Minimal Flavour Violation and Beyond

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

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Lecture I

1. Grand View
2. TH Framework

Lecture II

3. Minimal Flavour Violation
4. Motivations for BSM and BMFV
5. Models for BMFV (SUSY, LHT, RS, 4G, 2HDM)

Lecture III

6. Patterns of Flavour Violations BSM
7. Outlook

1.

Grand View

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

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

$$\Downarrow$$

$$\underbrace{U(1)_{QED}}_{\text{Electroweak Interactions}}$$

Neutral Higgs

QCD
Strong Interactions
(Gluons)

Electroweak Interactions
$(W^{\pm}, Z^0, \gamma)$

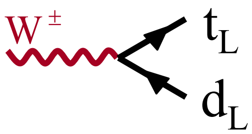
Mesons

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

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 }

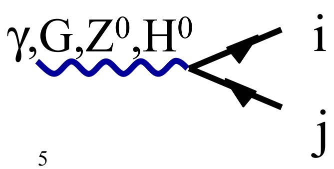
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{ub} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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

3. GIM Mechanism

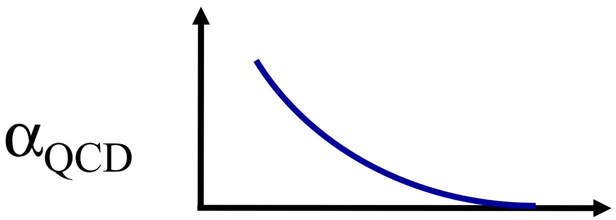
Natural suppression of FCNC

$$\left\{ \vphantom{\int} \right.$$

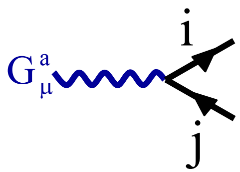


$= 0 \Big\} \Rightarrow \Big\{$ Loop Induced Decays, sensitive to short distance flavour dynamics $\Big\}$

4. Asymptotic Freedom



LD ⇦ RG ⇨ SD



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

Q

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

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

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

SD = Short Distances (Perturbation Theory)

⇧

RG = Renormalization Group Effects

⇩

LD = Long Distances (Non-Perturbative Physics)

~~CP~~

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

	d	s	b
u	$1-\frac{\lambda^2}{2}$	λ	V_{ub}
c	$-\lambda$	$1-\frac{\lambda^2}{2}$	V_{cb}
t	V_{td}	V_{ts}	1

$\lambda=0.22$

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

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

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

$(A=0.83\pm0.02)$

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

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

(AJB, Lautenbacher, Ostermaier, 94)

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

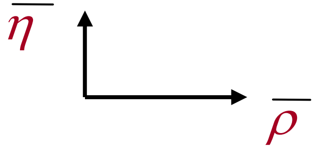
Circle around $(\bar{\rho},\bar{\eta}) = (0,0)$

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

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

Unitarity Triangle

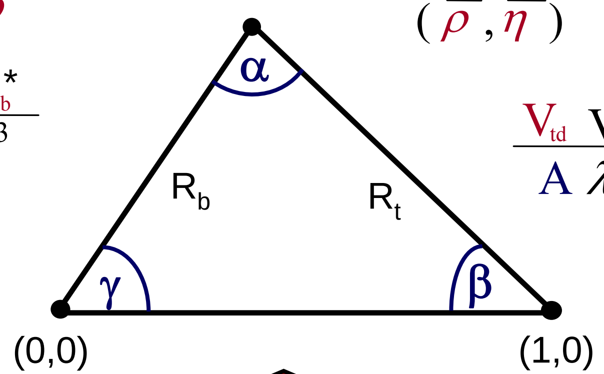
$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$



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

$(\bar{\rho}, \bar{\eta})$

$$\frac{V_{ud}V_{ub}^{*}}{A\lambda^{3}}$$

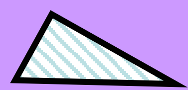


$$\frac{V_{td}V_{tb}^{*}}{A\lambda^{3}}$$

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

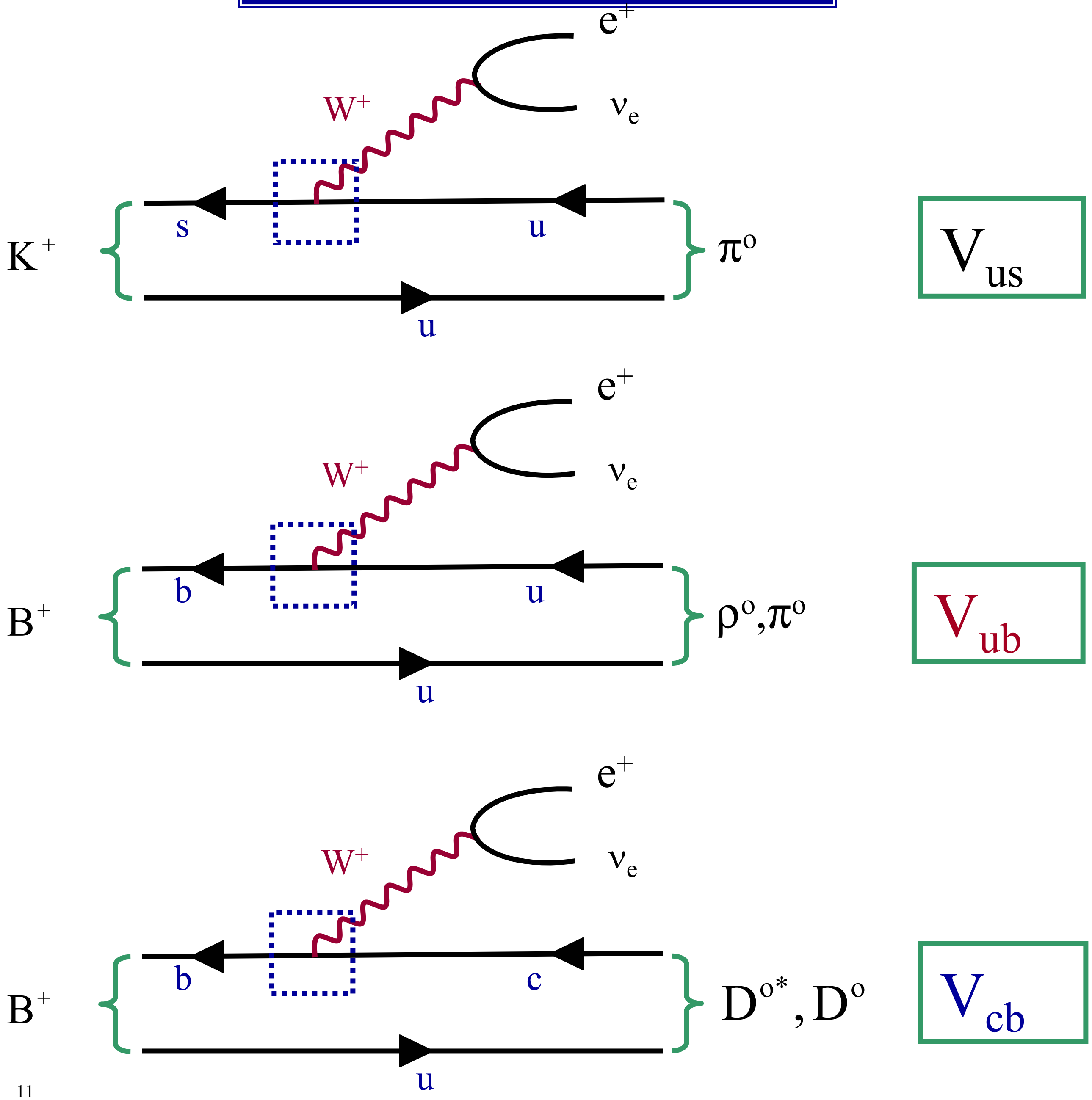
$$V_{td} = |V_{td}| e^{-i\beta}$$

An Important Target of Particle Physics

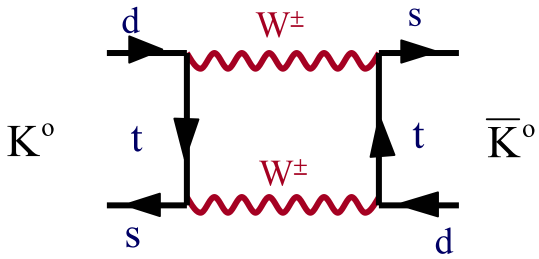
$$J_{CP} = \lambda^{2} |V_{cb}|^{2} \bar{\eta} = 2 \cdot$$ 

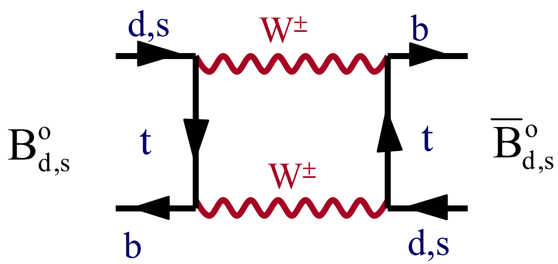
Area of unrescaled UT

Tree Level Decays



Loop Induced FCNC Processes





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

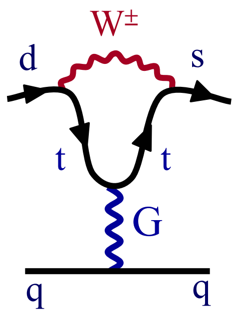
$B^o_d - \overline{B}^o_d$ Mixing

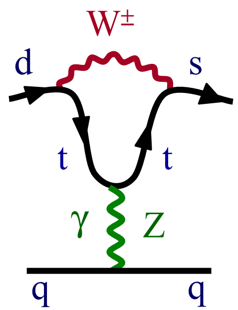
$B^0_s - \overline{B}^0_s$ Mixing

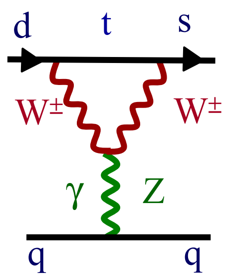
Discovered in 2006

(CDF, DØ)

ε'

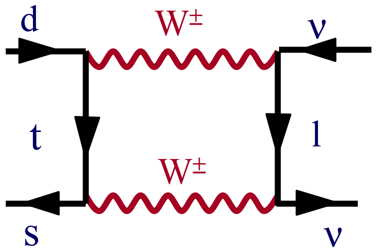


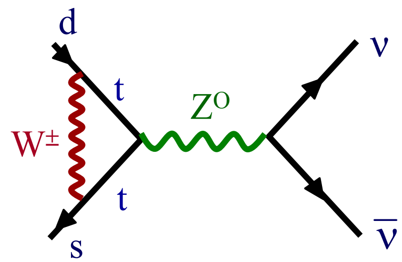


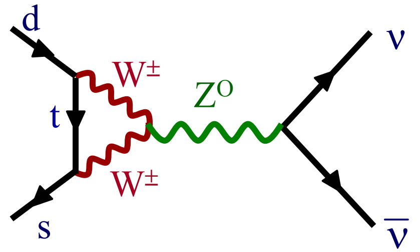


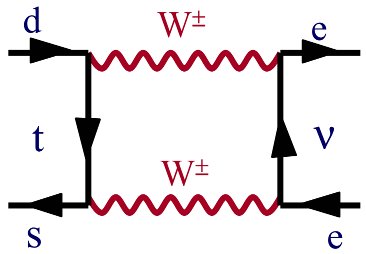
Loop Induced FCNC Processes

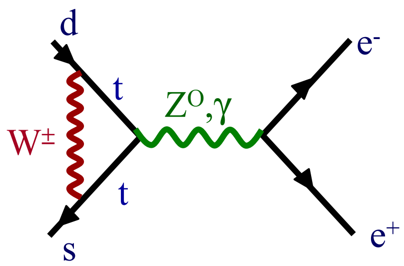
$\boxed{K^+ \to \pi^+ \nu\bar{\nu}}$, $K_L \to \pi^0 \nu\bar{\nu}$ $\boxed{K_L \to \mu\bar{\mu}}$, $B_{d,s} \to \mu\bar{\mu}$, $B \to X_S \nu\bar{\nu}$

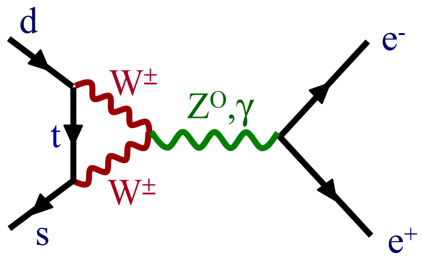




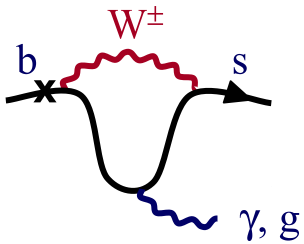








$K_L \to \pi^0 e^+ e^-$ $B \to X_S e^+ e^-$, $X_S \mu\bar{\mu}$



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

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

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

$$\left|V_{us}\right| = s_{12} = 0.2254 \pm 0.0008 \qquad \left|V_{ub}\right| = s_{13} = \left(3.9 \pm 0.4\right) \cdot 10^{-3}$$

$$\left|V_{cb}\right| = s_{23} = (41.2 \pm 1.1) \cdot 10^{-3} \qquad \delta_{CKM} = \gamma_{UT} = (75 \pm 15)^{o}$$

(-phase of V_{ub})

$$\left(\sin 2\beta\right)_{\psi K_s} = 0.672 \pm 0.023$$

(-phase of V_{td})

$$\Rightarrow \quad \beta = (21.1 \pm 0.9)^{o}$$

but could be subject to NP pollution

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

Hierarchical Structure of the CKM Matrix

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

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

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

$\Downarrow$

GIM Structure of FCNC´s

Large $\not{C}\not{P}$ effects in B_d

Small $\not{C}\not{P}$ effects in B_s

Tiny $\not{C}\not{P}$ effects in K_L

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

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

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

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

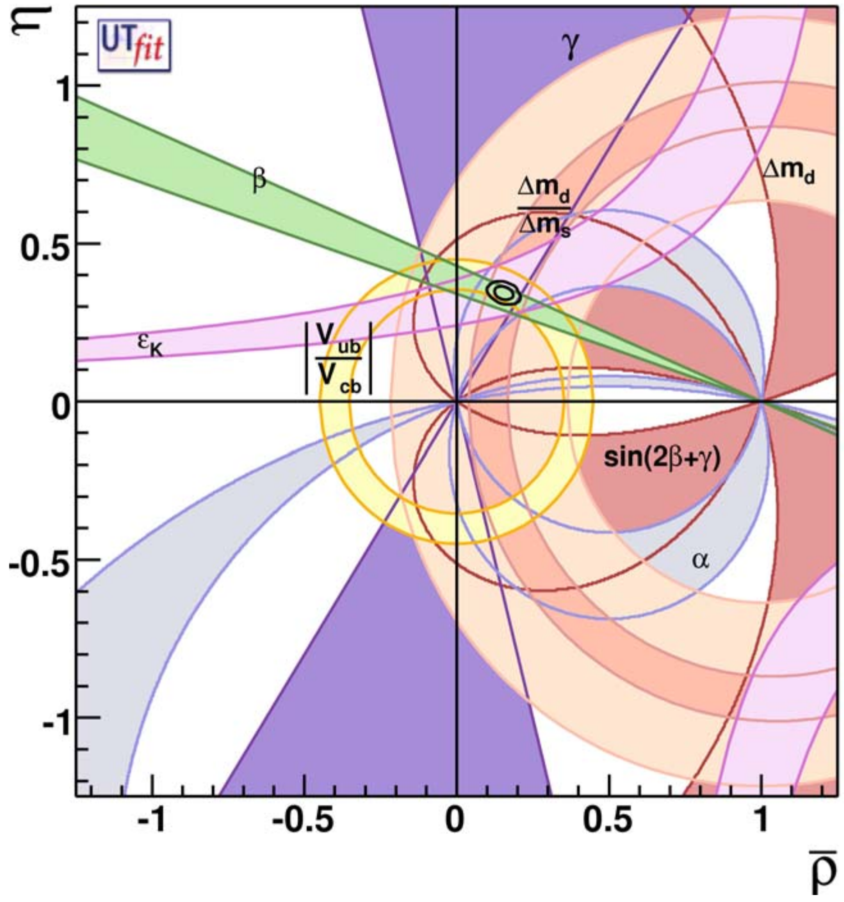
PMNS: Negligible LFV

(tiny ν masses)

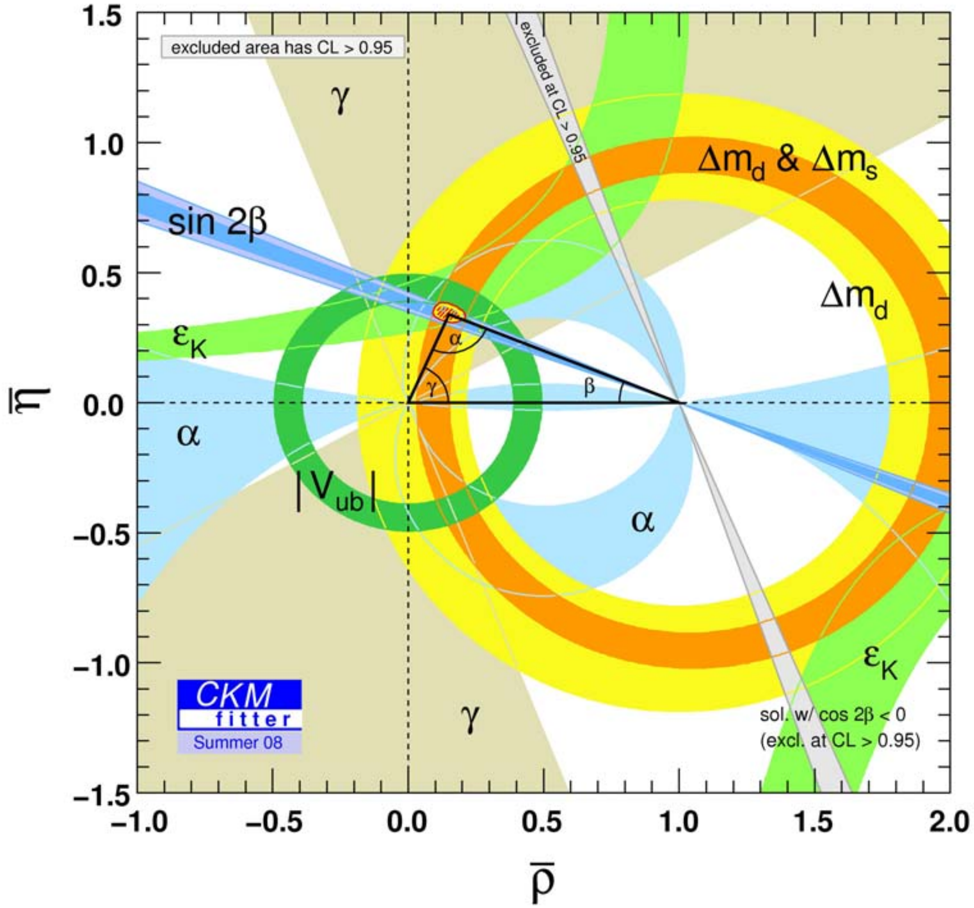
Unitarity Triangle Fits

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

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

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

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

Yet

Impressive Success of the CKM Picture of Flavour Changing Interactions

(GIM)

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.

Superstars of 2010 – 2015 (Flavour Physics)

$S_{\psi\varphi}$

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

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

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

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

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

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

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

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

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

Standard Model Predictions for Superstars

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

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

$$Br\left(B_s \to \mu^+\mu^-\right) = \left(3.2 \pm 0.3\right) \cdot 10^{-9}$$

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

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

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

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

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

$$\gamma = \left(68 \pm 7\right)^o$$

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

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

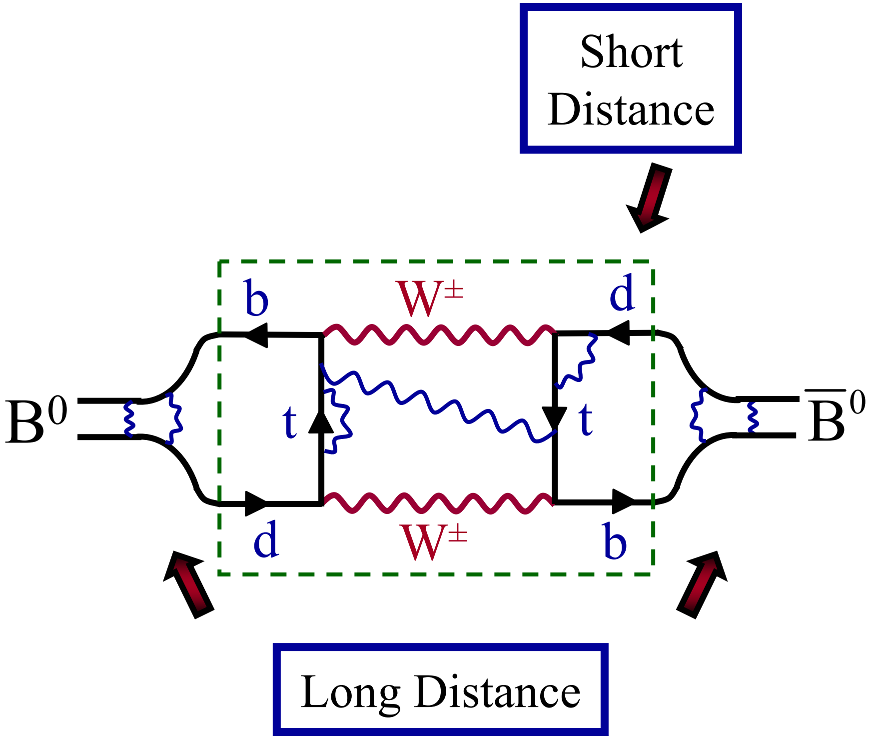
$$Br\left(K_L \to \pi^0\nu\bar{\nu}\right)_{exp} \leq 6 \cdot 10^{-8}$$

2.

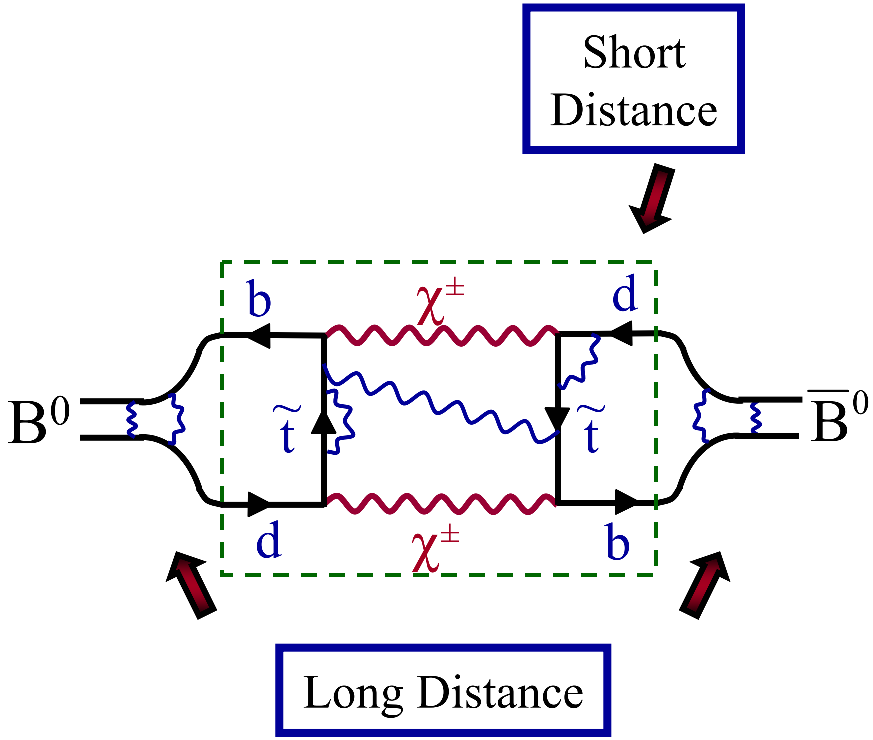
Theoretical Framework

The Problem of Strong Interactions

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



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



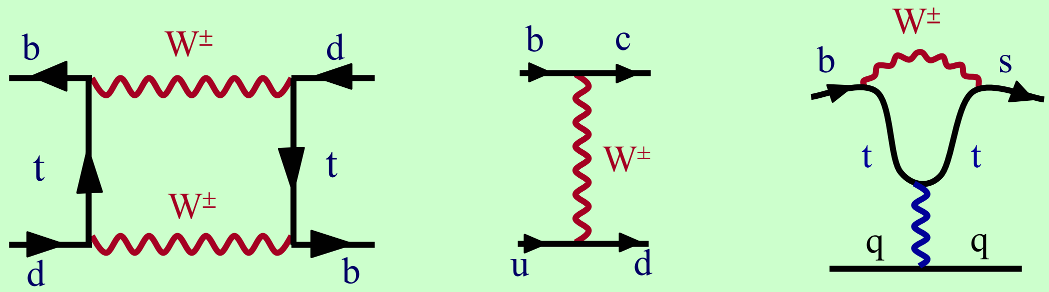
$\boxed{\text{SD}}$: <u>Perturbative</u>
(Asymptotic Freedom)

$\boxed{\text{LD}}$: <u>Non-Perturbative</u>
(Confinement)

Effective Field Theory

Full Theory

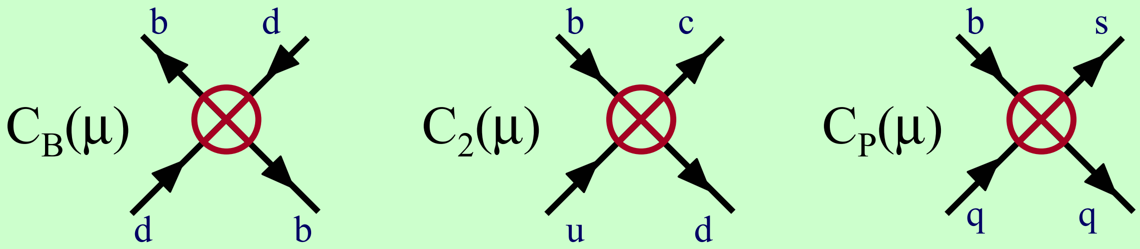
($W^{\pm}$, Z^0, G, γ, t, H^0, b, u, d, s, c, l)



$\mu \geq M_W$

Effective Theory

(G, γ, b, u, d, s, c, l)



$\mu \cong 0(m_b)$

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

Operator Product Expansion

$\left\{\begin{array}{l}\text{Wilson}\\\text{Coefficients}\end{array}\right\}$ $\left\{\begin{array}{l}\text{Local}\\\text{Operators}\end{array}\right\}$

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

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,...}

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

$\left\{\begin{array}{l}\pi\pi,\ \pi\nu\bar{\nu}\\ \mu\bar{\mu},\ K^*\gamma,\ldots\end{array}\right\}$

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

Short RG Long Distance

$\left\{\begin{array}{c}\text{Top}\\\text{SUSY}\\H^{\pm}\ldots\end{array}\right\}$ $\left\{\begin{array}{l}\text{Renormalization}\\\text{Group}\\\sum\left(\alpha_s \log\frac{M_w}{\mu}\right)^n\end{array}\right\}$ $\left\{\begin{array}{l}\text{Lattice, 1/N}\\\text{HQET, QCDS}\\\text{ChPTh}\end{array}\right\}$

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

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)

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

NP can add
new B_i´s absent
in SM

Renormalization
Group (QCD)
LD $\leftrightarrow$ SD

Only Loops
if GIM works

(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

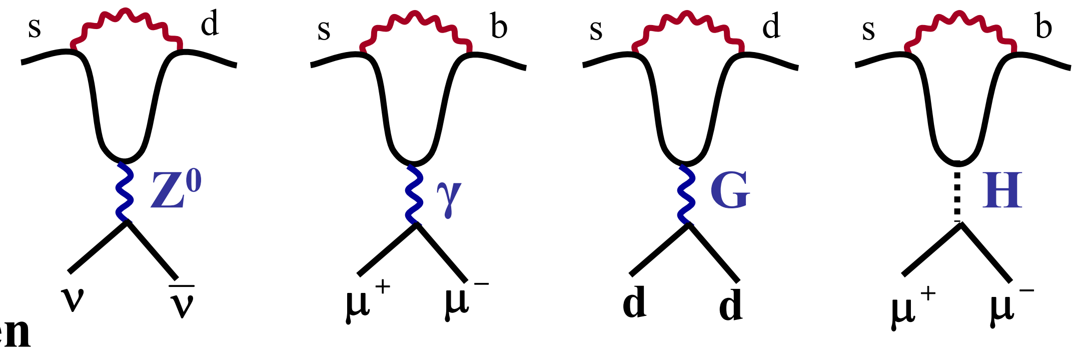
Warped Extra Dimensions

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

AJB, Misiak, Urban, Jäger

Basic Diagrams in FCNC Processes

Penguin Family :

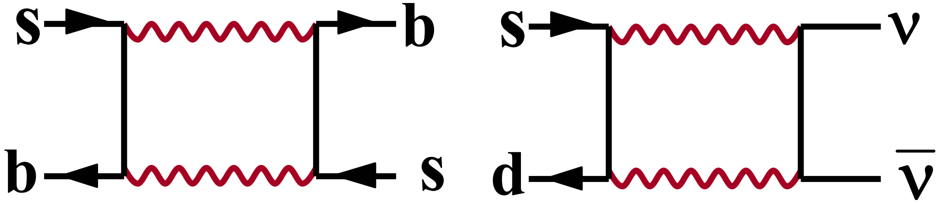


New Physics enters here

Similar diagrams in LFV and EDM´s

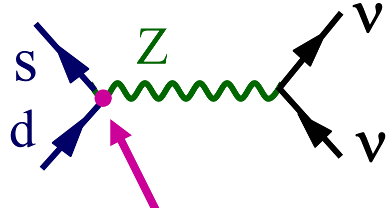
(GIM broken at one loop)

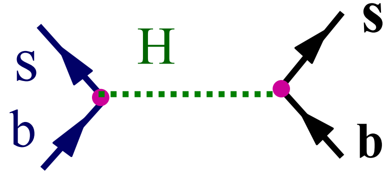
Box Diagrams



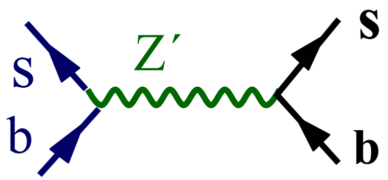
+ other box diagrams

Tree Diagrams





(GIM broken at tree level)



RS

Generated through mixing with New Gauge Bosons

Double Higgs Penguin in SUSY

Most popular BSM Directions

CMFV

(constrained MFV)

MFV

(NMFV)
(GMFV)

RHMFV

2HDM

LHT

(Littlest Higgs
with T-parity)

SUSY

(flavour models)

Z´

(Langacker…)

RS

(Randall-Sundrum)
(Warped Extra Dimensions)

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.

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

Little Hierarchy Problem

(generic)

$\Lambda_{NP} \approx 5$ TeV

Electroweak Precision Tests

+

Agreement of the CKM Picture of Flavour and CP Violation with existing Data (FCNC)

Very strong Constraints on Physics beyond SM with scales O (1 TeV)

Necessary to solve the hierarchy problem

$\Lambda_{NP} \approx 1000$ TeV (generic)

$(M_{PLANCK} \gg \Lambda_{EW})$

Message 1 : **New Physics at TeV-Scale must have a non-Generic Flavour Structure**

Message 2 : **Protection Mechanisms to suppress FCNCs generated by TeV-Scale New Physics required**

Ciuchini et al
Isidori et al
Agashe et al
+50

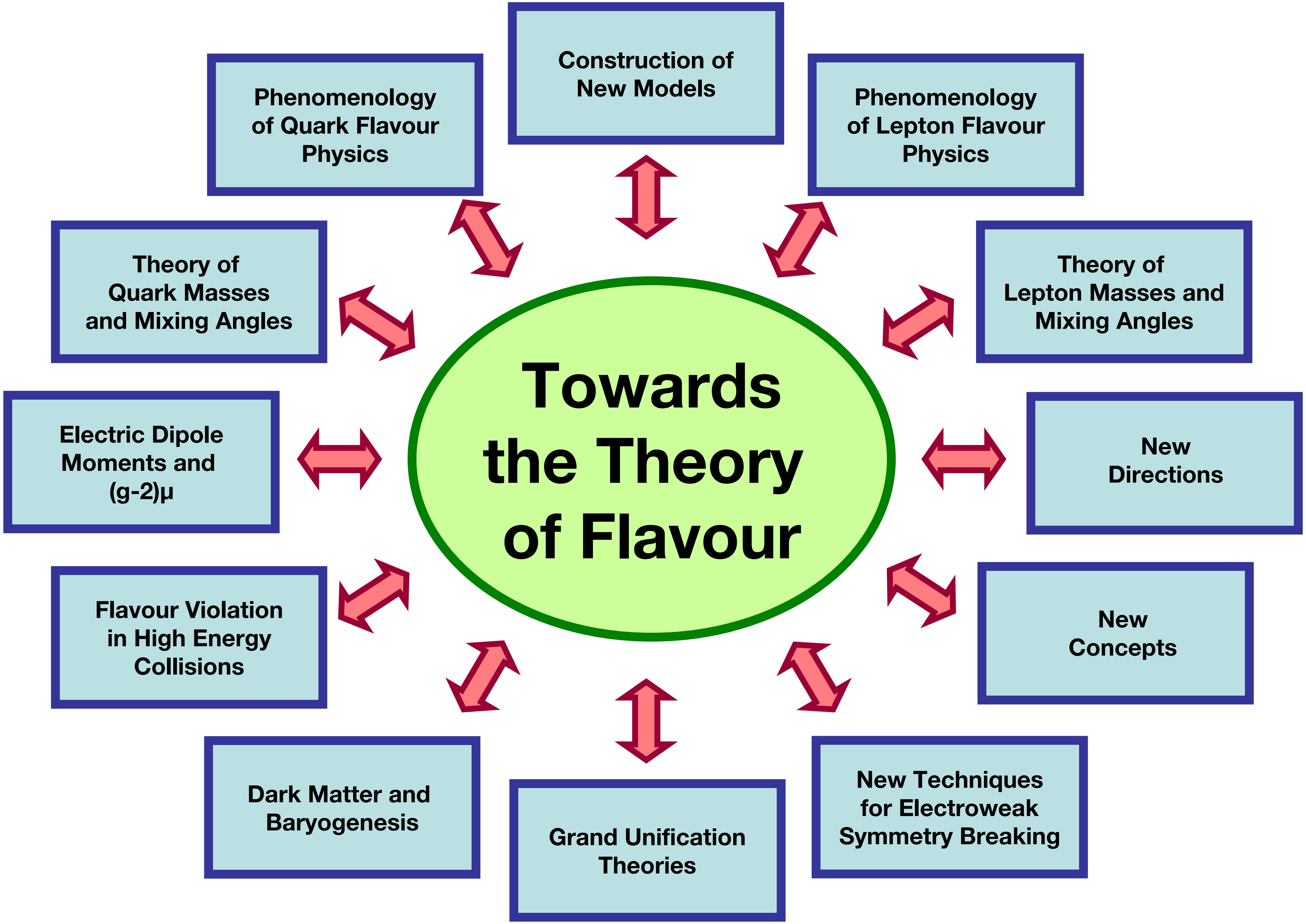
★

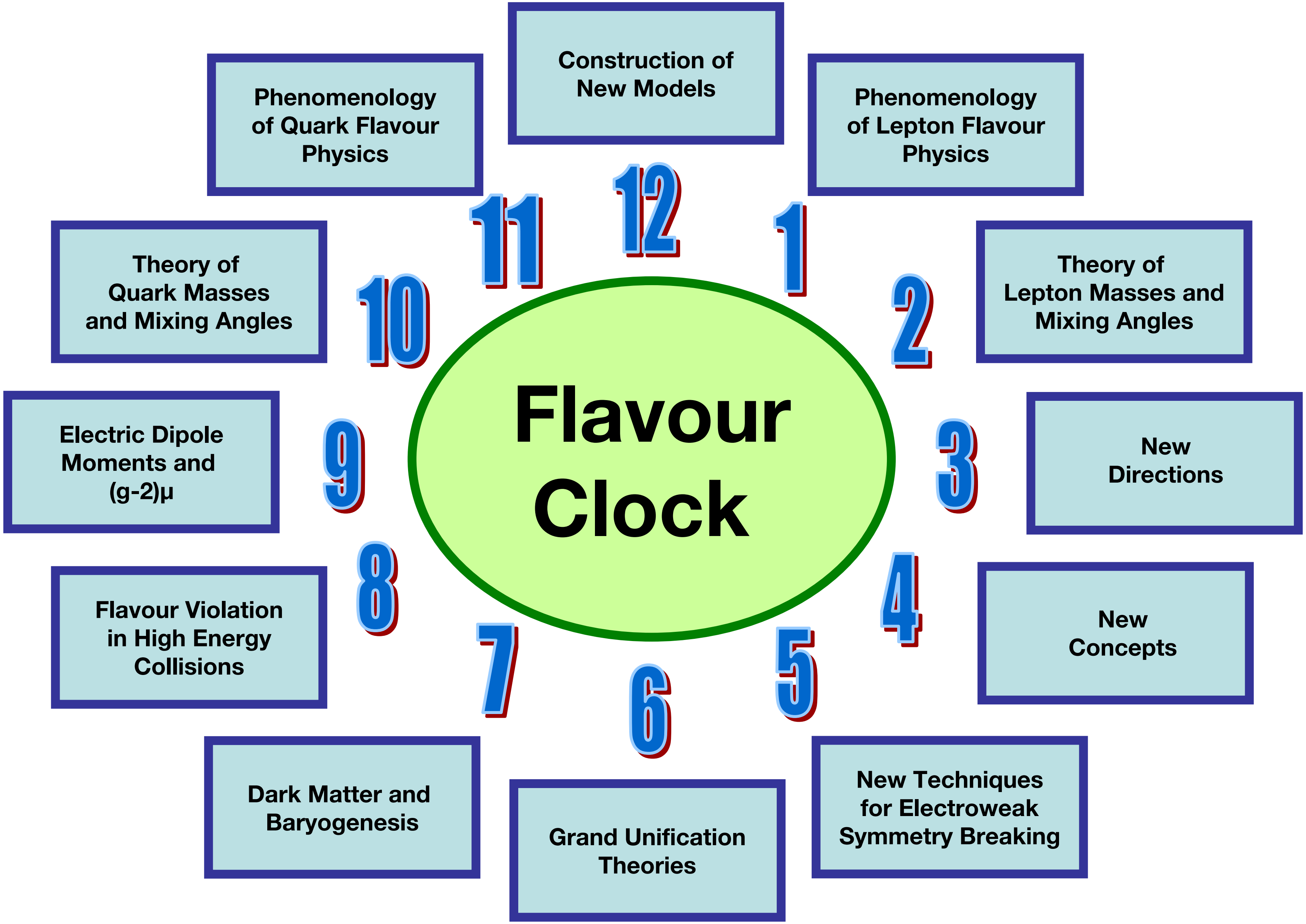
MFV | **GIM** | **RS-GIM** | **T-Parity** | **R-Parity**

Alignment | **Degeneracy** | **Flavour Symmetries** (abelian, non-abelian)

Custodial Symmetries (continuous, discrete)

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


Towards the Theory of Flavour
Construction of New Models
Phenomenology of Quark Flavour Physics
Phenomenology of Lepton Flavour Physics
Theory of Quark Masses and Mixing Angles
Theory of Lepton Masses and Mixing Angles
Electric Dipole Moments and (g-2)μ
New Directions
Flavour Violation in High Energy Collisions
New Concepts
Dark Matter and Baryogenesis
Grand Unification Theories
New Techniques for Electroweak Symmetry Breaking


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
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Dark Matter and
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Flavour Violation
in High Energy
Collisions
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Moments and
(g-2)μ
10
Theory of
Quark Masses
and Mixing Angles
11
Phenomenology
of Quark Flavour
Physics

Basic Questions for Flavour Physics

New Flavour violating CPV phases?

Flavour Conserving CPV phases?

Non-MFV Interactions?

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 ?

3.

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

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

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:

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

(CMFV)

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

(CMFV)

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

(MFV)

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

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

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

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

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

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

(No problems with chiral logs and quenching)

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

(AJB, hep-ph/0303060)

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

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

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)

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

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

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

SM:

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

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

(Example)

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

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

Moreover new Physics Effects can be easier seen

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.

4.

Motivations for BSM and BMFV

Yet

Impressive Success of the CKM Picture of Flavour Changing Interactions

(GIM)

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.**

Can SM describe simultaneously $\cancel{CP}$ in K and B_d Systems?

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

Can SM describe simultaneously $\cancel{CP}$ in K and B_d Systems?

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

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)

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

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

AJB Guadagnoli

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

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

Lunghi Soni

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

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

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

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

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

Diego Guadagnoli

Models investigated by TUM-Teams

(Last decade)

SM	MFV	MSSM+MFV	Z´-Models
General MSSM	Universal Extra Dimensions	RS with custodial protection	Right-Handed Currents
Littlest Higgs	Littlest Higgs with T-Parity	SUSY+Flavour Abelian Symmetry (Agashe+Carone)	2 Higgs Doublet Models
SUSY with SU(3) Flavour (Ross et al) (RVV2)	SUSY with SU(2) Flavour (LH-currents)	Flavour Blind MSSM	4G

My Collaborators

SUSY


W. Altmannshofer


S. Gori


P. Paradisi


D. Straub

LHT


M. Blanke


B. Duling


S. Recksiegel


C. Tarantino

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


I.Bigi


P. Ball

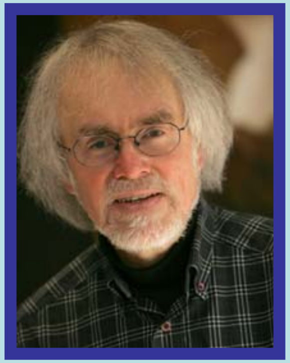

A. Bharucha


M. Wick


L. Calibbi


M. Nagai

4 Generations by 4 Physics Generations



AJB

T. Feldmann

S. Recksiegel

B. Duling

C. Promberger

T. Heidsieck

5.

Models for BMFV

Most popular BSM Directions

NEW

CMFV

(constrained MFV)

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

NEW

2HDM

NEW

LHT

(Littlest Higgs with T-parity)

SUSY

(flavour models)

Z′

(Langacker…)

RHMFV

NEW **RS**

(Randall-Sundrum)
(Warped Extra Dimensions)

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.

4G Model

The CKM4 matrix : New: s_{14}, s_{24}, s_{34}, δ_{14}, δ_{24}, m_t, m_b, 300-600 GeV

$c_{12}c_{13}c_{14}$	$c_{13}c_{14}s_{12}$	$c_{14}s_{13}e^{-i\delta_{13}}$	$s_{14}e^{-i\delta_{14}}$
$-c_{23}c_{24}s_{12} - c_{12}c_{24}s_{13}s_{23}e^{i\delta_{13}}$ $-c_{12}c_{13}s_{14}s_{24}e^{i(\delta_{14}-\delta_{24})}$	$c_{12}c_{23}c_{24} - c_{24}s_{12}s_{13}s_{23}e^{i\delta_{13}}$ $-c_{13}s_{12}s_{14}s_{24}e^{i(\delta_{14}-\delta_{24})}$	$c_{13}c_{24}s_{23}$ $-s_{13}s_{14}s_{24}e^{-i(\delta_{13}+\delta_{24}-\delta_{14})}$	$c_{14}s_{24}e^{-i\delta_{24}}$
$-c_{12}c_{23}c_{34}s_{13}e^{i\delta_{13}} + c_{34}s_{12}s_{23}$ $-c_{12}c_{13}c_{24}s_{14}s_{34}e^{i\delta_{14}}$ $+c_{23}s_{12}s_{24}s_{34}e^{i\delta_{24}}$ $+c_{12}s_{13}s_{23}s_{24}s_{34}e^{i(\delta_{13}+\delta_{24})}$	$-c_{12}c_{34}s_{23} - c_{23}c_{34}s_{12}s_{13}e^{i\delta_{13}}$ $-c_{12}c_{23}s_{24}s_{34}e^{i\delta_{24}}$ $-c_{13}c_{24}s_{12}s_{14}s_{34}e^{i\delta_{14}}$ $+s_{12}s_{13}s_{23}s_{24}s_{34}e^{i(\delta_{13}+\delta_{24})}$	$c_{13}c_{23}c_{34}$ $-c_{13}s_{23}s_{24}s_{34}e^{i\delta_{24}}$ $-c_{24}s_{13}s_{14}s_{34}e^{i(\delta_{14}-\delta_{13})}$	$c_{14}c_{24}s_{34}$
$-c_{12}c_{13}c_{24}c_{34}s_{14}e^{i\delta_{14}}$ $+c_{12}c_{23}s_{13}s_{34}e^{i\delta_{13}}$ $+c_{23}c_{34}s_{12}s_{24}e^{i\delta_{24}} - s_{12}s_{23}s_{34}$ $+c_{12}c_{34}s_{13}s_{23}s_{24}e^{i(\delta_{13}+\delta_{24})}$	$-c_{12}c_{23}c_{34}s_{24}e^{i\delta_{24}} + c_{12}s_{23}s_{34}$ $-c_{13}c_{24}c_{34}s_{12}s_{14}e^{i\delta_{14}}$ $+c_{23}s_{12}s_{13}s_{34}e^{i\delta_{13}}$ $+c_{34}s_{12}s_{13}s_{23}s_{24}e^{i(\delta_{13}+\delta_{24})}$	$-c_{13}c_{23}s_{34}$ $-c_{13}c_{34}s_{23}s_{24}e^{i\delta_{24}}$ $-c_{24}c_{34}s_{13}s_{14}e^{i(\delta_{14}-\delta_{13})}$	$c_{14}c_{24}c_{34}$

Extensive New Interest in 4G

Very many papers: Hou; Hung; Chanowitz; Novikov et al. Kribs et al. + ….

FCNC´s :

Hou, Nagashima, Soddu
Soni, Alok, Giri, Mohanta, Nandi
Herrera, Benovides, Ponce
Bobrowski, Lenz, Riedl, Rohrwild
Eilam, Melic, Trampetic
AJB, Duling, Feldmann, Heidsieck, Promberger, Recksiegel
Lacker, Menzel

New Interest in Higgs-mediated FCNC´s

Guidice, Lebedev (08); Agashe, Contino (09), Azatov, Toharia, Zhu (09), AJB, Gori, Duling (09); Duling (09)

<u>Recent:</u> **Botella, Branco, Rebelo (09); Joshipura, Kodrani (08, 10)**
Pich, Tuzon (09)
Gupta, Wells (10)

May – June 2010

	Dobrescu, Fox, Martin (1005.4238)	
(28 May)	**AJB, Carlucci, Gori, Isidori (1005.5310)**	**Neutral Higgs**
(29 May)	**Aranda, Montano, Ramirez-Zavaleta, Toscano, Tututi (1005.5452)**	
(31 May)	**Braeuninger, Ibarra, Simonetto**	
(2 June)	**Ligeti, Papucci, Perez, Zupan**	
(2 June)	**Jung, Pich, Tuzón**	**Charged Higgs**

Problems of the most general 2HDM

- H_1, H_2 two Higgs doublets with hypercharges $Y_1 = 1/2$ and $Y_2 = -1/2$
- Most general Yukawa interaction Hamiltonian

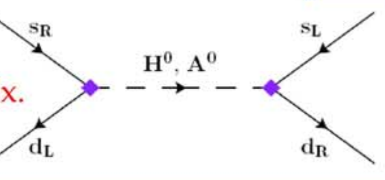
$$\mathcal{H}_Y^{\text{gen}} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2 + \text{h.c.}$$

where X_i are generic 3×3 matrices in flavor space

In general too large NP contributions to flavor changing neutral processes, since quark mass matrices and Yukawa couplings are not alligned

→ FCNCs at the tree level

Ex.



How to protect the model from too large FCNCs?

Protection mechanisms

$$\mathcal{H}_Y^{\text{gen}} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2 + \text{h.c.}$$

Largest group which commutes with the SM gauge Lagrangian:

$$\mathcal{G}_q = SU(3)_q^3 \otimes U(1)_B \otimes U(1)_Y \otimes U(1)_{PQ}$$

D'Ambrosio et al., '02

Glashow, Weinberg, '77
Paschos, '77

- Minimal Flavor Violation hypothesis:
  $SU(3)^3$ symmetry broken only by two spurions
  $Y_D \sim \bar{3}_Q \times 3_D\,,\quad Y_U \sim \bar{3}_Q \times 3_U$

- Tree level implication
  $X_{d1} \propto X_{d2}\,,\quad X_{u1} \propto X_{u2}$

See also Yukawa alignment, Pich, Tuzon, '09

- Including radiative corrections, one gets

$$\begin{cases} X_{d1} = Y_d \quad \text{(definition)} \\ X_{d2} = \epsilon_0 Y_d + \epsilon_1 Y_d^\dagger Y_d Y_d + \epsilon_2 Y_u^\dagger Y_u Y_d + \ldots \\ X_{u1} = \epsilon_0' Y_u + \epsilon_1' Y_u^\dagger Y_u Y_u + \epsilon_2' Y_d^\dagger Y_d Y_u + \ldots \\ X_{u2} = Y_u \quad \text{(definition)} \end{cases}$$

- Natural Flavor Conservation hypothesis:
  only one Higgs field can couple to a given quark species

- The hypothesis is enforced by the $U(1)_{PQ}$ symmetry

(also the Z_2 symmetry can do the job)

- Tree level implication
  $X_{d2} = X_{u1} = 0$

(D_R and H_1 with opposite PQ charges)

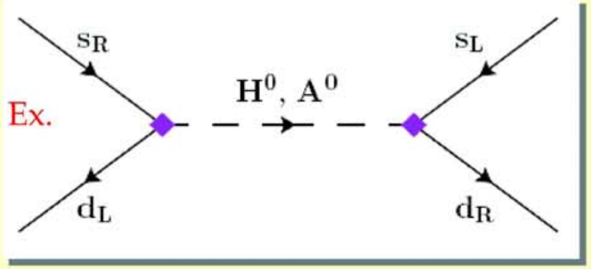
- The symmetry $U(1)_{PQ}$ is usually explicitly broken (otherwise appearance of a Goldstone boson)

$$\begin{cases} X_{d2} = \epsilon_d \Delta_d\,, & X_{d1} = Y_d \\ X_{u1} = \epsilon_u \Delta_u\,, & X_{u2} = Y_u \end{cases}$$

FCNCs

Constraints on the two hypothesis

Constraint from the K meson mixing system: ε_K



Buras, Carlucci, S.G., Isidori, '10

Natural flavor conservation

$$|\epsilon_d| \times \left|\mathrm{Im}[(\Delta_d)^*_{21}(\Delta_d)_{12}]\right|^{1/2} \lesssim \boxed{3 \times 10^{-7}} \times \frac{c_\beta M_H}{100\ \mathrm{GeV}}$$

A very high level of fine tuning is required!

found imposing $|\varepsilon_K^{\mathrm{NP}}| < 0.2\,|\varepsilon_K^{\mathrm{exp}}|$

A loop suppression $\epsilon_d \sim 10^{-2}$ is not sufficient

Minimal flavor violation

$$|a_0| \lesssim \boxed{8} \times \frac{M_H}{100\ \mathrm{GeV}} \frac{1}{t_\beta}$$

found imposing $|\varepsilon_K^{\mathrm{NP}}| < 0.05\,|\varepsilon_K^{\mathrm{exp}}|$

The constraint is satisfied very naturally, even for relatively light Higgs bosons!

where

$$a_0 = \frac{\epsilon_2 t_\beta (1 + r_V)^2}{y_t^2\,[1 + \epsilon_0 t_\beta]^2}$$

$$r_V \equiv \frac{(\epsilon_2 + \epsilon_3) t_\beta}{1 + (\epsilon_0 + \epsilon_1 - \epsilon_2 - \epsilon_3) t_\beta}$$

Few Messages on Higgs-mediated FCNC´s

	SUSY	2HDM	
ΔM_s	$(\tan\beta)^4$	$(\tan\beta)^2$	$\cdot 1/M_H^2$
$B_{s,d} \to \mu^+\mu^-$	$(\tan\beta)^6$	$(\tan\beta)^4$	$\cdot 1/M_H^4$

Glashow Weinberg 1977

MFV more powerful than Natural Flavour Conservation (BCGI)

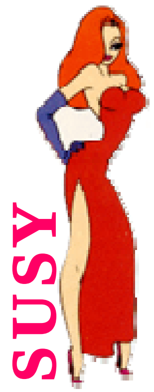
General 2HDM with MFV and flavour blind phases (AJB, Carlucci, Gori, Isidori) → **Aligned 2HDM (Pich, Tuzón) + flavour blind phases**

Flavour-Blind phases can be included in MFV

Mercoli, Smith (09)
Kagan, Perez, Volansky, Zupan (09) ⟵ (could help to generate large CP-phase in B_s-mixing)
Paradisi, Straub (09)

Little Higgs Models

SUSY vs Little Higgs



Problematic quadratic divergences in m_H^2

	SUSY	Little Higgs
Quadratic divergences canceled by:	(different statistics) super-partners	(same statistics) heavy partners
Coupling relationships due to:	boson-fermion symmetry	global symmetry

The most economical in matter content: Littlest Higgs (LH)

[N. Arkani-Hamed, A.G. Cohen, E. Katz, A.E. Nelson (2002)]

valid up to $(4\pi f) \equiv \Lambda$

Original model: Arkani-Hamed, Cohen, Katz, Nelson (2002)

LH

$f \approx O(1\text{TeV})$

Global: $SU(5) \longrightarrow SO(5)$

Local: $[SU(2) \otimes U(1)]_1 \otimes [SU(2) \otimes U(1)]_2 \longrightarrow SU(2)_L \otimes U(1)_Y$

$(g_1) \quad (g'_1) \quad (g_2) \quad (g'_2)$

Model with T-Parity: Cheng, Low (2003)

LHT

Theory symmetric under $[SU(2) \otimes U(1)]_1 \longleftrightarrow [SU(2) \otimes U(1)]_2$

$\Longleftrightarrow \quad g_1 = g_2 \qquad g'_1 = g'_2$

Littlest Higgs Models without and with T-Parity

New particles: (with O(f) masses)

LH

Gauge Bosons: $W^{\pm}_H$, Z^0_H, A^0_H

Fermions: T

Scalars: $\Phi^{\pm}$,…

LHT

T-even Sector

SM Particles + T_+

T-odd Sector

Gauge Bosons: $W^{\pm}_H$, Z^0_H, A^0_H

Fermions: T_-, Mirror Fermions

Scalars: $\Phi^{\pm}$,…

The World of Mirror Fermions

[I. Low, hep-ph/0409025]

Required to cut-off large 4-fermion operators constrained by LEP

$$\begin{pmatrix} u_{1H} \\ d_{1H} \end{pmatrix} \quad \begin{pmatrix} u_{2H} \\ d_{2H} \end{pmatrix} \quad \begin{pmatrix} u_{3H} \\ d_{3H} \end{pmatrix}$$

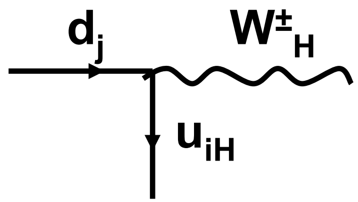
Vectorial couplings under $SU(2)_L$

Similarly for Leptons

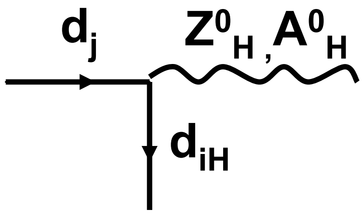
$m^u_{Hi} = m^d_{Hi}$ $\quad i=1,2,3$

to first order in v/f

New Flavour Interactions involving SM fermions, Mirror Fermions and $W^\pm_H$, Z^0_H, A^0_H



$\sim (V_{Hd})_{ij}\, \gamma_\mu\, (1-\gamma_5)$



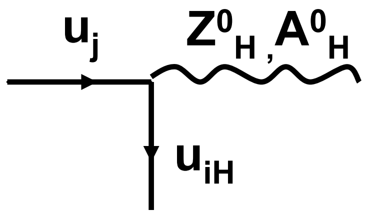
$\sim (V_{Hd})_{ij}\, \gamma_\mu\, (1-\gamma_5)$

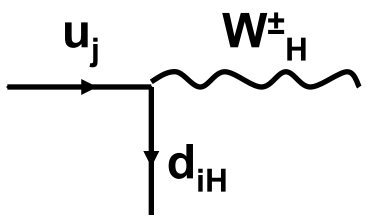
$$V^\dagger_{Hu}\, V_{Hd} = V_{CKM}$$

[I. Low, hep-ph/0409025]

[J. Hubisz, S.J. Lee, G. Paz]

$(V_{Hu})_{ij}$ for:

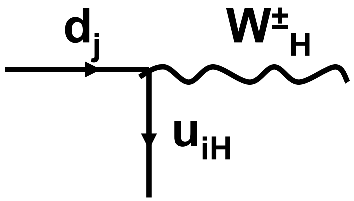




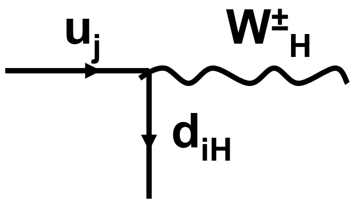
LHT goes beyond Minimal Flavour Violation (MFV)

(without introducing new operators and non-perturbative uncertainties)

``visible effects in flavour physics are possible´´



$\sim \; (V_{Hd})_{ij} \, \gamma_\mu \, (1-\gamma_5)$



$\sim \; (V_{Hu})_{ij} \, \gamma_\mu \, (1-\gamma_5)$

$V^{\dagger}_{Hu} \, V_{Hd} = V_{CKM}$

[Low], [Hubisz,Lee,Paz]

$$V_{Hd} = \begin{pmatrix} c^d_{12}c^d_{13} & s^d_{12}c^d_{13}e^{-i\delta^d_{12}} & s^d_{13}e^{-i\delta^d_{13}} \\ -s^d_{12}c^d_{23}e^{i\delta^d_{12}} - c^d_{12}s^d_{23}s^d_{13}e^{i(\delta^d_{13}-\delta^d_{23})} & c^d_{12}c^d_{23} - s^d_{12}s^d_{23}s^d_{13}e^{i(\delta^d_{13}-\delta^d_{12}-\delta^d_{23})} & s^d_{23}c^d_{13}e^{-i\delta^d_{23}} \\ s^d_{12}s^d_{23}e^{i(\delta^d_{12}+\delta^d_{23})} - c^d_{12}c^d_{23}s^d_{13}e^{i\delta^d_{13}} & -c^d_{12}s^d_{23}e^{i\delta^d_{23}} - s^d_{12}c^d_{23}s^d_{13}e^{i(\delta^d_{13}-\delta^d_{12})} & c^d_{23}c^d_{13} \end{pmatrix}$$

V_{Hd} parameterization similar to CKM, but with 2 additional phases (the phases of SM quarks are no more free to be rotated)

[Blanke,AJB,Poschenrieder,Recksiegel,Tarantino,Uhlig,Weiler]

[Similar new interactions and mixing matrices appear in the lepton sector]

General Structure of the Amplitudes

LH (CMFV Model)

Non-perturbative factors

Real functions

$$A(Decay) = \sum_i B_i^{SM} \eta_{QCD}^i V_{CKM}^i F_i(m_t, m_T, m_{W_H}, \ldots)$$

LHT

Real functions

$$A(Decay) = \sum_i B_i^{SM} \eta_{QCD}^i \left[V_{CKM}^i F_i(m_t, m_T) + V_{Hd}^i G_i(m_H^u, m_H^d, W_H^{\pm}, Z_H^0, A_H^0) \right]$$

T-even contribution: CMFV
T-odd contribution: New CP and Flavour violating Interactions
but only SM operators

LH(without T-parity) vs LHT(with T-parity)

Tree-level heavy gauge boson contributions and the triplet Φ vev make ew precision tests highly constraining
[Han, Logan, McElrath, Wang]
[Csaki, Hubisz, Kribs, Meade, Terning]

$\Rightarrow$ **f ≥ 2-3 TeV**

- The little hierarchy problem is back
- Only small effects in Flavour Physics

Buras, Poschenrieder, Uhlig, hep-ph/0410309//0501230
Buras, Poschenrieder, Uhlig, Bardeen, hep-ph/0607189
Choudhury, Gaur, Goyal, Mahajan, hep-ph/0407050
Lee, hep-ph/0408362
Fajfer, Prelovsek, hep-ph/0511048
Huo, Zhu, hep-ph/0306029
Choudhury, Gaur, Joshi, McKellar, hep-ph/0408125

These unwanted contributions are eliminated by a discrete symmetry:

T-parity

- SM particles are T-even,
- new particles are T-odd

(similarly to R-parity in SUSY)

smaller f allowed by ew tests
[Hubisz,Meade,Noble,Perelstein]

$\Downarrow$ **f ≥ 500 GeV**

- The little hierarchy problem is solved
- Large effects are possible in Flavour Physics

General Structure of New Physics Contributions

SM :

$$\lambda_t^{(K)} = V_{ts}^* V_{td} \qquad \lambda_t^{(d)} = V_{tb}^* V_{td} \qquad \lambda_t^{(s)} = V_{tb}^* V_{ts}$$

Amplitudes :

$$\boxed{\lambda_t^{(i)} X_{SM}(m_t)} \qquad \boxed{\lambda_t^{(i)} Y_{SM}(m_t)}$$

$\nu\bar{\nu}$ in the final state

$\mu^+\mu^-$ in the final state

Universality of short distance functions

i = K, B_d, B_s

LHT :

$$X_i = \underbrace{X_{SM}(m_t) + \bar{X}_{even}}_{\text{real}} + \underbrace{\frac{1}{\lambda_t^{(i)}} \xi_i \bar{X}_{odd}}_{\text{complex}} \equiv |X_i| e^{i\theta_X^i}$$

$\mathbf{V_{Hd}}$

$$Y_i = \overbrace{Y_{SM}(m_t) + \bar{Y}_{even}} + \overbrace{\frac{1}{\lambda_t^{(i)}} \xi_i \bar{Y}_{odd}} \equiv |Y_i| e^{i\theta_Y^i}$$

(mirror fermions)

Breakdown of Universality

Natural Expectations

$$X_i = X_{SM}(m_t) + \overline{X}_{even} + \frac{1}{\lambda_t^{(i)}} \xi_i \overline{X}_{odd} \equiv |X_i| e^{i\theta_X^i}$$

ξ_i: V_{Hd}

i = K, B_d, B_s

(similarly for Y_i)

$$\frac{1}{\lambda_t^{(K)}} \approx 2 \cdot 10^3$$

$$\frac{1}{\lambda_t^{(d)}} \approx 100$$

$$\frac{1}{\lambda_t^{(s)}} \approx 25$$

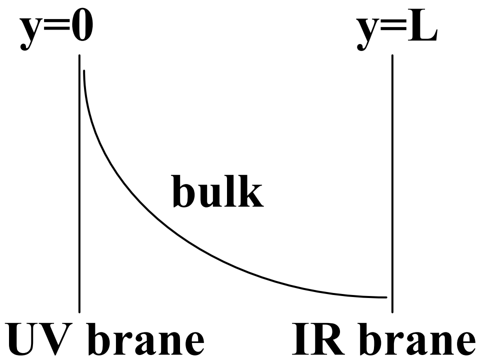
$\left\{ \begin{array}{c} \text{Natural} \\ \text{size} \\ \text{of NP} \\ \text{contributions} \end{array} \right\}$: $\boxed{\mathbf{K \gg B_d > B_s}}$

But can be reversed for special structures of V_{Hd}

Randall-Sundrum Framework (Express Summary)

5D spacetime with warped metric:

$$\boxed{ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu - dy^2 \qquad 0 \le y \le L}$$



- **fermions and gauge bosons live in the bulk**
- **Higgs localised on IR brane**

(Chang, Okada et al.
Grossman, Neubert
Gherghetta, Pomarol)

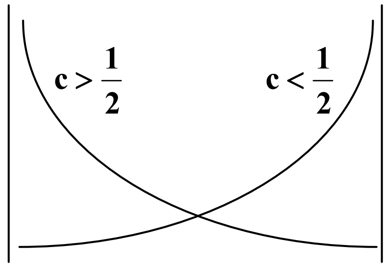
- **energy scales suppressed by warp factor e^{-ky}**
  natural solution to the gauge hierarchy problem.
- **Kaluza-Klein (KK) excitations of both SM fermions and gauge bosons live close to the IR brane.**

Fermion Localisation and Yukawa Couplings

SM fermion (zero mode) shape function depends strongly on bulk mass parameter characteristic for a given fermion:

$$\boxed{f^{(0)}(y,c)\ \alpha\quad e^{\left(\frac{1}{2}-c\right)y}}$$

UV brane IR brane



Higgs

$c > \frac{1}{2}$: localisation near UV brane

$c < \frac{1}{2}$: localisation near IR brane

effective 4D Yukawa couplings:
$$\boxed{\left(Y_{u,d}\right)_{ij} = \left(\lambda_{u,d}\right)_{ij} f_i^Q f_j^{u,d}}$$

- $\lambda_{u,d} \sim 0(1)$ anarchic complex 3 x 3 matrices $\equiv Y_{5D}$
- hierachical structure of quark masses and CKM parameters can be naturally generated by exponential suppression of $f^{Q,u,d}$ at IR brane.

Bulk Profiles of SM Gauge Bosons

- **Gluons and Photon : flat** (protection by Gauge symmetry)
- **$W^\pm$, Z : flat before EWSB**
  but

  distorted near the IR brane after EWSB $0\left(\frac{v^2}{M_{KK}^2}\right)$

  Equivalently : Mixing of KK gauge bosons with $W^\pm$, Z in the process of EWSB modifies the couplings of mass eigenstates $W^\pm$, Z

- **Recall : All KK gauge bosons live close to the IR brane**

  All KK fermions live close to the IR brane

First Implications for Phenomenology

1. **Gauge-Fermion Interactions: Overlaps of shape functions** $\Rightarrow$ **Non-universalities in Gauge Couplings** (in flavour)

of $\left\{ \begin{array}{l} \text{KK-gauge bosons} \\ W^{\pm}, Z \end{array} \right\}$

to {SM fermions}

2. **Impact on Electroweak Precision Observables**

$SU(2)_L \otimes U(1)_Y$

S parameter : $M_{KK} \geq (2\text{-}3)$ TeV
T parameter: $M_{KK} \gtrsim 10$ TeV

Agashe, Delgado, May, Sundrum (2003)
Csaki, Grojean, Pilo, Terning (2003)

Also problems with $Zb_L\bar{b}_L$

3.

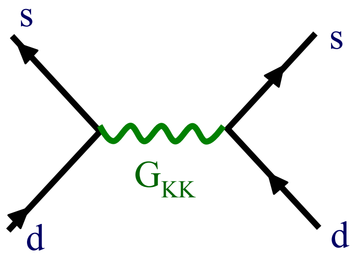
Tree Level FCNC mediated by KK gauge bosons and Z (breakdown of standard GIM mechanism)

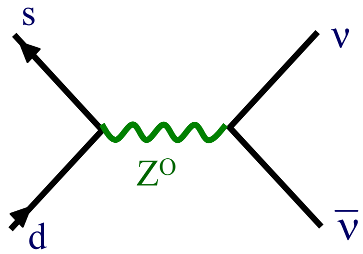
$$\mathbf{d} \equiv \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\overline{\mathbf{d}} D_L^{+} \begin{pmatrix} a & & \\ & b & \\ & & c \end{pmatrix} D_L \gamma_\mu Z^\mu \mathbf{d} \neq \overline{\mathbf{d}} \gamma_\mu Z^\mu \mathbf{d}$$

(non-universality)

$$0\left(\frac{v^2}{M_{KK}^2}\right)$$





$$0\left(\frac{v^2}{M_{KK}^2}\right)$$

But RS-GIM helps in avoiding disaster.

Gherghetta, Pomarol
Huber, Shafi
Agashe, Soni, Perez

4. **Mixing of KK fermions with SM fermions and mixing of KK gauge bosons with SM gauge bosons**

$\Rightarrow$ **Breakdown of Unitarity of the CKM matrix**

5. Tree level exchanges of G_{KK} and Z $\Rightarrow$ Contributions of new operators. In particular Q_{LR} operators in addition to Q_{LL}, Q_{RR}

6. The presence of three 3 x 3 hermitian bulk matrices c^q, c^u, c^d in addition to usual Yukawa couplings $\Rightarrow$ New flavour and CP violating parameters:

$3 * 6 = 18$ real

$3 * 3 = 9$ phases

Non-MFV

A RS Model with Custodial Protection

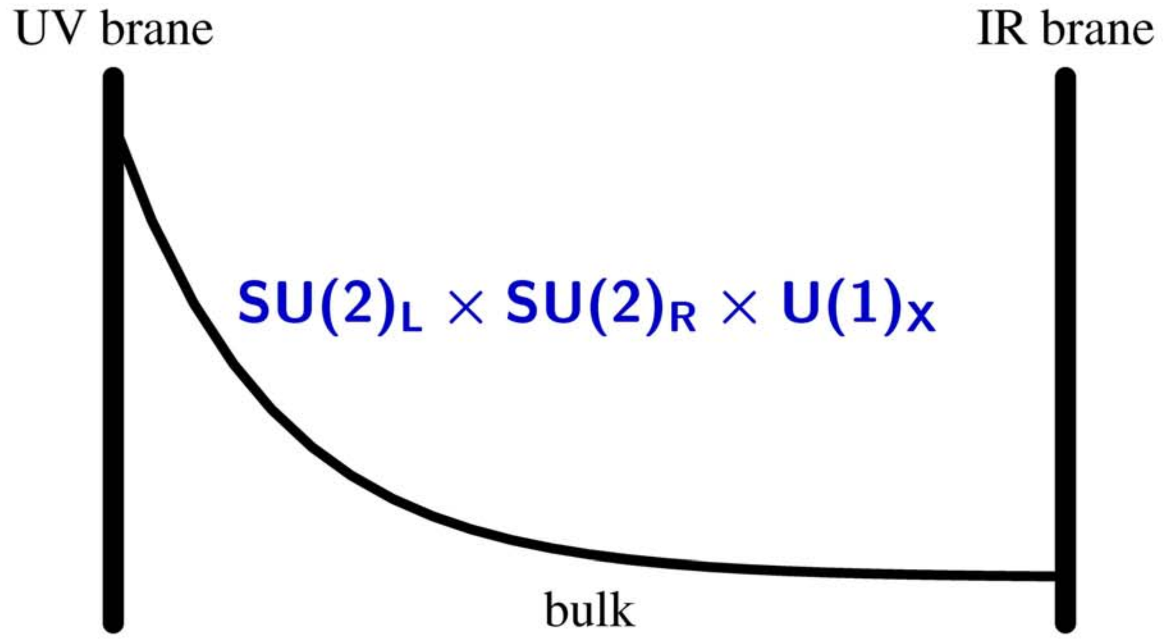
$$SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_X \otimes P_{LR}$$

Gauge Group in the Bulk

$$P_{LR} : SU(2)_L \leftrightarrow SU(2)_R$$

P_{LR} symmetric fermion representations

A Realistic Model in the Reach of the LHC



$\mathsf{SU(2)_R \times U(1)_X \rightarrow U(1)_Y}$
by boundary conditions

$\mathsf{SU(2)_L \times SU(2)_R \rightarrow SU(2)_V}$
by Higgs VEV

$+$ $(L \leftrightarrow R)$-symmetric fermion representations

low energy theory: $SU(2)_L \times U(1)_Y \rightarrow U(1)_{\mathrm{em}}$

What is protected in this Model?

(up to small symmetry breaking due to UV boundry conditions)

A. T-Parameter — Agashe, Delgado, May, Sundrum (0308036)
Csaki, Grojean, Pilo, Terning (0308038)

B. $Z\bar{b}_L b_L$ — Agashe, Contino, Rold, Pomarol (0605341)

C. $Z\bar{d}^i_L d^j_L$ — Blanke, AJB, Duling, Gori, Weiler (0809.1073)
Blanke, AJB, Duling, Gemmler, Gori (0812.3803)

D. $Z\bar{u}^i_R u^j_R$ — AJB, Duling, Gori (0905.2318)

But: $Z\bar{d}^i_R d^j_R, \quad Z\bar{u}^i_L u^j_L, \quad W^+\bar{u}^i_L d^j_L$ **not protected**

Particle Content of the Model

Albrecht, Blanke, AJB, Duling, Gemmler (0903.2415)

Gauge sector

$$W^\pm, \quad \boxed{W_H^\pm, \quad W'^\pm} \qquad\qquad A, \quad \boxed{A^{(\prime)}}$$

$$Z^0, \quad \boxed{Z_H, \quad Z'} \qquad\qquad G^a, \quad \boxed{G^{a(\prime)}}$$

KK KK

SU(2)$_L \otimes$ SU(2)$_R$

Quark sector

(i=1,2,3)

$$(2,2) = \begin{pmatrix} \chi^{u_i}(-+)_{5/3} & q^{u_i}(++)_{2/3} \\ \chi^{d_i}(-+)_{2/3} & q^{d_i}(++)_{1/3} \end{pmatrix}_L \qquad (1,1) = u_R^i(++)_{2/3}$$

$$(3,1) = \begin{pmatrix} \psi'^i(-+)_{5/3} \\ U'^i(-+)_{2/3} \\ D'^i(-+)_{-1/3} \end{pmatrix}_R \oplus \begin{pmatrix} \psi''^i(-+)_{5/3} \\ U''^i(-+)_{2/3} \\ D^i(++)_{-1/3} \end{pmatrix}_R = (1,3)$$

\+ states of opposite chirality

Q=5/3 Fermions!

(Feynman rules worked out for SM and n=1 KK modes)

6.

Patterns of Flavour Violation Beyond the SM

Three Strategies in Waiting for NP

1. **Precision Calculations** within the SM

Background to NP $\left(B \to X_s\gamma,\ K^+ \to \pi^+\nu\bar{\nu},\ B \to X_s l^+ l^-\right)$

2. **Bottom-Up Approach** Powerful in Electroweak Precision Physics

Personal View

In Flavour Physics less useful due to the presence of many operators (Buchmüller, Wyler: 1990)
Exception: Minimal Flavour Violation Hypothesis

3. **Top-Down Approach**

Study of patterns of flavour violation in concrete NP models. **Correlations between observables !**

Search for New Physics in 2010´s through Flavour Physics

★ To search for NP in rare K, B_d, B_s, D decays, ~~CP~~ in B_s, D decays, Lepton Flavour Violations

→

Specific Plots (Correlations)

$$\mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right) \text{ vs } \mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$$

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

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

$$\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) \text{ vs } S_{\psi\varphi}$$

$$d_n \text{ vs } S_{\varphi K_s}$$

$$A_{CP}\left(B \to X_S \gamma\right) \text{ vs } S_{\varphi K_s}$$

$$\mathrm{Br}\left(\tau \to \mu\gamma\right) \text{ vs } \Delta\left(g-2\right)_\mu$$

$$\mathrm{Br}\left(\tau \to \mu\mu\mu\right) \text{ vs } \mathrm{Br}\left(\tau \to \mu\gamma\right)$$

$$\mathrm{Br}\left(\mu \to 3e\right) \text{ vs } \mathrm{Br}\left(\mu \to e\gamma\right)$$

★ Correlations will be crucial to distinguish various NP scenarios

↓

Patterns of Flavour Violations in specific NP Models

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

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

Superstars enter the Scene

in the context of

SUSY **LHT** **RS** **4G** **2HDM**

(flavour models)

RHMFV

Number of new Flavour Parameters

(Quark Sector) (physical)

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

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 $B_s^0 - \bar{B}_s^0$ mixing

CDF : Hints for a much larger
D0   value

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

Prima Donna of 2010 – Flavour Physics

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

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$(\beta_s = -1°)$

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

CDF : Hints for a much larger
D0 value

Preliminary result from Lenz, Nierste + CKM fitters

(soon!)

$$S_{\psi\varphi} = 0.78 \begin{matrix} +0.12 \\ -0.17 \end{matrix}$$

3σ range : $[0.07,\ 1]$

(Without latest CDF result !) (0.8 σ)

Louise Oakes´s talk in Torino

But CDF cannot exclude values above 0.5 !

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

Patterns of Deviations from CPV – SM Predictions

$$K^0 - \overline{K}^0 \qquad (\varepsilon_K) \qquad \frac{|\varepsilon_K|_{SM}}{|\varepsilon_K|_{exp}} \approx 0.83 \pm 0.10$$

$$B_d^0 - \overline{B}_d^0 \qquad \left(S_{\psi K_s}\right) \qquad \left(S_{\psi K_s}\right) \cong \begin{array}{ll} 0.74 \pm 0.04 & \text{(SM)} \quad \text{(UTfit)} \\ 0.672 \pm 0.022 & \text{(exp)} \end{array}$$

$$B_s^0 - \overline{B}_s^0 \qquad \left(S_{\psi\varphi}\right) \qquad \frac{\left(S_{\psi\varphi}\right)_{exp}}{\left(S_{\psi\varphi}\right)_{SM}} \approx 10 - 20$$

Do these deviations signal non-MFV interactions at work ?

(non-SUSY)

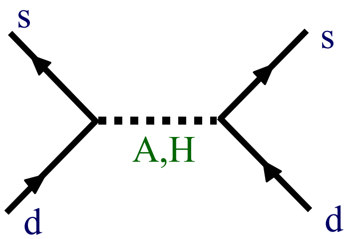
General 2HDM with MFV and Flavour Blind CPV Phases

(1005.5310)

(AJB, Carlucci, Gori, Isidori)

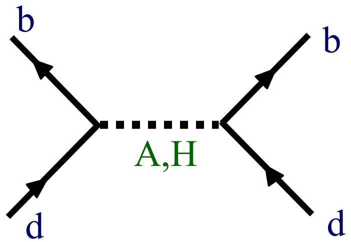
Provides correct pattern

ε_K :



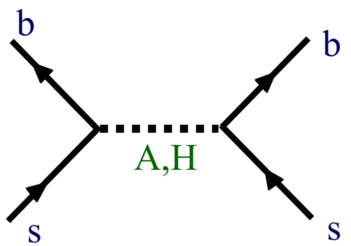
$$\approx \left[\frac{m_d m_s}{M_H^2}\right] m_t^4 (\tan\beta)^2 \left(V_{ts}^* V_{td}\right)^2$$ (tiny)

$S_{\psi K_s}$:



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

$S_{\psi\varphi}$:



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

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

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

Large RG QCD effects Q_{LR}

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

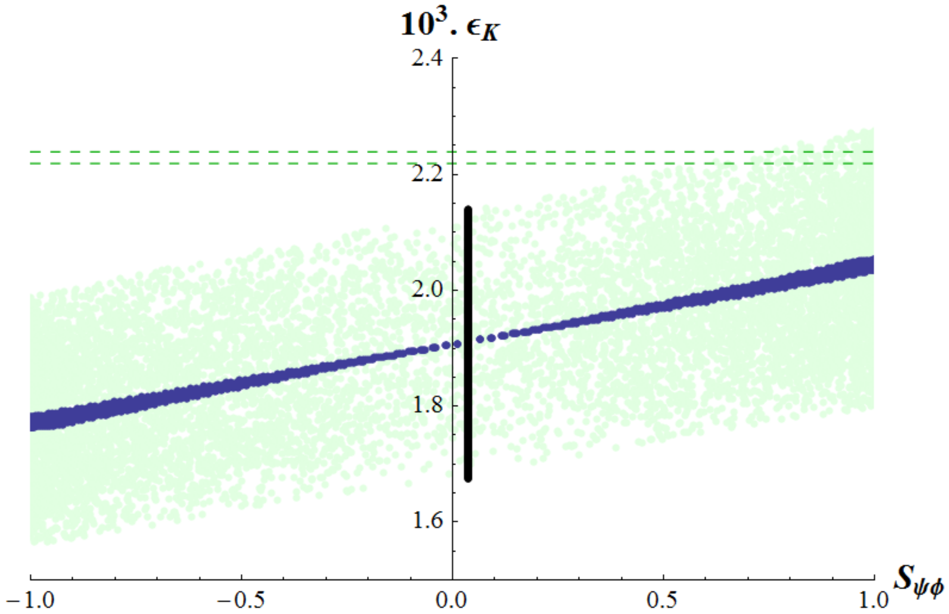
$\left(|\varepsilon_K| \text{ enhanced}\right)$

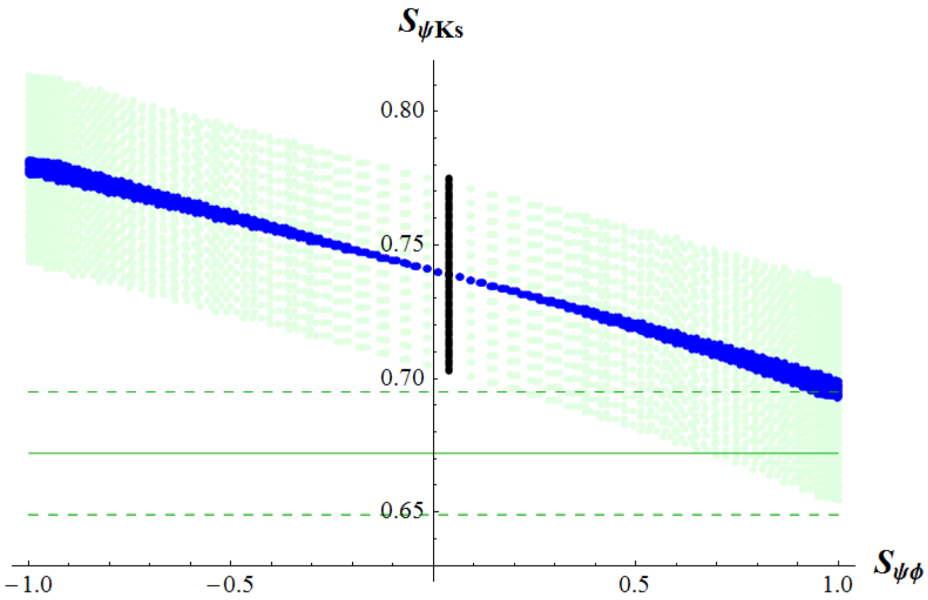
$$\frac{\tan\beta \approx 10-20}{M_H \approx 250\,\mathrm{GeV}}$$

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

(AJB, Carlucci, Gori, Isidori)

Correct pattern of NP effecs





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

Z-Penguin + Boxes (SM CMFV)

SM

$$Br(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \cdot 10^{-9}$$
$$Br(B_d \to \mu^+\mu^-) = (1.0 \pm 0.1) \cdot 10^{-10}$$

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

AJB (03)

CMFV "Golden Relation"

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

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

(0.95±0.03) Lattice

Valid in all CMFV models

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

95% CL

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

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

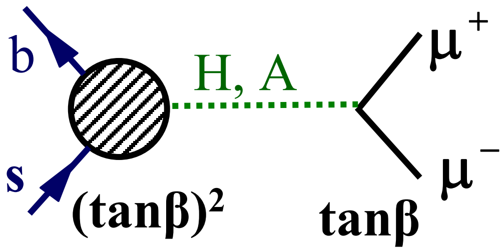
Fleischer et al

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

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

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

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

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

(Z-penguin)
(Blanke et al) (09)

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

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

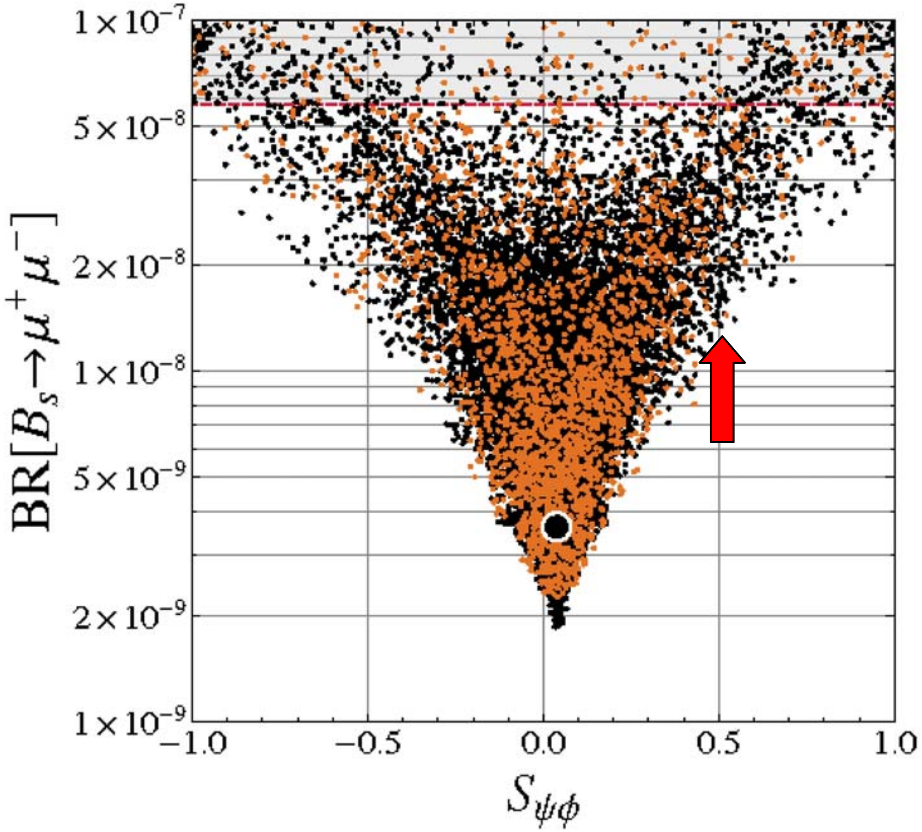
CDF, D0
LHCb

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

SUSY

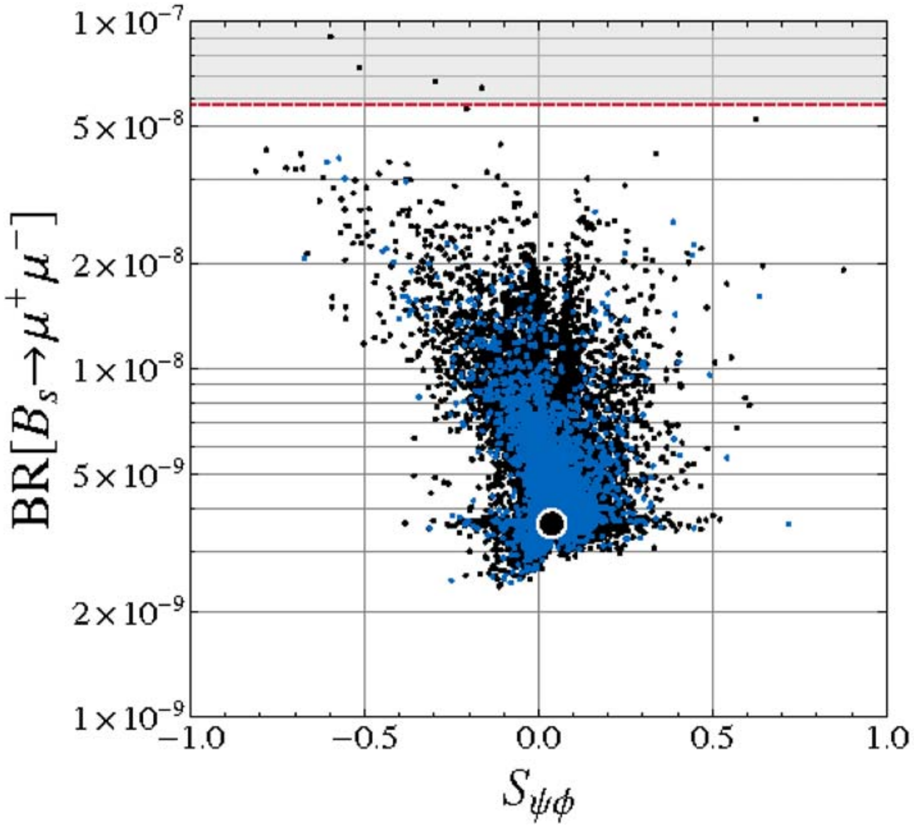
ABGPS

Solution 3 to ε_K-Anomaly
Abelian (AC)



(Large Effects in D^0-$\bar{D}^0$)

Solution 1 to ε_K-Anomaly
Non-Abelian (RVV)

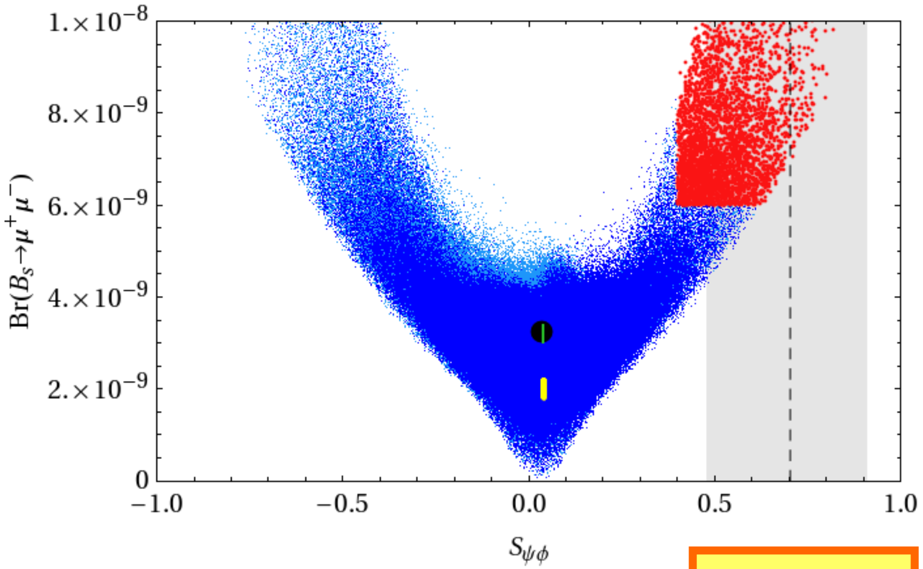


(Small Effects in D^0-$\bar{D}^0$)

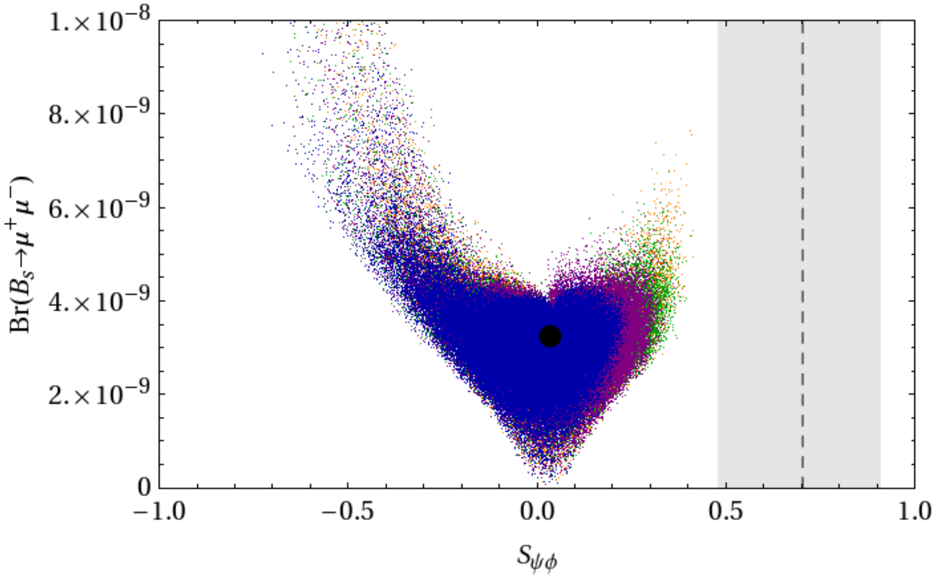
$\mathrm{Br}\left(B_s \to \mu^+\mu^-\right)$ vs $S_{\psi\varphi}$

4G

BDFHPR



CDF D0



Adding ε'/ε Constraint

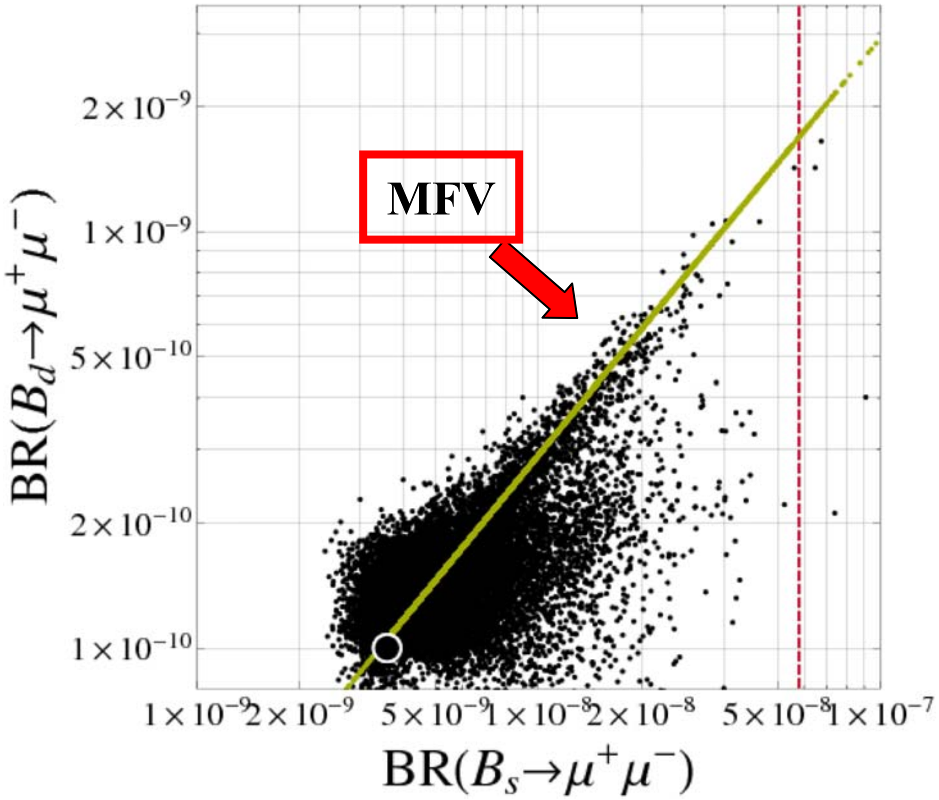
4G has hard time to describe simultaneously ε'/ε and $S_{\psi\varphi} > 0.2$ if $B_{6,8}$ within 20% from large N values

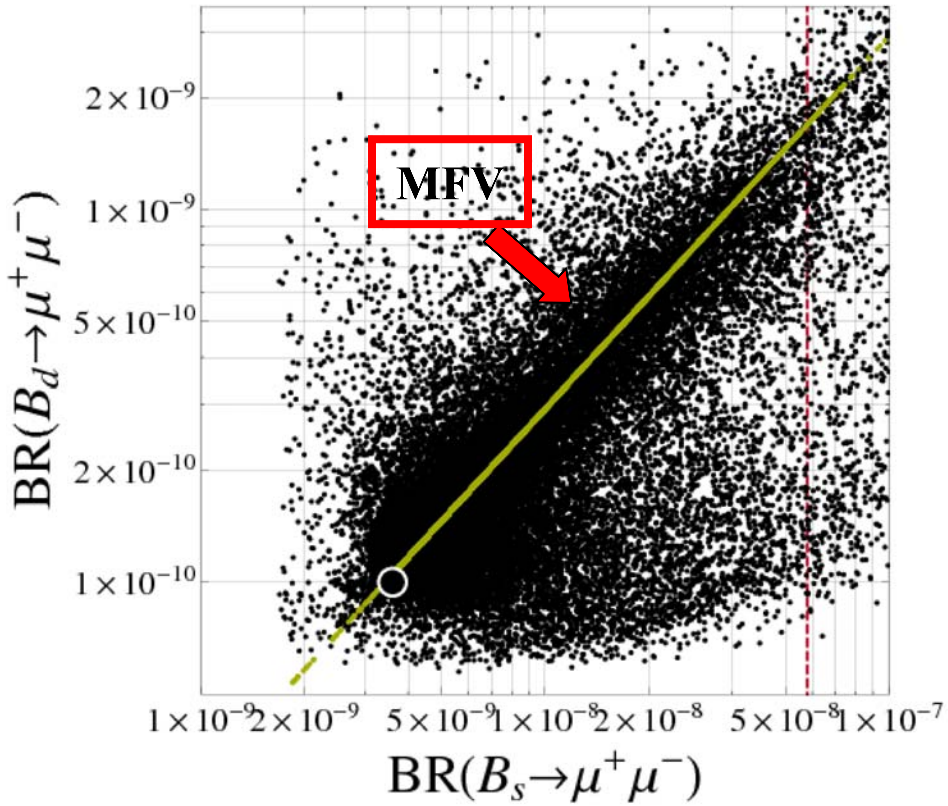
ABGPS

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

SUSY

MFV **AJB; Hurth, Isidori, Kamenik, Mescia**



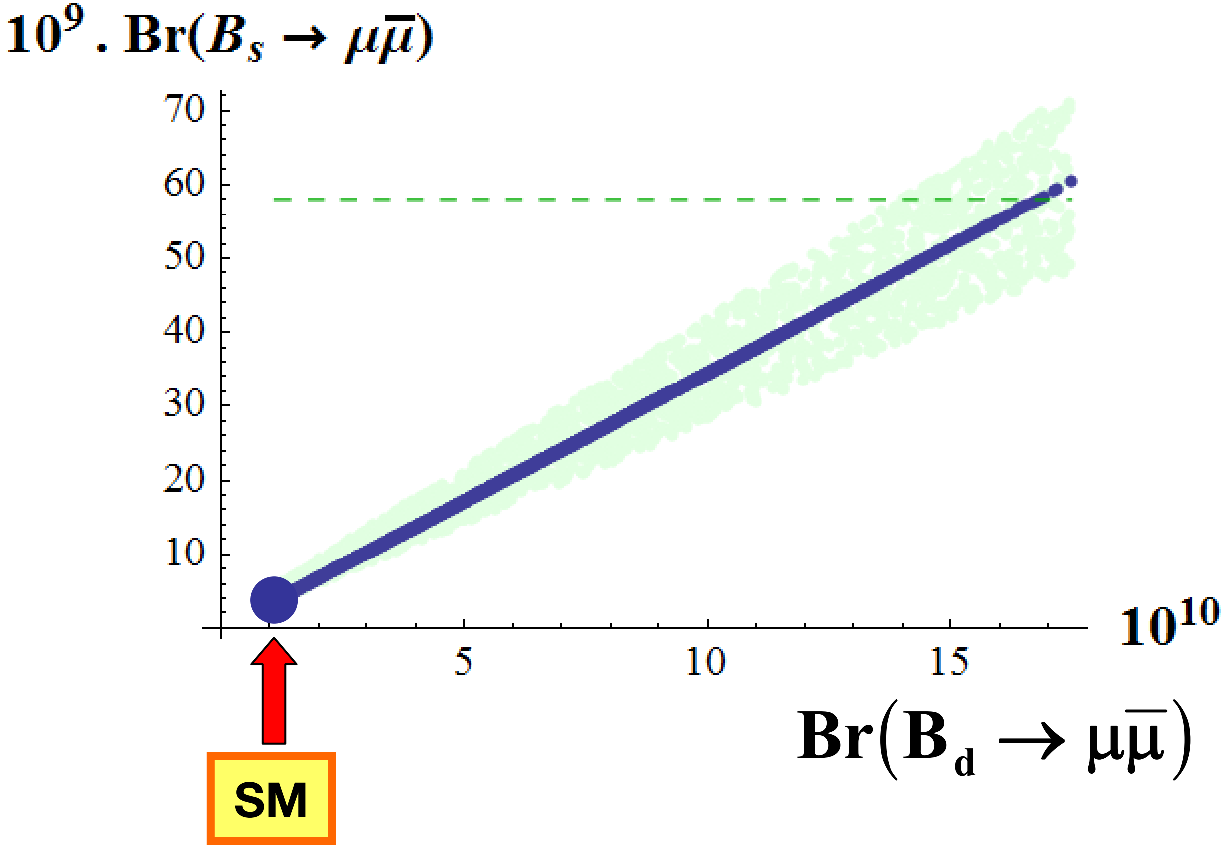


RVV2 **(RH currents)**

LH currents

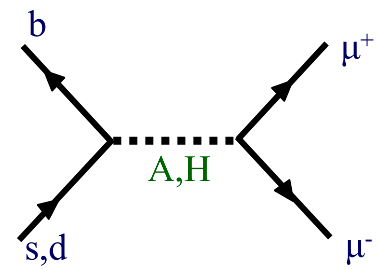
$$\boxed{B_{s,d} \to \mu^+\mu^- \text{ in 2HDM - MFV}} \approx (\tan\beta)^4 / M_A^4$$

(AJB, Carlucci, Gori, Isidori)



within few%
determined by

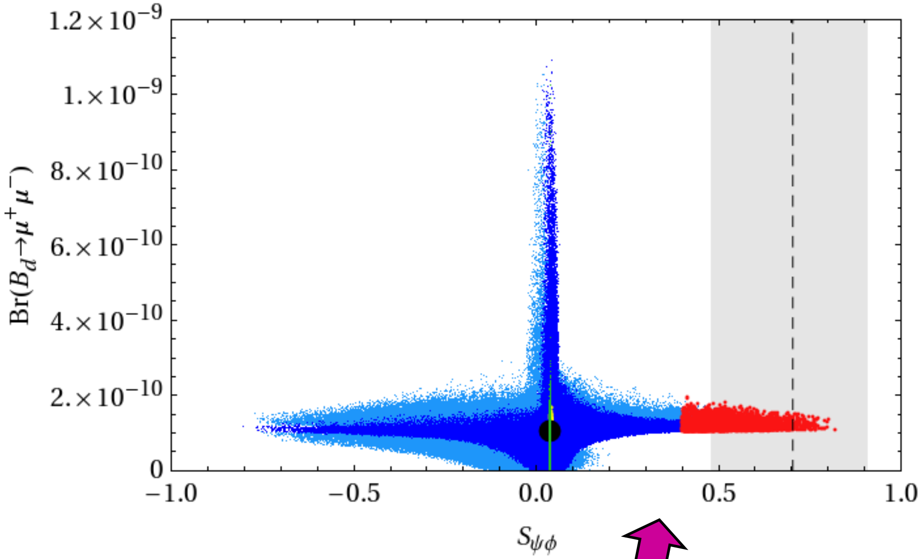
$$\frac{\Delta M_s}{\Delta M_d}$$

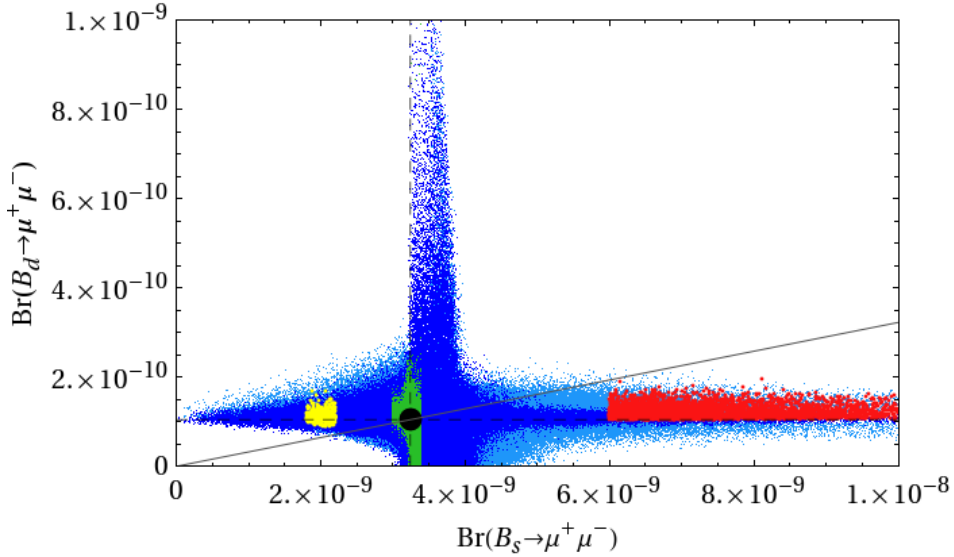


$Br(B_d \to \mu^+\mu^-)$ vs $Br(B_s \to \mu^+\mu^-)$

4G

BDFHPR





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

Very different patterns compared with SUSY, 2HDM, MFV

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

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

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

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

(E787, E949 Brookhaven) $\quad$ (E391a, KEK)

Future :

NA62
Project X (FNAL)

Both very sensitive to New Physics

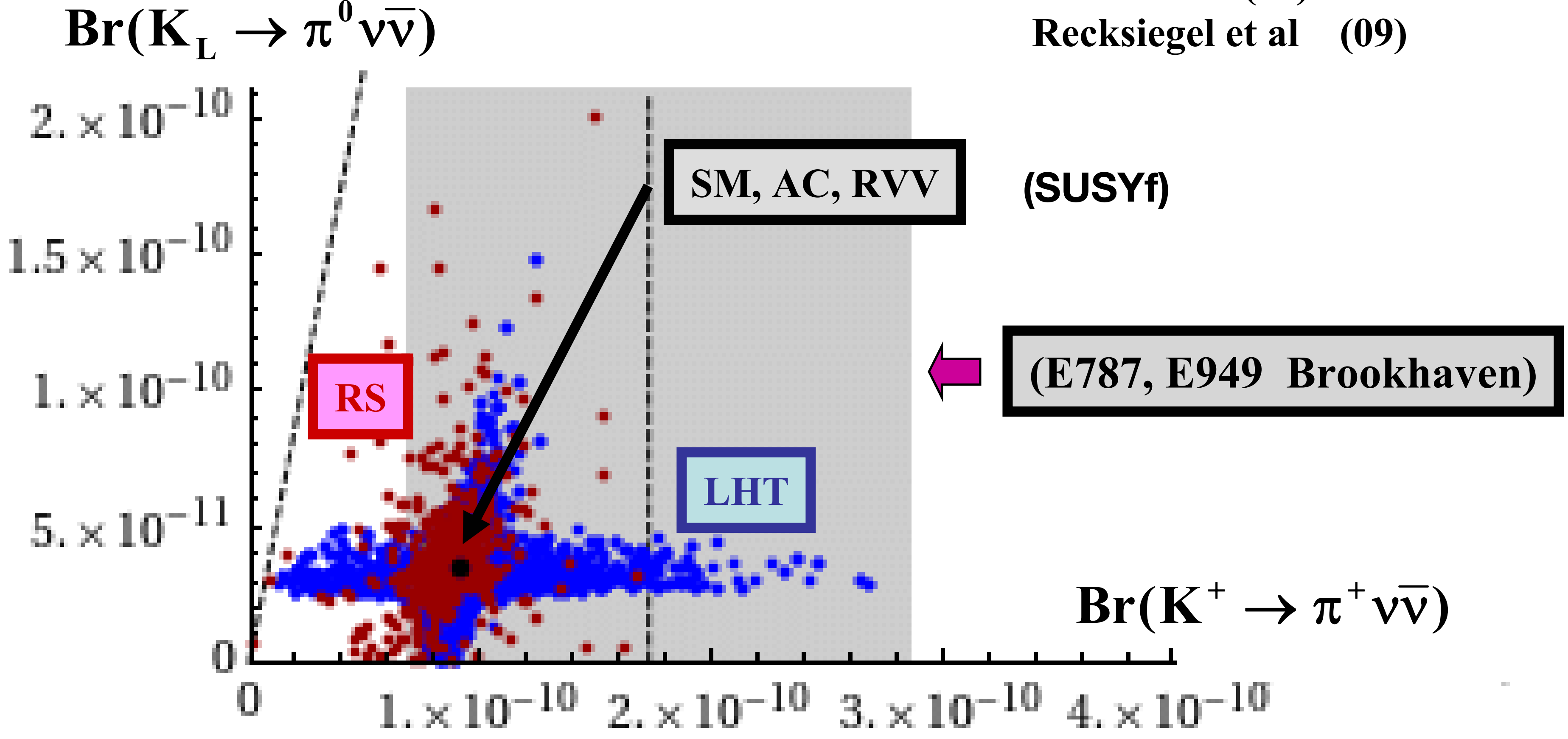
J-PARC KOTO

CP-conserving
TH uncertainty 2-3%

CP-Violation in Decay
TH uncertainty 1-2%

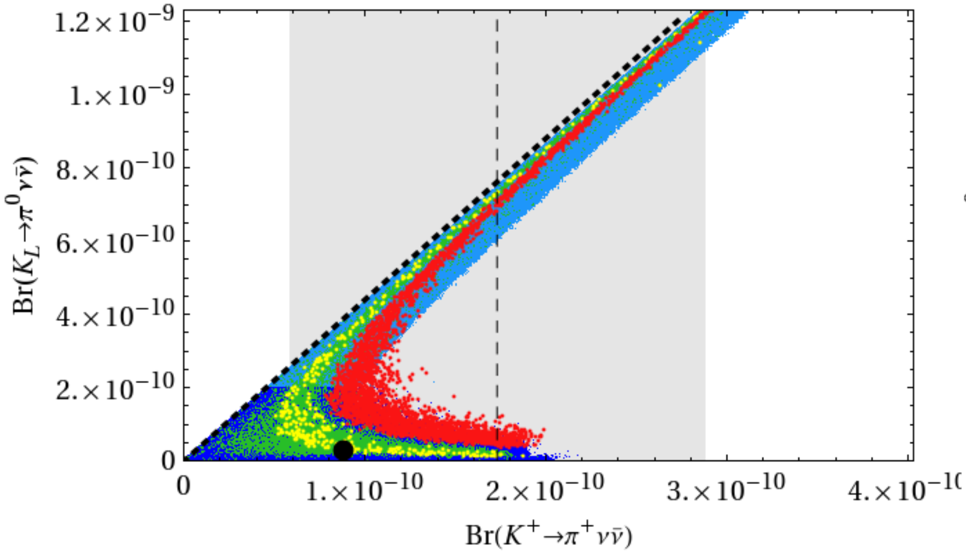
$K_L \to \pi^0 \nu\bar{\nu}$ vs. $K^+ \to \pi^+ \nu\bar{\nu}$

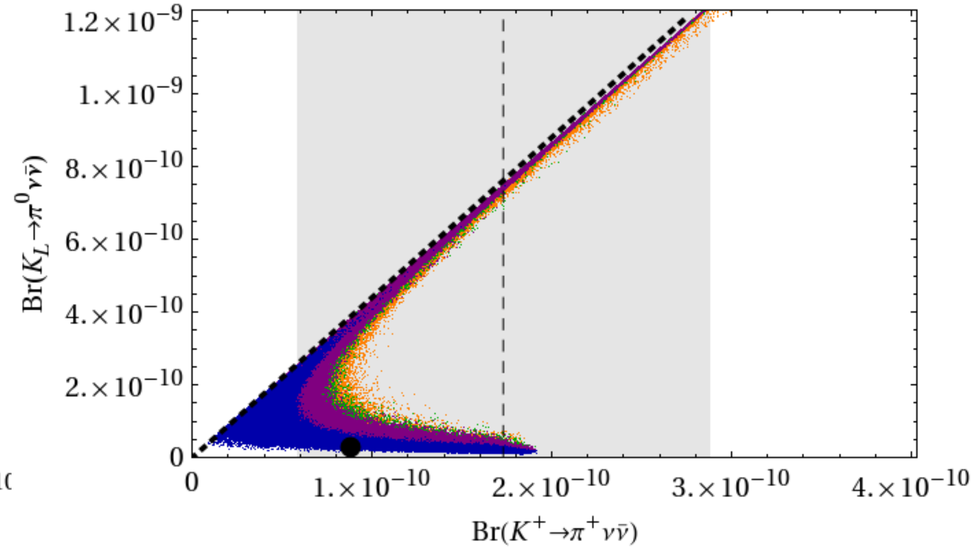
Blanke et al (08)
Goto et al (08)
Recksiegel et al (09)



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

BDFHPR



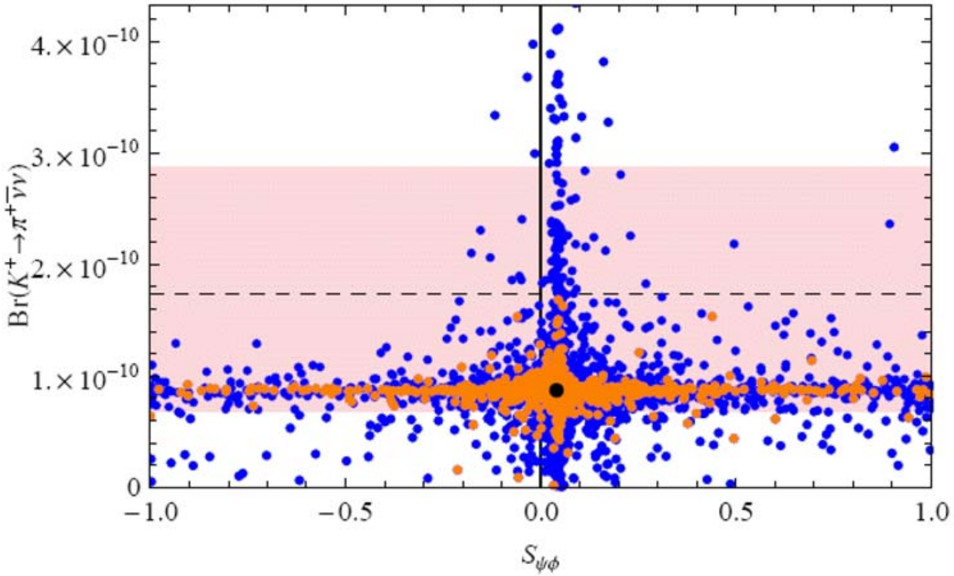


With ε'/ε Constraint

Much larger enhancements than in LHT, RS, SUSYf possible

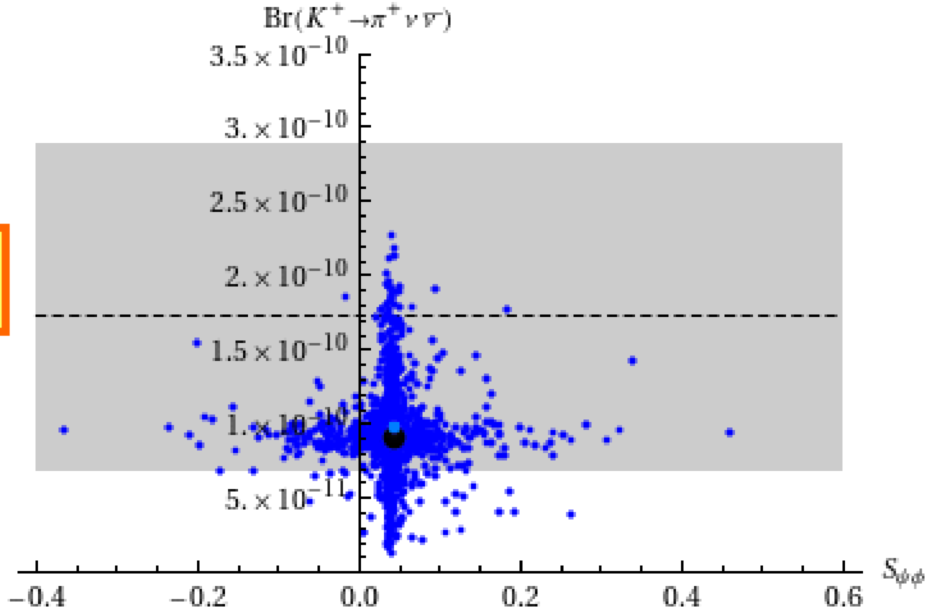
$K^+ \to \pi^+ \nu\bar{\nu}$ vs. $S_{\psi\varphi}$

(Simultaneous Large Enhancements unlikely)



RS

Blanke, AJB, Duling, Gori, Weiler

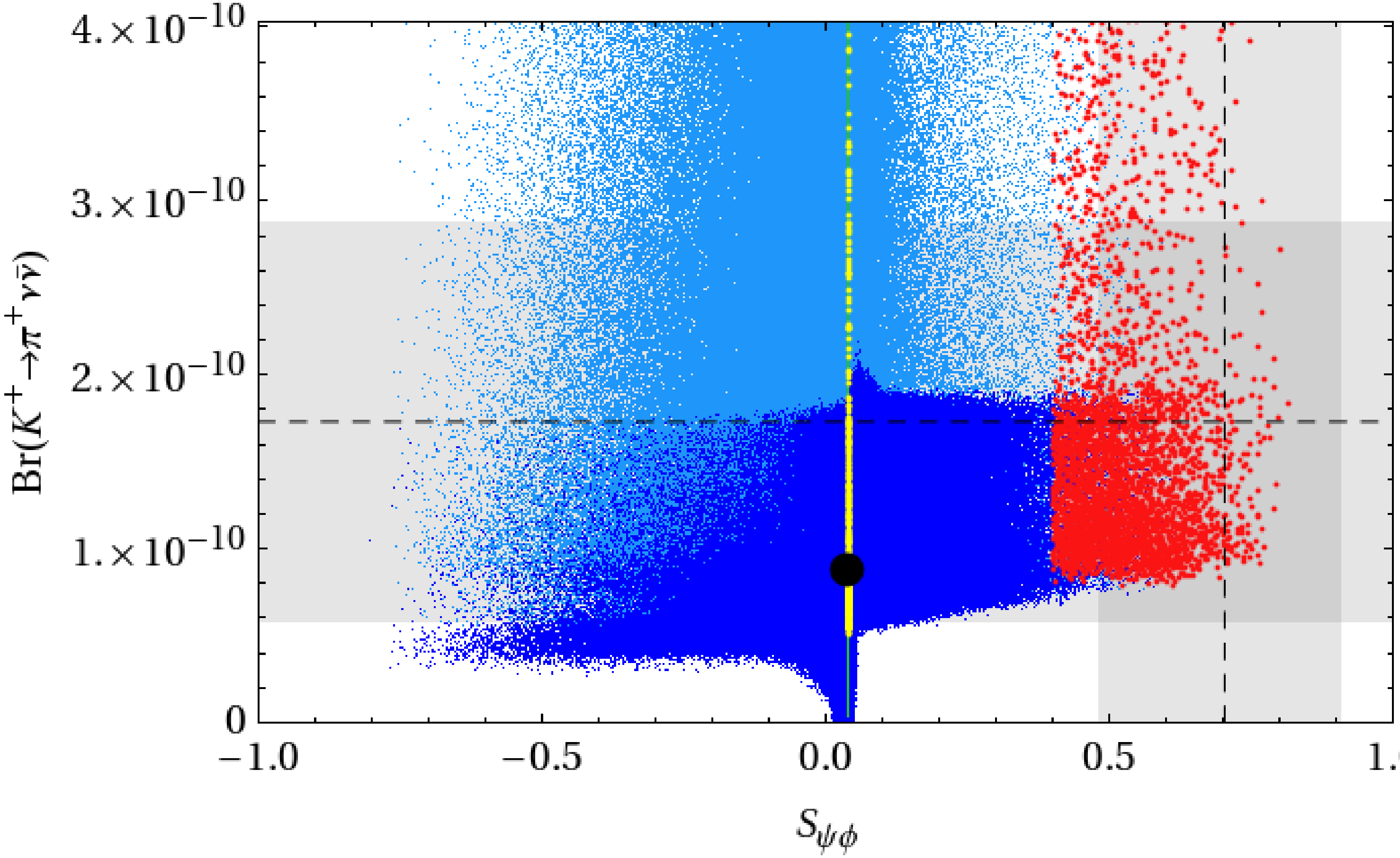


LHT

Blanke, AJB, Duling, Recksiegel, Tarantino

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ vs $S_{\psi\varphi}$ (4G)

(Simultaneous Large Enhancements Possible)



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

	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	★★★	★★★	★★	★	★★★	★	★★★	★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?	★

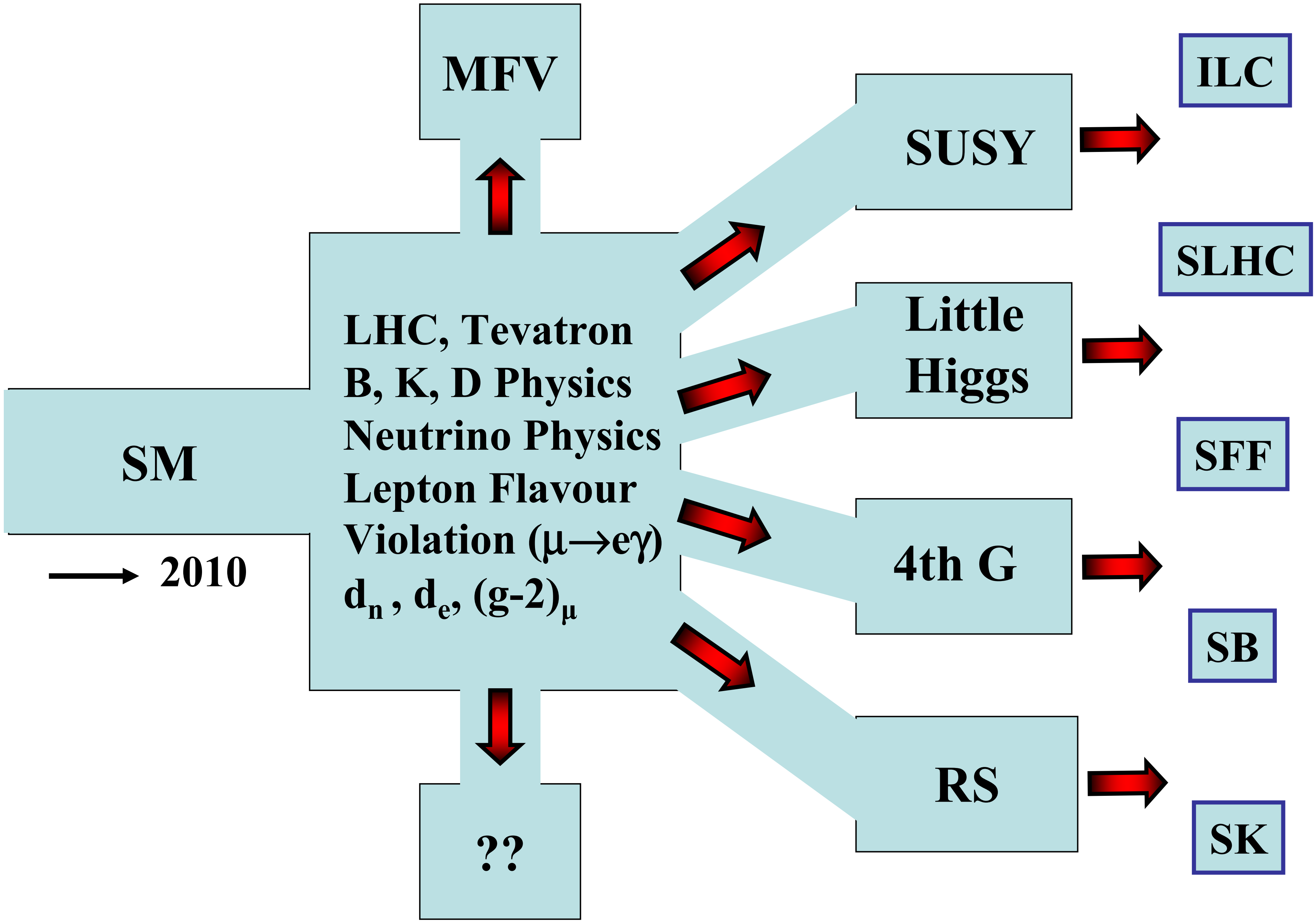
2020 Vision

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

7.

Outlook

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


MFV
SUSY
ILC
SLHC
Little Higgs
SFF
LHC, Tevatron
B, K, D Physics
Neutrino Physics
Lepton Flavour
Violation ($\mu \to e\gamma$)
d_n , d_e, $(g-2)_\mu$
SM
2010
4th G
SB
RS
SK
??

Final Messages of this Talk

Flavour Physics (Quarks and Leptons) :

Many observables (decays) not measured yet or measured poorly. Flavour Physics only now enters the precision era.

Spectacular deviations from SM still possible

Interplay

Direct searches at Tevatron, LHC, ILC

Final Messages of this Talk

Flavour Physics (Quarks and Leptons) :

Many observables (decays) not measured yet or measured poorly. Flavour Physics only now enters the precision era.

Spectacular deviations from SM still possible

Interplay

Direct searches at Tevatron, LHC, ILC

DNA Flavour Test of NP models

Correlations between various observables can distinguish NP scenarios easier than LHC !

Great discoveries and goals are just ahead of us !

Superstars of 2010 – 2015 (Flavour Physics)

$S_{\psi\varphi}$

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

★

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

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

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

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

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

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

γ
from Tree
Level
Decays

$\mu \to e\gamma$

$\tau \to \mu\gamma$

$\tau \to e\gamma$

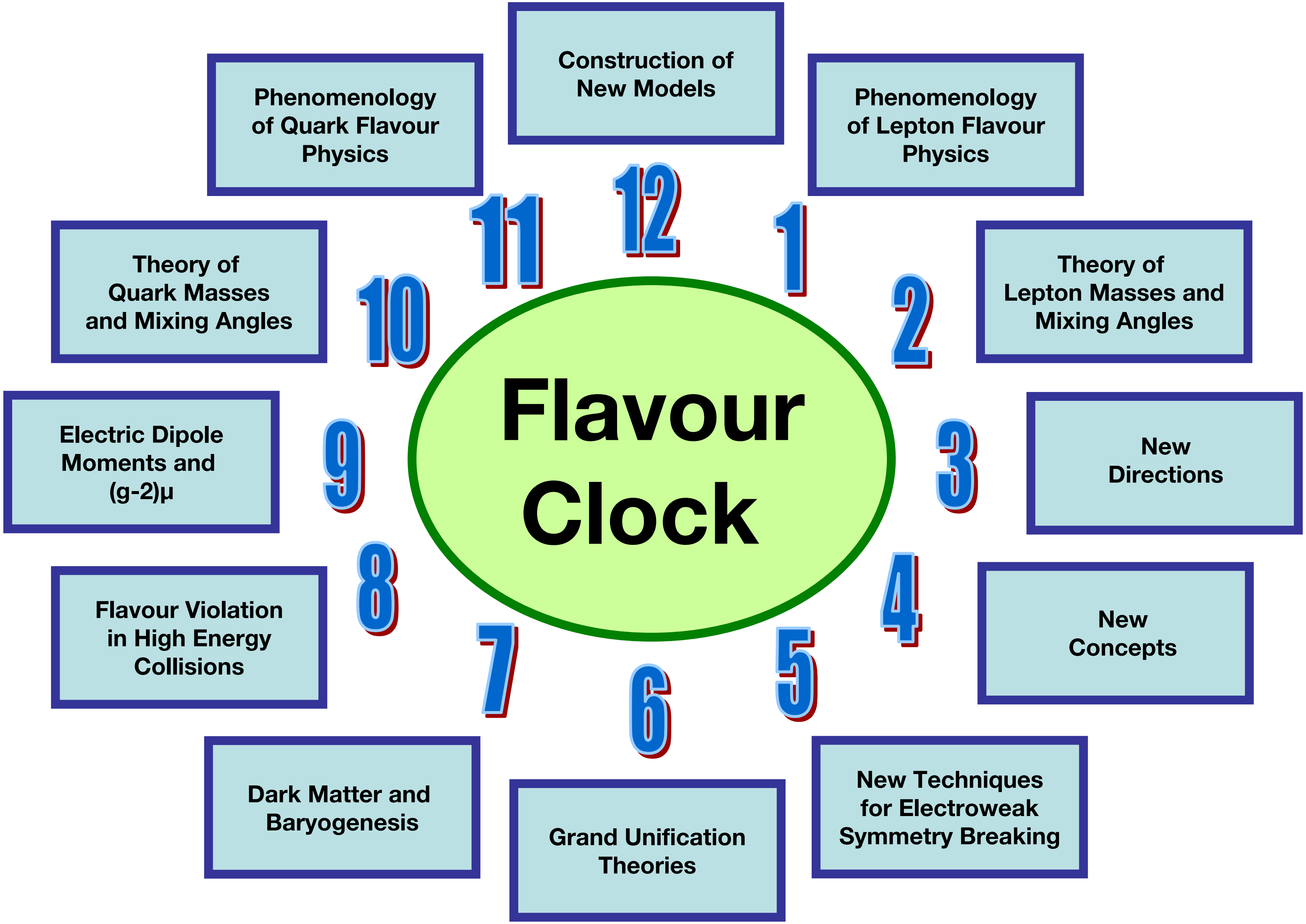
$\mu \to 3e$

$\tau \to 3$ leptons

ε'/ε

(Lattice)

EDM´s
$(g\text{-}2)_\mu$


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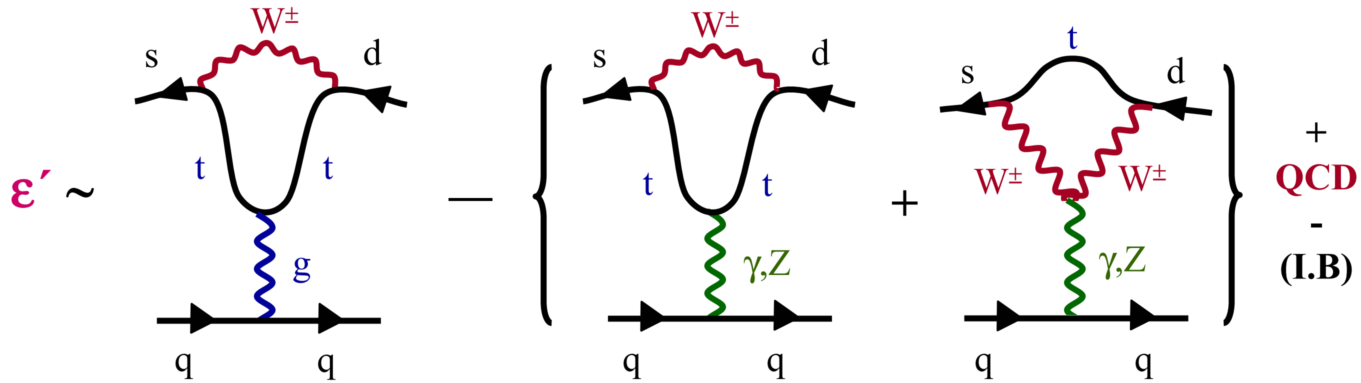
Electric Dipole Moments and (g-2)μ
10
Theory of Quark Masses and Mixing Angles
11
Phenomenology of Quark Flavour Physics
Thank You!

Backup

ε'/ε in the Standard Model



QCD - Penguins

Electroweak - Penguins

$$\frac{\varepsilon'}{\varepsilon} = 10^{-4}\left[\frac{\mathrm{Im}\,\lambda_t}{1.20\cdot 10^{-4}}\right] F\left(m_t, \Lambda^{(4)}_{\overline{MS}}, m_s, B_6, B_8, \Omega_{IB}\right)$$

$$F \approx 16\cdot\left[\frac{110\ \mathrm{Mev}}{m_s(2\ \mathrm{GeV})}\right]^2 \left[\underbrace{B_6}_{P_{QCD}}\left(1-\Omega_{IB}\right) - \tilde{Z}(m_t)\underbrace{B_8}_{P_{EW}}\right]\left(\frac{\Lambda^{(4)}_{\overline{MS}}}{340\ \mathrm{MeV}}\right)$$

$$\tilde{Z}(m_t) \cong 0.4\left[\frac{m_t}{165\ \mathrm{GeV}}\right]^{2.5} \quad ; \quad \Omega_{IB} = \text{Isospin Breaking}$$

$$\mathrm{Im}\,\lambda_t = \mathrm{Im}\left(V^*_{ts}V_{td}\right) = |V_{ub}||V_{cb}|\sin\delta$$

Basic Parameters : $\mathrm{Im}\,\lambda_t,\ \Lambda^{(4)}_{\overline{MS}},\ B_6,\ B_8,\ m_s,\ \Omega_{IB}$

First Round of Measurements

$$\frac{\varepsilon'}{\varepsilon} = \begin{cases} (23 \pm 6.5) \cdot 10^{-4} & \text{(NA31)} \\ (7.4 \pm 5.9) \cdot 10^{-4} & \text{(E731)} \end{cases}$$

Second Round of Measurements

$$\frac{\varepsilon'}{\varepsilon} = \begin{cases} (14.7 \pm 2.2) \cdot 10^{-4} & \text{(NA48)} \\ (20.7 \pm 2.8) \cdot 10^{-4} & \text{(KTeV)} \end{cases}$$

Grand Average :

$$\frac{\varepsilon'}{\varepsilon} = (16.6 \pm 1.6) \cdot 10^{-4}$$

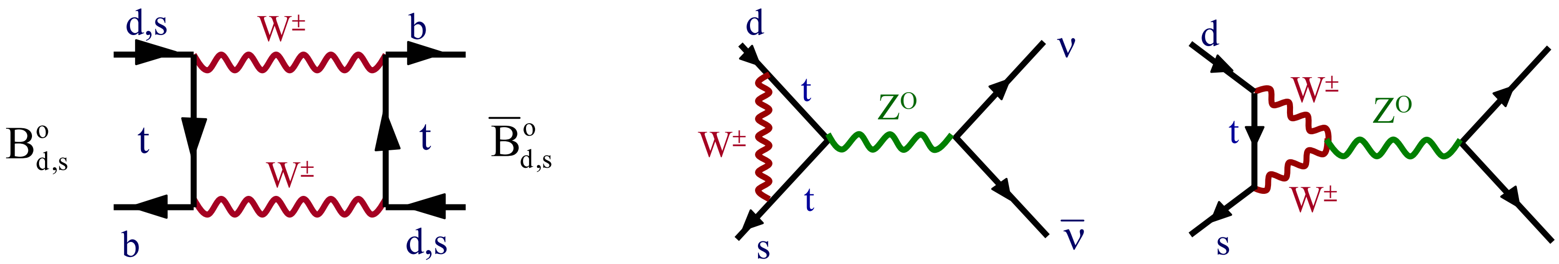
Waiting for KLOE

Direct CP Violation firmly established

Starting Point : $\mathcal{L} = \mathcal{L}_{SM}\left(g_i, m_i, V^i_{CKM}\right) + \mathcal{L}_{NP}\left(g_i^{NP}, m_i^{NP}, V^i_{NP}\right)$

Goal : Identify the effects of $\mathcal{L}_{NP}$ in weak decays in the presence of the background from $\mathcal{L}_{SM}$

First Implication from $\mathcal{L}$: Feynman Diagrams



+ NP

$B_d^o - \overline{B}_d^o$ Mixing

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

Putting S0(10)-SUSY-GUT of Dermisek-Raby into difficulties

M. Albrecht, W. Altmannshofer, AJB, D. Guadagnoli, D. Straub

1. The Model gives a nice description of quark and lepton masses, PMNS and most of CKM elements.

Also SUSY Spectrum

2. But fails to describe simultaneously the data on

$$B_{s,d} \to \mu^+\mu^-,\ B \to X_s\gamma,\ B \to X_s l^+l^-,\ B_u \to \tau\nu$$

Generally too low

3. Gives $|V_{ub}| \approx 3.2 \cdot 10^{-3}$

$$< \underbrace{(4.2 \pm 0.3) \cdot 10^{-3}}_{\text{Exp.}}$$

Some recent solutions: Altmannshofer et al.

Very strong Constraints on New Physics

$$\mathrm{Br}\left(B \to X_S\gamma\right)_{\mathrm{exp}} = \left(3.52 \pm 0.24\right)\cdot 10^{-4}$$

$$\mathrm{Br}\left(B \to X_S\gamma\right)_{\mathrm{SM}} = \begin{cases} \left(3.15 \pm 0.23\right)\cdot 10^{-4} & \text{(Misiak et al)} \\ \left(2.98 \pm 0.26\right)\cdot 10^{-4} & \text{(Becher, Neubert)} \end{cases}$$

$$\mathrm{Br}\left(B \to X_S l^+ l^-\right)_{\mathrm{exp}} = \begin{cases} \left(1.6 \pm 0.5\right)\cdot 10^{-6} & (\text{low } q^2) \\ \left(4.4 \pm 1.3\right)\cdot 10^{-7} & (\text{high } q^2) \end{cases}$$

$$\mathrm{Br}\left(B \to X_S l^+ l^-\right)_{\mathrm{SM}} = \begin{cases} \left(1.6 \pm 0.1\right)\cdot 10^{-6} & (\text{low } q^2) \\ \left(2.3 \pm 0.8\right)\cdot 10^{-6} & (\text{high } q^2) \end{cases}$$

Isidori et al. (incl.)
Gorbahn et al. (incl.)
Feldmann et al. (excl.)

Zero in A_{FB}

$$\hat{s}_0 = \left(3.50 \pm 0.12\right)\mathrm{GeV}^2$$

TH
very clean

$$A_{CP}\left(B \to X_S\gamma\right)_{\mathrm{exp}} = 0.004 \pm 0.036$$

$$A_{CP}\left(B \to X_S\gamma\right)_{\mathrm{SM}} = 0.004 \pm 0.002$$

All this can be improved at Super-B
Super-Belle

(Still factor 10 enhancement possible !)

$B^+ \to \tau^+ \nu$

$$\boxed{Br(B^+ \to \tau^+ \nu)_{exp} = (1.4 \pm 0.4) \cdot 10^{-4}}$$

(Belle, BaBar)

$$Br(B^+ \to \tau\nu)_{SM} \approx G_F^2 F_B^2 |V_{ub}|^2 = (0.95 \pm 0.20) \cdot 10^{-4}$$

$$\frac{Br(B^+ \to \tau\nu)_{MSSM}}{Br(B^+ \to \tau\nu)_{SM}} = \left[1 - \left(\frac{m_B}{m_{H^\pm}}\right)^2 \frac{\tan^2\beta}{1 + \varepsilon_0 \tan\beta}\right]^2$$

(Hou)
(Isidori, Paradisi)

Tree-Level
H^+ exchange

This decay could be problematic for MSSM-MFV with large tanβ

Altmannshofer, AJB, Guadagnoli, Wick (07)

The General Mechanism of Little Higgs Models

The "little Higgs" is a pseudo-Nambu-Goldstone boson of a spontaneously broken symmetry. This symmetry is also explicitly broken but only "collectively", i.e. the symmetry is broken when two or more couplings in the Lagrangian are non-vanishing. Setting any one of these couplings to zero restores the symmetry and therefore the masslessness of the "little Higgs".

[N. Arkani-Hamed, A.G. Cohen, H. Georgi (2001)]

1. The **light Higgs** is interpreted as a **Goldstone boson** of a spontaneously broken global symmetry **(G)**

2. **Gauge and Yukawa couplings** of the Higgs are introduced by **gauging a subgroup of G**

3. ``Dangerous´´ **quadratic corrections** are **avoided at one-loop** through **Collective Symmetry Breaking**
   (the Higgs becomes massive only when two couplings are non-vanishing)

- The Higgs dynamics is described (similarly to ChPT) by a **non-linear sigma model up to Λ ~10TeV**
- The **UV completion** is **unknown** (another LH?,SUSY?,ED?)

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) — $SU(3)_F$

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

$S_{\varphi K_s} = 0.44 \pm 0.17$ $\quad$ $(S_{\varphi K_s})_{SM} \approx (S_{\psi K_s})_{SM} + 0.02 \approx 0.70$

(Beneke)

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

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

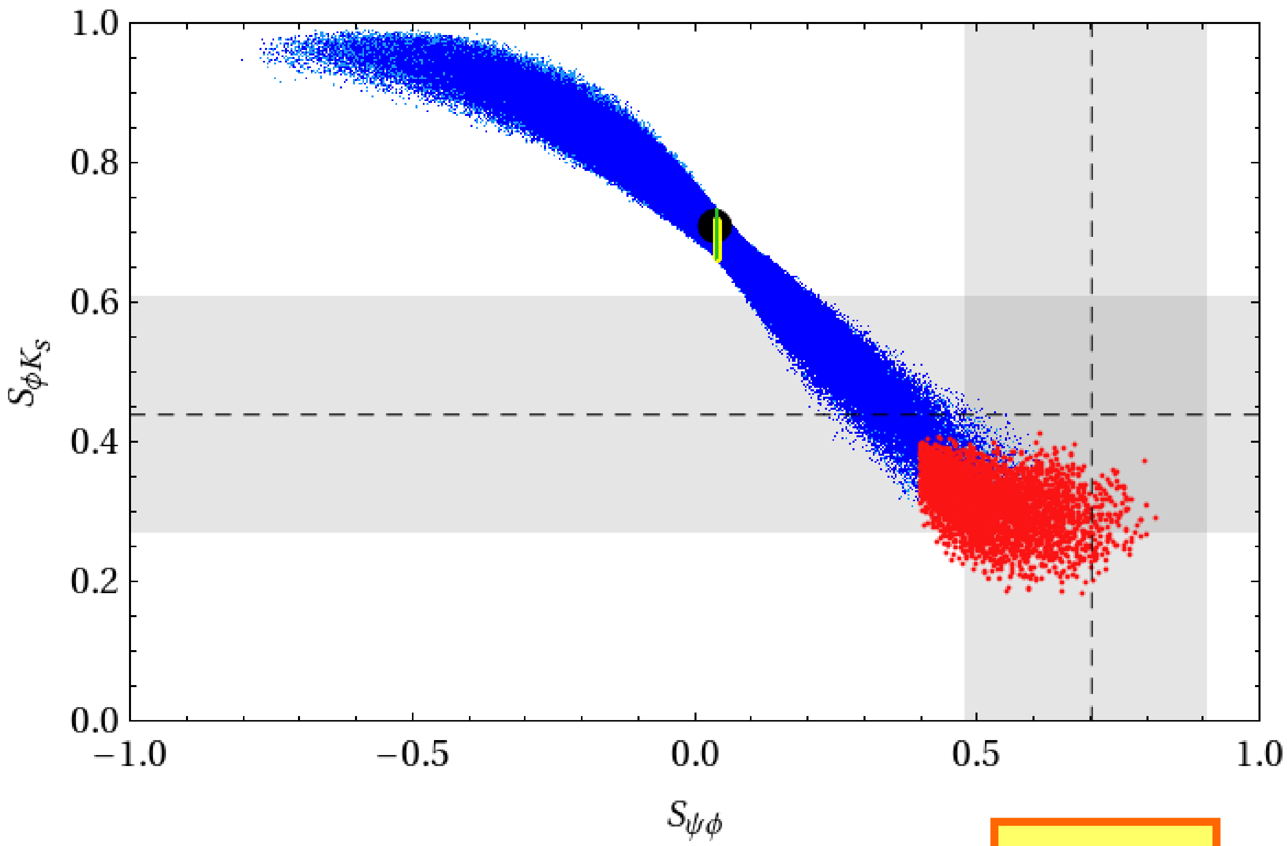
$a_\mu = \frac{1}{2}(g-2)_\mu$

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

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

[e cm]

Simultaneous Solution to $S_{\varphi K_S}$ and $S_{\psi\varphi}$ Anomalies in 4G Model



BaBar Belle

CDF D0

$\mu \to e\gamma$: State of the Art

- **SM (+ Dirac ν_R):**

very much suppressed due to the smallnes of m_ν

$$Br(\mu \to e\gamma)_{SM} \approx 10^{-54}$$

- **Experimental bound:**

[MEGA Collaboration]

$$Br(\mu \to e\gamma)_{\exp} < 1.2 \cdot 10^{-11} \quad (90\% C.L.)$$

It will be improved to ~10^{-13} by MEG in 2008

- **MSSM and LHT could explain such high values.**

WED too (Agashe et al.)

Other interesting Processes

- $\mu^- \to e^- e^+ e^-$: even more constrained than $\mu \to e\gamma$

$$Br(\mu^- \to e^- e^+ e^-)_{\exp} < 1.0 \cdot 10^{-12}$$

[SINDRUM Collaboration]

- $\tau \to \mu\gamma$ and $\tau \to e\gamma$: similar to $\mu \to e\gamma$

$$Br(\tau \to \mu\gamma)_{exp} < 1.6 \cdot 10^{-8}$$

[Belle, BaBar]

$$Br(\tau \to e\gamma)_{exp} < 9.4 \cdot 10^{-8}$$

[BaBar, Belle]

- $\tau \to \mu\pi$: semileptonic decay

$$Br(\tau \to \mu\pi)_{exp} < 5.8 \cdot 10^{-8}$$

[Belle, BaBar]

(Future: Super B)

- $\mu \to e$ conversion

$$R(\mu T_i \to e T_i) < 4.3 \cdot 10^{-12}$$

10^{-18} (J-Parc)

- $K_L \to \mu e$: flavour violating in both quark and lepton sectors

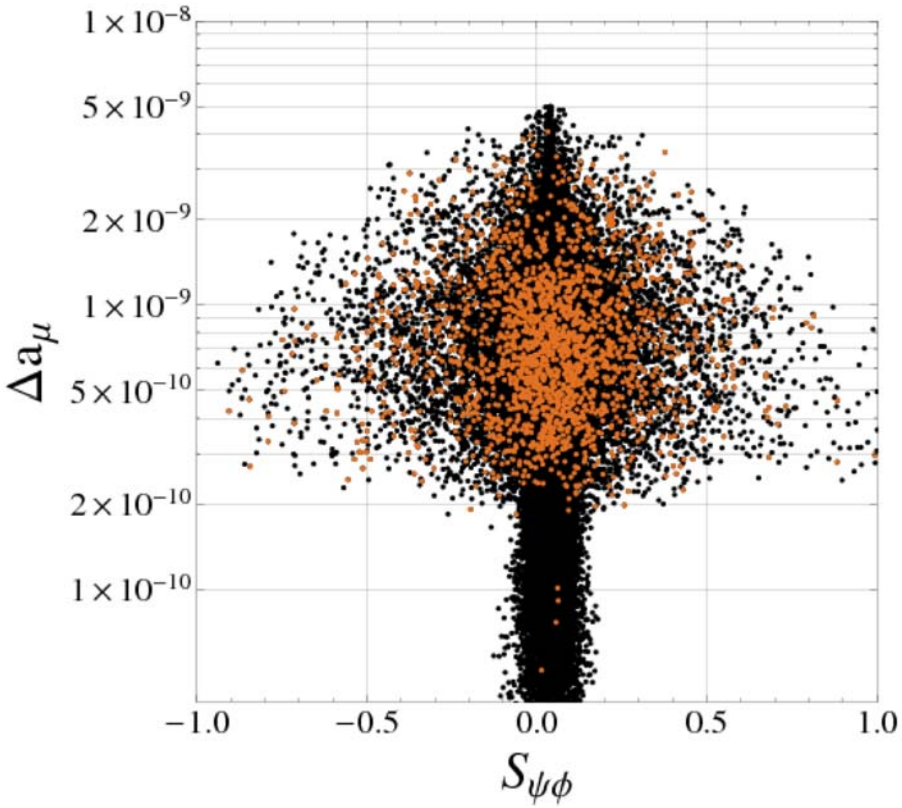
$$Br(K_L \to \mu e)_{\exp} < 4.7 \cdot 10^{-12}$$

[BNL E871 Collaboration]

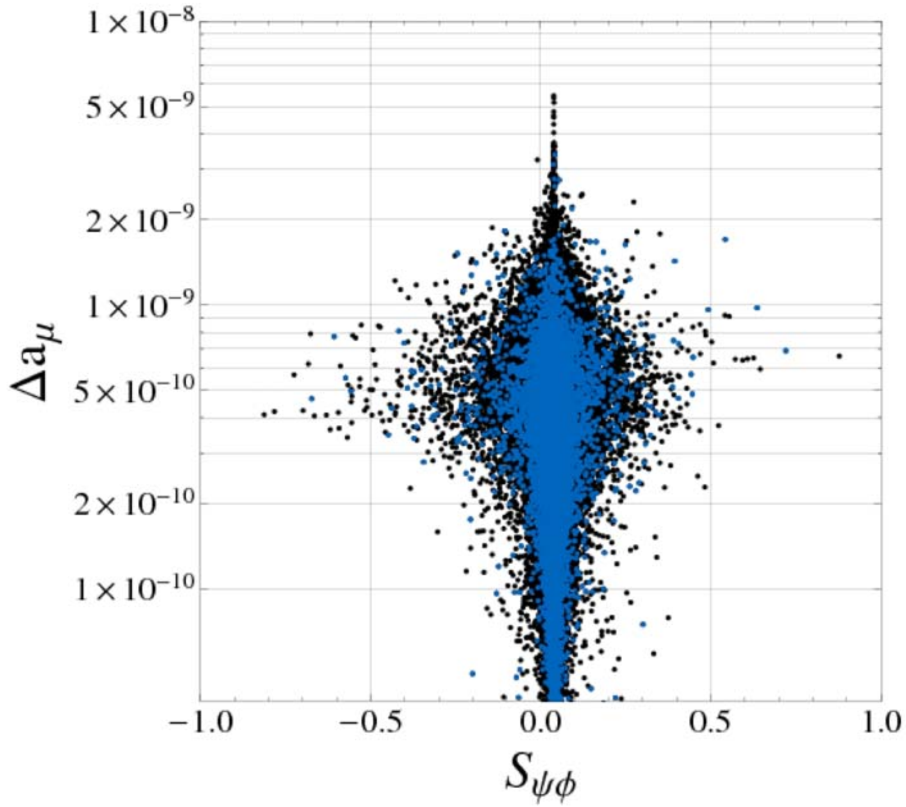
Simultaneous Solution to Δa_μ and $S_{\psi\varphi}$ Anomalies

Solution 3 to ε_K-Anomaly
Abelian (AC)

Solution 1 to ε_K-Anomaly
Non-Abelian (RVV)



(Large Effects in D^0-$\bar{D}^0$)

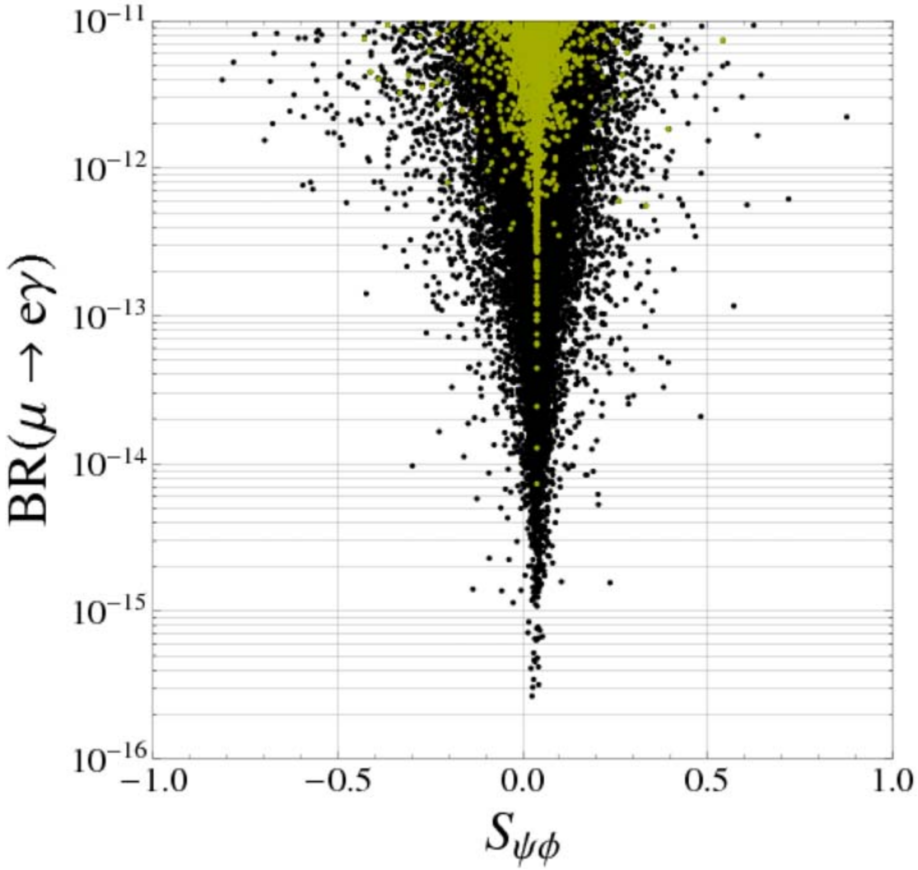


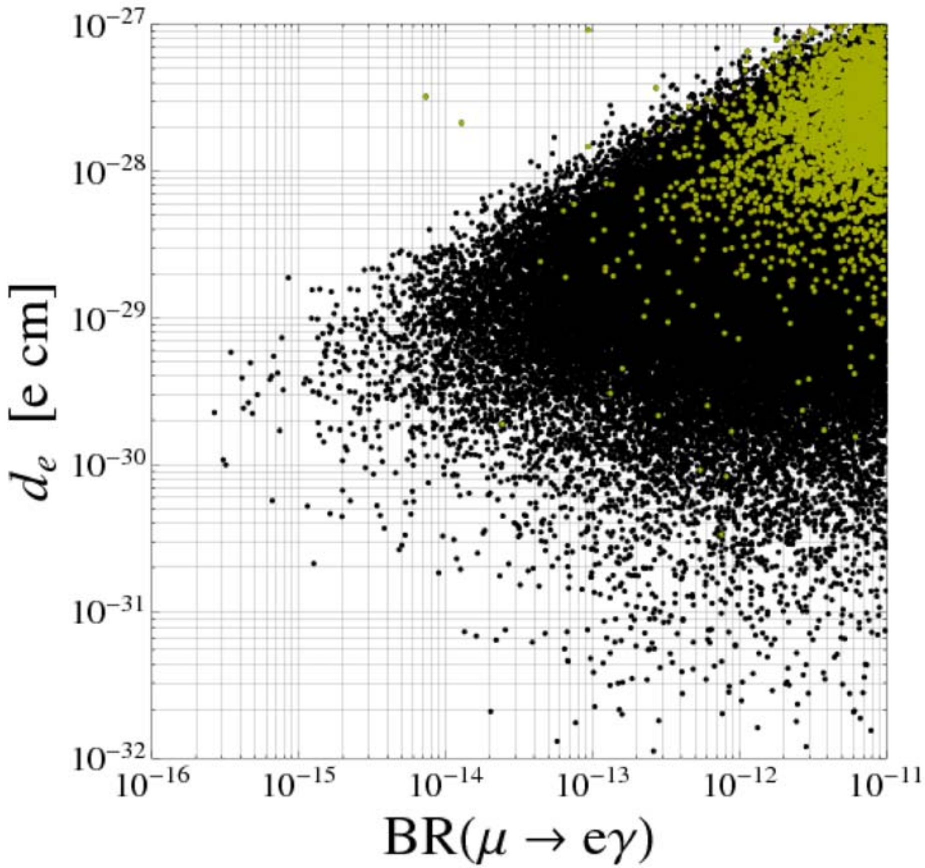
(Small Effects in D^0-$\bar{D}^0$)

ABGPS

Correlations in the SU(3) Flavour Model (RVV2)

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





Clear Distinction between MSSM and LHT

MSSM	LHT
$$\frac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu^- \to e^- \gamma)} \approx \frac{1}{161}$$	0.02 – 1
$$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau^- \to \mu^- \gamma)} \approx \frac{1}{435}$$	0.04 – 0.4

Both can reach MEGA´s μ→eγ bound

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)