} - \tfrac{1}{4} B_{\mu\nu} B^{\mu\nu} - \tfrac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} \\
& + \overline{L}\gamma^\mu \left(i\partial_\mu + g_2 \tfrac{\sigma^a}{2} W^a_\mu + g_1 Y B_\mu \right) L \\
& + \overline{\ell_R}\gamma^\mu (i\partial_\mu + g_1 Y B_\mu)\ell_R \\
& + \overline{Q}\gamma^\mu \left(i\partial_\mu + g_s \tfrac{\lambda^a}{2} G^a_\mu + g_2 \tfrac{\sigma^a}{2} W^a_\mu + g_1 Y B_\mu \right) Q \\
& + \overline{d_R}\gamma^\mu \left(i\partial_\mu + g_s \tfrac{\lambda^a}{2} G^a_\mu + g_1 Y B_\mu \right) d_R \\
& + \overline{u_R}\gamma^\mu \left(i\partial_\mu + g_s \tfrac{\lambda^a}{2} G^a_\mu + g_1 Y B_\mu \right) u_R \\
& + \left| \left(i\partial_\mu + g_2 \tfrac{\sigma^a}{2} W^a_\mu + g_1 Y B_\mu \right) \Phi \right|^2 \\
& + \mu^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi \right)^2 \\
& - \overline{L} Y_\ell \Phi \ell_R - \overline{Q} Y_d \Phi d_R - \overline{Q} Y_u \Phi^c u_R + h.c.
\end{aligned}
$$

The Standard Model

Quarks

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L \begin{pmatrix} c \\ s' \end{pmatrix}_L \begin{pmatrix} t \\ b' \end{pmatrix}_L \quad \begin{matrix} u_R & c_R & t_R \\ d_R & s_R & b_R \end{matrix} \qquad \begin{matrix} +2/3 \\ -1/3 \end{matrix}$$

+ Leptons

Fundamental Forces

$$\left.\begin{matrix}\textbf{Gauge} \\ \textbf{Theory}\end{matrix}\right\} : \underbrace{SU(3)}_{QCD} \otimes \underbrace{SU(2)_L \otimes U(1)_Y \Rightarrow U(1)_{QED}}_{\text{Electroweak Interactions}}$$

Neutral Higgs

Strong Interactions **(Gluons)**

Electroweak Interactions **($W^\pm$, Z^0, γ)**

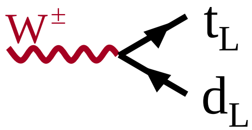
Mesons

$$\left.\begin{matrix}
K^0 = (d\bar{s}) & K^+ = (u\bar{s}) & K^- = (\bar{u}s) \\
\pi^+ = (u\bar{d}) & \pi^0 = (\bar{u}u - \bar{d}d)/\sqrt{2} & \pi^- = (\bar{u}d) \\
B_d^0 = (d\bar{b}) & \bar{B}_d^0 = (\bar{d}b) & B^+ = (u\bar{b}) \\
B_s^0 = (s\bar{b}) & \bar{B}_s^0 = (\bar{s}b) & B^- = (\bar{u}b)
\end{matrix}\right\} \quad q\bar{q}$$

Bound States

Four Basic Properties in the SM

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

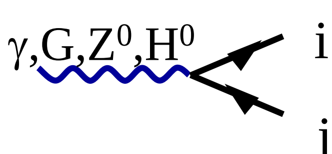
{ Weak Eigenstates } ≠ {Mass Eigenstates }

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

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

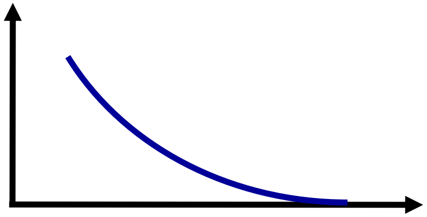
3. GIM Mechanism

Natural suppression of FCNC

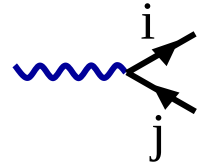
$\Bigg\{$  $= 0 \Bigg\}$ ⇒ { **Loop Induced Decays, sensitive to short distance flavour dynamics** }

4. Asymptotic Freedom

α_{QCD}



Q

G^a_μ 

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

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

LD $\Leftarrow$ RG $\Rightarrow$ SD

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

$\Lambda^{(5)}_{\overline{MS}} = 240 \pm 10\,\text{MeV}$ $\qquad$ $\alpha^{(5)}_{\overline{MS}}(M_Z) = 0.1185 \pm 0.0007$

SD = Short Distances (Perturbation Theory)

$\Uparrow$

RG = Renormalization Group Effects

$\Downarrow$

LD = Long Distances (Non-Perturbative Physics)

First Questions

1. Why only three generations ?
2. Why only four families ?
3. Why these special charges (0, ±1, ± 2/3, ±1/3)?
4. Why only γ, $W^{\pm}$, Z and gluons?
5. Why the hierarchical structure of quark and lepton masses?

More Open Questions

Essential for our Existence !

6. Why is neutron heavier than proton ?

7. Why is our universe dominated by matter ?
(Violation of CP-Symmetry soon after BIG BANG !)

8. What is Dark Matter (25% of the Universe) ?

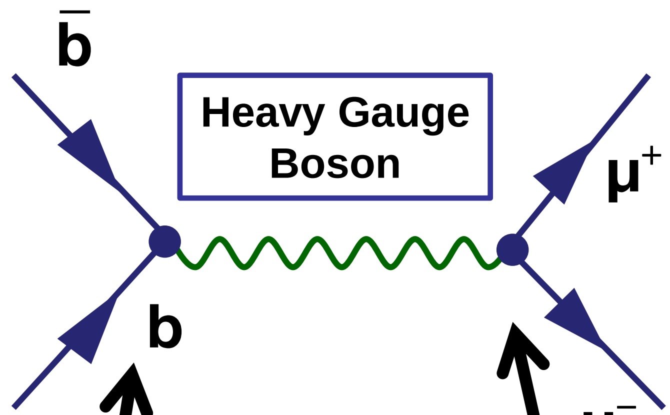
None of these questions can be answered within the Standard Model

New Physics beyond the SM must exist !!!

It is our duty to find it.
If not at the LHC then through high precision experiments.

Quark Flavour Physics
Lepton Flavour Violation
EDMs + $(g\text{-}2)_{\mu,e}$

Calculating Probabilities



$$P = C_{const} \left| Q^{b}_{weak}\sqrt{\alpha_{weak}} \; \frac{1}{M_G^2} \; Q^{\mu}_{weak}\sqrt{\alpha_{weak}} \right|^2$$

Weak charge

Analog of electric charge

Analog of $\alpha_{QED} \approx \frac{1}{137}$

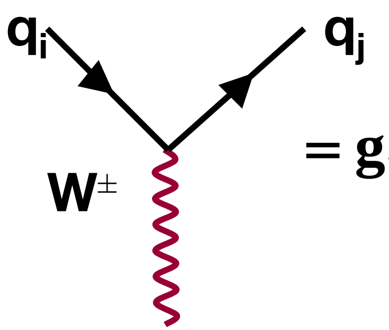
$$P = C \left| Q^{b}_{weak} \cdot Q^{\mu}_{weak} \cdot \alpha_{weak} \right|^2 \frac{1}{M_G^4}$$

Virtual Exchange of a Very Heavy Particle

Probability decreases with increasing mass of exchanged object

2nd Movement: Flavour Physics

Hierarchical Structure of Quark Flavour-Changing Interactions



$= g_{Weak} V_{ij}$

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

Cabibbo-Kobayashi-Maskawa matrix

V_{ud}	V_{us}	V_{ub}
V_{cd}	V_{cs}	V_{cb}
V_{td}	V_{ts}	V_{tb}

(would be a unit matrix for m_i=0)

u	c	t
d	s	b
1	2	3

≈ 1	≈ 0.2	$0.004e^{-i\gamma}$
≈ -0.2	≈ 1	0.04
$0.008e^{-i\beta}$	-0.04	≈ 1

Complex Phases (β,γ) responsible for violation of CP Symmetry

Matter – Antimatter Symmetry

$\beta \approx 23^o$

$\gamma \approx 70^o$

CKM

(Nobel Prize 2008)

Dirac Medal
(2010)

N. Cabibbo
(1935-2010)

M. Kobayashi

T. Maskawa

Kobayashi-Maskawa Picture of CP Violation

CP Violation arises from a single phase δ in $W^{\pm}$ interactions of Quarks

ud $c_{12}c_{13}$	us $s_{12}c_{13}$	ub $s_{13}e^{-i\delta}$
cd $-s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta}$	cs $c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta}$	cb $s_{23}c_{13}$
td $s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta}$	ts $-s_{23}c_{12}-s_{12}s_{23}s_{13}e^{i\delta}$	tb $c_{23}c_{13}$

Four Parameters: $(\theta_{12} \approx \theta_{cabibbo})$

$$s_{12} = |V_{us}|, \quad s_{13} = |V_{ub}|, \quad s_{23} = |V_{cb}|, \quad \delta$$

$$c_{ij} \equiv \cos\theta_{ij} \;;\; s_{ij} \equiv \sin\theta_{ij} \;;\; c_{13} \cong c_{23} \cong 1$$

Wolfenstein Parametrization

Parameters: λ, A, ρ, η

$$\begin{array}{c|ccc} & d & s & b \\ \hline u & 1-\frac{\lambda^2}{2} & \lambda & V_{ub} \\ c & -\lambda & 1-\frac{\lambda^2}{2} & V_{cb} \\ t & V_{td} & V_{ts} & 1 \end{array}$$

$\lambda=0.22$

$V_{us}=\lambda+0(\lambda^7)$

$V_{cb}=A\lambda^2+0(\lambda^8)$

$V_{ts}=-A\lambda^2+0(\lambda^4)$

$(A=0.83\pm0.02)$

$$V_{ub} \equiv A\lambda^3(\rho - i\eta) \qquad V_{td} = A\lambda^3(1-\bar{\rho}-i\bar{\eta})$$

$$\bar{\rho} = \rho\left(1-\frac{\lambda^2}{2}\right) \qquad \bar{\eta} = \eta\left(1-\frac{\lambda^2}{2}\right)$$

(AJB, Lautenbacher, Ostermaier, 94)

$$R_b \equiv \sqrt{\bar{\rho}^2+\bar{\eta}^2} = \left(1-\frac{\lambda^2}{2}\right)\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|$$

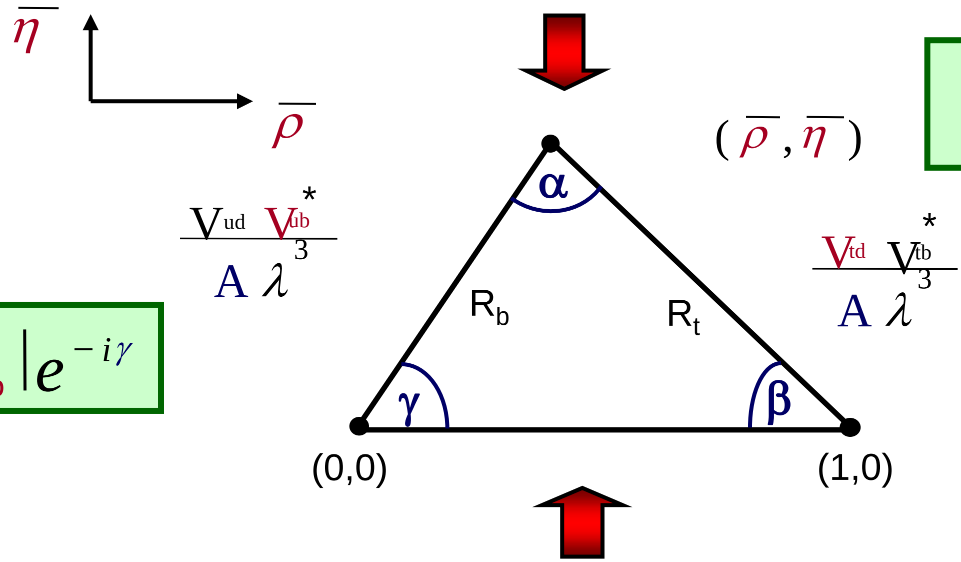
Circle around $(\bar{\rho},\bar{\eta}) = (0,0)$

$$R_t \equiv \sqrt{(1-\bar{\rho})^2+\bar{\eta}^2} = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{cb}}\right|$$

Circle around $(\bar{\rho},\bar{\eta}) = (1,0)$

Unitarity Triangle

$$V_{ud} V_{ub}^{*} + V_{cd} V_{cb}^{*} + V_{td} V_{tb}^{*} = 0$$

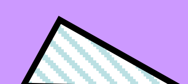


$\bar{\eta} \neq 0$ Signals CP Violation

$$V_{ub} = |V_{ub}| e^{-i\gamma}$$

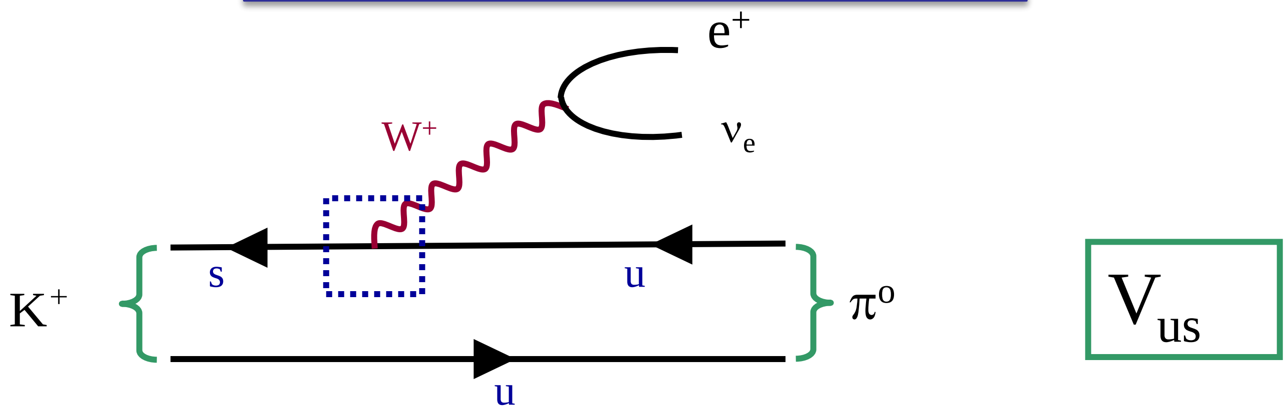
$$V_{td} = |V_{td}| e^{-i\beta}$$

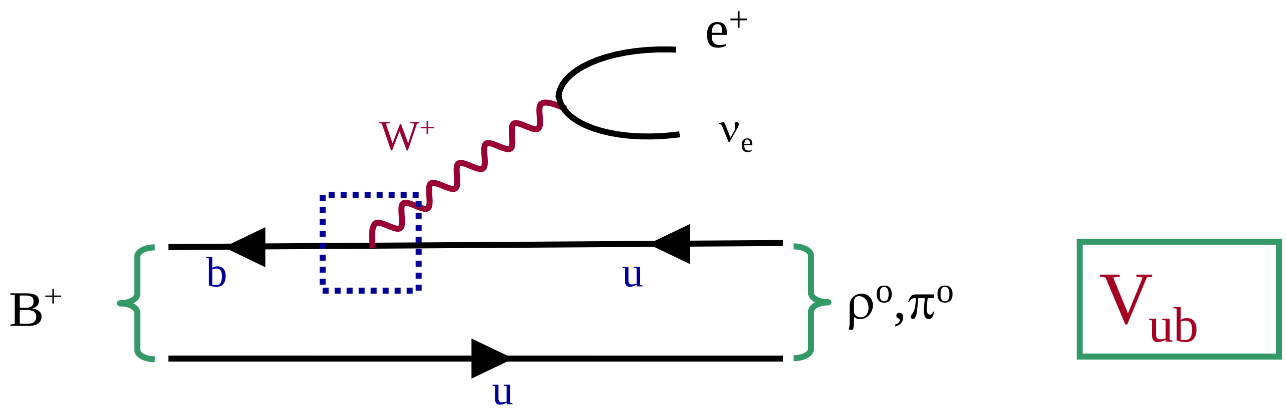
An Important Target of Particle Physics

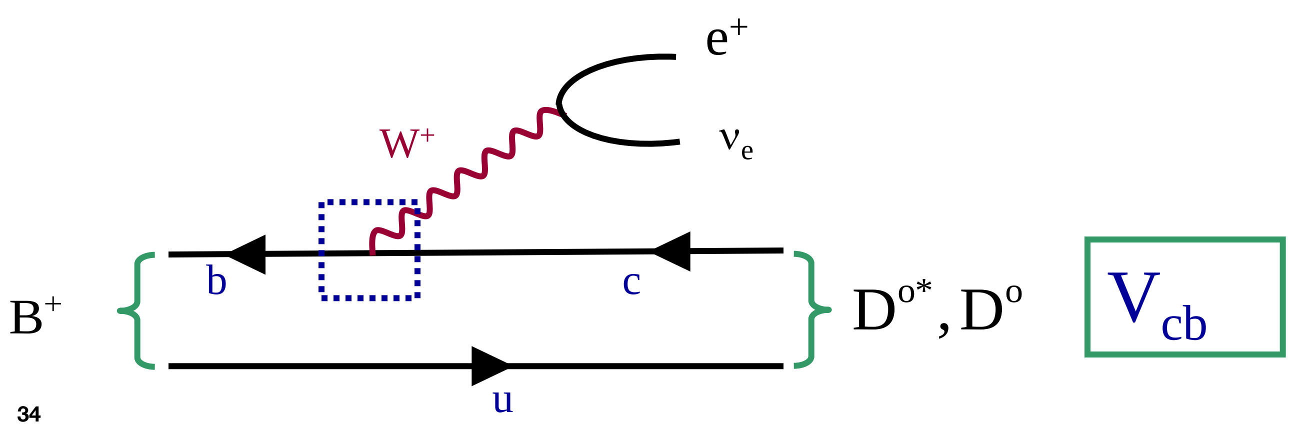
$$J_{CP} = \lambda^2 |V_{cb}|^2 \bar{\eta} = 2 \cdot$$ 

Area of unrescaled UT

Tree Level Decays







CKM Parameters from Tree-Level Decays
(subject to very small NP Pollution)

$$|V_{us}| = s_{12} = 0.2252 \pm 0.0008$$

$$|V_{cb}| = s_{23} = (40.9 \pm 1.1) \cdot 10^{-3}$$

$$|V_{ub}| = s_{13} = \left(3.9 \pm 0.4\right) \cdot 10^{-3}$$

$$\delta_{CKM} = \gamma_{UT} = (67 \pm 12)^{\circ}$$

(-phase of V_{ub})

$$\boxed{\left(\sin 2\beta\right)_{\psi K_s} = 0.68 \pm 0.02}$$

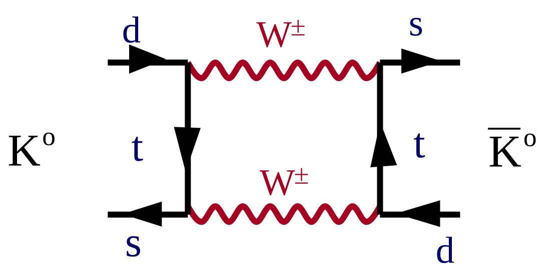
(-phase of V_{td})

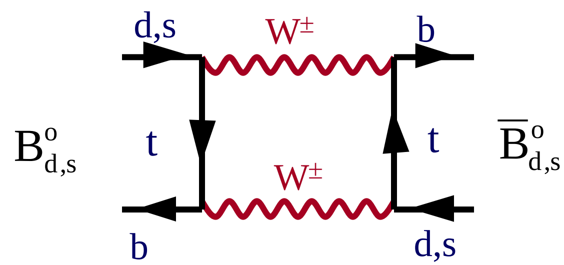
$\Rightarrow$ $\boxed{\beta = (21.4 \pm 0.8)^{o}}$

but could be subject to NP pollution

$$\boxed{\text{Phase of } V_{ts}\text{: } \approx -(1.2 \pm 0.1)^{o}}$$

Loop Induced FCNC Processes





★ $\cancel{CP}$ ε_K-Parameter
ΔM (K_L-K_S)

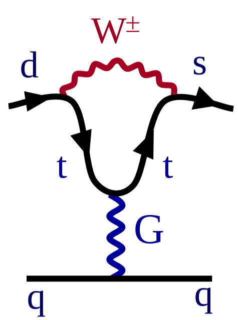
$B^o_d - \overline{B}^o_d$ Mixing ★

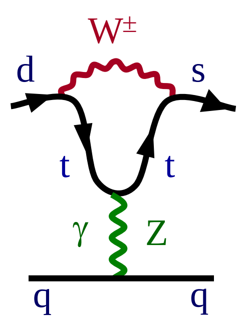
$B^0_s - \overline{B}^0_s$ Mixing ★

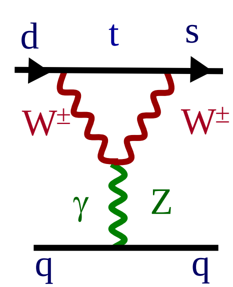
Discovered in 2006

(CDF, DØ)

★ ε'

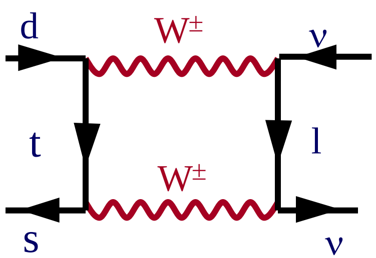


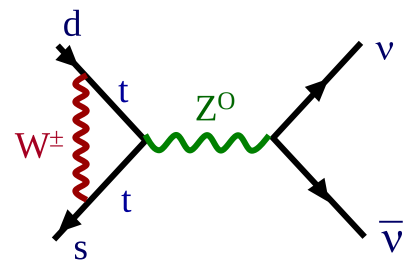


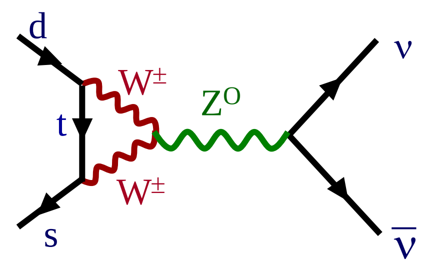


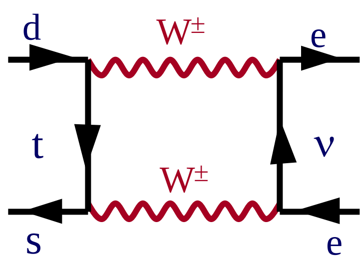
Loop Induced FCNC Processes

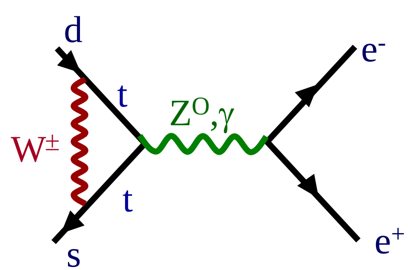
$\boxed{K^+ \to \pi^+ \nu\bar{\nu},}$ $K_L \to \pi^0 \nu\bar{\nu}$ $\boxed{B_{d,s} \to \mu\bar{\mu},}$ $B \to K(K^*)\mu\bar{\mu}$

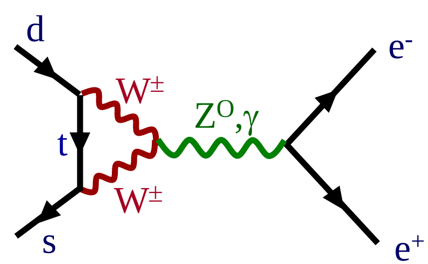




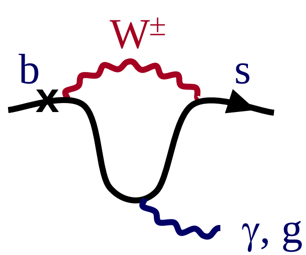








$K_L \to \pi^0 e^+ e^-$ $B \to X_S e^+ e^-,\ X_S \mu\bar{\mu}$



$\boxed{B \to X_S \gamma \quad B \to K^* \gamma}$

$B \to X_d \gamma$ $b \to s$ gluon

Hierarchical Structure of the CKM Matrix

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

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

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

GIM Structure of FCNC´s

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

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

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

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

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

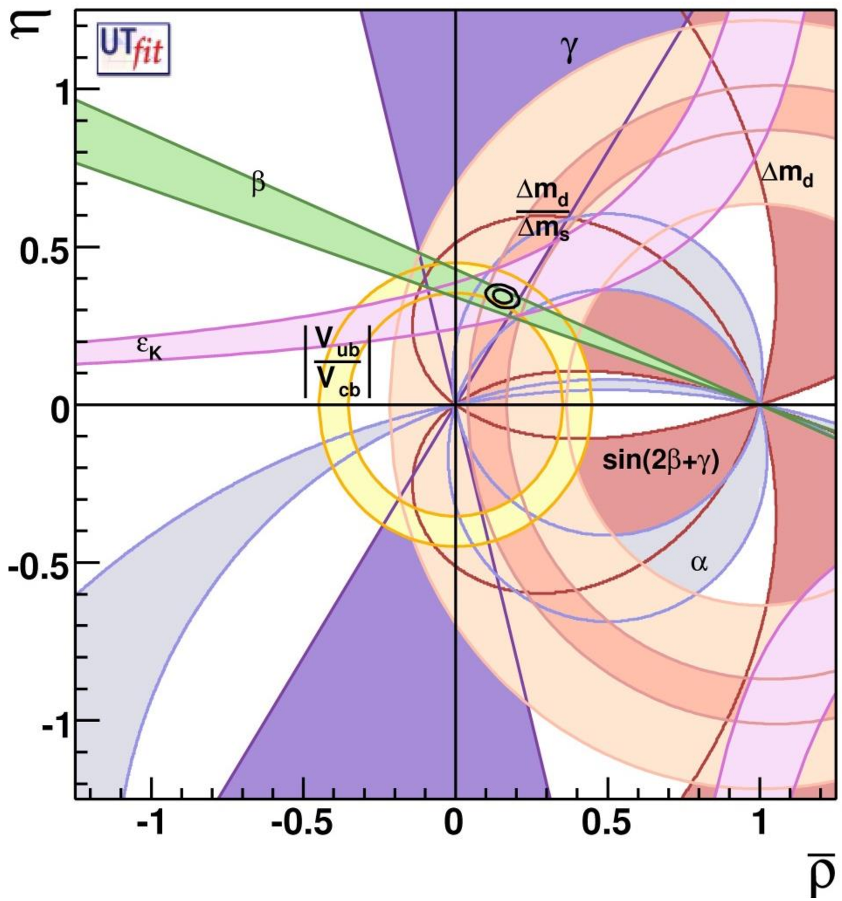
PMNS: Negligible LFV

(tiny ν masses)

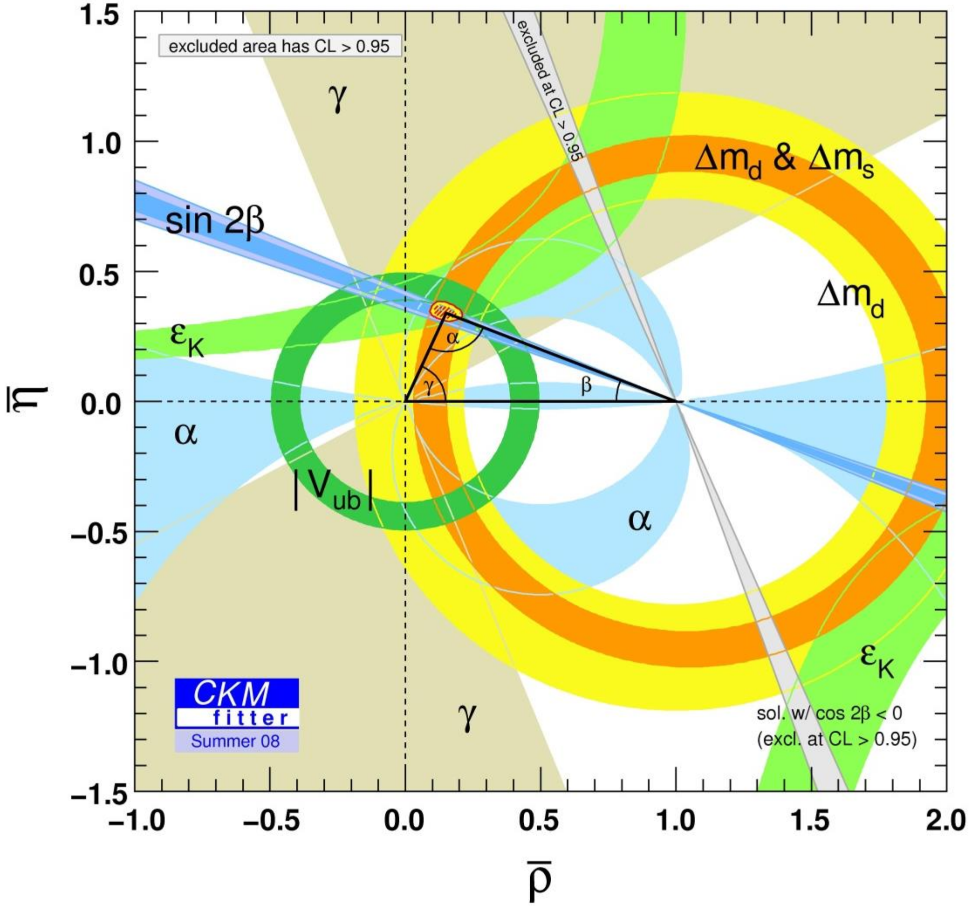
Unitarity Triangle Fits

(Icons of Flavour Physics)

UT fit



CKM fitter



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 : $K^0 - \bar{K}^0$, $B_d^0 - \bar{B}_d^0$, $B_s^0 - \bar{B}_s^0$ mixings found at suppressed level**

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

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

5. Very very highly suppressed transitions in the SM consistent with experiment:

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

Impressive Success of the CKM Picture of Flavour Changing Interactions

(GIM)

Yet

1. **EW-Symmetry Breaking has to be better understood.**

2. **Hierarchies in Fermion Masses and Mixing Angles have to be understood with the help of some New Physics (NP). This NP could have impact on Low Energies.**

3. **There is still a lot of room for NP contributions, in particular in rare decays of mesons and leptons, in ~~CP~~ flavour violating transitions and EDM´s.**

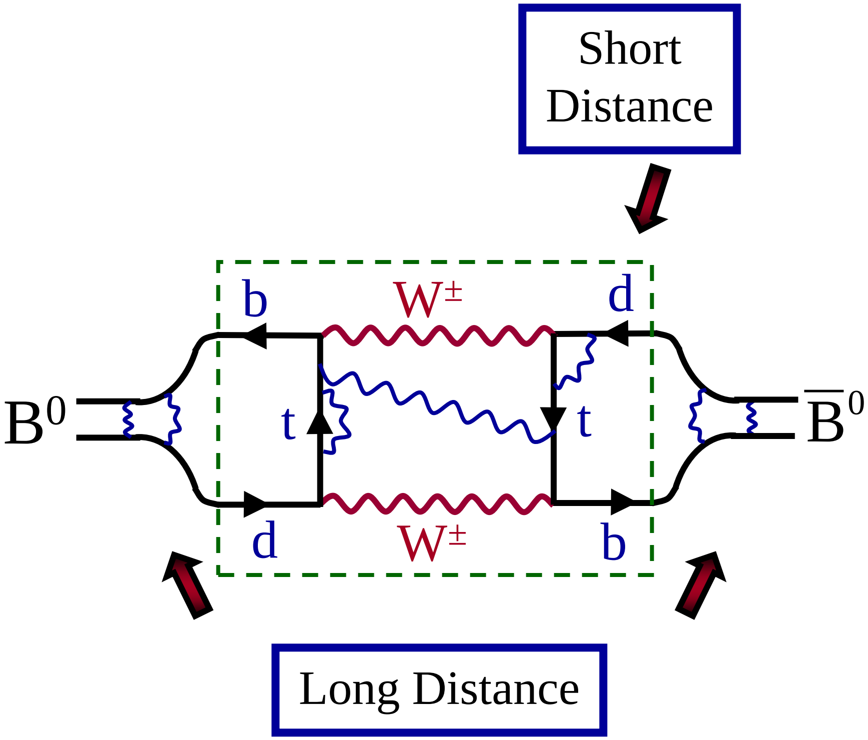
4. **Matter-Antimatter Asymmetry → New CP Phases needed.**

5. **Several tensions between the flavour data and the SM exist.**
   (see Movement 3)

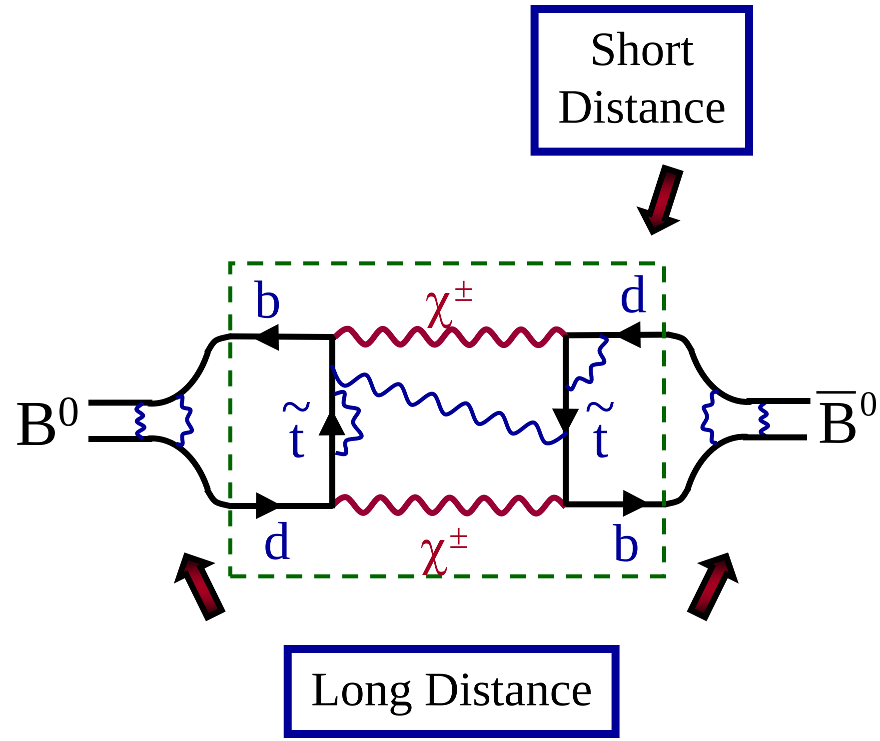
Theoretical Framework

The Problem of Strong Interactions

$B_d^0 - \overline{B}_d^0$ Mixing (SM)



$B_d^0 - \overline{B}_d^0$ Mixing (MSSM)



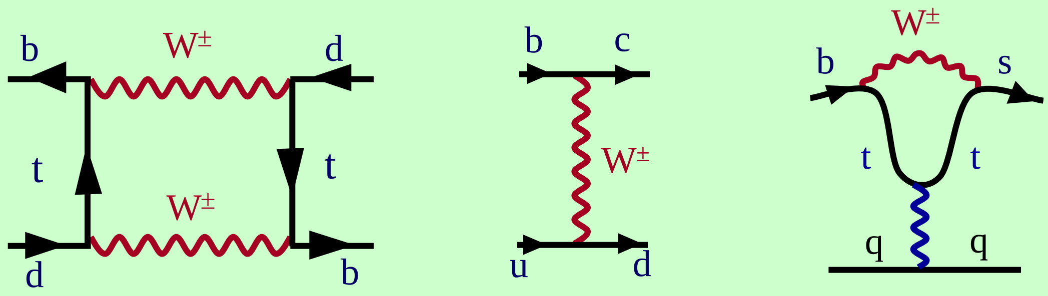
SD : Perturbative
(Asymptotic Freedom)

LD : Non-Perturbative
(Confinement)

Effective Field Theory

Full Theory

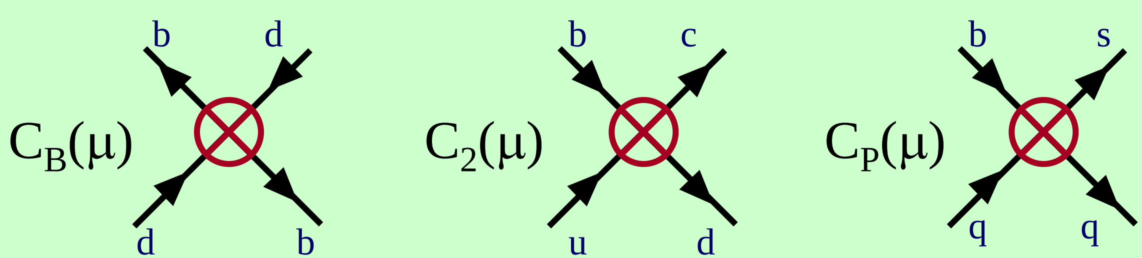
($W^{\pm}$, Z^0, G, γ, t, H^0, b, u, d, s, c, l)



$\mu \geq M_W$

Effective Theory

(G, γ, b, u, d, s, c, l)



$\mu \simeq 0(m_b)$

"Generalized Fermi Theory" with calculable "couplings" $C_B(\mu)$, $C_2(\mu)$,...

Operator Product Expansion

9806471

Wilson Coefficients — Local Operators

$$H_{eff} = \frac{G_F}{\sqrt{2}} V_{CKM} \sum_i C_i(\mu)\, Q_i$$

Q_i ⟷ **Four Quark Interaction Vertex** $(\bar{s}d)_{V-A}(\bar{s}d)_{V-A}$

$C_i(\mu)$ ⟷ **Coupling Constants** $C(\mu) = \left[\frac{\alpha_s(M_W)}{\alpha_s(\mu)}\right]^{\frac{6}{23}}$

$\{K, B, D, \ldots\}$

$$A(M \to F) = \frac{G_F}{\sqrt{2}} V_{CKM} \sum_i C_i(\mu) \langle F | Q_i(\mu) | M \rangle$$

$\{\pi\pi,\ \pi\nu\bar{\nu},\ \mu\bar{\mu},\ K^*\gamma, \ldots\}$

M_W $\mu = 0(1\ \text{GeV}, m_b)$ 0

Short   RG   Long Distance

{Top, SUSY, $H^\pm$...}

{Renormalization Group $\sum\left(\alpha_s \log\frac{M_W}{\mu}\right)^n$}

{Lattice, 1/N, HQET, QCDS, ChPTh}

$$\langle \bar{K}^0 | (\bar{s}d)_{V-A}(\bar{s}d)_{V-A} | K^0 \rangle = \frac{8}{3} \hat{B}_K F_K^2 m_K^2 [\alpha_s(\mu)]^{2/9}$$

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)

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

Renormalization
Group (QCD)
LD $\leftrightarrow$ 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

Possible Dirac Structures in $K^0 - \bar{K}^0$ and $B^0_{d,s} - \bar{B}^0_{d,s}$

SM:

$$\gamma_\mu(1-\gamma_5) \otimes \gamma^\mu(1-\gamma_5)$$

Beyond SM:

$$\gamma_\mu(1-\gamma_5) \otimes \gamma^\mu(1+\gamma_5)$$

$$(1-\gamma_5) \otimes (1+\gamma_5)$$

$$(1-\gamma_5) \otimes (1-\gamma_5)$$

$$\sigma_{\mu\nu}(1-\gamma_5) \otimes \sigma^{\mu\nu}(1-\gamma_5)$$

MSSM with large tanβ

General Supersymmetric Models

Models with complicated Higgs System

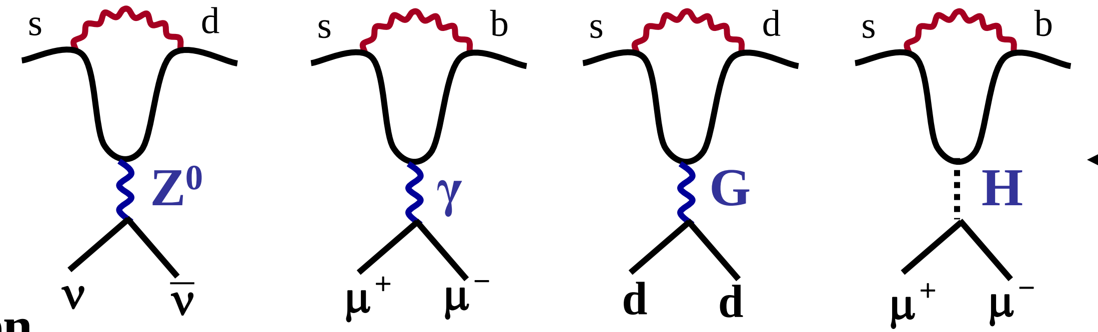
Warped Extra Dimensions

$\mathrm{NLO}\left[\eta^i_{QCD}\right]^{\mathrm{New}}$: Ciuchini, Franco, Lubicz, Martinelli, Scimemi, Silvestrini

AJB, Misiak, Urban, Jäger

Basic Diagrams in FCNC Processes

Penguin Family :

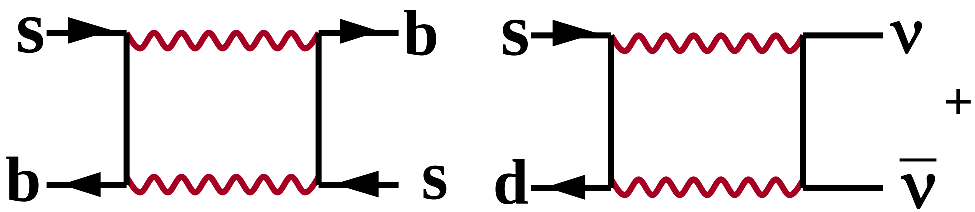


New Physics enters here

(GIM broken at one loop)

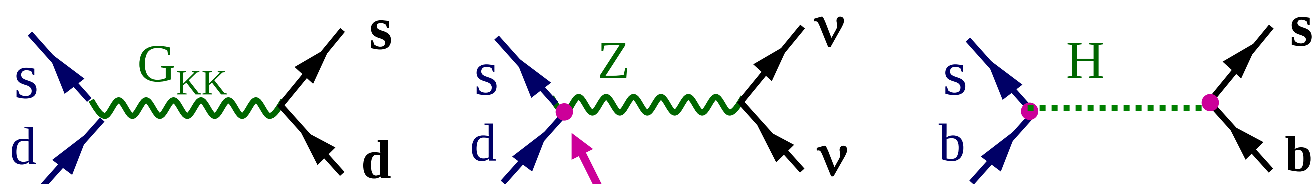
Similar diagrams in LFV and EDM´s

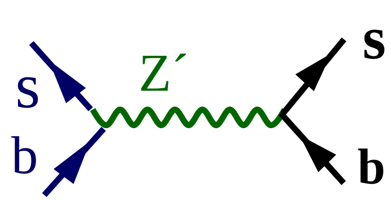
Box Diagrams



+ other box diagrams

Tree Diagrams





(GIM broken at tree level)

RS

Generated through mixing with New Gauge Bosons

Double Higgs Penguin in SUSY

Minimal Flavour Violation

General Structure in Models with Constraint Minimal Flavour Violation

Ciuchini, Degrassi, Gambino, Giudice;
AJB, Gambino, Gorbahn, Jäger, Silvestrini;

- No new Operators (Dirac and Colour Structures) beyond those present in the SM
- Flavour Changing Transitions governed by CKM. No new complex phases beyond those present in the SM

$$\boxed{A(\mathrm{Decay}) = B_i\, \eta^i_{QCD}\, V^i_{CKM} \Big[\underbrace{F^i_{SM} + F^i_{New}}_{\text{real}} \Big]}$$

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

Model independent Relations:

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

(CMFV)

$$\boxed{\frac{Br(B \to X_s \nu\bar{\nu})}{Br(B \to X_d \nu\bar{\nu})} = \frac{|V_{ts}|^2}{|V_{td}|^2} = \frac{m_{B_d}}{m_{B_s}} \frac{1}{\xi^2} \frac{\Delta M_s}{\Delta M_d}}$$

(CMFV)

$$\boxed{(\sin 2\beta)_{B \to \psi K_S} = (\sin 2\beta)_{K \to \pi\nu\bar{\nu}}}$$

(MFV)

The violation of these model independent MFV (CMFV) relations would signal new flavour and CP-violating interactions (and/or new operators)

3rd Movement

Rare Processes: Technology to reach Zeptouniverse

Common Belief : There must be **New Physics** (New Particles and New Forces)

In order to search for it (Theory + Experiment) : **Need Resolution of Distance Scales 10^{-21}m - 10^{-19}m**

Large Hadron Collider : Resolution down to $5 \cdot 10^{-20}$m

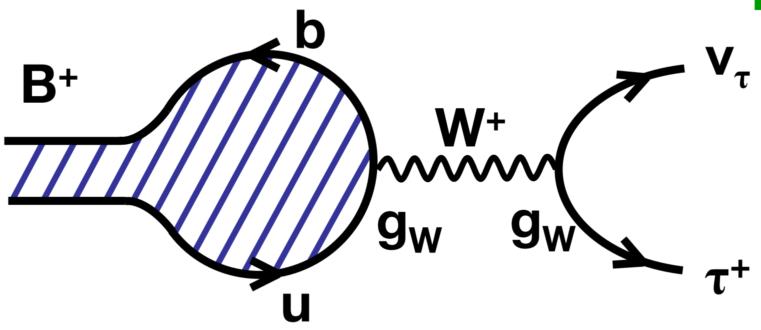
Rare Processes : 10^{-21}m (Quantum Fluctuations)

Equivalent to the status of the Universe 10^{-14} - 10^{-12}sec after the BIG BANG !

In our search for a more fundamental theory we need to improve our understanding of $\boxed{\text{Flavour}}$

Indirect Search: Precision Measurement of Decays of Mesons and Leptons

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

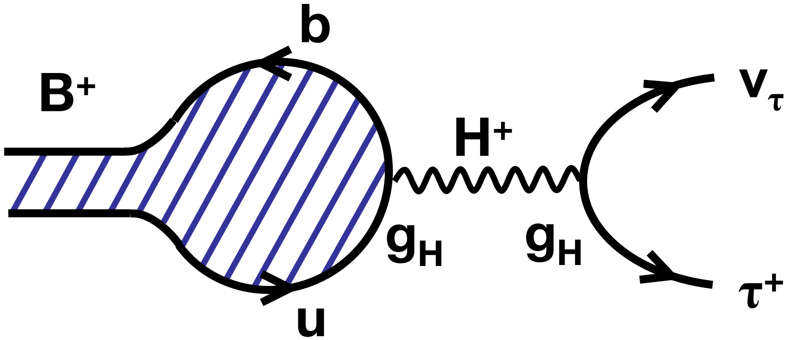


Standard Model

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

$m_B \approx 5\ \mathrm{GeV}$

A, B – parameters of a given theory



Contribution of a new charged Heavy Particle

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

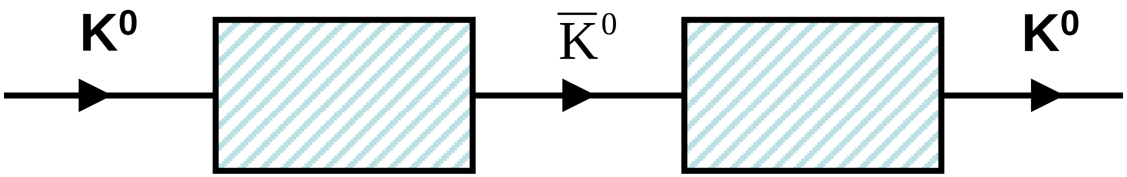
$$\Delta = \mathrm{Br}\left(B^+ \to \tau^+ \nu_\tau\right) - \mathrm{Br}\left(B^+ \to \tau^+ \nu_\tau\right)_{SM} \neq 0$$

Signal of a new particle

$K^0 - \overline{K}^0$ Mixing (Oscillations)

$K^0 = d\bar{s}$

$\overline{K}^0 = \bar{d}s$



(discovered in 1960)

K^0 and $\overline{K}^0$ are not Mass Eigenstates

Mass Eigenstates:

$$K_L = \frac{K^0 + \overline{K}^0}{\sqrt{2}} \qquad K_S = \frac{K^0 - \overline{K}^0}{\sqrt{2}}$$

(L = Long) **(S = Short)**

$$M(K_L) \cong M(K_S) = 0.5\ \text{GeV}$$

$$M(K_L) - M(K_S) = 3.5 \cdot 10^{-15}\,\text{GeV}$$

III

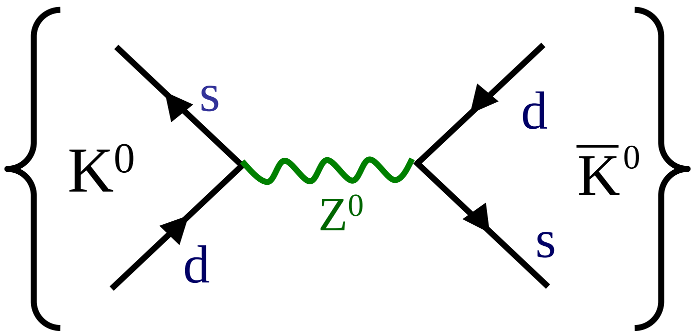
$$\Delta M_K$$

$$\frac{\tau(K_L)}{\tau(K_S)} \cong 600$$

M ≡ mass

τ ≡ Life Time

Could ordinary Weak Interactions explain ΔM_K ?



$$\Delta M_K = 2 \cdot 10^{-2}\,\mathrm{GeV}^3\; G_F \left[\frac{M_W^2}{M_Z^2}\right]$$

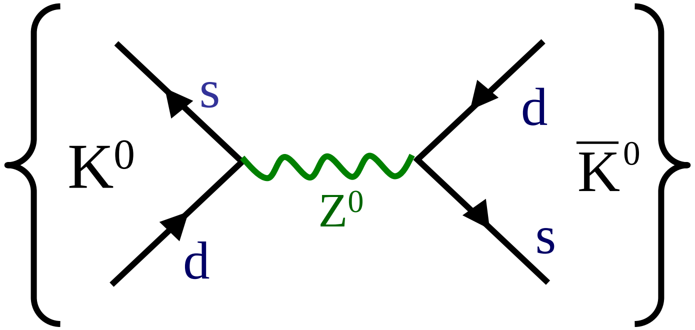
$$G_F \cong 1.1 \cdot 10^{-5}\,\mathrm{GeV}^{-2}$$

$$M_Z \cong 90\ \mathrm{GeV}$$

$$\boxed{\Delta M_K \cong 2 \cdot 10^{-7}\,\mathrm{GeV}}$$

Disaster !!!
Missed by
8 orders of
magnitude !!!

Could ordinary Weak Interactions explain ΔM_K ?



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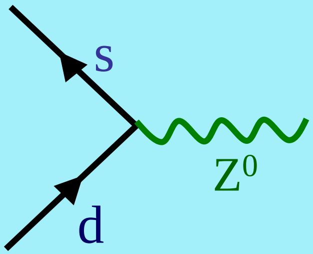
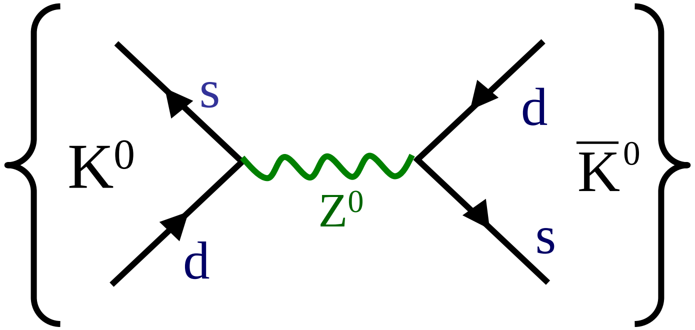


$= 0$

GIM Mechanism

(1971)

Could ordinary Weak Interactions explain ΔM_K ?



$$\left\{ \begin{array}{l} \Delta M_K = 2\cdot 10^{-2}\,\mathrm{GeV}^3 \; G_F \left[\dfrac{M_W^2}{M_Z^2} \right] \\ G_F \cong 1.1\cdot 10^{-5}\,\mathrm{GeV}^{-2} \end{array} \right\}$$

$M_Z \cong 90$ GeV

$$\Delta M_K \cong 2\cdot 10^{-7}\,\mathrm{GeV}$$

Disaster !!!
Missed by
8 orders of
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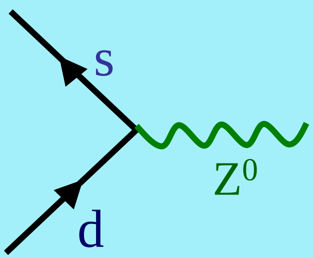
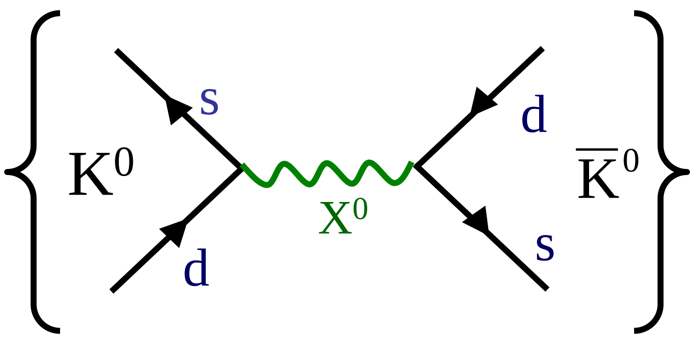


$= 0$

GIM Mechanism **(1971)**



$$\left\{ \Delta M_K \cong 2\cdot 10^{-7} \left[\frac{M_Z^2}{M_X^2} \right] \mathrm{GeV} = 3.5\cdot 10^{-15}\,\mathrm{GeV} \right\}$$

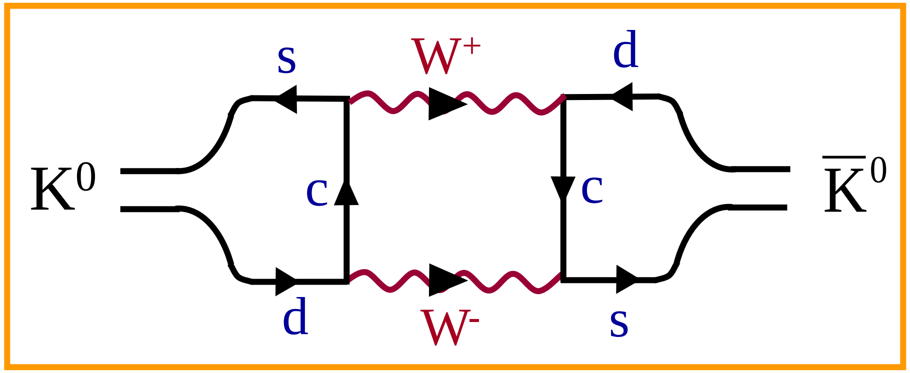
New very heavy neutral boson ! $\left\{ M_X \cong 10^6\,\mathrm{GeV} \right\}$

Testing 10^{-22}m !

ΔM_K in the Standard Model

Gaillard-Lee (March 1974)

$$\lambda \cong 0.22$$



$$\Delta M_K = 1.4\ \mathrm{GeV}^5\ G_F^2 \lambda^2 \left[\frac{m_c^2}{M_W^2}\right]$$

$$G_F \cong 1.2 \cdot 10^{-5}\,\mathrm{GeV}^{-2}$$

$$\Delta M_K = 10^{-11}\,\mathrm{GeV}\left[\frac{m_c^2}{M_W^2}\right] = 3.5 \cdot 10^{-15}\,\mathrm{GeV}$$

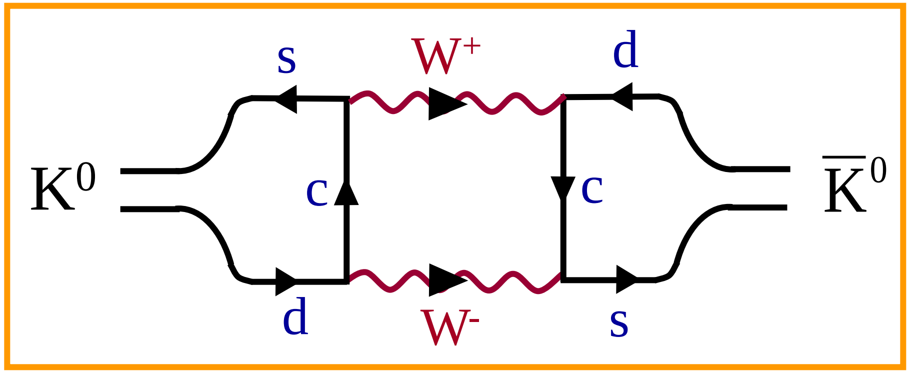
$$m_c = \sqrt{3.5} \cdot 10^{-2} M_W = 1.5\ \mathrm{GeV}$$

(Prediction !!)

ΔM_K in the Standard Model

Gaillard-Lee (March 1974)

$\lambda \cong 0.22$



$$\Delta M_K = 1.4\ \mathrm{GeV}^5\ G_F^2 \lambda^2 \left[\frac{m_c^2}{M_W^2}\right]$$

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$$m_c = \sqrt{3.5} \cdot 10^{-2} M_W = 1.5\ \mathrm{GeV}$$

(Prediction !!)

November Revolution 1974
Discovery of $\overline{c}c$ State
(SLAC, Brookhaven)

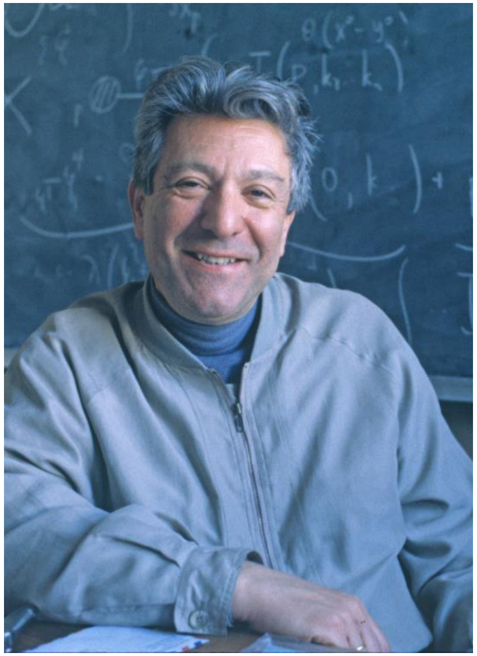
$$M_{\overline{c}c} \cong 3.1\ \mathrm{GeV}$$

$$m_c \cong 1.5\ \mathrm{GeV}$$ **!!**

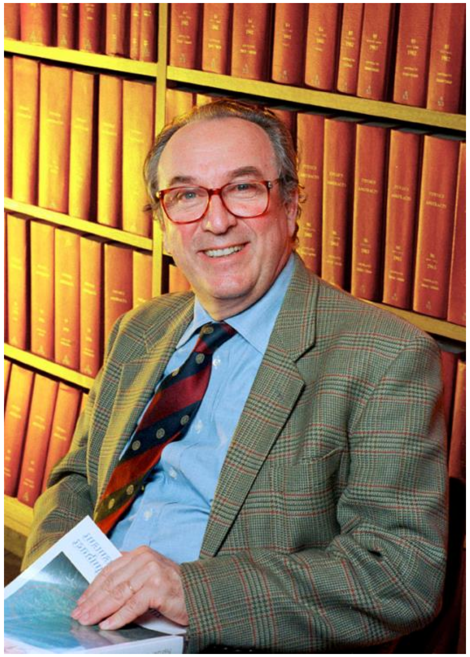
Prediction confirmed !

EPS (High Energy Prize 2011)

Sheldon Glashow



John Iliopoulos



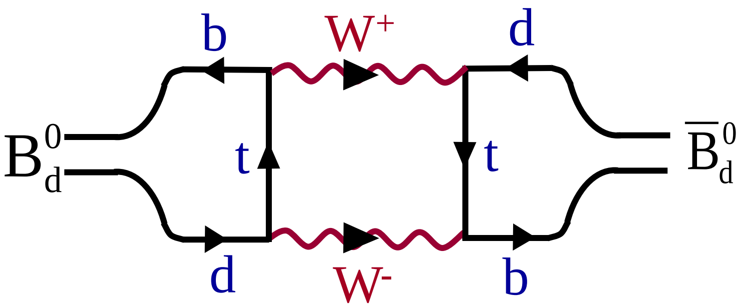
Luciano Maiani

GIM

Similar Studies: 1974-1994

$B_d^0 = d\bar{b}$

$B_d^0 - \bar{B}_d^0$ Oscillations



\+

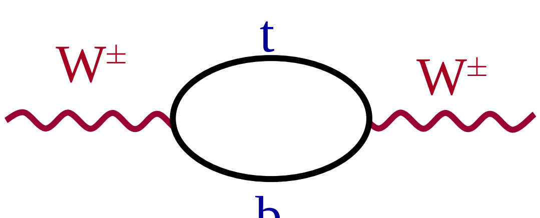
DESY 87

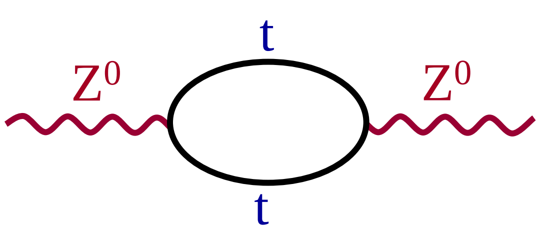
$\Delta M_{B_d} \cong 4 \cdot 10^{-13}\,\mathrm{GeV}$

(Prediction)

$m_t \approx 150\ \mathrm{GeV}$
± 30

Electroweak Precision Studies





CERN, SLAC (1989-1994)

$m_t \approx 150\ \mathrm{GeV}$
± 20

(Prediction)

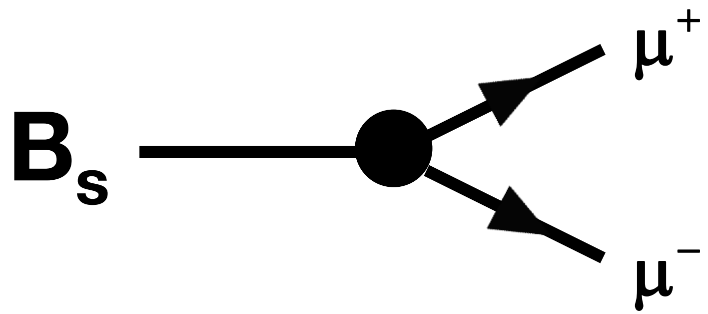
1994 Discovery of the Top Quark (Fermilab)

$m_t = 171 \pm 2\ \mathrm{GeV}$

2013

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

$$B_s = \left(\bar{b}s\right)$$



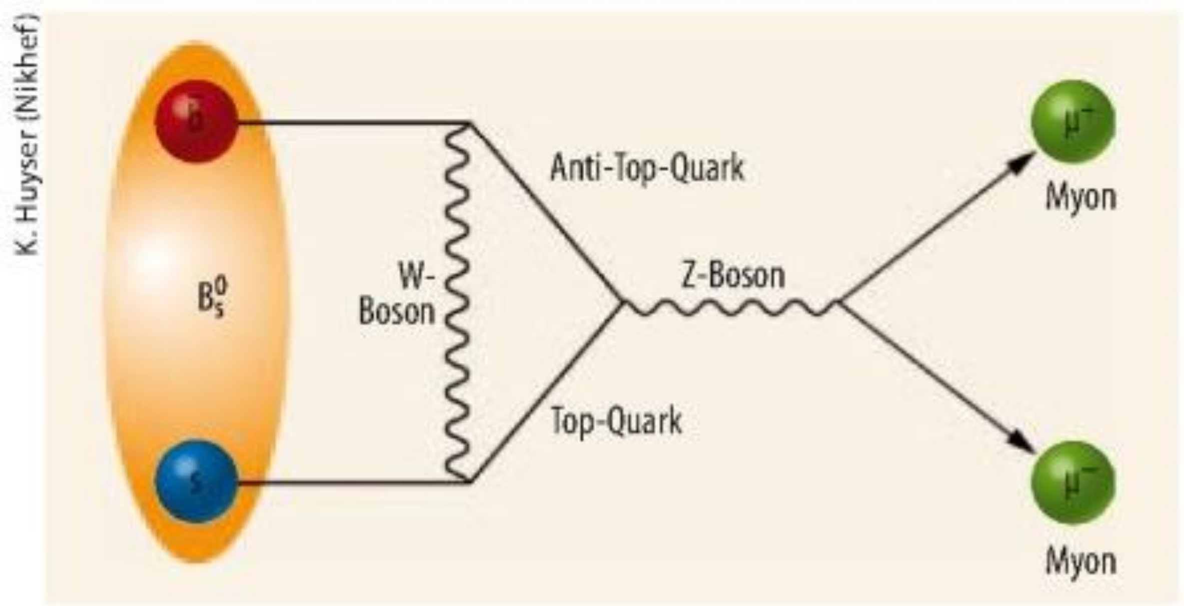
Quantum fluctuations at very short distance scales

The probability for this decay to occur depends on the dynamics hidden in ● : particles and forces at short distance scales

Searching for New Particles through Rare Processes

$B_s^0 \rightarrow \mu^+\mu^-$

Standard Model



What is the Probability for this Decay to occur?

100% ↔ $\boxed{P = 1}$

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

$B_s \equiv (b\bar{s})$

1993	Buchalla + AJB (LMU)	$P = (3.5 \pm 1.5) \cdot 10^{-9}$
2003	AJB	$P = (3.4 \pm 0.5) \cdot 10^{-9}$
2012	AJB, Girrbach Guadagnoli, Isidori	$P = (3.5 \pm 0.3) \cdot 10^{-9}$
2013	Bobeth, Gorbahn, Hermann, Misiak, Stamou, Steinhauser	$\boxed{P = (3.65 \pm 0.23) \cdot 10^{-9}}$

<u>Note</u>: Only about 3 among 1 Milliard (Billion) produced B_s^0 mesons are predicted to decay into $\mu^+\mu^-$

LHC: proton + proton $\Rightarrow$ B_s, $\bar{B}_s^0$, ... + many other particles

$\boxed{\text{8 TeV}}$

$B_s \to \mu^+\mu^-$, $\bar{B}_s^0 \to \mu^+\mu^-$

But Prediction for $B_s \to \mu^+\mu^-$ could be different in other Theories with New Particles

Some Versions of Supersymmetric Models

2010

$P \approx 10^{-7} - 10^{-8}$
(10 – 100 among 1 Milliard B_s can decay into $\mu^+\mu^-$)

2011

Minimal Theory of Fermion Masses

(New Particles = New heavy quarks)
(AJB, Grojean, Pokorski, Ziegler)

2013
(January)

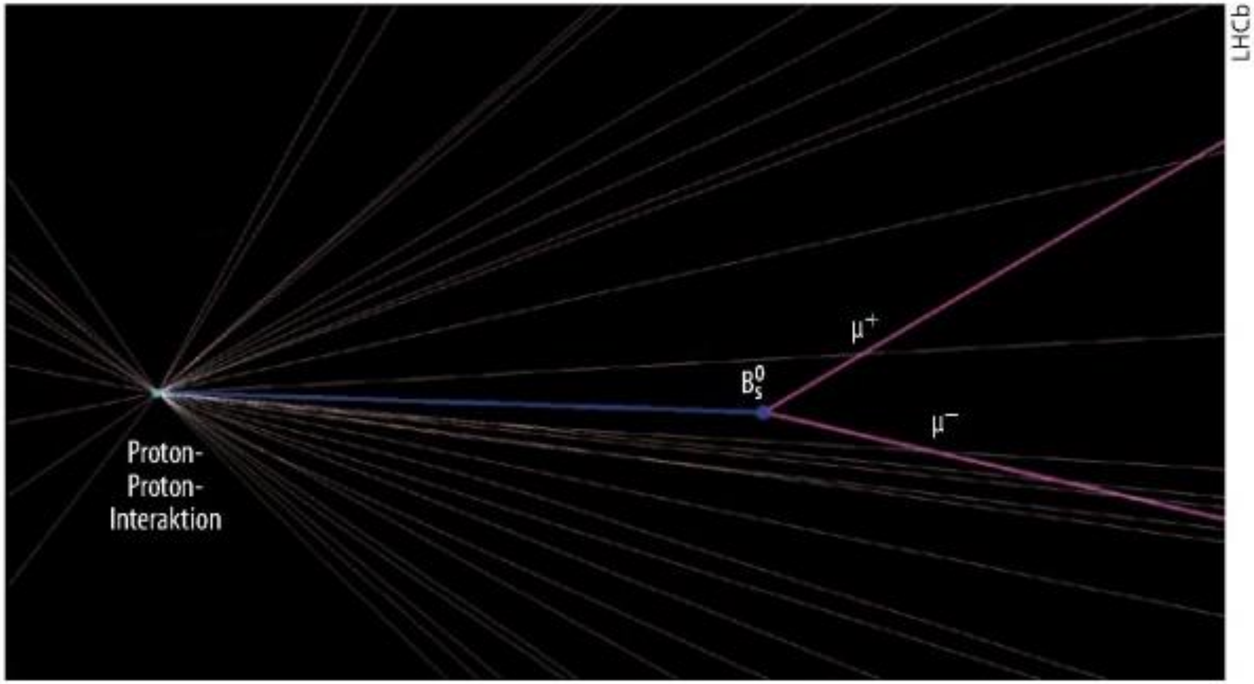
AJB, Girrbach, Ziegler

$P = (4.6 \pm 0.4) \cdot 10^{-9}$

about 4-5 per Milliard $B_s \to \mu^+\mu^-$

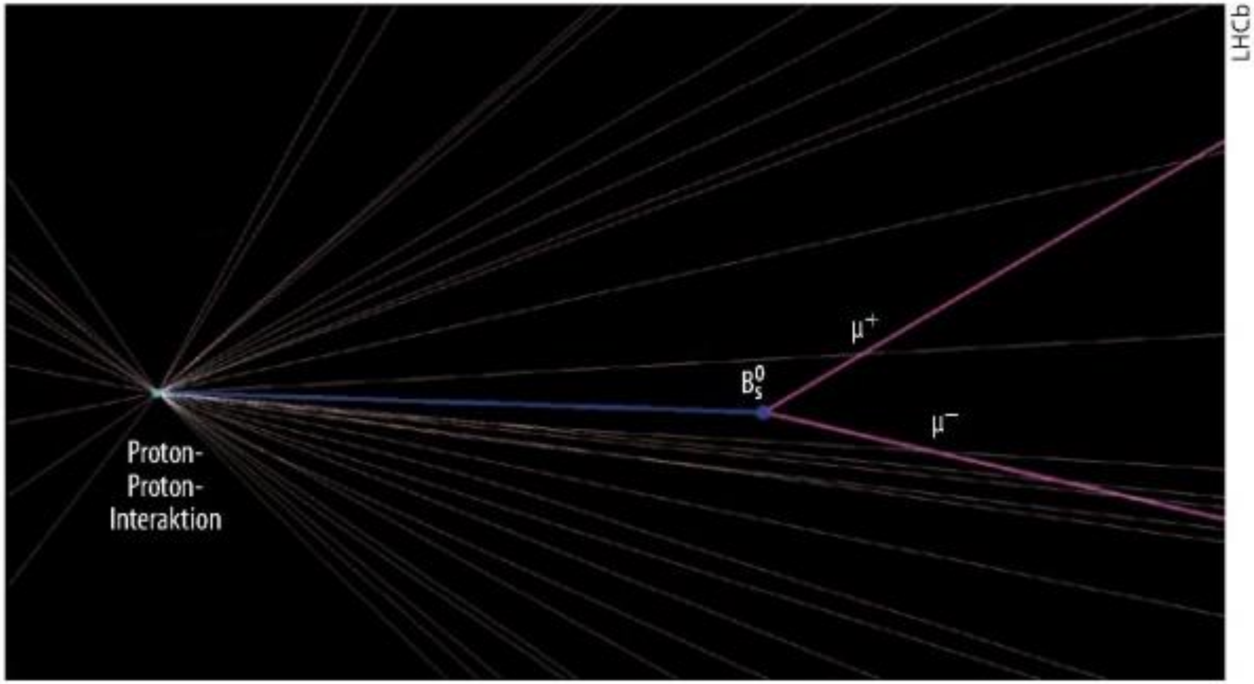
Messages from the LHC

July 2013



Messages from the LHC

July 2013



LHCb

CMS

$$P_{exp} = \left(2.9 \pm 0.7\right) \cdot 10^{-9}$$

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

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

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

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

Values of $Br(B_s \to \mu^+\mu^-)_{SM} \sim 3 - 4 \cdot 10^{-9}$

$Br(B_d \to \mu^+\mu^-)_{SM} \sim 1 \cdot 10^{-10}$

were with us for last 15 years

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

September 2013

Recently: full NLO Electroweak, NNLO QCD

Bobeth, Gorbahn, Hermann, Misiak, Stamou, Steinhauser

$$\overline{Br}(B_s \to \mu^+\mu^-)_{SM} = (3.65 \pm 0.23) \cdot 10^{-9}$$

$$Br(B_d \to \mu^+\mu^-)_{SM} = (1.06 \pm 0.09) \cdot 10^{-10}$$

Data (LHCb)

$$(2.9 \pm 0.7) \cdot 10^{-9}$$

$$\left(3.6 {}^{+1.6}_{-1.4}\right) \cdot 10^{-10}$$

Warning: $|V_{cb}|$ ($|V_{ts}|$) Dependence

BGHMSS use $|V_{cb}|_{incl} \approx 42 \cdot 10^{-3}$

$$\overline{Br}(B_s \to \mu\bar{\mu})_{SM} = (3.65 \pm 0.23) \cdot 10^{-9}$$

$$(2.9 \pm 0.7) \cdot 10^{-9}$$

(LHCb+CMS)

But for $|V_{cb}|_{excl} \simeq 39 \cdot 10^{-3}$

$$\boxed{\overline{Br}(B_s \to \mu\bar{\mu})_{SM} \approx (3.1 \pm 0.2) \cdot 10^{-9}}$$

Different Route

(AJB 2003)
(Knegjens 2014)

$$\overline{Br}(B_s \to \mu\bar{\mu})_{SM} = (3.5 \pm 0.2) \cdot 10^{-9} \left[\frac{(\Delta M_s)^{SM}}{(\Delta M_s)^{Data}}\right]\left[\frac{1.33}{\hat{B}_s}\right]$$

(No V_{cb}, F_{B_s} dependence)

Lattice

Present Status

July 2014

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

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

   ?

3. $B \to D^*\tau\nu,\ B \to D\tau\nu$ (2-3 σ) (BaBar)
   (4 σ) (+ Belle)

4. Breakdown of Lepton-Universality in $B^+ \to K^+ l^+ l^-$

5. Some Tensions in UT-fits (present already since 2008)

Basic Questions for remaining min

1. Can Quark Flavour Physics give us insight into the dynamics at very SD scales if no direct clear signal of NP will be seen at the LHC? No new particles below 6 TeV.

2. Can we reach Zeptouniverse 10^{-21}m (~ 200 TeV) by means of Quark Flavour Physics?

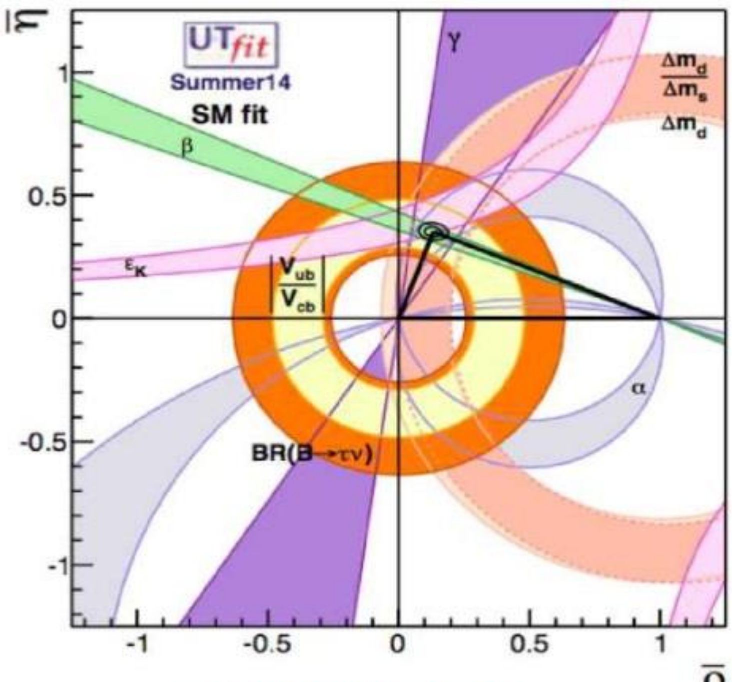
3. Which Processes could give us the best resolution of SD scales?

See also Charles et al. (1309.2293)

- *Are there other sources of flavor symmetry breaking (beside the SM Yukawa couplings)?*

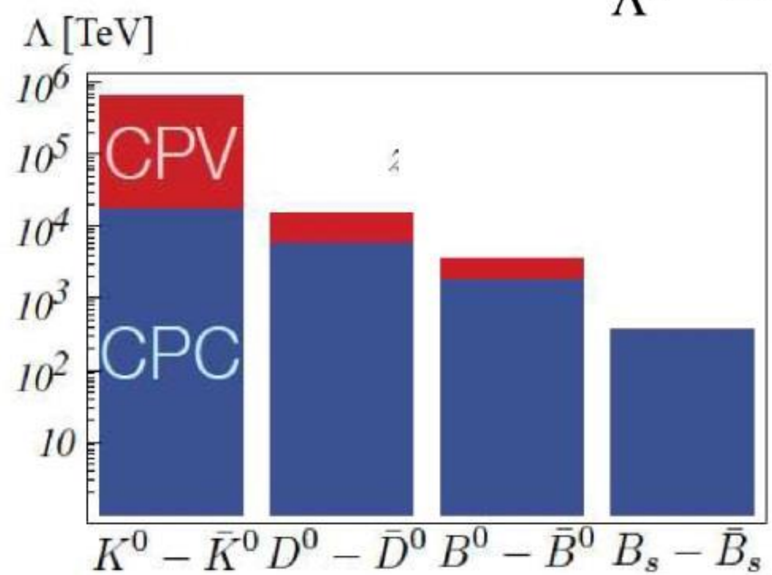
- *What determines the observed pattern of quark & lepton mass matrices?*

That's the question addressed by precision measurements (& searches) of flavor-changing processes of quarks & charged-leptons → So far everything seems to fit well with the SM→ Strong limits on NP



→ talks by Derkach

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda^2}\, O_{\Delta F=2}$$



Kamenik '13, G.I. '13, ...
[*wide literature*]

The sensitivity of $\Delta F=2$ processes to scales $\Lambda_{NP} > 1000$ TeV is impressive !!!

Yet Three points to be made in this talk

1 New Physics at these scales cannot be measured in K, B_s, B_d, D rare decays (NP effects negligible)

2 We cannot learn much about the nature of this physics through $\Delta F=2$ processes and Effective Theory approach except when flavour symmetries $U(3)^3$ (MFV), $U(2)^3$ are involved.

3 We need badly rare decays to learn about physics beyond the LHC.

? What are the maximal scales at which NP can be seen in rare K, B_s, B_d, D decays?

2015-2025 : Expedition

Attouniverse $\rightarrow$ Zeptouniverse

10^{-18}m $\rightarrow 10^{-21}$m

Quark Flavour Physics =

2015-2025 : Expedition

Attouniverse → Zeptouniverse

10^{-18}m → 10^{-21}m

Quark Flavour Physics =

Searching for New Physics on the Way to Zeptouniverse

Searching for New Physics on the Way to Zeptouniverse

21st Century

Three Basic Requirements

1

Precise CKM parameters from tree level decays (negligible NP contributions)

Main Targets : $|V_{ub}|,\ |V_{cb}|,\ \gamma$

2

Precise Lattice QCD Calculations

Main Targets : $F_{B_s}, F_{B_d}, \hat{B}_{B_d}, \hat{B}_{B_s}, B_8^{(2/3)}, B_6^{(1/2)}$ $+$ formfactors $(B \to K^*, K)$

Significant progress in the last years (dynamical fermions) but higher precision needed in order to see small NP effects.

Determination of $|V_{ub}|$ and $|V_{cb}|$ Crucial for Identification of New Physics

AJB + Girrbach-Noe, 1306.3755 ⇦ **(Dependently on $|V_{ub}|$ and $|V_{cb}|$ different NP is required to fit the data)**

Crivellin + Pokorski; 1407.1320
(NP explanation in the difference between exclusive and inclusive determinations currently ruled out)

Scenarios

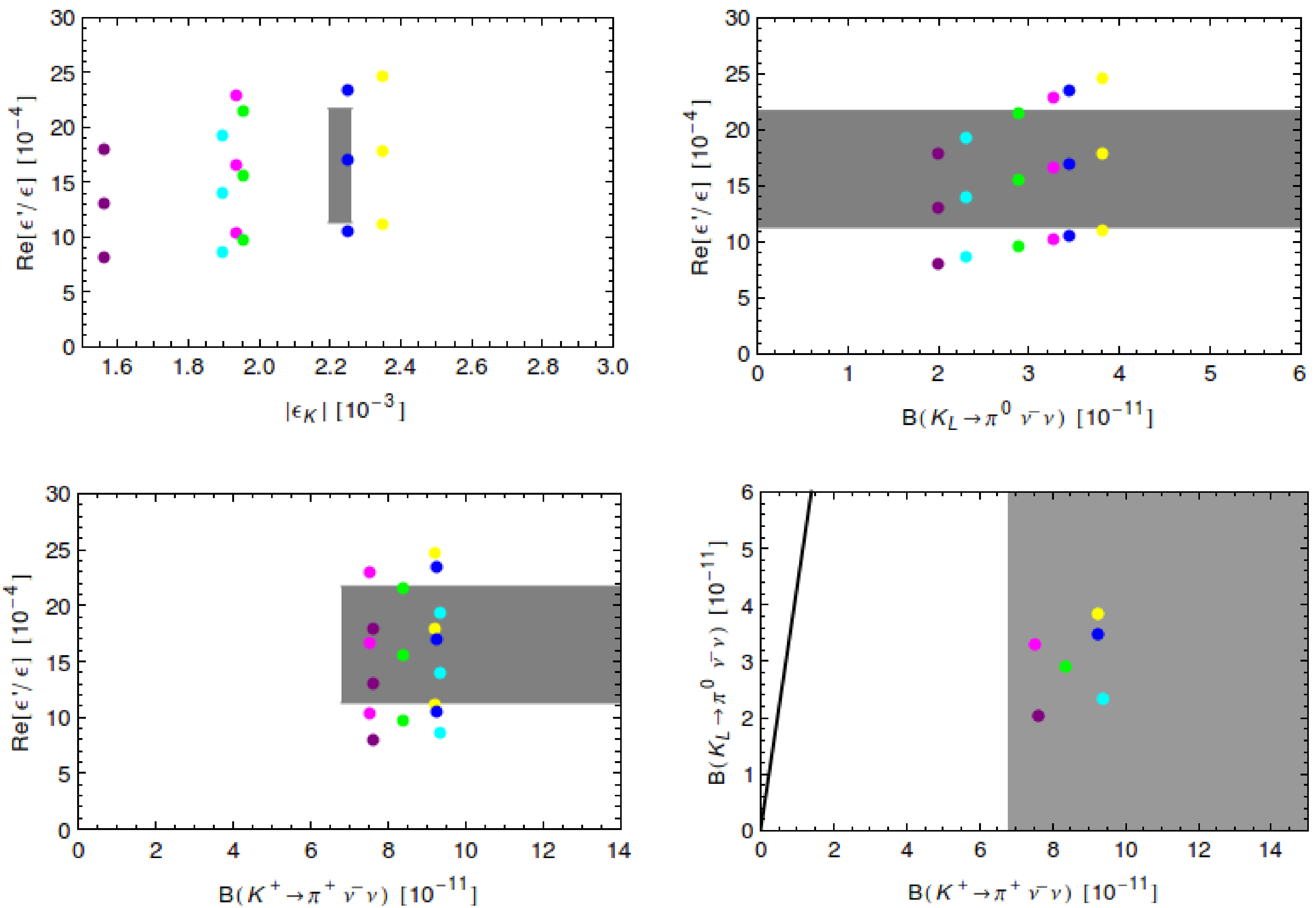
$\lvert V_{ub}\rvert \cdot 10^{-3}$	$\lvert V_{cb}\rvert \cdot 10^{-3}$
3.2	39.0
3.2	42.0
4.1	39.0
4.1	42.0
3.7	40.5
3.9	42.0

Data

$$10^3 \left|V_{ub}\right|_{exc} \approx 3.4 \pm 0.3$$
$$10^3 \left|V_{ub}\right|_{inc} \approx 4.3 \pm 0.3$$
$$10^3 \left|V_{cb}\right|_{exc} \approx 39 \pm 1.0$$
$$10^3 \left|V_{cb}\right|_{inc} \approx 42 \pm 1.0$$

AJB, De Fazio, Girrbach-Noe, 1404.3824

SM Predictions for different $|V_{ub}|$, $|V_{cb}|$



3

NLO + NNLO QCD Corrections and NLO Electroweak Corrections to Wilson Coefficients

1988 - 2014

Task completed !!

26 Years !

AJB: 1102.5650 (Update, Sept. 2014)

Most recent

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

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

Bobeth, Gorbahn, Stamou

Hermann, Misiak, Steinhauser

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

Effective Theory Approach ($\Delta F=2$)

$$H_{\text{eff}}(\Delta F=2) = \underbrace{H_{\text{eff}}^{\text{SM}}(\Delta F=2)}_{\text{Must be precisely known to identify NP}} + H_{\text{eff}}^{\text{NP}}(\Delta F=2)$$

$$H_{\text{eff}}^{\text{NP}}(\Delta F=2) = \sum_{ij} \frac{c_{ij}}{\Lambda_{\text{NP}}^2} \underbrace{Q_{ij}(\Delta F=2)}_{\text{4-quark operators}}$$

Utfitters

Isidori, Nir, Perez

For $c_{ij} = 0(1)$ sensitivity to physics $\Lambda_{\text{NP}} > 1000$ TeV (LR operators) $(\varepsilon_K, \Delta M_K)$

But with the help of $\Delta F=2$ only it is not possible to learn with ET about the nature of the dynamics at Λ_{NP}

We need **$\Delta F=1$ transitions : Rare K, $B_{s,d}$, D decays**

Effective Theory Approach ($\Delta F=1$)

$$H_{eff}(\Delta F=1) = H_{eff}^{SM}(\Delta F=1) + H_{eff}^{NP}(\Delta F=1)$$

$$H_{eff}^{NP}(\Delta F=1) = \sum_{ij} \frac{d_{ij}}{\Lambda_{NP}^{2}} Q_{ij}(\Delta F=1)$$

Limitations of ET :

a) ET does not provide concrete relations between the c_{ij} ($\Delta F=2$) and d_{ij}($\Delta F=1$) present in concrete models.

Impossible to incorporate

Impact of $\Delta F=2$ transitions on rare K, $B_{s,d}$ decays

b) ET does not provide relations between different coefficients in concrete models:

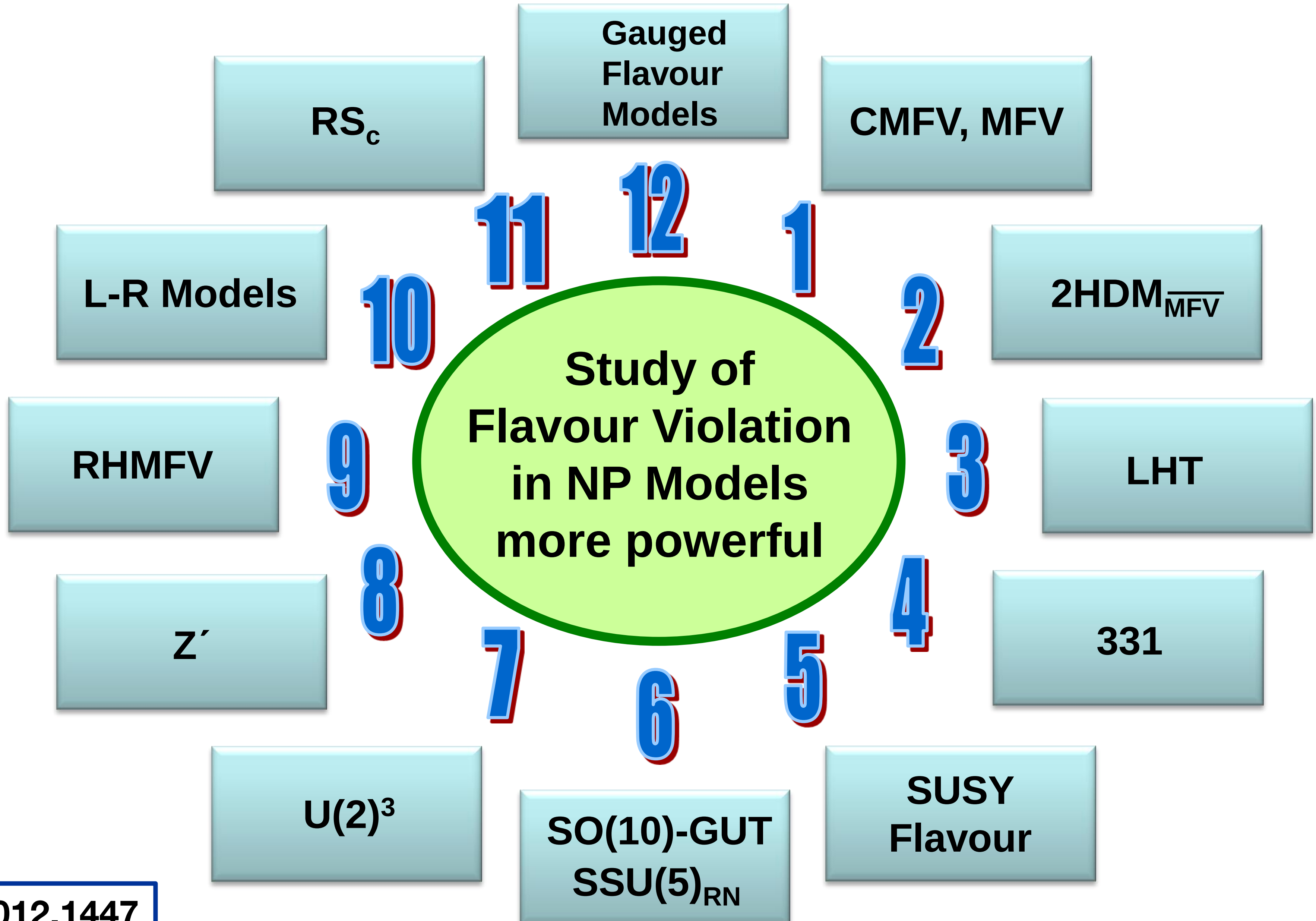
Example

331 Models

Beyond ET :

In models with Z´ and Z FCNCs their contribution can interfere constructively and destructively implying very different results

AJB
De Fazio
Girrbach-Noe
1405.3850



1012.1447
1204.5065

1306.3755

Towards New SM In 12 Steps

1 CKM from Trees

2 Lattice

3 $\Delta F=2$ Observables

4 $B_{s,d} \to \mu^+\mu^-$, $B_{s,d} \to \tau^+\tau^-$

5 $B^+ \to \tau^+\nu_\tau$

6 $B \to X_s\gamma$, $B \to K^*\gamma$

7 $B \to X_s l^+l^-$, $B \to K^*(K)l^+l^-$

8 $K \to \pi\nu\bar{\nu}$

9 $B \to X_s\nu\bar{\nu}$, $B \to K^*(K)\nu\bar{\nu}$

10 ε'/ε

11 Charm, Top

12 LFV, EDMs, $(g-2)_{\mu,e}$

Superstars and Stars of Quark Flavour Physics

Superstars

ε_K, ΔM_s, ΔM_d, $S_{\psi K_S}$ (TH)

$B_s \to \mu^+\mu^-$, $B_d \to \mu^+\mu^-$, $S_{\psi\varphi}(\varphi_s)$ (LHCb, CMS, ATLAS)

$B \to K\nu\bar{\nu}$, $B \to K^*\nu\bar{\nu}$, $B \to X_s\nu\bar{\nu}$ (Belle II)

$K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$ (NA62, J-Parc)

Stars

$B \to K^*\mu^+\mu^-$ $B \to K\mu^+\mu^-$

$B \to D^*\tau\nu_\tau$ $B \to D\tau\nu_\tau$

Old Superstar

ε'/ε will strike back provided B_6 (QCD Penguins) will be precisely known.

B_8 (EW Penguins) $\approx 0.65 \pm 0.05$ (UK-QCD)

The Power of Correlations between Flavour Observables (Correlation Primer)

Crucial Tool for exploring Attouniverse $\rightarrow$ Zeptouniverse

Important Messages

1. Correlations between decays of a given meson test the Dirac structure of couplings.

2. Correlations between decays of different mesons test the flavour structure of couplings (flavour symmetries).

Stressed by Monika Blanke (CKM 2014)

Two Simplest General Frameworks

MFV (CMFV) $U(3)^3$

(symmetry between 3 generations)

Stringent Correlations between K, B_s, B_d

No new sources of flavour and CP violation

$$S_{\psi K_s} = \sin 2\beta \quad , \quad S_{\psi\varphi} = S_{\psi\varphi}^{SM} = \text{small}$$

No Right-handed currents

$U(2)^3$ Flavour Symmetry

(symmetry between two light generations)

Stringent Correlations between B_s and B_d

Correlations $K \leftrightarrow B_{s,d}$ absent

New sources of CP violation in B_s, B_d but

$S_{\psi K_s} \leftrightarrow S_{\psi\varphi}$ anticorrelated

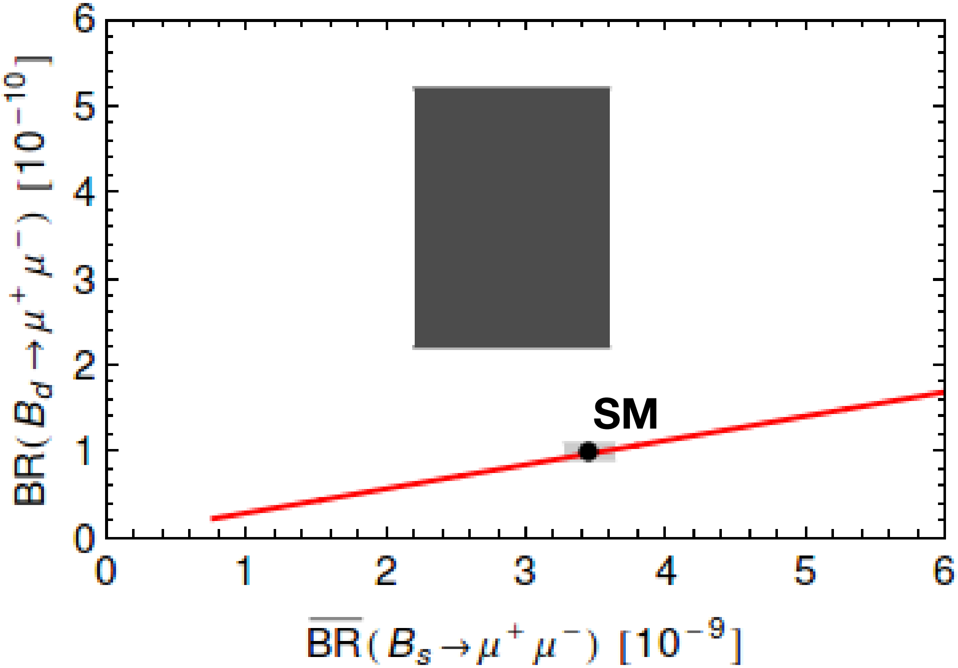
Right-handed currents strongly suppressed

Constrained Minimal Flavour Violation

$[U(3)]^3$ flavour symmetry

Valid also in $U(2)^3$

AJB
Hurth, Isidori, Kamenik, Mescia



Golden Relation

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

AJB 2003

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

No CKM
No weak decay constants

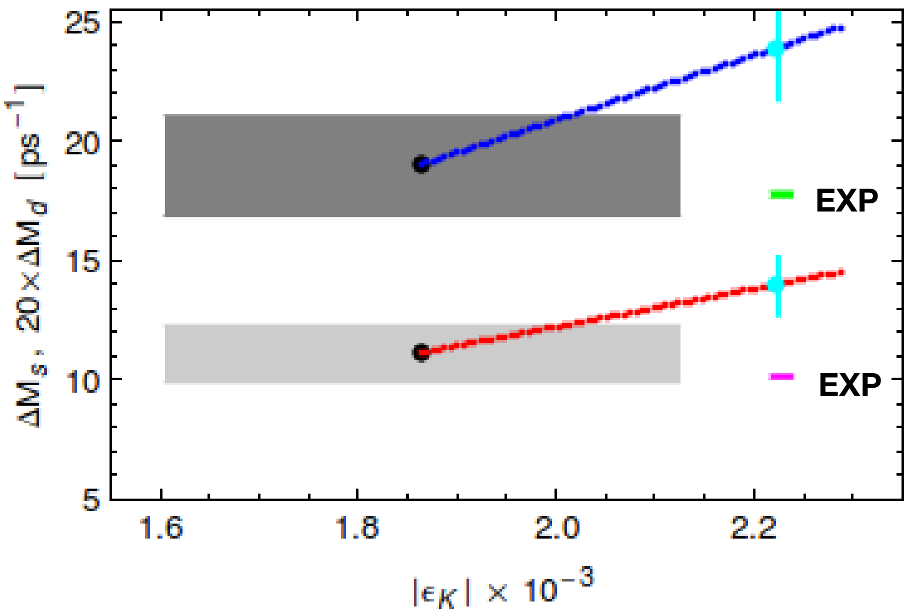
$$\overline{\mathrm{Br}}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \cdot 10^{-9}$$

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

(LHCb + CMS)

2 Tensions in $\Delta F=2$ within MFV

$\varepsilon_K \leftrightarrow \Delta M_{s,d}$



AJB + Girrbach 1306.3755

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

$\varepsilon_K \leftrightarrow S_{\psi K_s}$

$$\left\{|V_{ub}|_{excl}\right\} \Rightarrow \left\{\begin{matrix} \varepsilon_K^{SM} < \varepsilon_K^{exp} \\ S_{\psi K_s}^{SM} \approx S_{\psi K_s}^{exp} \end{matrix}\right\}^{*)} \quad (2\sigma)$$

$$\left\{|V_{ub}|_{incl}\right\} \Rightarrow \left\{\begin{matrix} \varepsilon_K^{SM} \approx \varepsilon_K^{exp} \\ S_{\psi K_s}^{SM} > S_{\psi K_s}^{Data} \end{matrix}\right\} \quad (3\sigma)$$

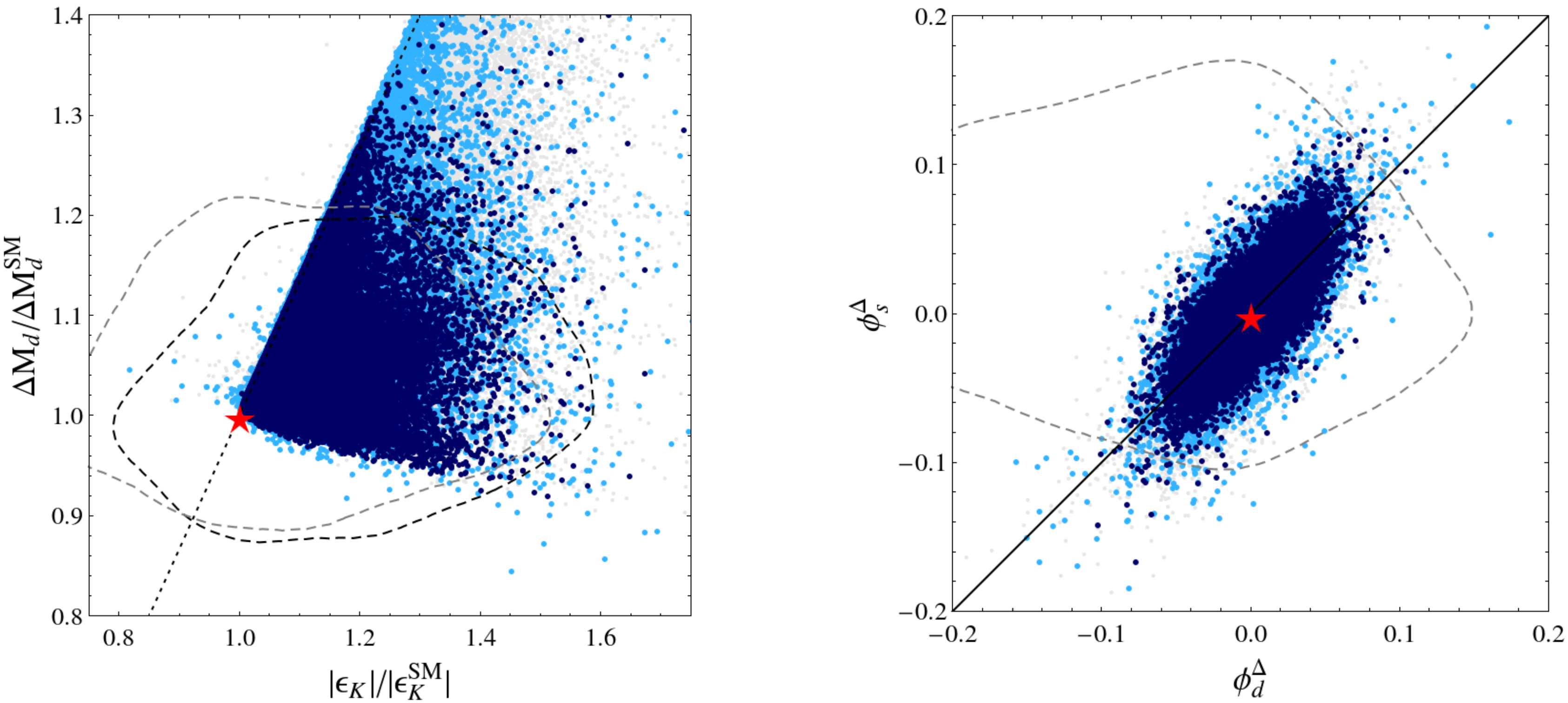
Lunghi + Soni (2008)
AJB + Guadagnoli (2008)

*) **Can still work within MFV ($\Delta\varepsilon_K > 0$ in MFV) Blanke + AJB (2006)**

Both tensions can only be clarified through improved $|V_{ub}|$, $|V_{cb}|$ + Lattice Input and improved measurement of $S_{\psi K_s}$

ΔF=2 Observables in Split-Family or "Natural" SUSY with U(2)³ Flavour Symmetry

Barbieri, Buttazzo, Sala, Straub (2014)



$\varepsilon_K \leftrightarrow S_{\psi K_s}$

$\varepsilon_K \leftrightarrow \Delta M_{s,d}$

Tensions removed

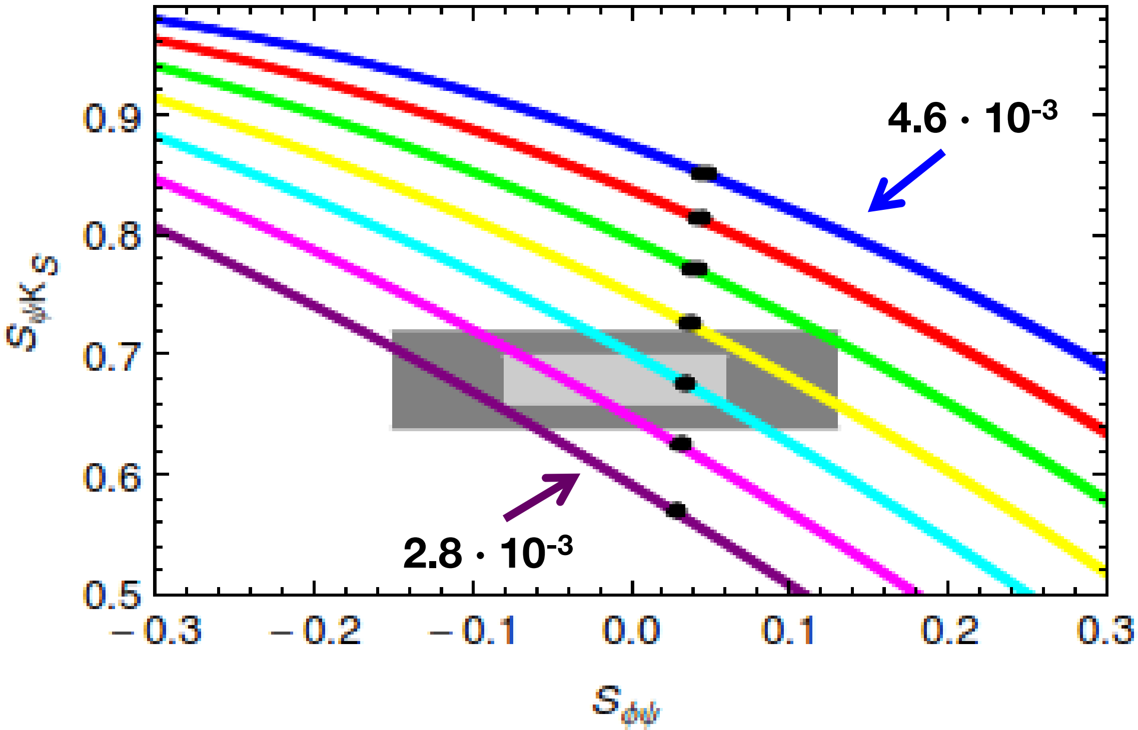
$$S_{\psi K_s} = \sin(2\beta + \varphi_d^\Delta)$$
$$S_{\psi\varphi} = \sin(2|\beta_s| - \varphi_s^\Delta)$$

$$\varphi_d^\Delta = \varphi_s^\Delta$$

AJB
Girrbach
(1206.3878)

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

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



Assuming absence of RH currents

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

L and R Quark Couplings in Tree Level FCNCs

$\Delta F=2$ — **Cannot distinguish between L and R** (square)

$$\varepsilon_K,\ \Delta M_{s,d} \sim a g_L^2 + a g_R^2 + c g_L g_R$$

$|c| \gg |a|$
Hadronic matrix elements + RG

K: $c \sim 150\, a$ $B_{s,d}$: $c \sim 7\, a$

$\Delta F=1$ — **Can distinguish between L and R**

$L \to R$

A Decays governed by V-quark couplings (γ_μ) : $K^+ \to \pi^+ \nu\bar{\nu},\ K_L \to \pi^0 \nu\bar{\nu},\ B \to K \nu\bar{\nu}$ — No sign flip in NP contribution

B Decays governed by A-quark couplings ($\gamma_\mu \gamma_5$) : $K_L \to \mu^+\mu^-,\ B_{s,d} \to \mu^+\mu^-,\ B \to K^* \nu\bar{\nu}$ — Sign flip in NP contribution

$L \to R$ ⇒ Correlations $A \leftrightarrow B$ change to Anticorrelations $A \leftrightarrow B$

DNA - Charts

1306.3755

AJB + Girrbach

- SM-like

- suppression relative to SM

- enhancement relative to SM

correlation

anti-correlation

DNA - Charts

1306.3755

AJB + Girrbach

- SM-like

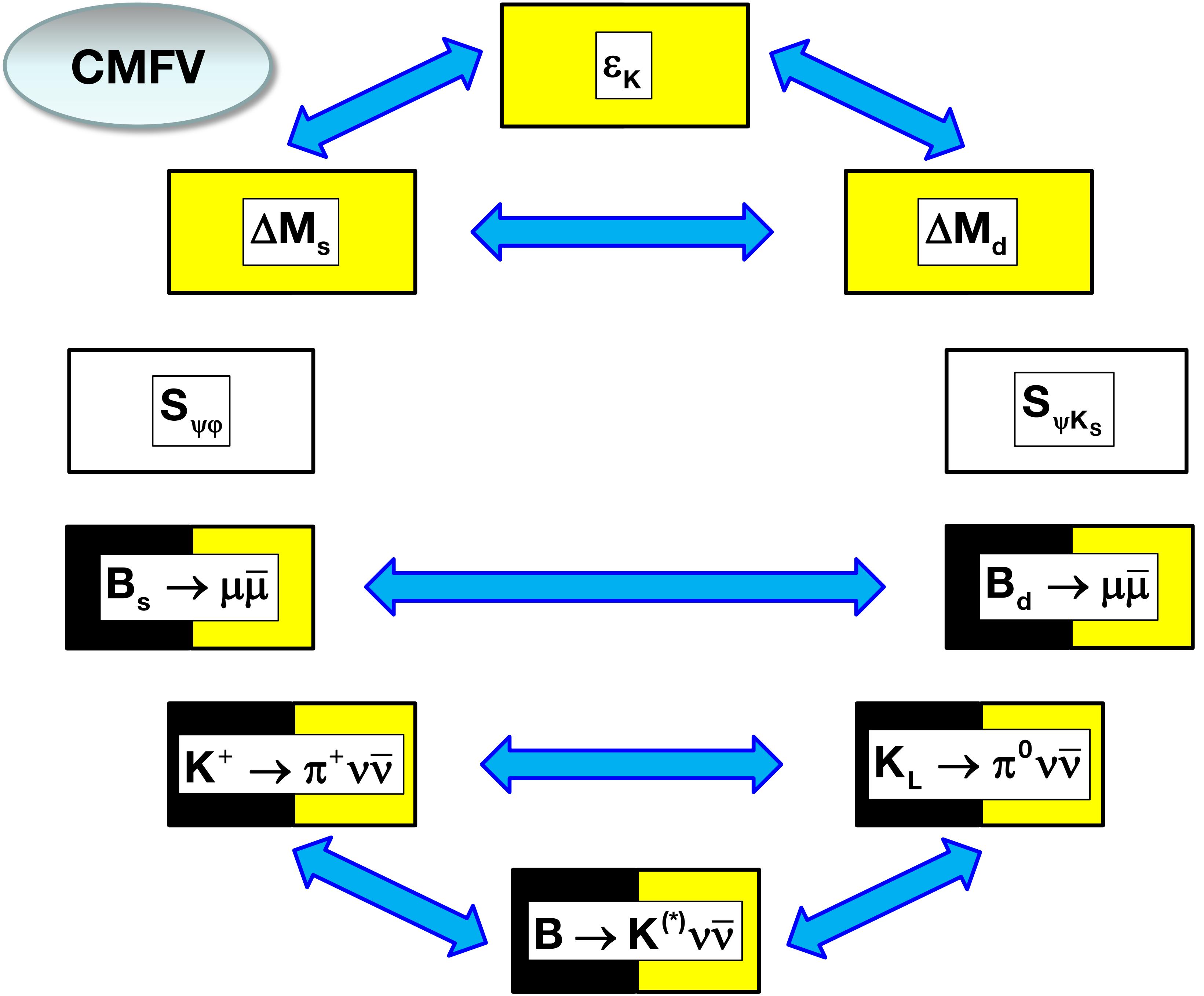
- suppression relative to SM

- enhancement relative to SM

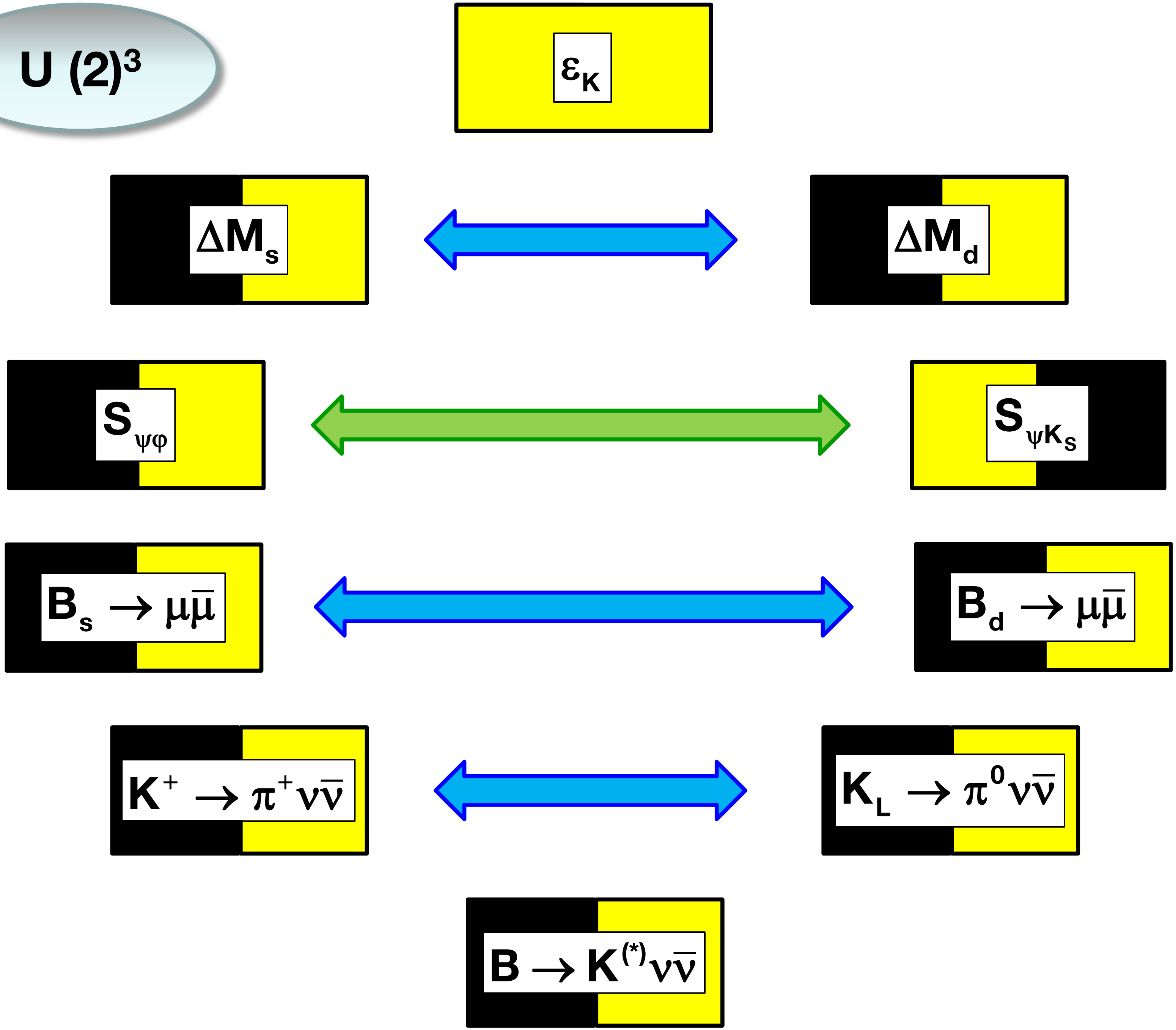
correlation

anti-correlation

Searching for New Physics on the Way to Zeptouniverse


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

$U(2)^3$


ε_K
ΔM_s
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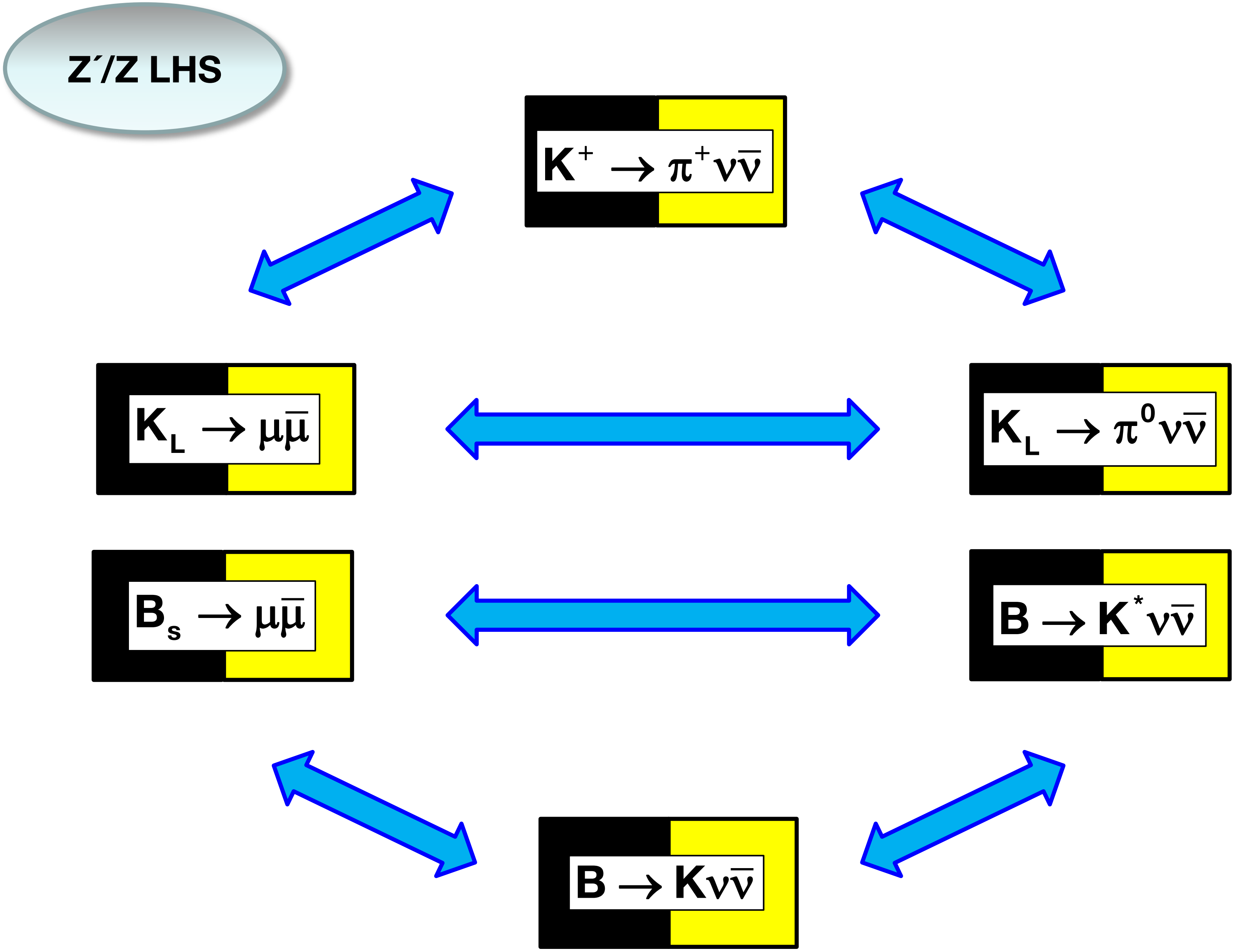
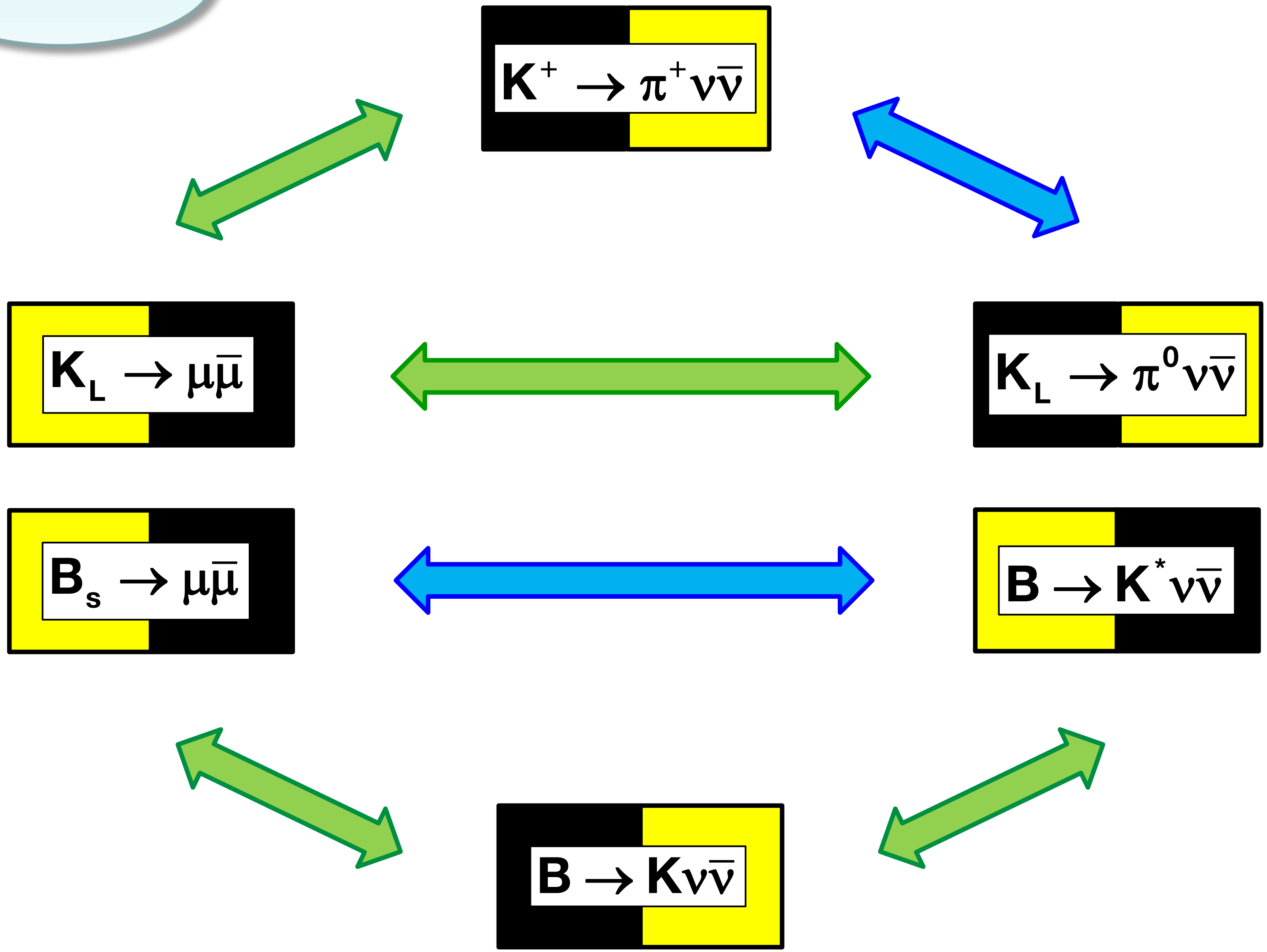

Z′/Z LHS
$K^+ \to \pi^+ \nu\bar{\nu}$
$K_L \to \mu\bar{\mu}$
$K_L \to \pi^0 \nu\bar{\nu}$
$B_s \to \mu\bar{\mu}$
$B \to K^* \nu\bar{\nu}$
$B \to K \nu\bar{\nu}$

Z′/Z RHS



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

3 Correlated Anomalies

(LHCb)

$$R_{K\mu\mu} = \frac{Br\left(B^+ \to K^+\mu^+\mu^-\right)^{[15,22]}}{Br\left(B^+ \to K^+\mu^+\mu^-\right)^{[15,22]}_{SM}} < 1$$

$$R_{K^*\mu\mu} = \frac{Br\left(B^0 \to K^{*0}\mu^+\mu^-\right)^{[15,22]}}{Br\left(B^0 \to K^{*0}\mu^+\mu^-\right)^{[15,22]}_{SM}} < 1$$

$$R_{\mu\mu} = \frac{Br\left(B_s \to \mu^+\mu^-\right)}{Br\left(B_s \to \mu^+\mu^-\right)_{SM}} < 1$$

Can be reproduced by Z or Z´ with left-handed FCNC couplings.

$$\boxed{C_9^{NP} \approx -C_{10}^{NP}}$$

(V) (A) $\mu^+\mu^-$

$R_{K^*(K)} \equiv R_{K^*(K)\nu\bar{\nu}}$

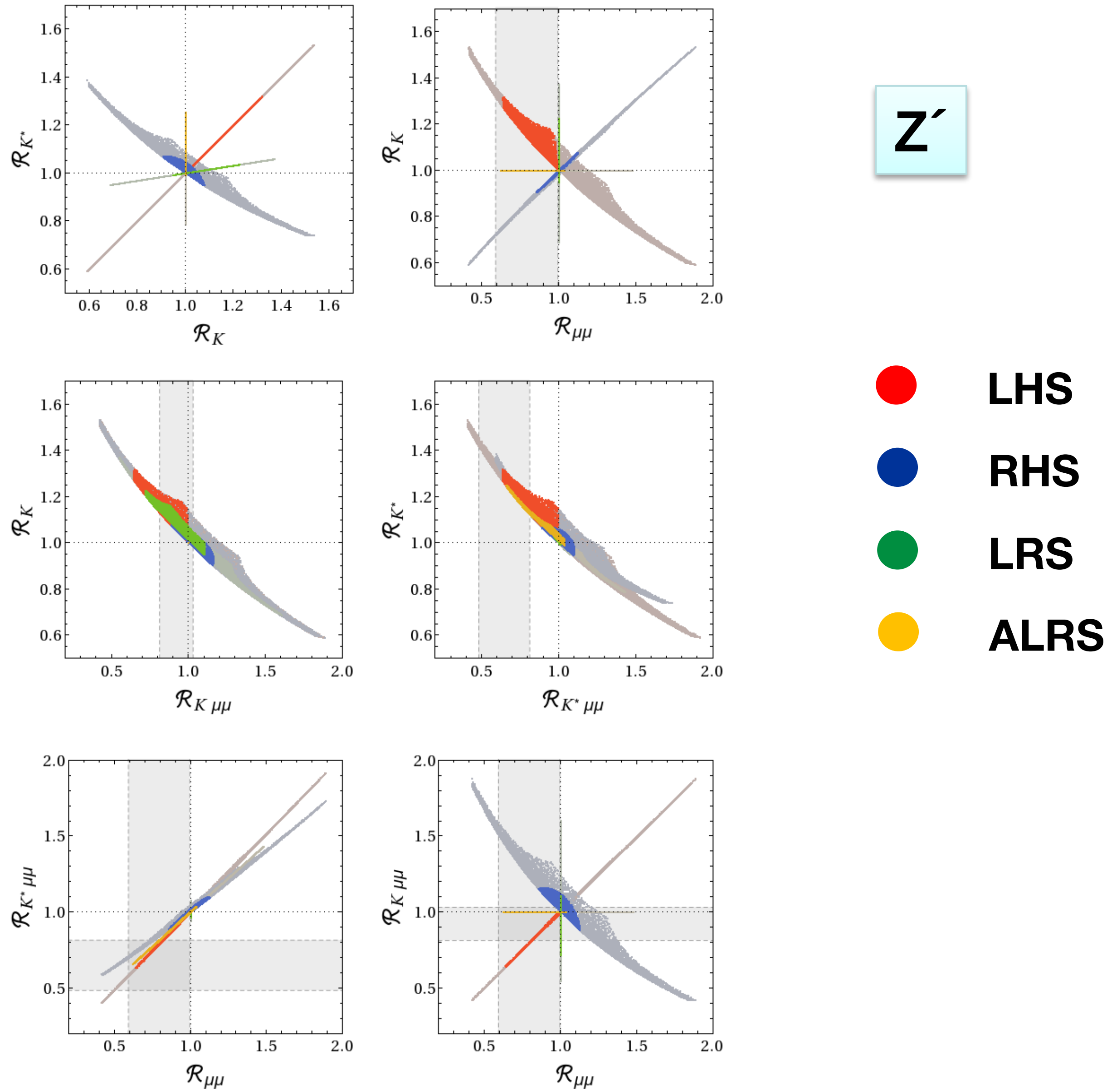
can distinguish between Z and Z´ solution

 Schwarzwald2014

$B \to K(K^*)\nu\bar{\nu}$, $B \to \mu^+\mu^-$, $B \to K(K^*)l^+l^-$

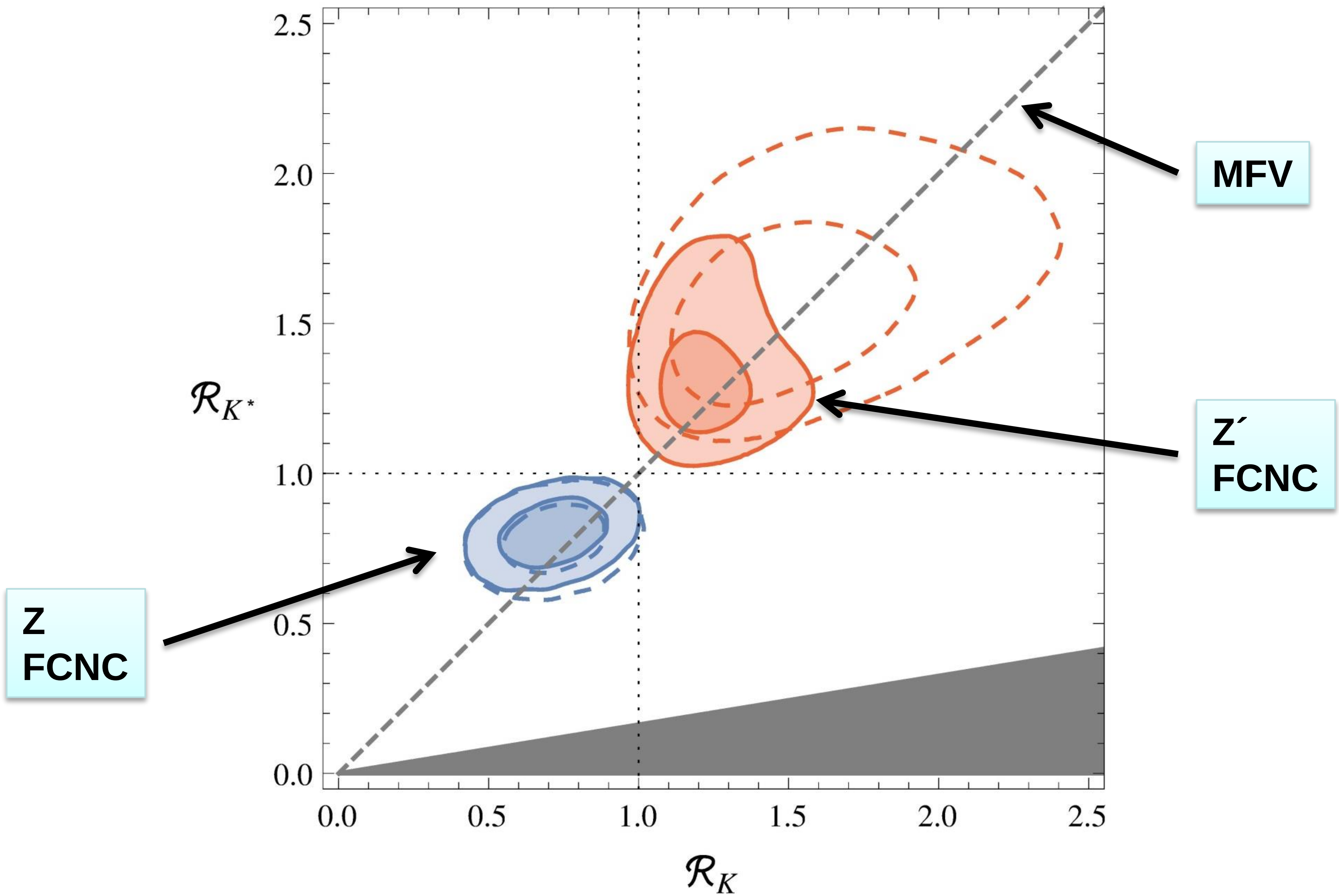
AJB
Girrbach-Noe
Niehoff
Straub

1409.4557



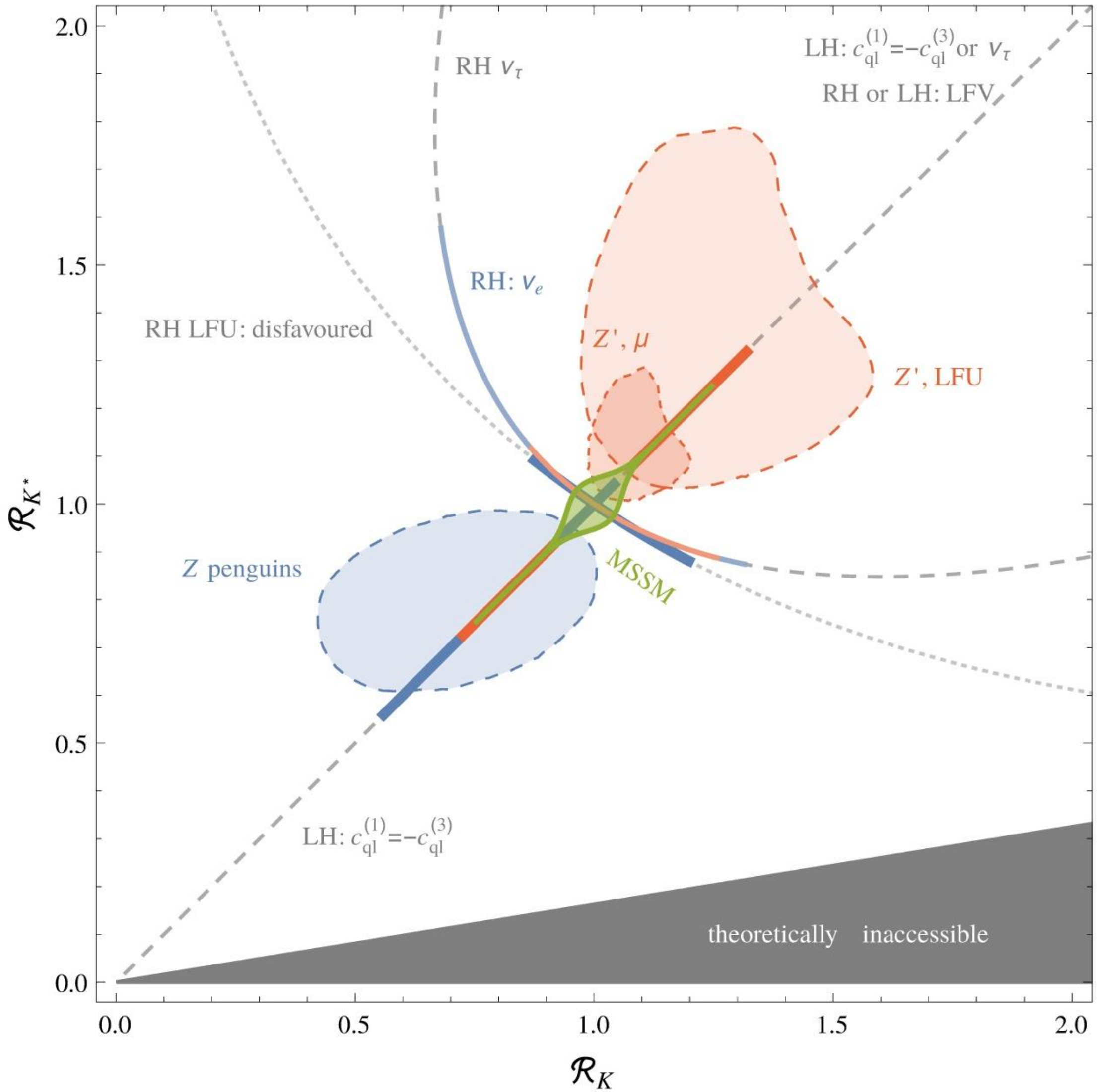
$B \to K(K^*)\nu\bar{\nu}$

BGNS 1409.4557



$B \to K(K^*)\nu\bar{\nu}$

BGNS 1409.4557



Can we reach Zeptouniverse through Quark Flavour Physics ?

AJB, Buttazzo, Girrbach-Noe, Knegjens, 1407.0728

Due to limits of theory and experiment the answer depends on whether Zeptouniverse is “populated“ by

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AJB, Buttazzo, Girrbach-Noe, Knegjens, 1407.0728

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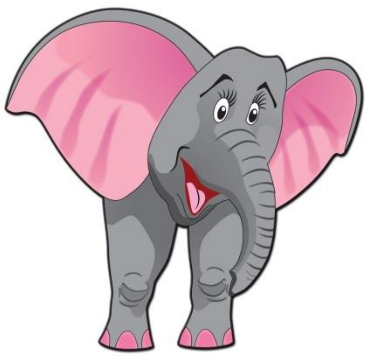

In QFT :

Large couplings

(still consistent with perturbativity)

Can we reach Zeptouniverse through Quark Flavour Physics ?

AJB, Buttazzo, Girrbach-Noe, Knegjens, 1407.0728

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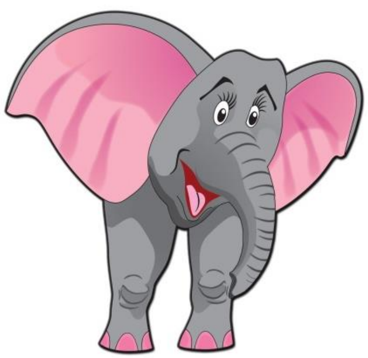

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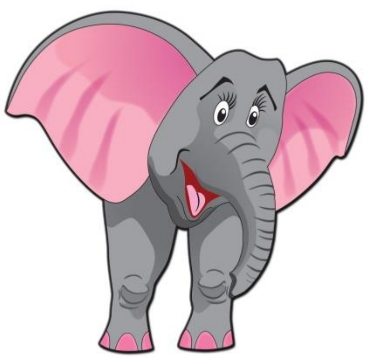
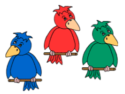




In QFT :

Large couplings

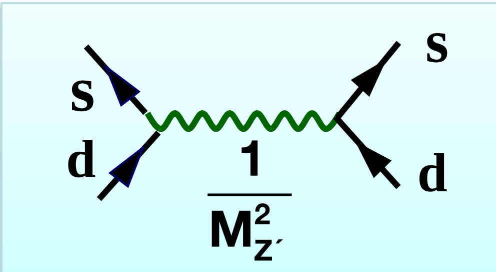
(still consistent with perturbativity)

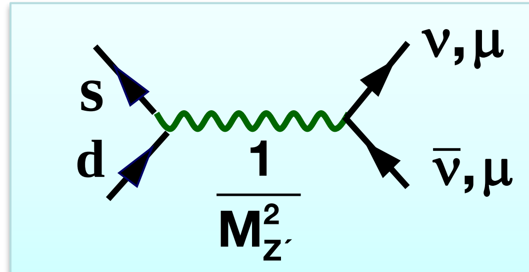
Moderate couplings

Small couplings

Answer within Z´-Models

(Stringent correlations between $\Delta F=2$ and $\Delta F=1$)





Similar for B_s,B_d,D,…

For fixed lepton couplings, after $\Delta F=2$ constraints, NP effects in rare decays decrease as $1/M_{Z'}$

Strategy:

Assume largest g_{ij} and $g_{\nu\nu}$, $g_{\mu\mu}$ couplings subject to $\Delta F=2$ constraints on g_{sd} ,g_{sb} ,g_{db}

$g_{ij} \approx 3$ still allowed by perturbativity but often not by $\Delta F=2$ constraints.

NP effects should still be sufficiently large to be able to see correlations.

Main Messages from this Study

(Maximal Resolution of Short Distance Scales)

1

If only g_L or g_R flavour changing Z´ couplings to quarks present and $\Delta F=2$ constraints taken into account:

$K_L \to \pi\nu\bar{\nu}$ ~ 200 TeV

B_d physics: ~ 15 TeV

B_s physics: ~ 15 TeV

Maximal scales that can be explored

2

If $g_L = \pm g_R$ the scales are lower:
LR operator in $\Delta F=2$ enhanced through RG + chiral enhancement in ΔM_K, ε_K

→ Smaller couplings

→ Lower scales at which NP dynamics can be tested

3

In order to probe scales above 50 TeV even with B_s, B_d physics we need either left-handed or right-handed elefants:

$g_L \neq g_R$ $g_R \neq 0$ $g_L \neq 0$

but $g_L \gg g_R$ or $g_R \gg g_L$

Allows us to obtain significant NP effects in rare K, $B_{s,d}$ decays while satisfying $\Delta F=2$ constraints

Important: Cannot be distinguished through $\Delta F=2$ observables

(Help from LR operators with some fine-tuning)

But: Can be distinguished through correlations in rare K and B decays

(See DNA Charts)

Can we reach Zeptouniverse through Quark Flavour Physics ?

(Z′)

AJB, Buttazzo, Girrbach-Noe, Knegjens, 1407.0728

If only left-handed or only right-handed couplings present in NP : Only with K rare Decays $B_s \sim 15$ TeV, $B_d \sim 15$ TeV

If both LH and RH present but $g_L^{ij} << g_R^{ij}$ or $g_L^{ij} >> g_R^{ij}$:

$K \to \pi\nu\bar{\nu}$: $\Lambda_{NP}^{max} \simeq 2000$ TeV

B_d : $\Lambda_{NP}^{max} \simeq 160$ TeV

B_s : $\Lambda_{NP}^{max} \simeq 160$ TeV

Can we reach Zeptouniverse through Quark Flavour Physics ?

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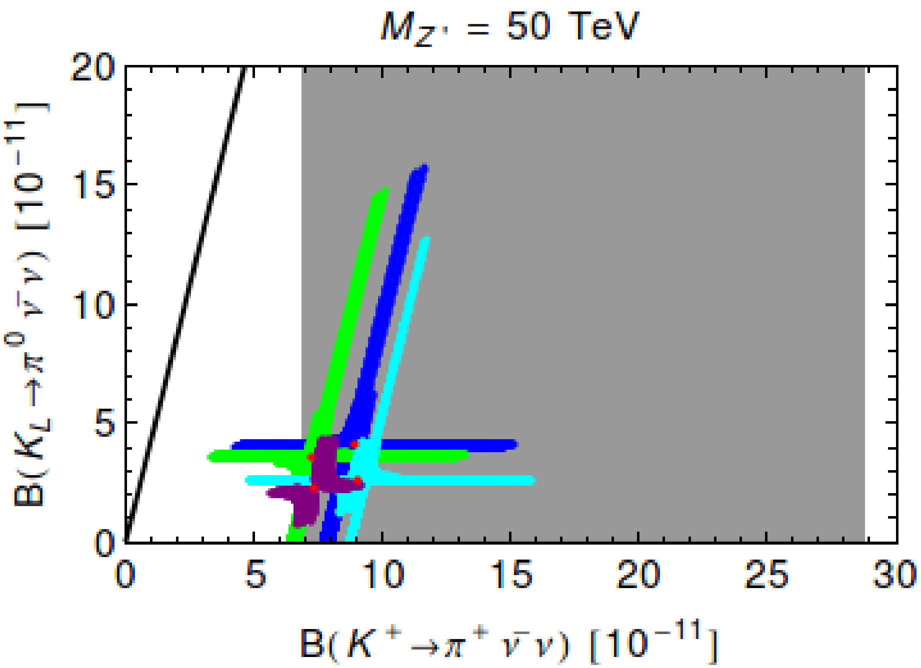
$$B_d : \ \Lambda_{NP}^{max} \simeq 160 \text{ TeV}$$

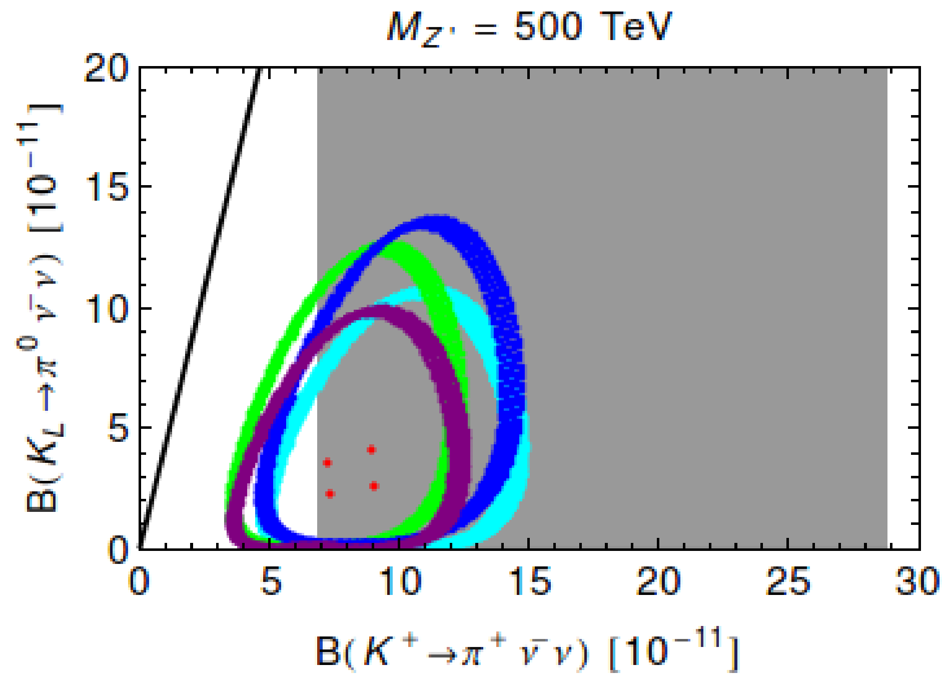
$$B_s : \ \Lambda_{NP}^{max} \simeq 160 \text{ TeV}$$

Yes we can !!

Heavy Z´ at Work

AJB, Buttazzo, Girrbach-Noe, Knegjens, 1407.0728



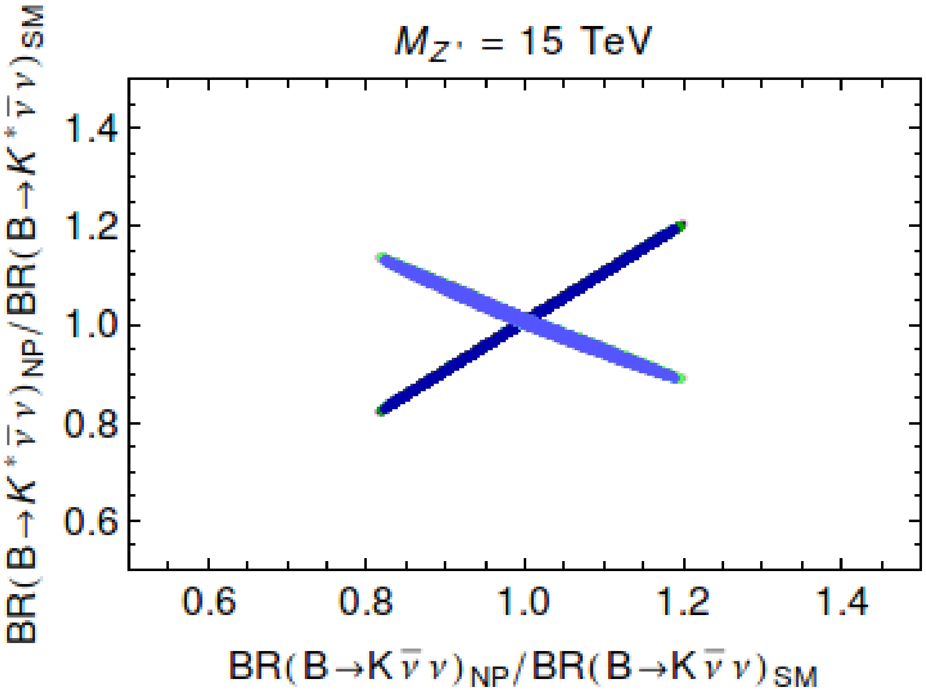


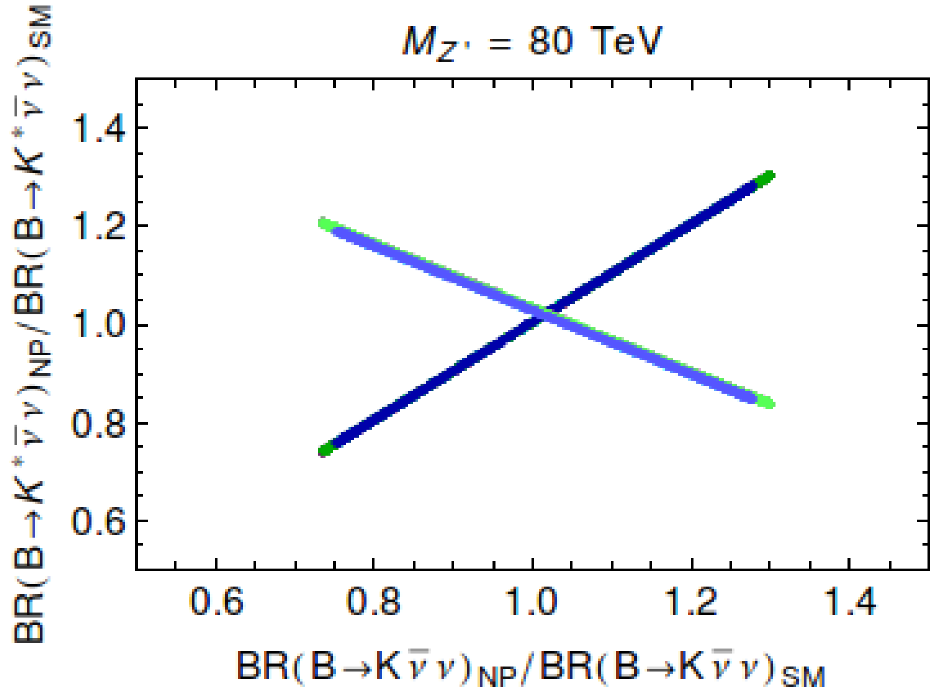
ε_K constraint

General discussion:
Blanke 0904.2528

No ε_K constraint

Heavy Z´ at Work

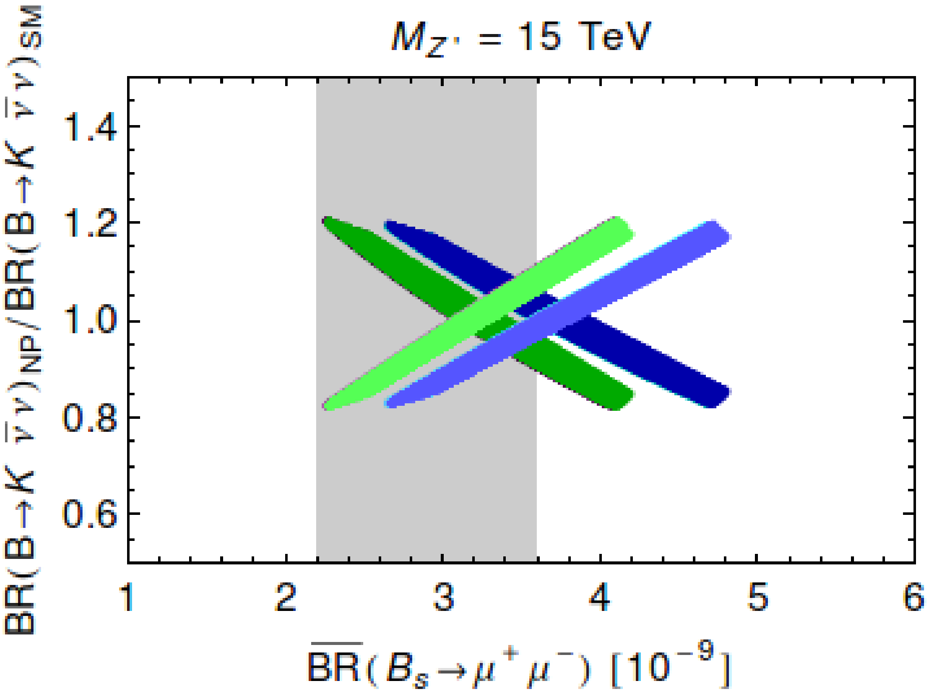


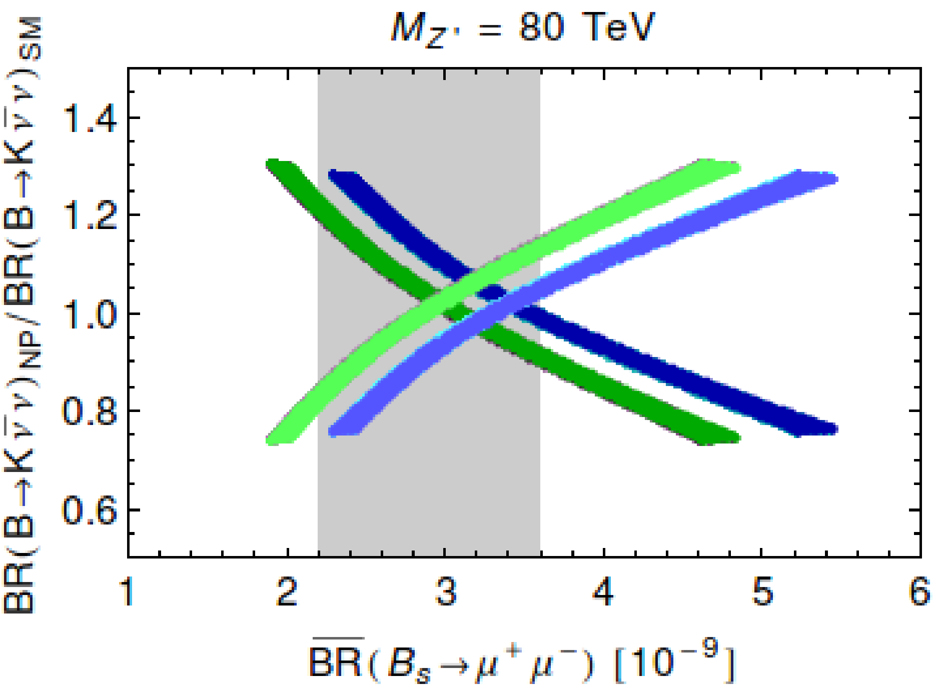


ΔF=2 constraint

No ΔF=2 constraint

Heavy Z´ at Work





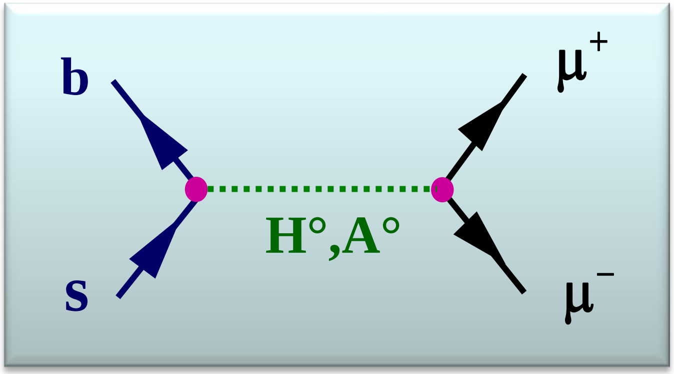
ΔF=2 constraint

No ΔF=2 constraint

Can we reach Zeptouniverse through S and P

AJB, Buttazzo, Girrbach-Noe, Knegjens, 1407.0728

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



S : ≈ 350 TeV

P : ≈ 700 TeV

Pseudoscalars more powerful than scalars because of the interference with SM contribution

Similar to $K \to \pi\nu\bar{\nu}$ (Z′): No fine-tuning neccessary to reach Zeptouniverse

S=H°

P=A°

Finale: Vivace !

Finale: Vivace !

We are approaching a Happy End !!

Main Message

Rare K, B_s, B_d Decays will play crucial role in identifying New Physics hopefully present on the route

Attouniverse → Zeptouniverse

Coming Years : Flavour Precision Era

LHC Upgrade
E = 14 TeV
(CERN)

Precision
$B_{d,s}$ – Meson Decays
LHC
KEK (Japan)

$$K^+ \to \pi^+ \nu\bar{\nu} \quad (\sim 10^{-10})\ \text{(CERN)}$$
$$K_L \to \pi^0 \nu\tilde{\nu} \quad (\sim 3 \cdot 10^{-11})\ \text{J-PARC (Japan)}$$

Lepton Flavour Violation
$\mu \to e\gamma$
$\mu \to eee$

Electric Dipole Moments

Improved Lattice Gauge Theory Calculations

Neutrinos

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

Exciting Times are just ahead of us !!!

Towards Zeptouniverse In 12 Steps

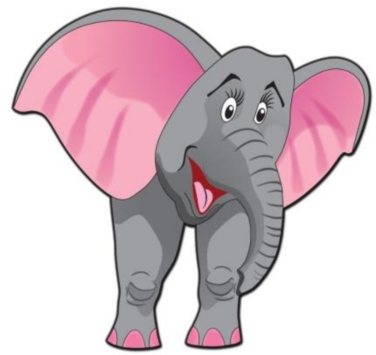
1. CKM from Trees
2. Lattice
3. $\Delta F=2$ Observables
4. $B_{s,d} \to \mu^+\mu^-$, $B_{s,d} \to \tau^+\tau^-$
5. $B^+ \to \tau^+\nu_\tau$
6. $B \to X_s\gamma$, $B \to K^*\gamma$
7. $B \to X_s l^+l^-$, $B \to K^*(K) l^+l^-$
8. $K \to \pi\nu\bar{\nu}$
9. $B \to X_s\nu\bar{\nu}$, $B \to K^*(K)\nu\bar{\nu}$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

A Zeptouniverse Vision

Seen only in

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

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

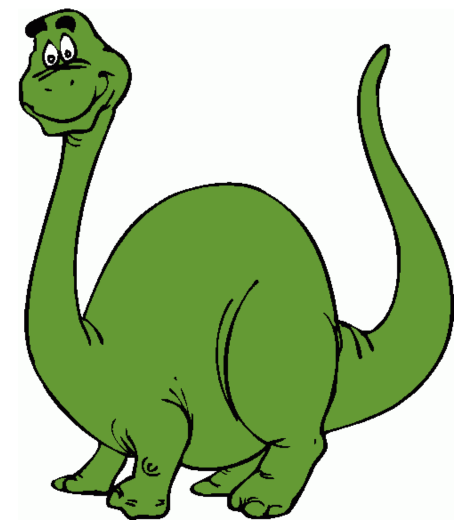


Seen in

Rare B_d

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

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



Seen in

Rare B_s

Rare B_d

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

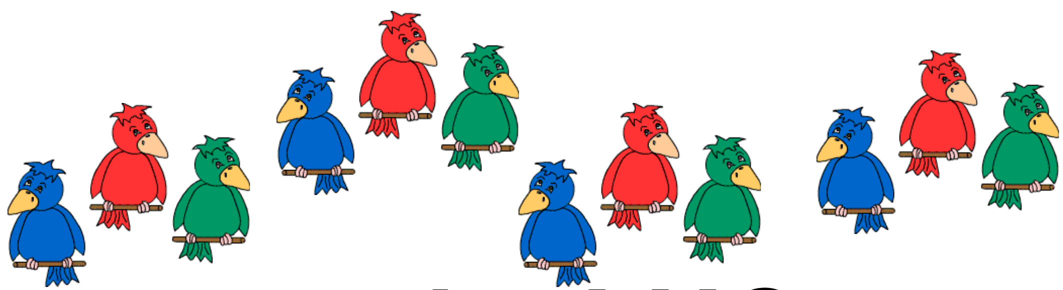
$B_{d,s} \to \mu^+\mu^-$

Final Message

Great hopes to
see many oases
on the way
Attouniverse → Zeptouniverse

Final Message

Great hopes to
see many oases
on the way
Attouniverse → Zeptouniverse
and



at the LHC

Backup

Relations between $\Delta M_{s,d}$ and $B_{s,d} \to \mu\bar{\mu}$ in Models with Minimal Flavour Violation

(AJB, hep-ph/0303060)

$$\Delta M_q \sim \hat{B}_q F_{B_q}^2 \left|V_{tq}\right|^2 S(x_t, x_{new})$$

$$Br(B_q \to \mu\bar{\mu}) \sim F_{B_q}^2 \left|V_{tq}\right|^2 Y^2(x_t, \bar{x}_{new})$$

Large hadronic uncertainties due to $F_{B_q}^2$

2003

$$F_{B_d}\sqrt{\hat{B}_d} = \left(235 \pm 33 \begin{matrix} +0 \\ -24 \end{matrix}\right) \mathrm{MeV} \qquad F_{B_d} = (189 \pm 27)\ \mathrm{MeV}$$

$$F_{B_s}\sqrt{\hat{B}_d} = (276 \pm 38)\ \mathrm{MeV} \qquad F_{B_s} = (230 \pm 30)\ \mathrm{MeV}$$

$$\hat{B}_d = 1.34 \pm 0.12$$

$$\hat{B}_s = 1.34 \pm 0.12 \qquad \frac{\hat{B}_s}{\hat{B}_d} = 1.00 \pm 0.03$$

(No problems with chiral logs and quenching)

Superstars of 2010 – 2015 (Flavour Physics)

$S_{\psi\varphi}$

$(B_s \to \varphi\varphi)$

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

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

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

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

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

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

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

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

Relations between $\Delta M_{s,d}$ and $B_{s,d} \to \mu\bar{\mu}$ in Models with Minimal Flavour Violation

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$$\Delta M_q \sim \hat{B}_q F_{B_q}^2 \left|V_{tq}\right|^2 S\left(x_t, x_{new}\right)$$

$$Br\left(B_q \to \mu\bar{\mu}\right) \sim F_{B_q}^2 \left|V_{tq}\right|^2 Y^2\left(x_t, \bar{x}_{new}\right)$$

Moderate hadronic uncertainties due to $F_{B_q}^2$

2010

$$F_{B_d}\sqrt{\hat{B}_d} = \left(216 \pm 15 \right) \text{MeV} \qquad F_{B_d} = (193 \pm 10)\ \text{MeV}$$

$$F_{B_s}\sqrt{\hat{B}_d} = \left(275 \pm 13\right) \text{MeV} \qquad F_{B_s} = (239 \pm 10)\ \text{MeV}$$

$$\hat{B}_d = 1.26 \pm 0.11$$

$$\hat{B}_s = 1.33 \pm 0.06 \qquad \frac{\hat{B}_s}{\hat{B}_d} = 0.95 \pm 0.03$$

(No problems with chiral logs and quenching)

Testing MFV through $B_{s,d} \to \mu\bar{\mu}$ and $\Delta M_{s,d}$

$$\boxed{\frac{Br(B_s \to \mu\bar{\mu})}{Br(B_d \to \mu\bar{\mu})} = \underbrace{\frac{\hat{B}_d}{\hat{B}_s}}_{(0.95\pm 0.03)} \underbrace{\frac{\tau(B_s)}{\tau(B_d)} \frac{\Delta M_s}{\Delta M_d}}_{\text{Experiment}}}$$

Valid in MFV models in which only SM operators relevant.

Violation of this relation would indicate the presence of new operators and generally of non-minimal flavour violation.

$Br\left(B_{s,d} \to \mu\bar{\mu}\right)$ from $\Delta M_{s,d}$

$$Br\left(B_q \to \mu\bar{\mu}\right) = 4.39\cdot 10^{-10}\,\frac{\tau\left(B_q\right)}{\hat{B}_q}\,\frac{Y^2\left(x_t,\bar{x}_{new}\right)}{S\left(x_t,x_{new}\right)}\,\Delta M_q$$

No dependence on $F^2_{B_q}$

SM:

$$Br\left(B_s \to \mu\bar{\mu}\right) = 3.2\cdot 10^{-9}\left[\frac{\tau\left(B_s\right)}{1.43\mathrm{ps}}\right]\left[\frac{1.33}{\hat{B}_s}\right]\left[\frac{\overline{m}_t\left(m_t\right)}{164\ \mathrm{GeV}}\right]^{1.6}\left[\frac{\Delta M_s}{17.8/\mathrm{ps}}\right]$$

$$Br\left(B_d \to \mu\bar{\mu}\right) = 1.0\cdot 10^{-10}\left[\frac{\tau\left(B_d\right)}{1.52\mathrm{ps}}\right]\left[\frac{1.26}{\hat{B}_d}\right]\left[\frac{\overline{m}_t\left(m_t\right)}{164\ \mathrm{GeV}}\right]^{1.6}\left[\frac{\Delta M_d}{0.51/\mathrm{ps}}\right]$$

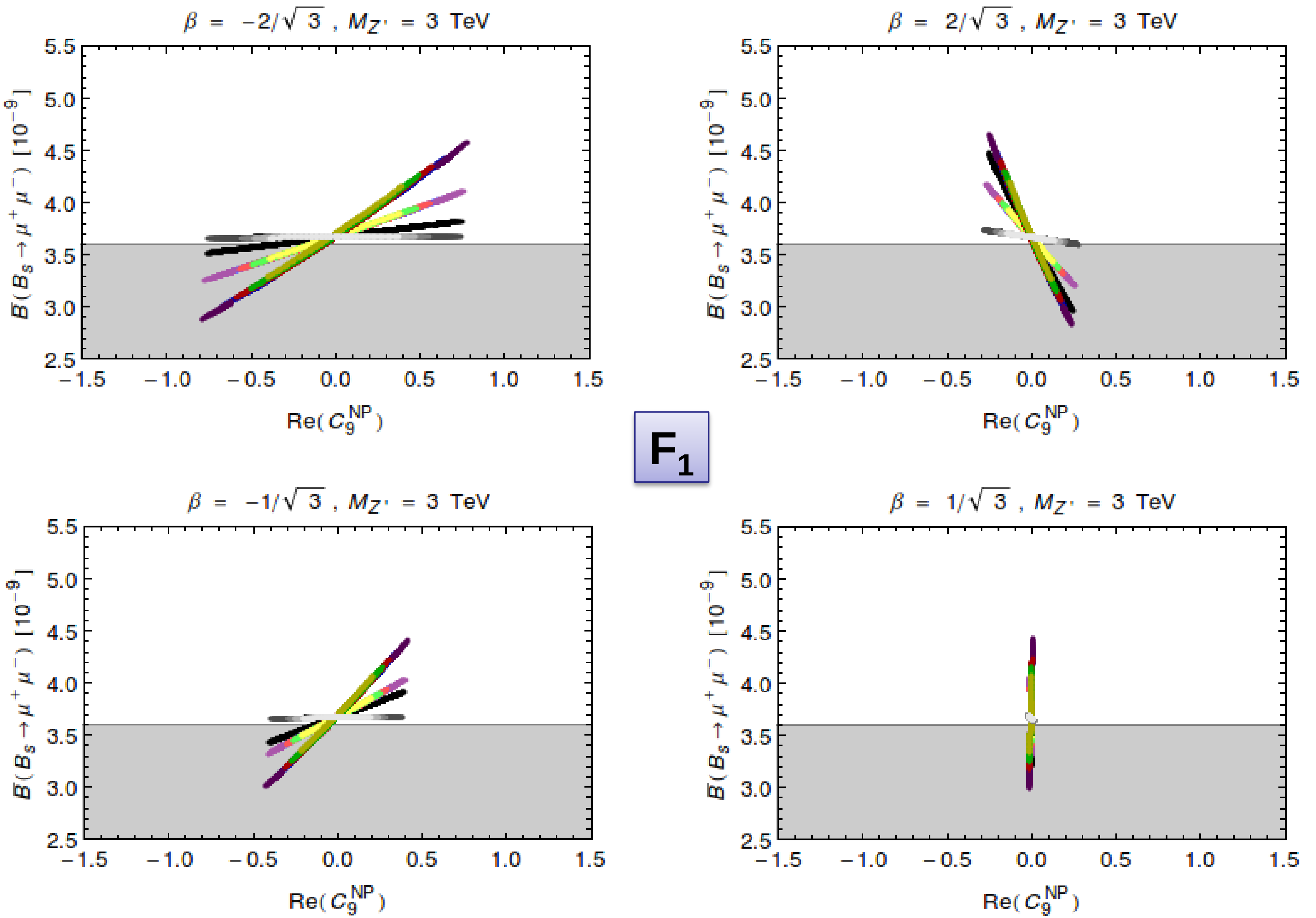
(Example)

$$\Delta M_s = \left(17.8 \pm 0.1/\mathrm{ps}\right) \Rightarrow Br\left(B_s \to \mu\bar{\mu}\right) = \left(3.2 \pm 0.2\right)\cdot 10^{-9}$$

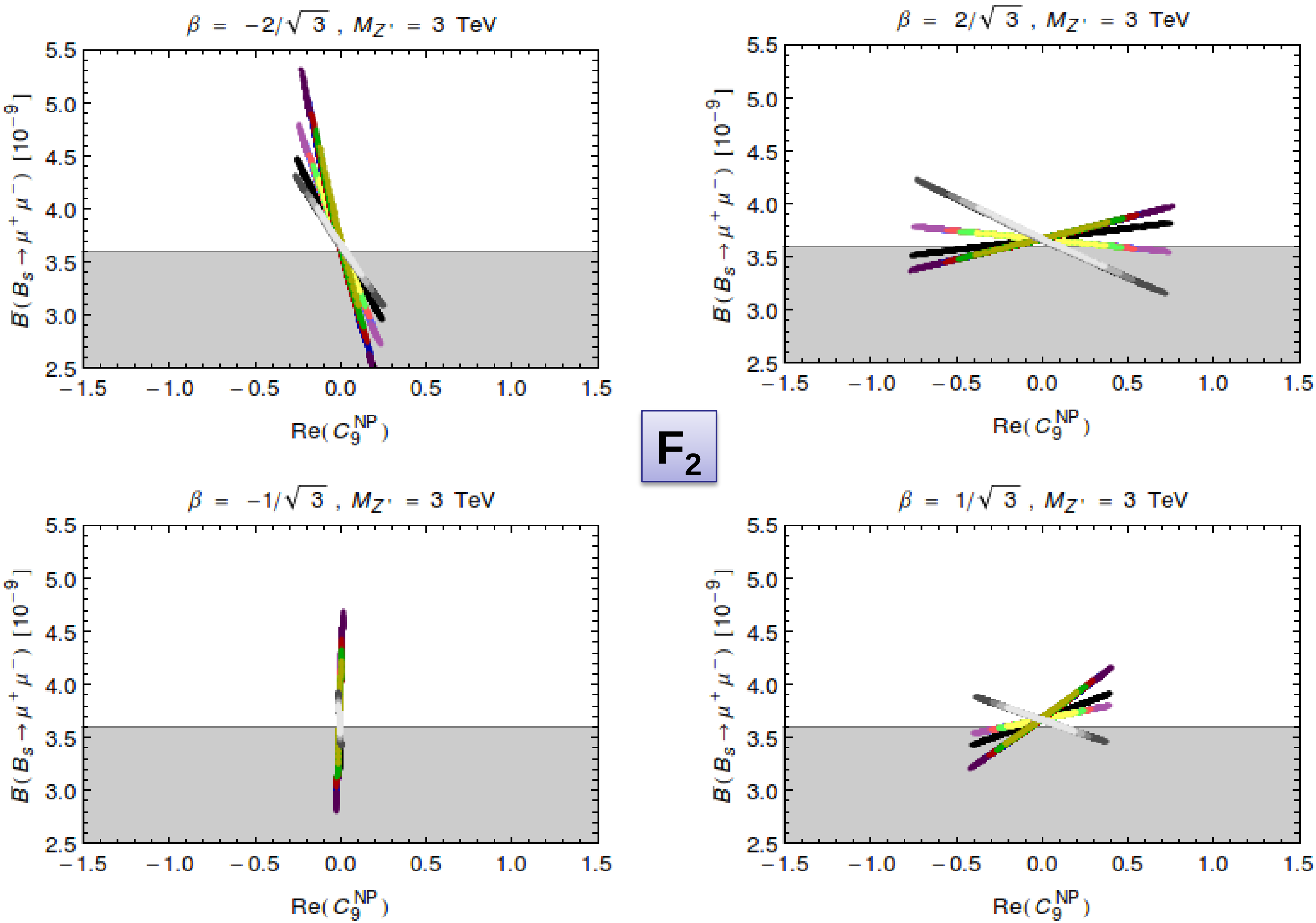
$$\Delta M_d = \left(0.507 \pm 0.006/\mathrm{ps}\right) \Rightarrow Br\left(B_d \to \mu\bar{\mu}\right) = \left(1.0 \pm 0.1\right)\cdot 10^{-10}$$

Moreover new Physics Effects can be easier seen

Correlations in 331 Models | 1405.3850

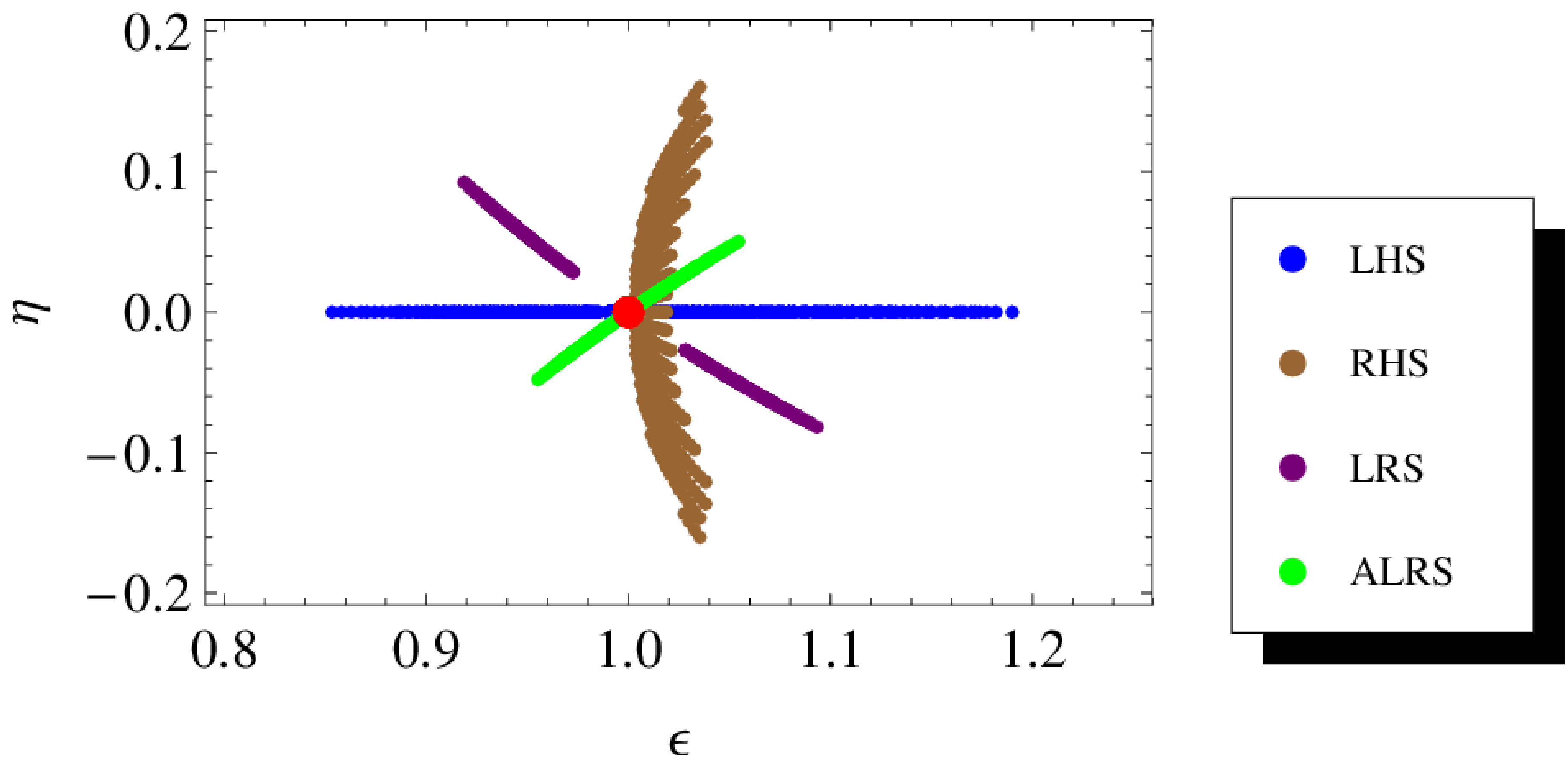


Correlations in 331 Models 1405.3850



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

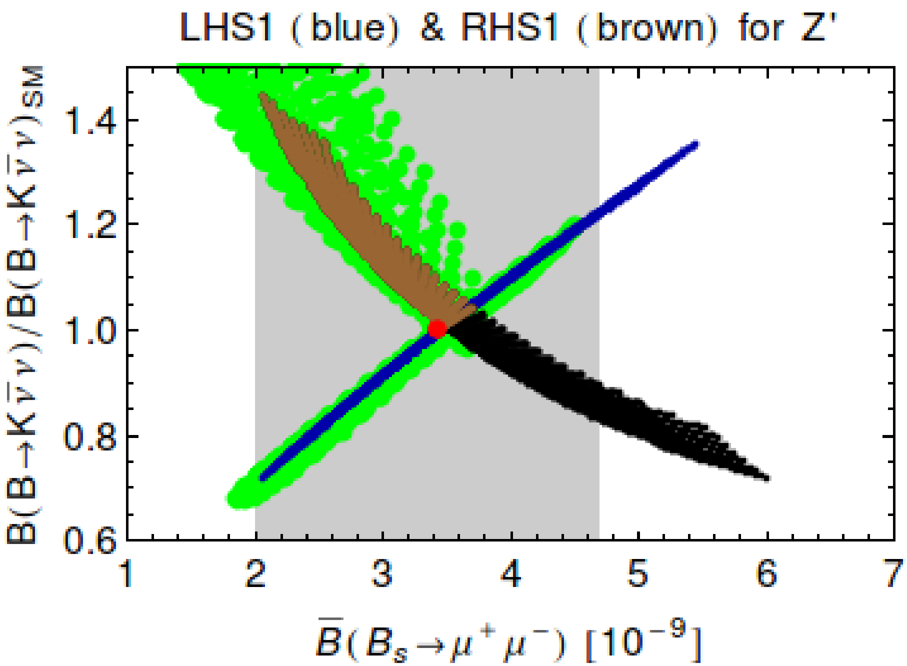
$B \to K^* \nu\bar{\nu}$ $B \to K\nu\bar{\nu}$ $B \to X_s\nu\bar{\nu}$ 1211.1896

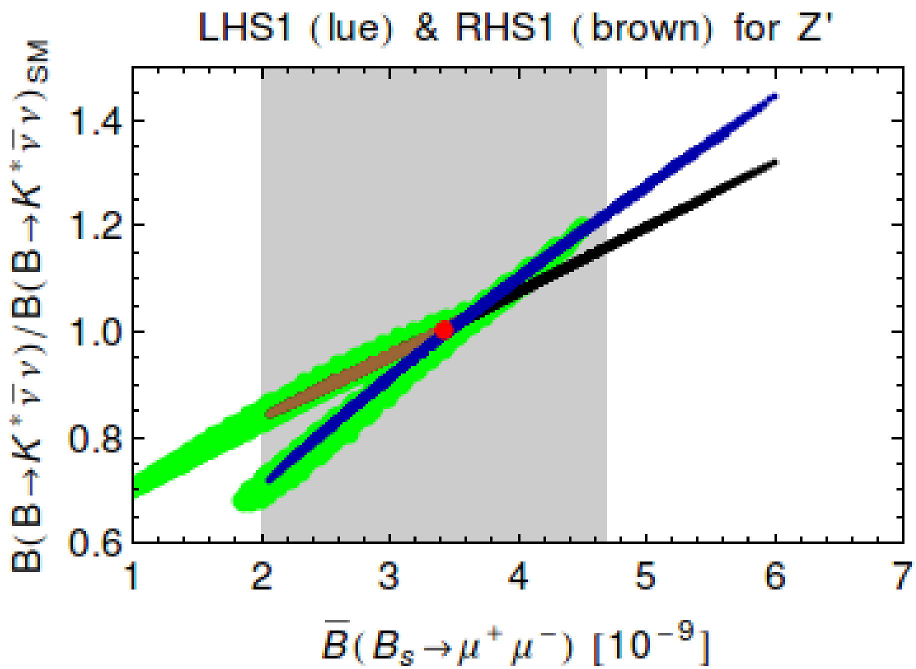


Powerful tests of right-handed currents

Altmannshofer, AJB, Straub, Wick 0902.0160

Distinguishing Left-Handed Currents from Right-Handed Currents





AJB, De Fazio, Girrbach
1211.1896

Altmannshofer et al.
0902.0160

: forbidden by $b \to sll$

: allowed by $b \to sll$

Two Versions of Effective Theories

Wilson Coefficients

Local operators

1.

$$L_{eff} = L_{SM} + \sum_i \frac{c_i}{\Lambda_i^2} Q_i$$

which results from integrating out heavy fields (c_i, Λ_i depend on parameters of a given theory)

<u>Very powerful framework</u> in flavour physics, RG, etc.

2.

ET $\equiv$

The coefficients c_i, Λ_i are free parameters. Completion unknown. Very limited framework in flavour physics except for cases when flavour symmetries and their breakdown are assumed: MFV $(U(3))^3$, $U(2)^3$,…