Searching for New Physics with Rare Decays and CP Violation

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

Cornell University, March 25th, 2009

Overture

Main Goal of Elementary Particle Physics

→

Search for Physics Laws at very short distance scales

Heisenberg Principle : **To test 10^{-18} m we need $E \cong 200$ GeV**

Main Goal of Elementary Particle Physics → **Search for Physics Laws at very short distance scales**

Heisenberg Principle : **To test 10^{-18} m we need $E \cong 200$ GeV**

LHC $E = 4$ TeV → **Tests at $5 \cdot 10^{-20}$ m possible**

Unlikely that we can do better before 2046 through high energy collider experiments.

Main Goal of Elementary Particle Physics → **Search for Physics Laws at very short distance scales**

Heisenberg Principle : **To test 10^{-18} m we need $E \cong 200$ GeV**

LHC $E = 4$ TeV → **Tests at $5 \cdot 10^{-20}$ m possible**

Unlikely that we can do better before 2046 through high energy collider experiments.

Flavour Physics governed by Quantum Fluctuations is sensitive to $E \approx 200$ TeV and even higher energy scales → **Tests at 10^{-21} m and shorter scales possible** → **Frontiers in testing very very short distance scales belong to Flavour Physics**

but **Very high precision required !!**

Standard Model of Strong and Electroweak Interactions

Low Energy Effective Quantum Field Theory based on

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

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

2	+	4	+	6	+	6	+	4	+	6	=	28
QCD (α_{QCD}, θ_{QCD})		Electroweak Gauge Boson and Higgs Sector		Quark Masses		Lepton Masses		V_{CKM}		V_{PMNS}		

22 in the Flavour Sector ★

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

$s_{12} = |V_{us}|$, $s_{13} = |V_{ub}|$, $s_{23} = |V_{cb}|$, δ

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

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)

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

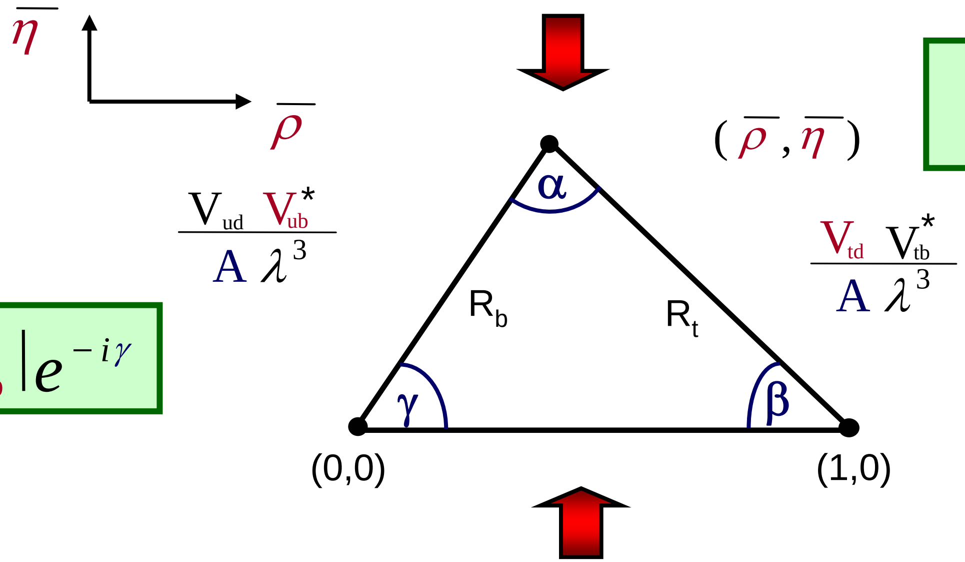
Circle around $(\bar\rho,\bar\eta) = (0,0)$

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

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

Unitarity Triangle

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

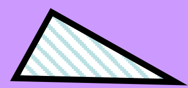


$\bar{\eta} \neq 0$ Signals CP Violation

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

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

An Important Target of Particle Physics

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

Area of unrescaled UT

Impressive Success of the CKM Picture of Flavour Changing Interactions

(GIM)

(Once quark masses determined : only 4 parameters)

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

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

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

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

~~CP~~ in B_s?

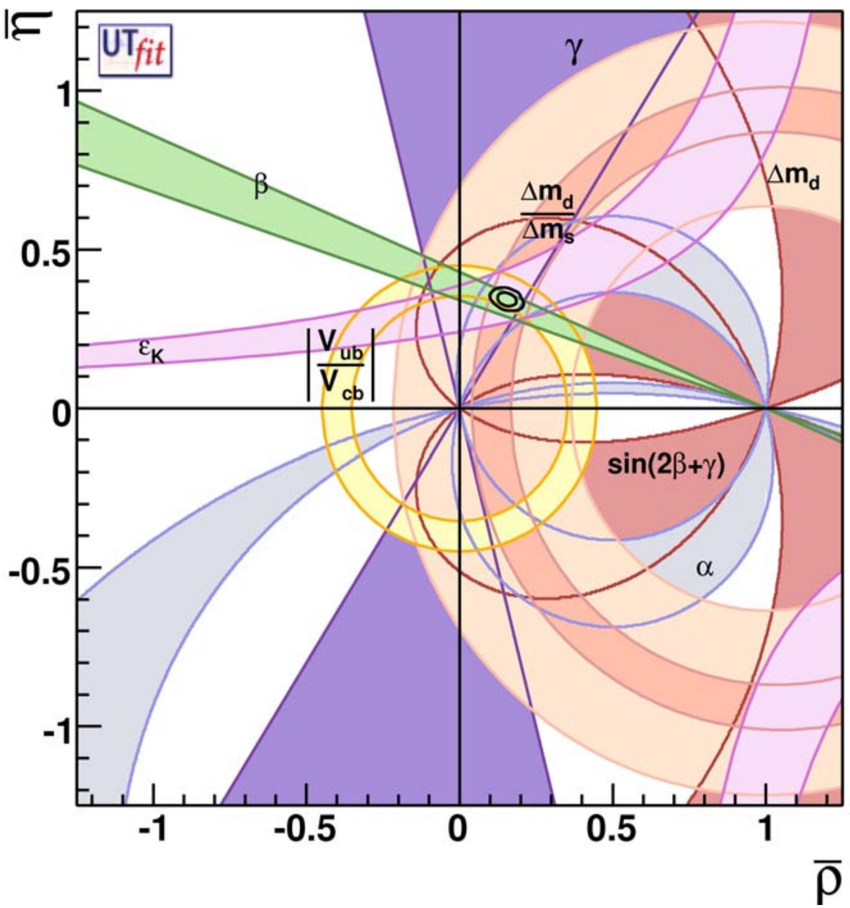
$(g-2)_\mu$?

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

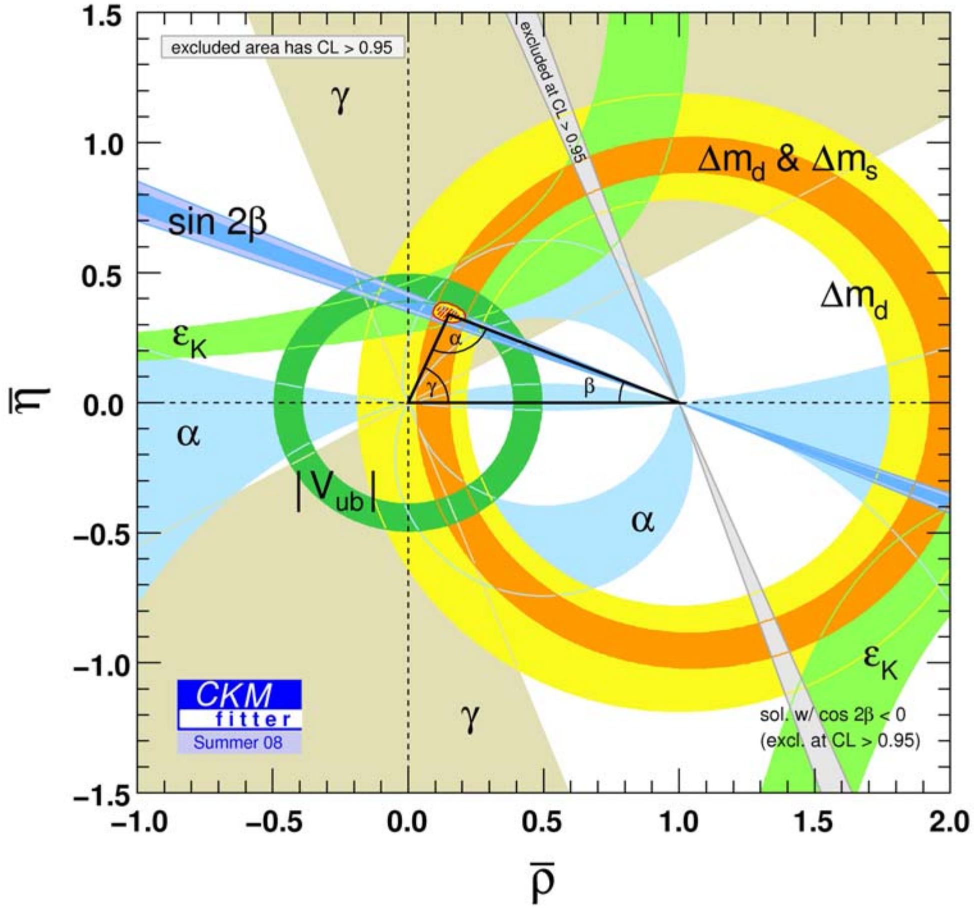
Standard Model	Exp Upper Bound
$\mathrm{Br}\left(B_s \to \mu^+\mu^-\right) \cong 3\cdot 10^{-9}$	$\sim 6\cdot 10^{-8}$
$\mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right) \cong 3\cdot 10^{-11}$	$\sim 6\cdot 10^{-8}$
$\mathrm{Br}\left(K_L \to \mu e\right) \cong 10^{-40}$	$\sim 10^{-12}$
$\mathrm{Br}\left(\mu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

Unitarity Triangle

UT fit

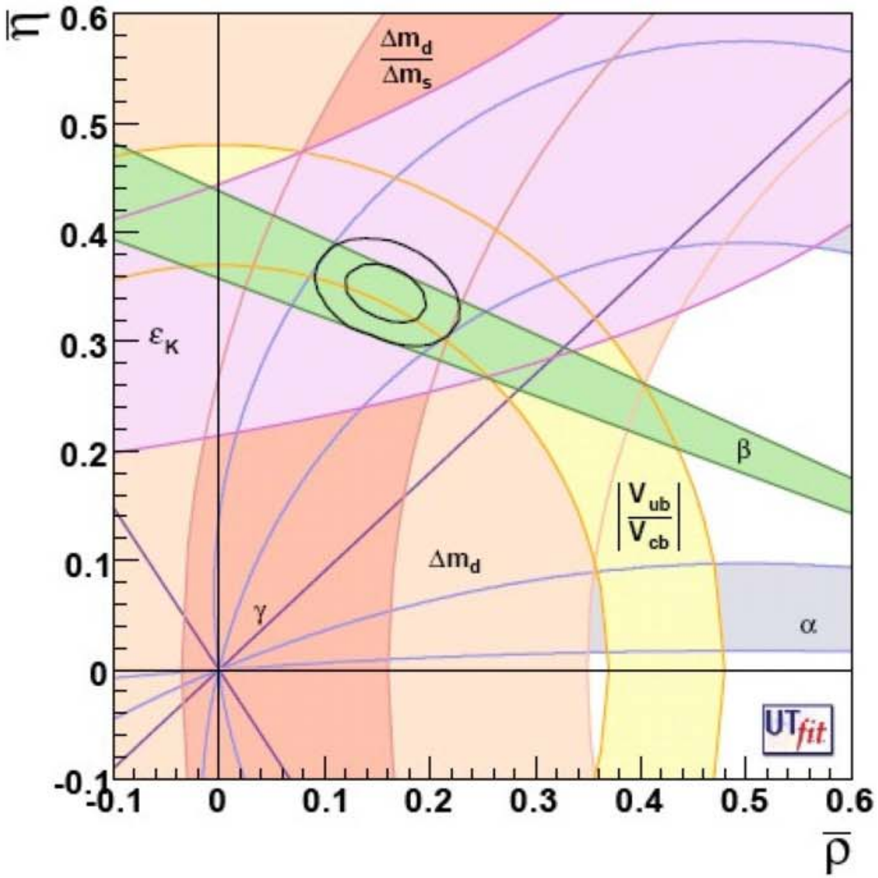


CKM fit

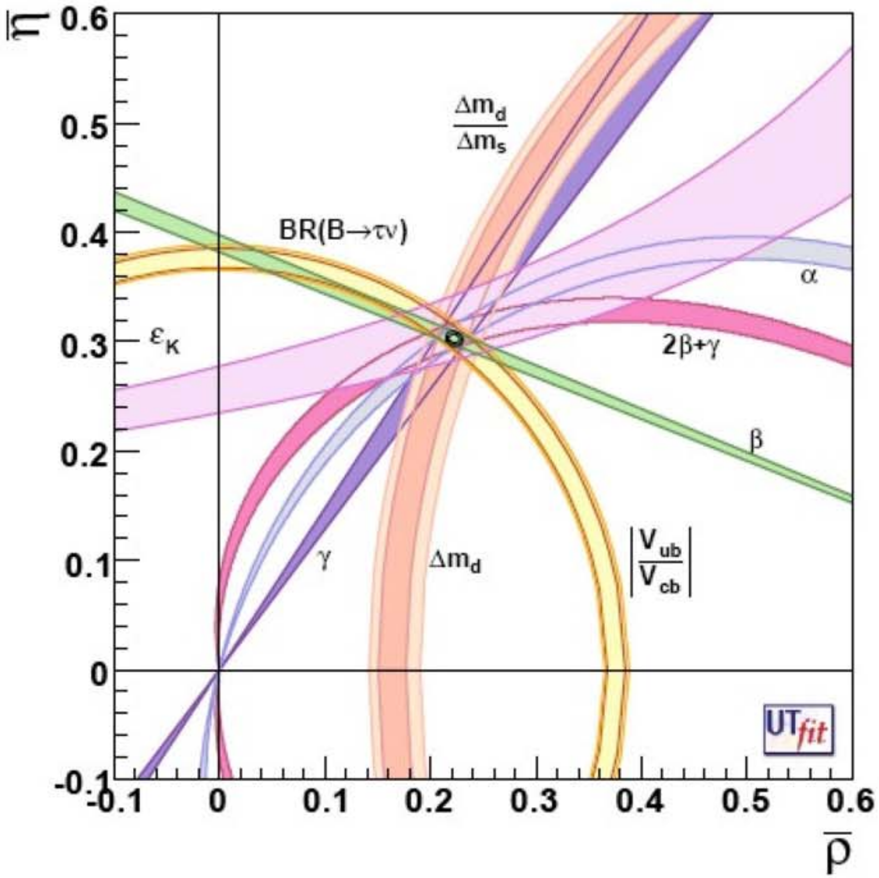


Unitarity Triangle

2008



2015



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)

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

$$A_{CP}(B_d \to \psi K_s) \approx 0(1)$$

$$A_{CP}(B_s \to \psi \varphi) \approx 0(10^{-2})$$

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

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

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

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

Little Hierarchy Problem

Electroweak Precision Tests

+

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

(generic)

$\Lambda_{NP} \approx 5$ TeV

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

Necessary to solve the hierarchy problem

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

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

Simplest New Physics : Minimal Flavour Violation (MFV)

Recent : **AJB, Gambino, Gorbahn, Jäger, Silvestrini (2000)**
D´Ambrosio, Giudice, Isidori, Strumia (2002)

Earlier Discussions : **Chivukula, Georgi (1987)**
Hall, Randall (1990)

(CKM) Flavour Violation entirely from Yukawas

Simple, elegant

Simplest New Physics : Minimal Flavour Violation (MFV)

Recent : **AJB, Gambino, Gorbahn, Jäger, Silvestrini (2000)**
D´Ambrosio, Giudice, Isidori, Strumia (2002)

Earlier Discussions : **Chivukula, Georgi (1987)**
Hall, Randall (1990)

(CKM) Flavour Violation entirely from Yukawas

Simple, elegant

but pessimistic and not exciting

MFV Picture of FCNC´s

1. **Most rare decay branching ratios enhanced by at most 50% relative to SM**

2. **Only $Br\left(B_{s,d} \rightarrow \mu^{+}\mu^{-}\right)$ could still be enhanced by a factor of 10**
   (and other helicity suppressed processes in the SM)

3. **All ~~CP~~ asymmetries SM-like**

Only Super-Belle and Super-B will be able to distinguish between various MFV-scenarios ★

Most popular non-MFV models

1. MSSM with non-MFV

2. Littlest Higgs Model with T-Parity (LHT)

3. Models with a warped extra dimension (WED)

4. Flavour Blind MSSM ★

Most popular Approaches to address the Hierarchy Problems

1. Supersymmetry

Cancellation of divergences with the help of new particles of different spin-statistic } Perturbative up to GUT scales

2. Little Higgs (LHT)

Cancellation of divergences with the help of new particles of the same spin-statistic } Perturbative up to 10 – 20 TeV

(Higgs = Pseudogoldstone Boson of a new spontaneously broken global symmetry)

(New strong force at 10 – 20 TeV)

3. Warped Extra Dimensions (Higgsless models)

RS

Higgs = 5th component of a Gauge Field in D = 5 dimensions (Gauge-Higgs-Unification)

composite pseudo-Goldstone Higgs

4.

Flavour Blind MSSM

Baek, Ko (98)
Bartl, Lunghi,
Masiero, Vives et al (2001)

Altmannshofer, AJB, Paradisi (2008)

MSSM with MFV and new flavour conserving but CP-Violating phases

Main role played by one complex parameter combination
μA_t

⇒

Interesting correlations between

$S_{\varphi K_s}$, d_n, $A_{CP}(b \to s\gamma)$, ...

How to test these scenarios ?

Direct Searches : **Production of New Heavy Particles and Study of their Interactions in High Energy Processes**

(Limited by the available Energy)

Tevatron
LHC

Indirect Searches : **Quantum Fluctuations (Loop Induced Processes) Rare Decays of Mesons (K,B,D) and Leptons Neutrino Physics**

(Limited by precision)

Belle (KEK)
Babar (SLAC)
LHCb (CERN)
J-Parc (KEK)
Borexino
Double Chooz
GERDA
CERN (K)
Super B (SFF)
Super Belle

Collider Signatures of these Proposals

New Particles with masses 500 – 3000 GeV

SM Gauge Group

1. Supersymmetry

(R-Parity) → (Dark matter candidate)

Superpartners: squarks, sleptons, gluinos, charginos, neutralinos

2. Little Higgs

(T-Parity) → New heavy Gauge Bosons: W_H, Z_H, A_H

New heavy Fermions: Mirror Fermions

(Dark matter candidate) (Scalars)

$$SU(2)_1 \otimes U(1)_1 \otimes SU(2)_2 \otimes U(1)_2$$

3. Warped Extra Dimensions (RS)

Kaluza-Klein Particles

(New Fermions, New Gauge Bosons)

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_X$$

Dominant New Flavour and CP Violating Interactions at $0(\mu_{NP})$

SUSY:

a) Misalignment of quark- and squark mass matrices, similarly for lepton sector
b) Effects enhanced at large $\tan\beta$: δ_{ij}^{AB}

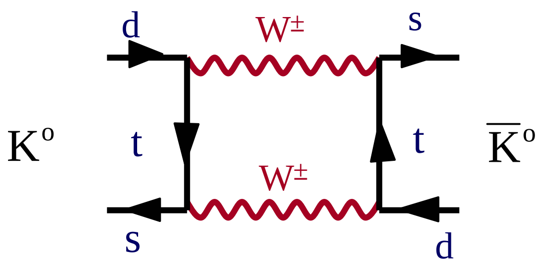
LHT:

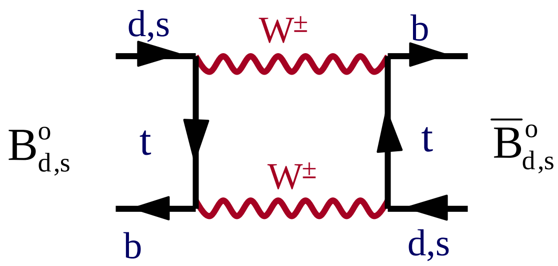
New flavour and CP violating mixing matrices in the interactions of SM fermions with mirror fermions mediated by W_H, Z_H, A_H

RS:

Tree Level $\Delta F=2$ KK-Gluon contributions
Tree Level Rare Decays ($\Delta F=1$) KK-Weak gauge boson contributions
5-D Yukawa couplings and bulk mass parameters

Impact through Quantum Fluctuations





★ ~~CP~~ ε_K-Parameter
$\Delta M\ (K_L\text{-}K_S)$

$B^o_d - \overline{B}^o_d$ Mixing ★ (ΔM_d)

$B^0_s - \overline{B}^0_s$ Mixing ★ ★ (ΔM_s)

(CDF, DØ)

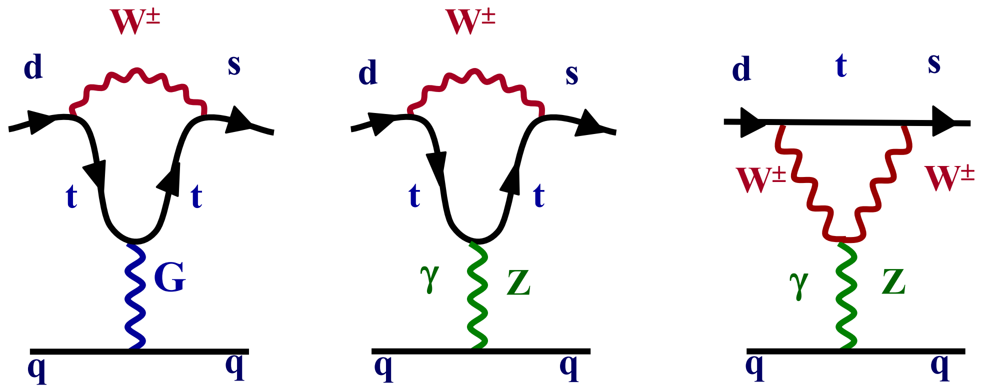
<u>CP-Asymmetries</u>

$$S_{\psi K_s} = \sin\left(2\beta + 2\varphi_d^{new}\right) \qquad (\text{Babar, Belle})$$

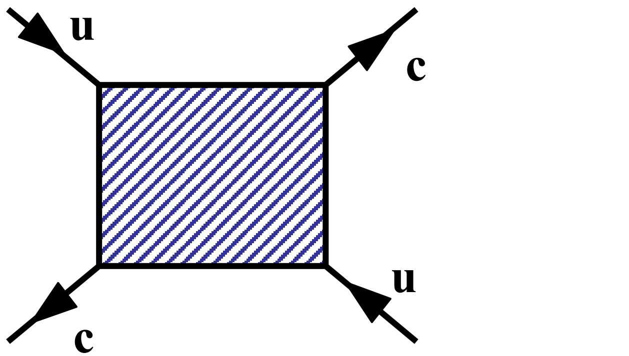
$$S_{\psi\varphi} = \sin\left(2|\beta_s| - 2\varphi_s^{new}\right) \qquad (\text{CDF, DØ, LHC})$$

Impact through Quantum Fluctuations

★ ε'



(NA48, KTEV)

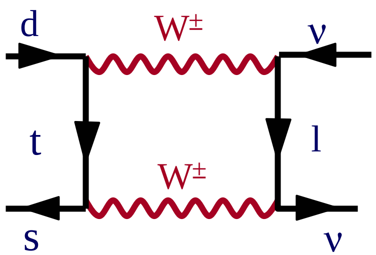


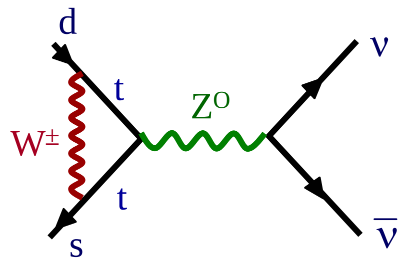
$D^0 - \overline{D}^0$ **Mixing** ★

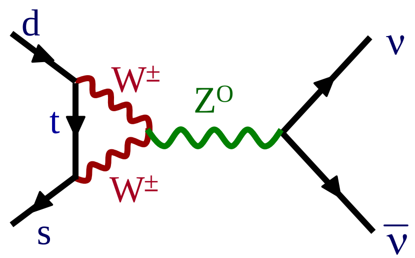
(BaBar, Belle)

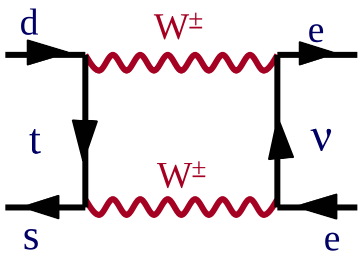
Impact through Quantum Fluctuations

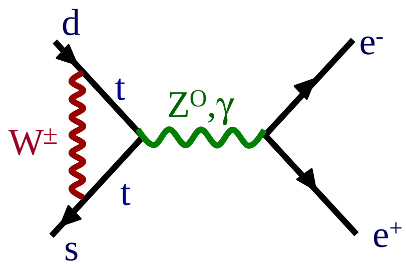
$K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$ $K_L \to \mu\bar{\mu}$, $B_{s,d} \to \mu\bar{\mu}$, $B \to X_S \nu\bar{\nu}$

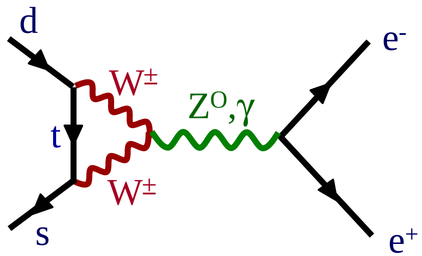




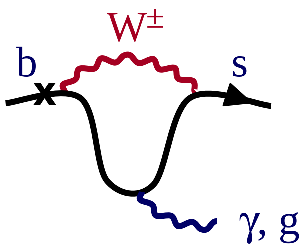








$K_L \to \pi^0\ l^+l^-$ $B \to X_s e^+ e^-,\ X_s \mu\bar{\mu}$



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

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

Lepton Flavour Violation

$\mu \to e\gamma$

$\tau \to \mu\gamma$

$\tau \to e\gamma$

$\mu^- \to e^- e^+ e^-$

$\tau^- \to \mu^- \mu^+ \mu^-$

$\tau^- \to e^- e^+ e^-$

$K_L \to \mu e$

$B_{d,s} \to \mu e$

$B_{d,s} \to \tau e$

$B_{d,s} \to \tau\mu$

ΔL=1
ΔS=1
(ΔB=1)

$K_L \to \pi^0 \mu e$

$\mu - e$ Conversion in nuclei

$\tau^- \to e^- \mu^+ e^-$

$\tau^- \to \mu^- e^+ \mu^-$

ΔL=2

$\tau^- \to \mu^- e^+ e^-$

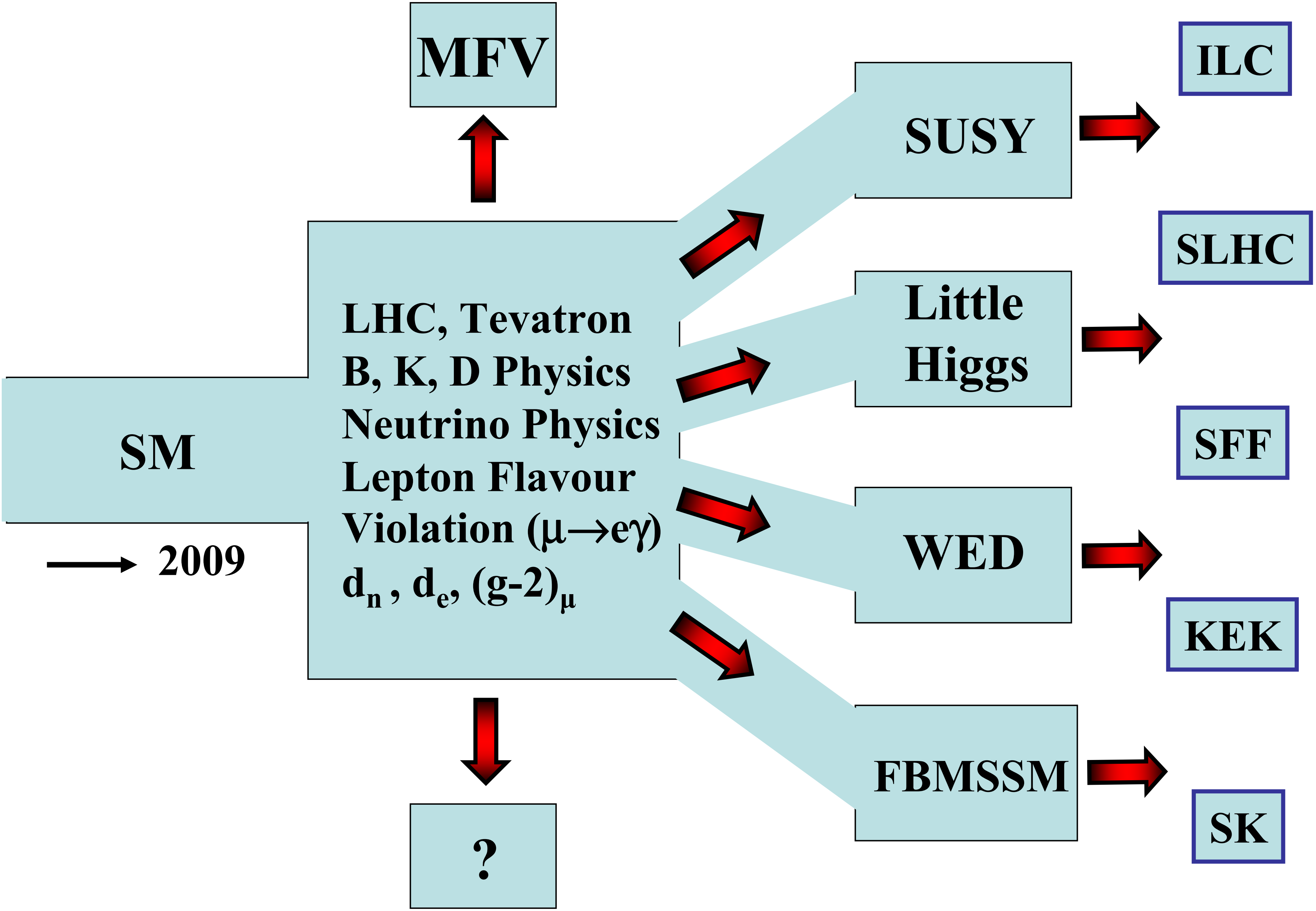
$\tau^- \to e^- \mu^+ \mu^-$

(ΔL=1, ΔL=2)

$\tau^- \to \mu^- P$

$P = \pi, \eta, \eta'$

$(g-2)_\mu$


MFV
SM
2009
LHC, Tevatron
B, K, D Physics
Neutrino Physics
Lepton Flavour
Violation (μ→eγ)
d_n , d_e, $(g-2)_\mu$
?
SUSY
Little Higgs
WED
FBMSSM
ILC
SLHC
SFF
KEK
SK

2019 Vision
New Discoveries

$S_{\psi\varphi}$ (B_s)

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

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

LFV ($\mu\to e\gamma$, $\tau\to\mu\gamma$)

EDM´s

$(g-2)_\mu$

CP asymmetries in non-leptonic Decays

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

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

$K_L \to \pi^0 l^+ l^-$

~~CP~~ in D-decays

~~CP~~ in Neutrino Oscillations

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

Constraints on NP improved

$(\Delta F=2)$: $S_{\psi K_s}$ | ε_K | ΔM_s | ΔM_d | ΔM_K

$(\Delta F=1)$: $B \to X_s\gamma$ | $B \to X_s l^+ l^-$ | $B \to K^*\gamma$ | $K^+ \to l^+\nu$

Goals for the Next 40 Min

1. **Theoretical Framework**

★ 2. **Collection of 20 Super-Goals for the LHC Era (this means LHC, LHCb, Super-Belle, SFF, Super-B, Super-K, LFV)**

3. **Final Messages**

1.

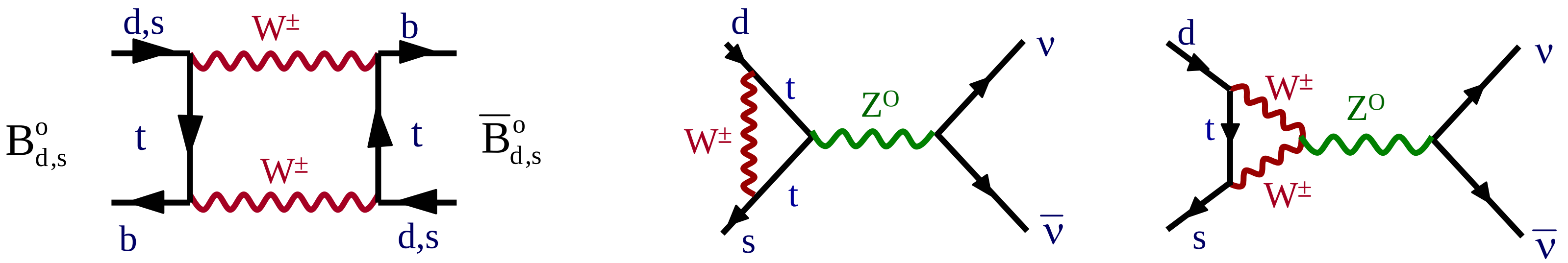
Theoretical Framework

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



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

$K^+ \to \pi^+ \nu\overline{\nu}, \; K_L \to \pi^0 \nu\overline{\nu}$

+ NP

Two challenges :

1. Theory formulated in terms of quarks but experiments involve their bound states (K, B, D)

2. NP takes place at very short distance scales (10^{-19}-10^{-18}m), while K, B, D live at 10^{-16}-10^{-15}m.

Solution : Effective Theories, OPE, Renormalization Group

⇒ Separation of SD from LD
+ Summation of large $\log(\mu_{SD} / \mu_{LD})$

Operator Product Expansion

{Wilson Coefficients} {Local Operators}

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

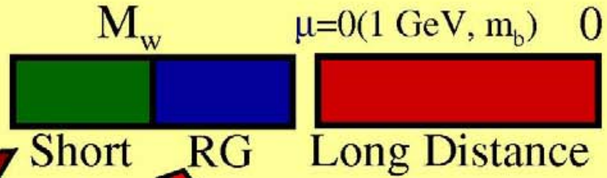
Q_i ⇔  **Four Quark Interaction Vertex** $(\bar{s}d)_{V-A}(\bar{s}d)_{V-A}$

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

{K, B, D,...}

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

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



{Top, SUSY, $H^\pm$...} **(NP)**

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

{Lattice, 1/N, HQET, QCDS, ChPTh, PQCD, QCDF, SCET}

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

Basic Structure of FCNC Amplitudes

$$\mathbf{A}(\mathbf{FCNC}) = \sum_{\mathbf{i}} \mathbf{B}_{\mathbf{i}} \eta_{\mathbf{i}}^{\mathbf{QCD}} \mathbf{V}_{\mathbf{i}}^{\mathbf{CKM}} \mathbf{F}_{\mathbf{i}}(\mathbf{m}_{\mathbf{t}}, \mathbf{NP})$$

Basic Structure of 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)

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

Renormalization Group (QCD) LD $\leftrightarrow$ SD

Basic Structure of 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)

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

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)

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:

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

LHT

Beyond SM:

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

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

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

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

WED (first two structures)

SUSY (all four structures)

Strong enhancements →

MSSM with large tanβ
General Supersymmetric Models
Models with complicated Higgs System; RS Models

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

AJB, Misiak, Urban, Jäger

Enhancements of Q_{LR} versus Q_{LL} in $\Delta F=2$ Transitions

$$\mu \cong 3\text{TeV} \xrightarrow{\text{RG}} \begin{matrix} \mu_B \approx 5\text{GeV} \\ \mu_K \approx 2\text{GeV} \end{matrix}$$

	Wilson Coefficient (RG Enhancement)	Hadronic Matrix Element (Chiral Enhancement)	Total
$K^0 - \overline{K}^0$	~ 7	20	140
$B^o_{d,s} - \overline{B}^0_{d,s}$	~ 4.3	1.5	6.5

2 x 2 Flavour Matrix of Basic NP Scenarios

(AJB, hep-ph/0101336, Erice)

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

Comparison of Beyond-MFV Scenarios

Scenario	New Flavour and CP Violation	New Operators	FCNC at Tree Level
LHT	★		
SUSY	★	★	
RS	★	★	★

(non-universitalities in gauge couplings implied by the manner CKM and mass hierarchies are explained)

Number of new Flavour Parameters

(Quark Sector) (physical)

	Real	~~CP~~ Phases	
SUSY	36	27	(R-parity)
FBMSSM	6	1	
LHT	7	3	some sensitivity to UV
RS	18	9	
SM	9	1	

Few Messages : The Role of Correlations

★ In view of many parameters it will be difficult to rule out models with non-MFV interactions.

Correlations between observables will be crucial here

★ Models with MFV can easily be ruled out through very predictive correlations, large CP asymmetries in $b \to s$ transitions, rare decays $\left(K^+ \to \pi^+ \nu\bar{\nu},\ K_L \to \pi^0 \nu\bar{\nu},\ K_L \to \pi^0 l^+ l^-\right)$ and lepton flavour violation.

★ Correlations between Flavour Conserving CPV (EDMs) and Flavour Violating CPV could be a crucial test.

FBMSSM

2.

20 Super-Goals in Flavour Physics for the Coming Years

CKM Parameters from Tree-Level Decays

(subject to very small NP Pollution)

$$|V_{us}| = s_{12} = 0.2255 \pm 0.0010$$

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

$$|V_{cb}| = s_{23} = (41.2 \pm 1.1) \cdot 10^{-3}$$

$$\delta_{CKM} = \gamma_{UT} = (75 \pm 25)^{o}$$

(-phase of V_{ub})

$$(\sin 2\beta)_{\psi K_s} = 0.670 \pm 0.023$$

(-phase of V_{td})

⇒ $\beta = (21.1 \pm 0.9)^{o}$

but could be subject to NP pollution

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

1.

Precise measurement of $|V_{ub}|$ and γ from tree-level decays

→ Reference UT (RUT)

↓ $|V_{us}|, |V_{cb}|$

CKM Matrix without NP pollution

2.

Continuation of the standard UT fits and improvements on processes that turned out to be close to SM expectations (both TH and EXP should be improved) (No spectacular effects are expected here but this study is important for SM and MFV models)

3. Lattice Calculations of $\hat{B}_i$, F_{B_s}, F_{B_d}

$\hat{B}_K = 0.75 \pm 0.07$

(Lubicz + Tarantino)

$\sqrt{\hat{B}_s} F_{B_s} = (270 \pm 30)\,\text{MeV}$

$\sqrt{\hat{B}_d} F_{B_d} = (225 \pm 25)\,\text{MeV}$

$\xi = 1.21 \pm 0.04$ (ratio)

HPQCD

266 ± 18

216 ± 15

1.26 ± 0.03

ΔM_s, ΔM_d

$(B^0_{d,s} - \overline{B}^0_{d,s})$

Related Questions:

Does SM describe simultaneously:

ε_K, ΔM_d, ΔM_s and $S_{\psi K_s}$?

ε_K: CP̸ in K

ΔM_d, ΔM_s: $B^0_{d,s} - \hat{B}^0_{d,s}$ mixing

$S_{\psi K_s}$: CP̸ in B_d

Also $\Delta\Gamma_{d,s}$

Considerable progress expected in coming years : $\pm 10\% \rightarrow \pm 3\%$

Is $\not{CP}$ in $B_d - \bar{B}_d^0$ Mixing consistent with ε_K within SM ?

AJB, D. Guadagnoli

arXiv: 0805.3887

$$\left(S_{\psi K_s}\right)_{exp} \Rightarrow \left|\varepsilon_K\right|_{SM} < \left|\varepsilon_K\right|_{exp}$$

(Smaller $\hat{B}_K$ and additional suppressions in $|\varepsilon_K|_{SM}$)

Resolution will require improvement on

$$\hat{B}_K, V_{cb}, V_{ub}, \gamma$$

★

$$\hat{B}_K = 0.72 \pm 0.04$$

(RBC)

$$\frac{\left(\left|\varepsilon_K\right|\right)_{SM}}{\left|\varepsilon_K\right|_{exp}} \approx 0.8 \pm 0.1$$

(See Lunghi + Soni for related work)

Diego Guadagnoli

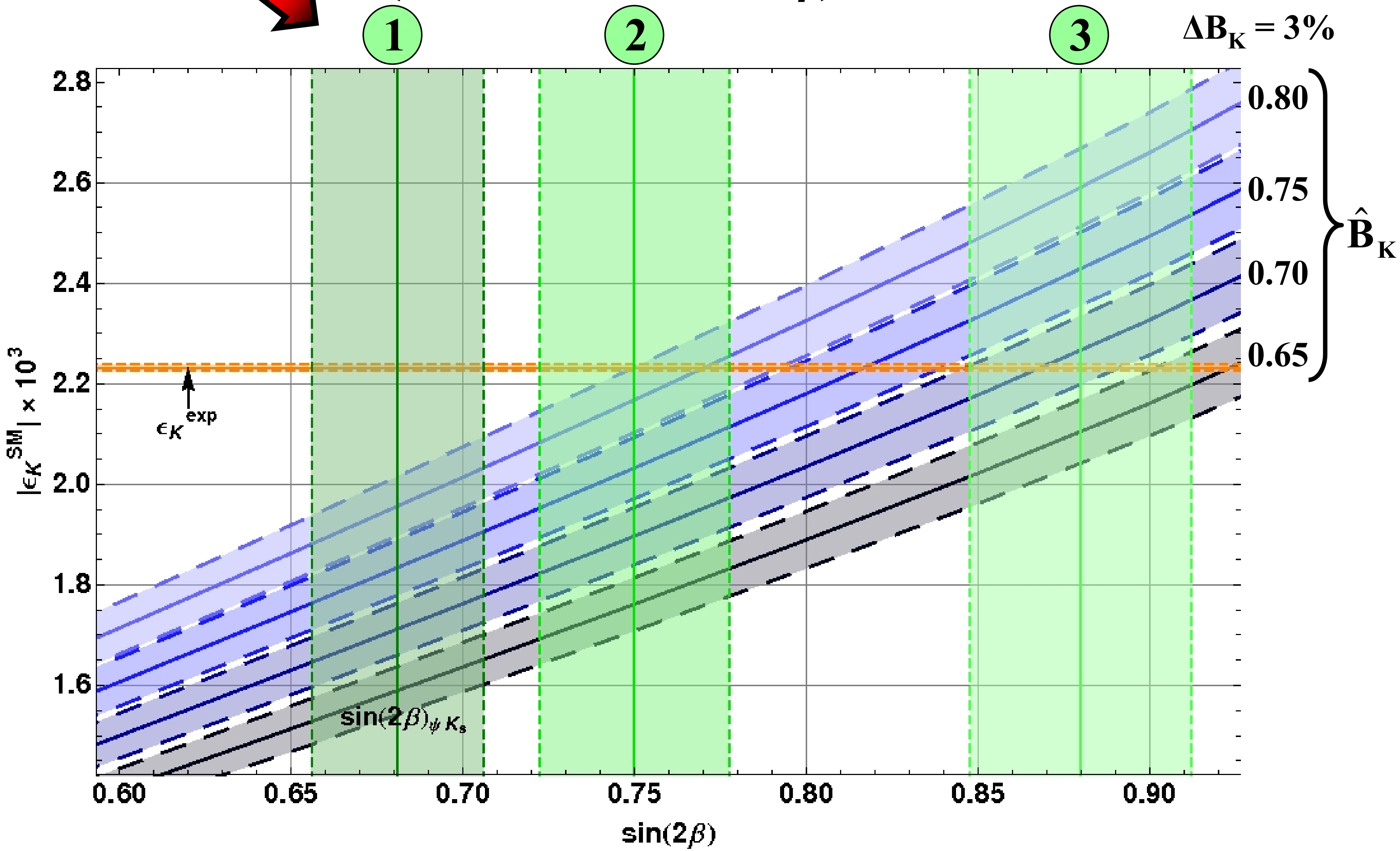
SM

$\left|\varepsilon_K^{SM}\right|$ vs. $\sin 2\beta$

(3 scenarios for $\sin 2\beta$)

Central values of parameters

BG



4. Crucial Measurements of clean CP-asymmetries

$$S_{\psi\varphi} = \sin\left(2|\beta_s| - 2\varphi_s^{new}\right) \overset{\varphi_s^{new} = 0}{\approx} 0.04$$

1^o SM

But: CDF, DØ, + UTfit: CKMfit $0.17 < S_{\psi\varphi} \leq 0.87 \ (95\% \ C.L.)$

$$\varphi_s^{new} = -\left(18^o \pm 7\right)$$

(2008)

Hint of a spectacular deviation from MFV

First hints: Lenz + Nierste (06)

Recall:

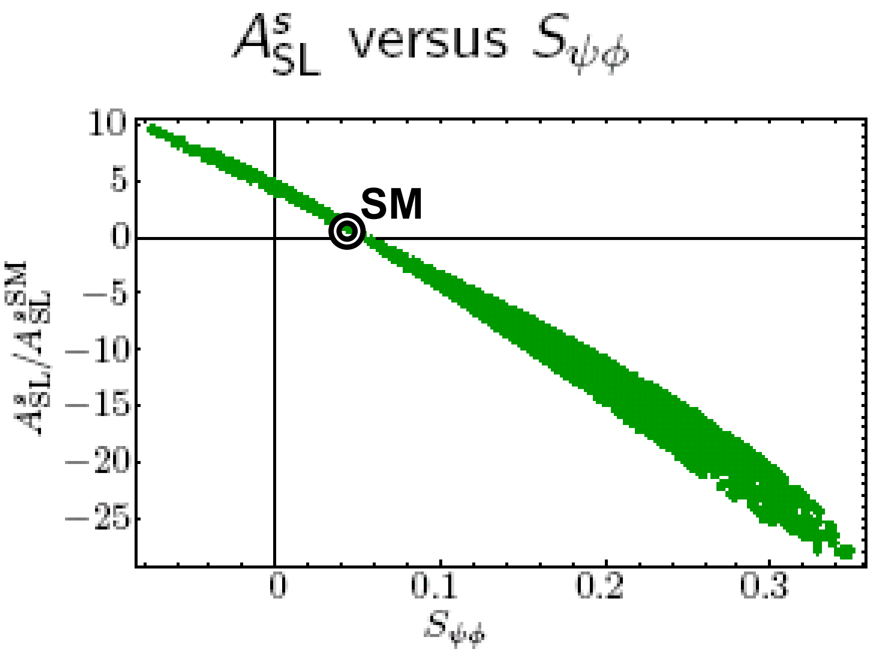
$$S_{\psi K_s} = \sin\left(2\beta + 2\varphi_d^{new}\right) = 0.671 \pm 0.024$$

Utfit, Blanke et al.
Ball, Fleischer
Lunghi + Soni, BG

Faller et al.

$$\varphi_d^{new} \approx -\left(7 \pm 3\right)^o$$

Correlation A^s_{SL} ⇔ $S_{\psi\varphi}$



Ligeti
Papucci
Perez (06)

Example from LHT

(Blanke
AJB
Poschenrieder
Recksiegel
Tarantino
Uhlig
Weiler)

- A^s_{SL} **enhanced by 10-20**
- $S_{\psi\Phi}$ **can be as high as +0.3**

★

Mixing, $\not{CP}$ and $B \to X_s \gamma$ [hep-ph/0605214]

M. Blanke   AJB   A. Poschenrieder

C. Tarantino   S. Uhlig   A. Weiler

K and B rare decays [hep-ph/0610298]

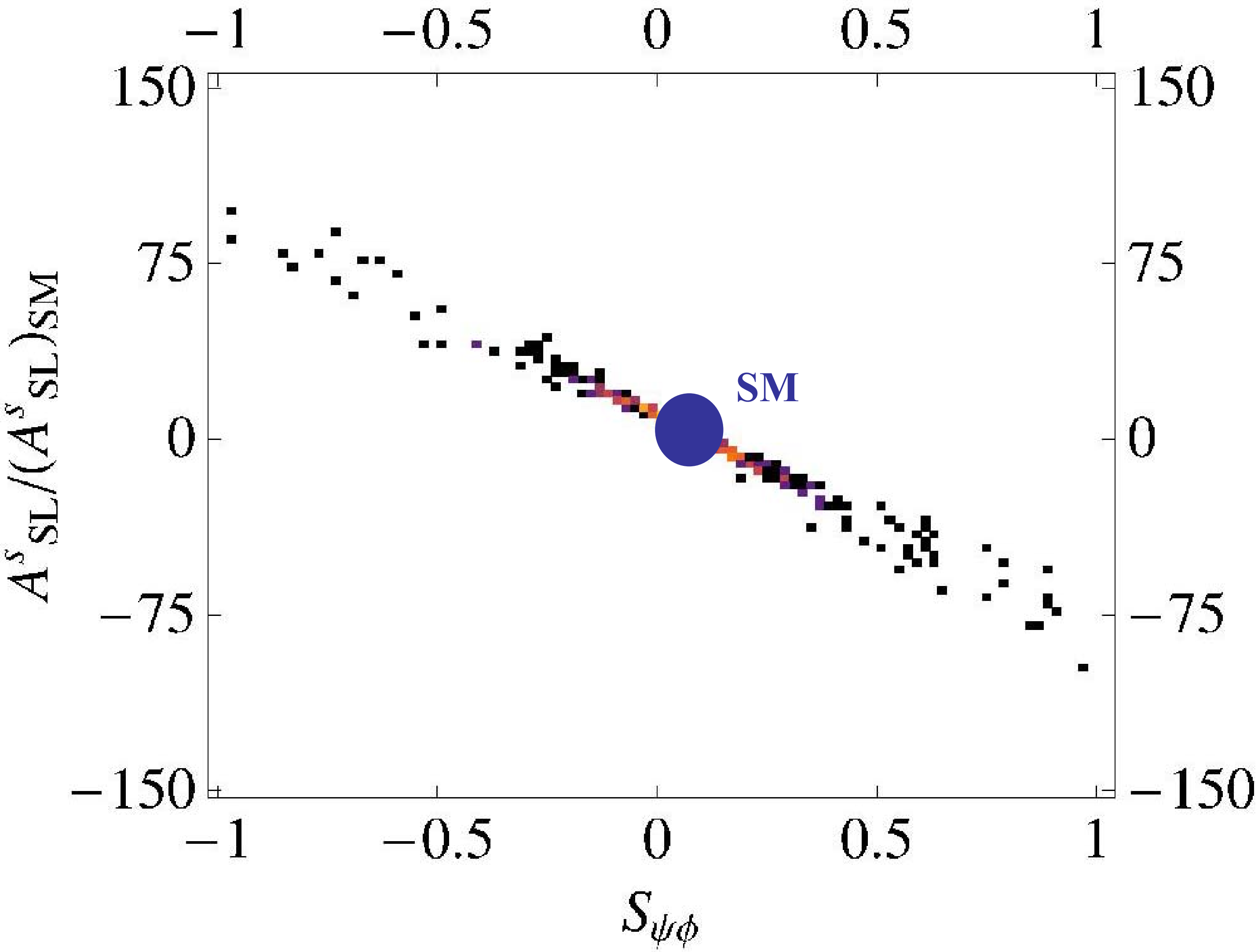
M. Blanke   AJB   A. Poschenrieder   S. Recksiegel   C. Tarantino   S. Uhlig   A. Weiler

Lepton flavour violating decays [hep-ph/0702136]

M. Blanke   AJB   A. Poschenrieder   B. Duling   C. Tarantino

TUM Little Higgs Team

Correlation in Warped Extra Dimensions



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

Mixing, $\not{CP}$ in RS model [hep-ph/0809.1073]

M. Blanke

AJB

B. Duling

S. Gori

A. Weiler

(50)

Rare K and B Decays in RS model [hep-ph/0812.3803]

M. Blanke

AJB

B. Duling

K. Gemmler

S. Gori

(49)

TUM RS Team

5.

Resolution of the

$$\left(\sin 2\beta\right)_{\varphi K_s} < \left(\sin 2\beta\right)_{\psi K_s}$$

(penguin dominated) **(tree dominated)**

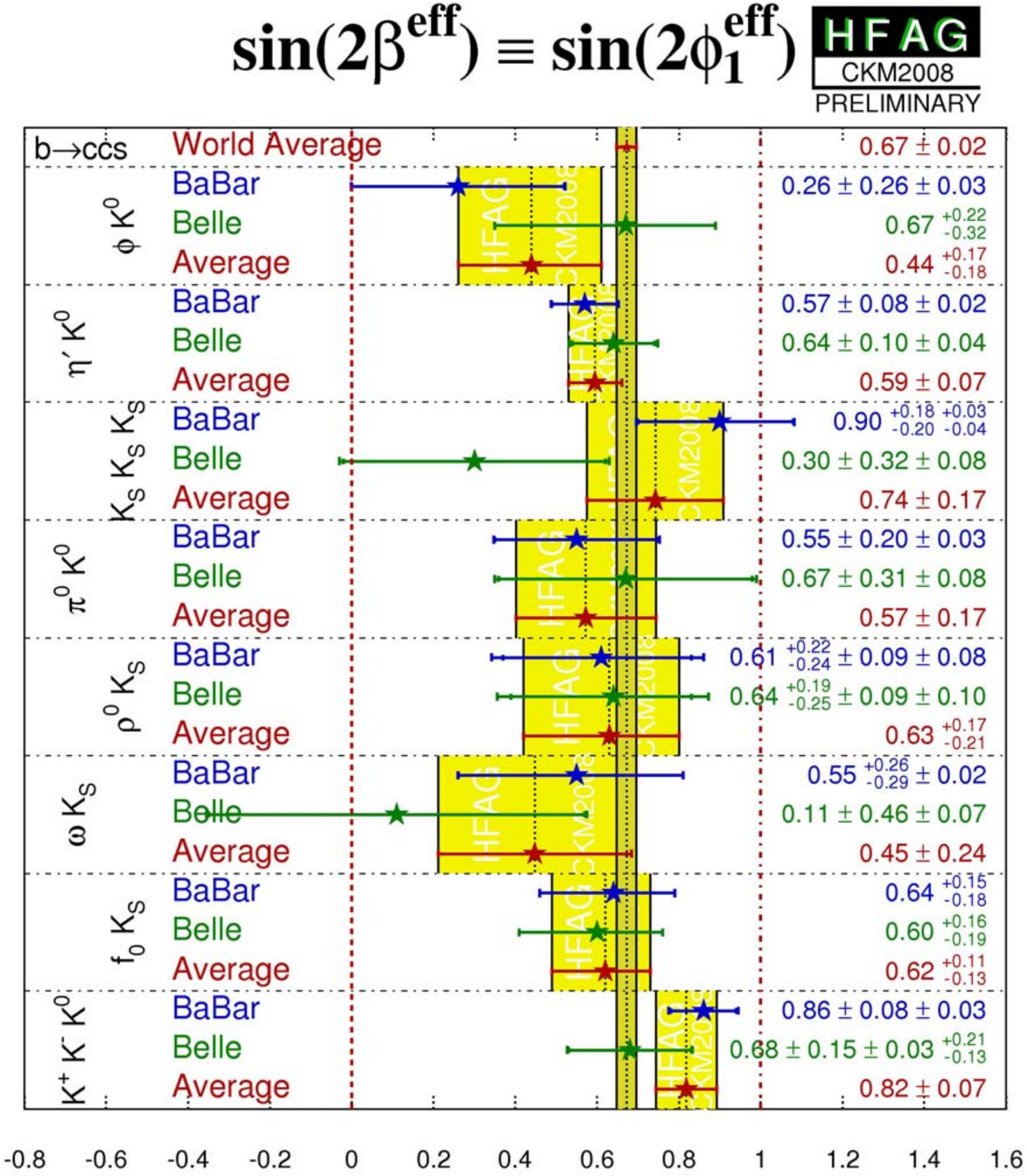
Cannot be solved at LHC

$$\left(\sin 2\beta\right)_{\psi K_s} = 0.671 \pm 0.024$$

$$\left(\sin 2\beta\right)_{\varphi K_s} = 0.44 \pm 0.17$$

★

$\sin(2\beta^{\text{eff}}) \equiv \sin(2\phi_1^{\text{eff}})$



6. Goals in Non-Leptonic B-Decays

See Reviews: Buchalla; Fleischer; Jäger; Silvestrini

Flavour symmetries, QCDF, SCET and improved measurements can give some insight in NP

$B \to \rho\rho$ ➡ $\alpha = (91.4 \pm 4.6)^{\circ}$

7. Improved Measurements of

$$B \rightarrow X_{s,d}\gamma,\ B \rightarrow X_s l^+ l^-,\ A_{FB},$$

$$A_{CP}\left(B \rightarrow X_s\gamma\right)$$

Very strong Constraints on New Physics

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

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

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

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

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

Zero in A_{FB}

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

★ TH very clean

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

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

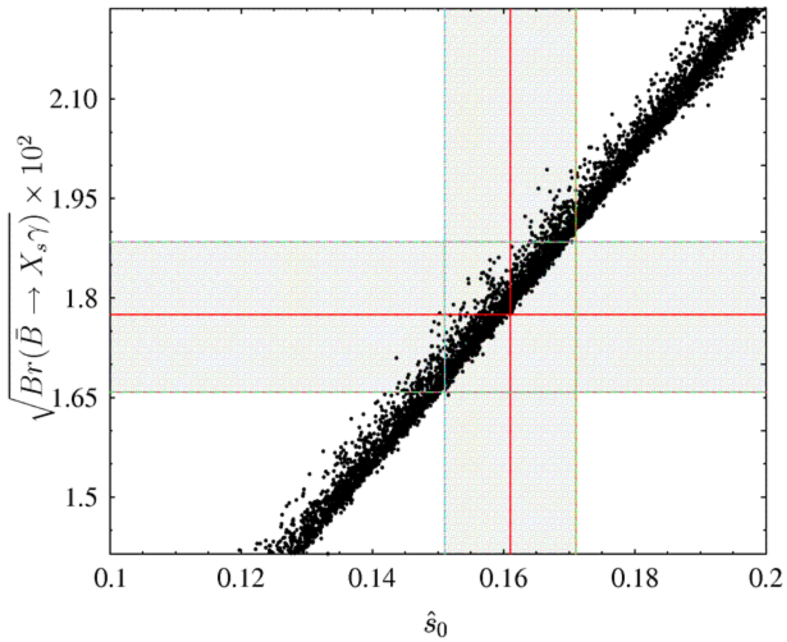
(Still factor 10 enhancement possible !)

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

Correlation: $Br(B \to X_s\gamma) \leftrightarrow \hat{s}_0$ in $A_{FB}(B \to X_s l^+ l^-)$

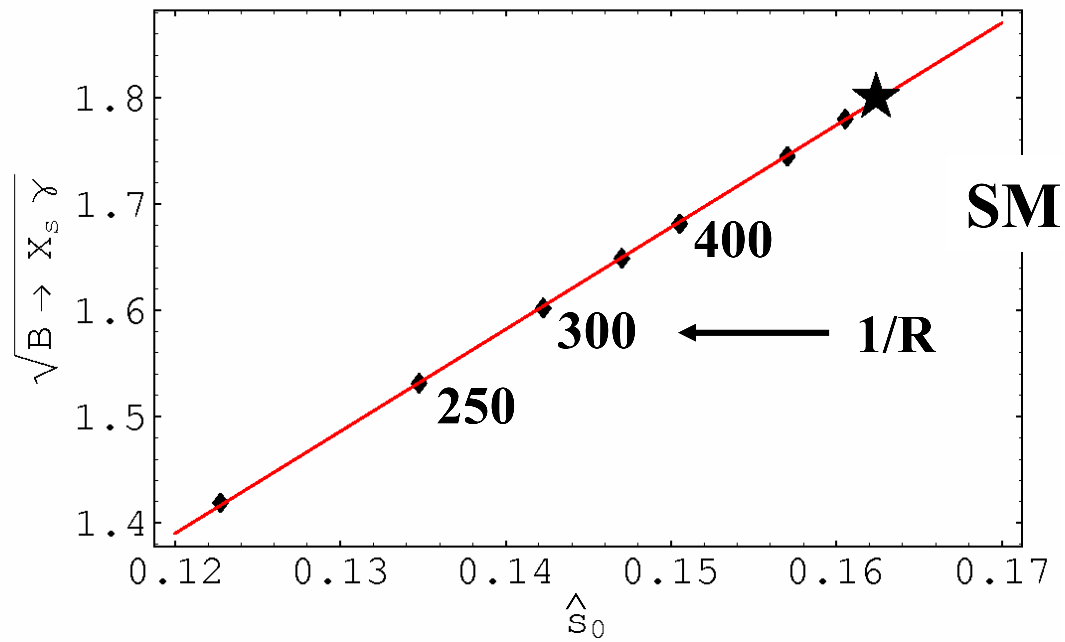
MSSM (MFV)

(Bobeth, AJB, Ewerth)



Universal Extra Dimensions

(AJB, Poschenrieder, Spranger, Weiler)

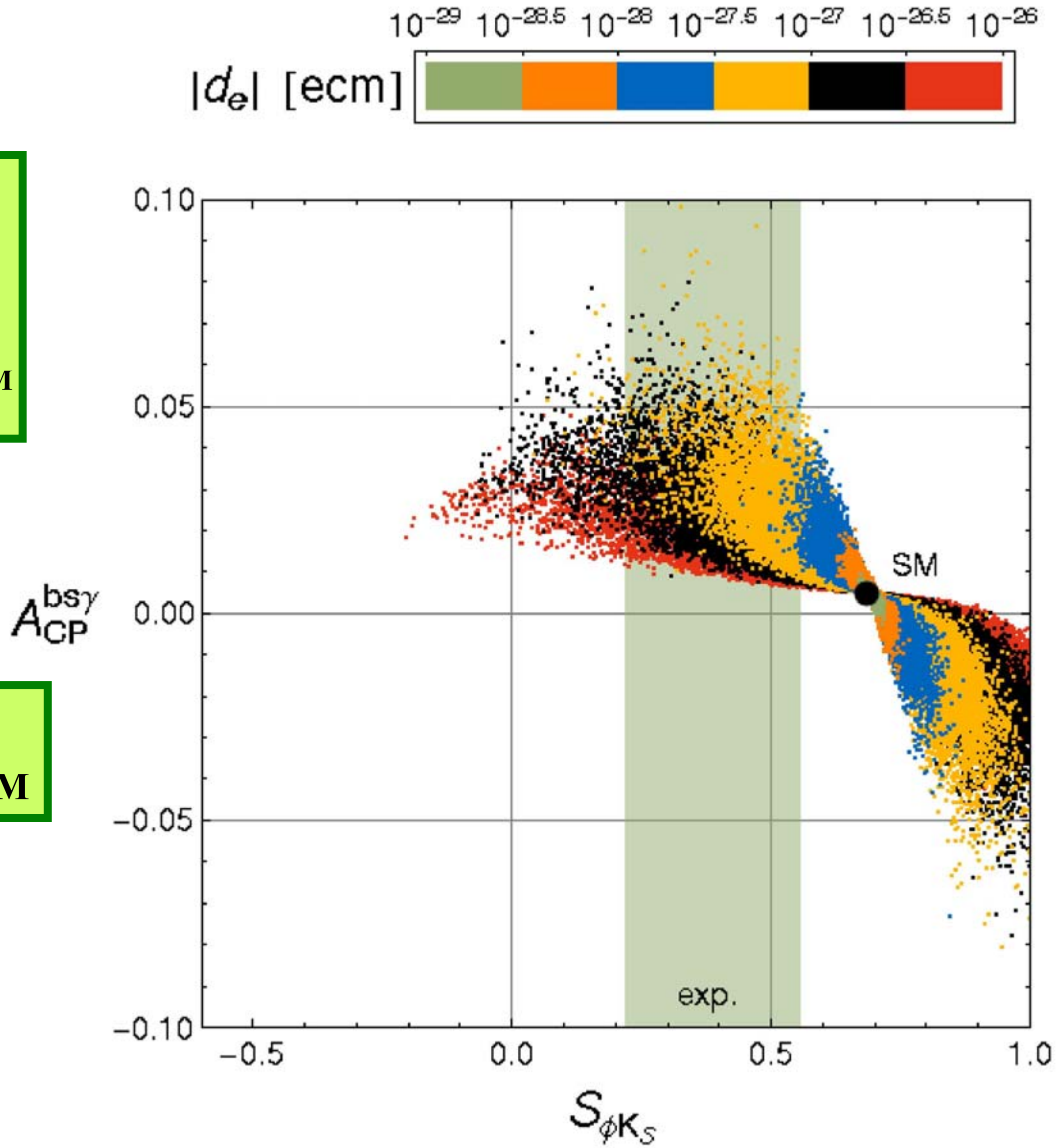


Correlation between $A_{CP}(B \to X_s\gamma)$ and $S_{\varphi K_s}$

Desire to explain

$$(S_{\varphi K_s})_{exp} < (S_{\varphi K})_{SM}$$

$$A_{CP}^{bs\gamma} > 5\left(A_{CP}^{bs\gamma}\right)_{SM}$$



FBMSSM

Altmannshofer
AJB
Paradisi (08)

W. Altmannshofer **AJB** **P. Paradisi**

8. A Goldmine of Observables: $B \to K^* l^+ l^-$

Work for LHCb

Basis: Ali, Ball, Handoko, Hiller (99)
Krüger et al. (00)
Beneke, Feldmann, Seidel (01)

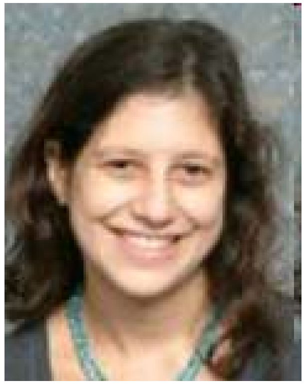
New: Bobeth, Hiller, Piranishvili (08)
Egede, Hurth, Matias, Ramon, Reece (08)
Altmannshofer, Ball, Bharucha, AJB, Straub, Wick (08)

CP ⇒ $S_i^{(a)}$, $A_i^{(a)}$ ⇐ $\not{CP}$ $(i = 1,\ldots 9)$
$(a = s,c)$

The ABBBSW Collaboration

W. Altmannshofer

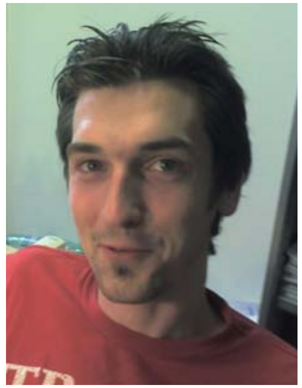
P. Ball



A. Bharucha

AJB

D. Straub



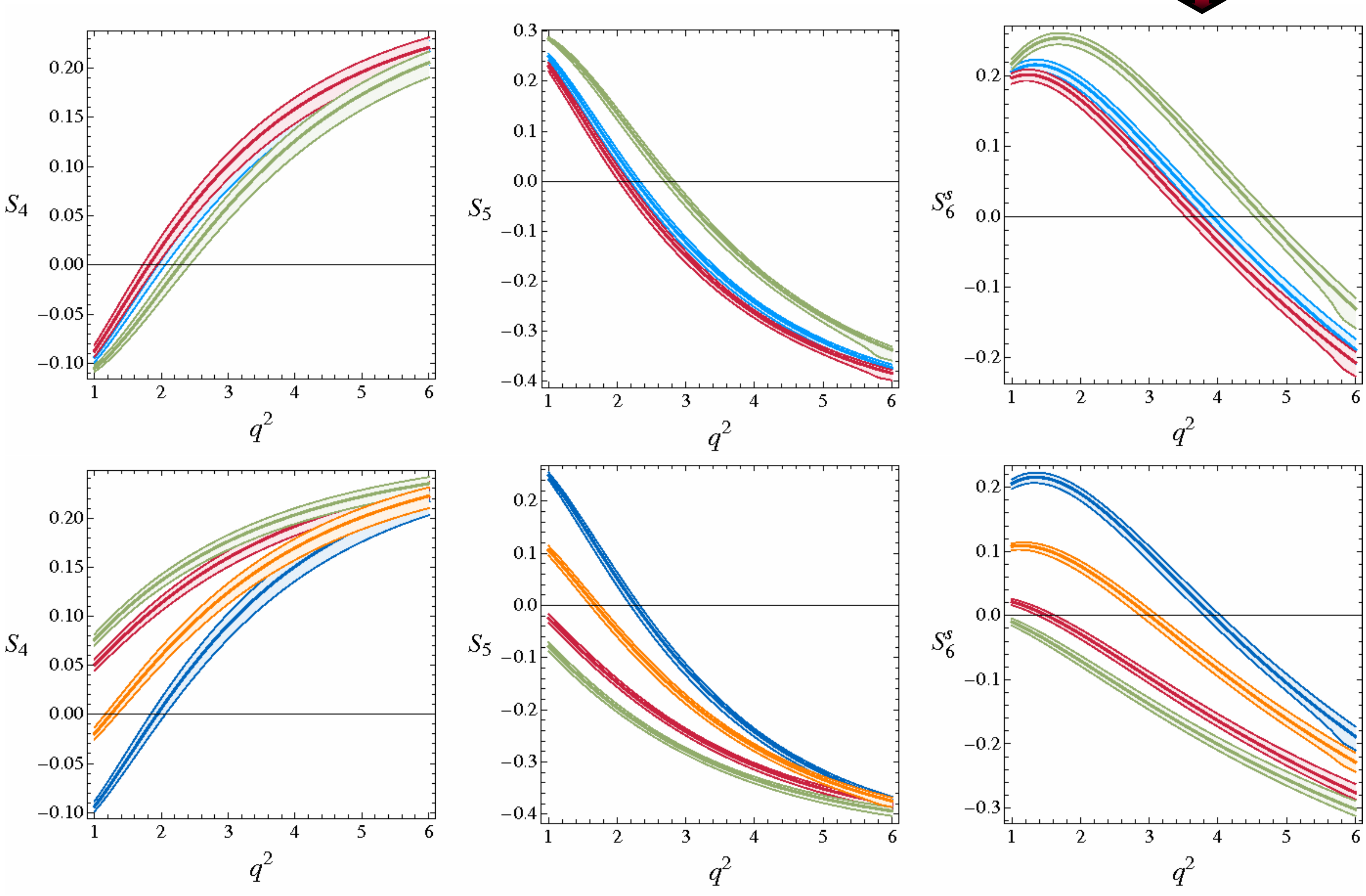
M. Wick

S_i in MFV MSSM and FB MSSM

ABBBSW (08)

Blue ≡ SM

A_{FB}



9. Measurement of Br ($B_{s,d} \to \mu^+\mu^-$) ($\tau^+\tau^-$) ★

SM:

$$Br(B_s \to \mu^+\mu^-)_{SM} = (3.37 \pm 0.31) \cdot 10^{-9}$$

$$Br(B_d \to \mu^+\mu^-)_{SM} = (1.02 \pm 0.09) \cdot 10^{-10}$$

$< 6 \cdot 10^{-8}$ CDF (95% C.L.)

$< 2 \cdot 10^{-8}$ DØ

LHCb !

Helicity suppressed : $(m_\mu / m_B)^2$

AJB (03)

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

(CMFV)

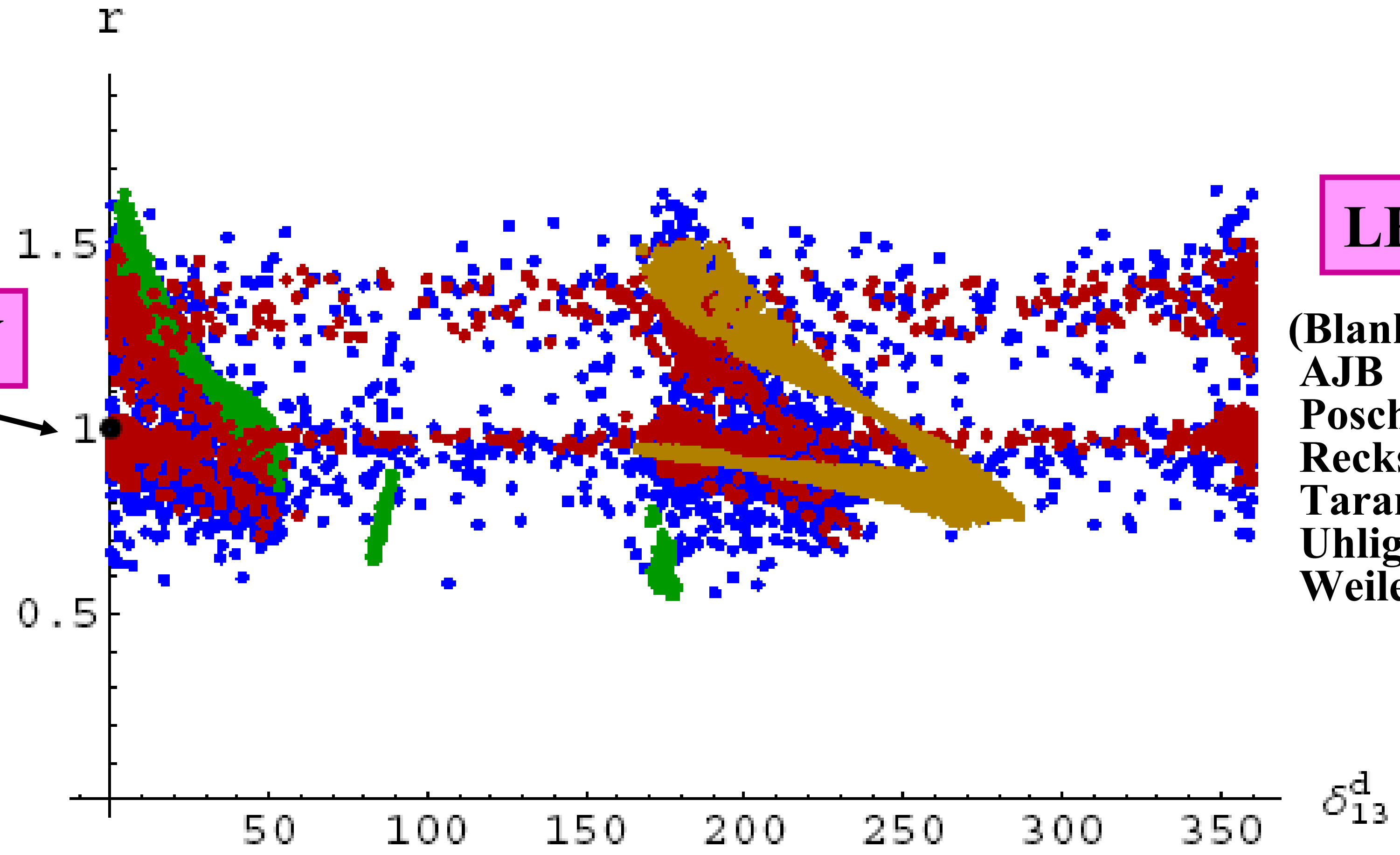
r = 1

"Golden" Relation **TH: ±2%**

(Can be strongly violated beyond CMFV)

Violation of the Golden Relation

CMFV



LHT

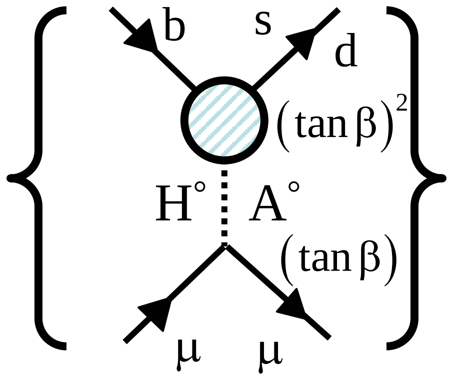
**(Blanke
AJB
Poschenrieder
Recksiegel
Tarantino
Uhlig
Weiler)**

Similar in Z´models: Promberger, Schatt, Schwab (07)

$B_{s,d} \to \mu^+\mu^-$ and MSSM with MFV at large tanβ

In MSSM at large tanβ
(CKM still the only source of Flavour and CP Violation)

Strong Enhancement



$$\mathrm{Br}\left(B_{s,d} \to \mu\bar{\mu}\right) \sim \left(\tan\beta\right)^6$$

$10^{-6}\left(10^{-7}\right)$ possible

$\mathrm{SM} \sim 10^{-9}$

Babu, Kolda
Chankowski, Slawianowska
Bobeth, Ewerth, Krüger, Urban
Huang, Liao, Yan, Zhu
Isidori, Retico
Dedes, Dreiner, Nierste
Dedes, Pilaftis
Chankowski, Rosiek
Foster, Okumura, Roszkowski
Carena et al.
Isidori, Paradisi

$$\mathbf{Br\left(B_s \to \mu\bar{\mu}\right) < 6 \cdot 10^{-8}}$$

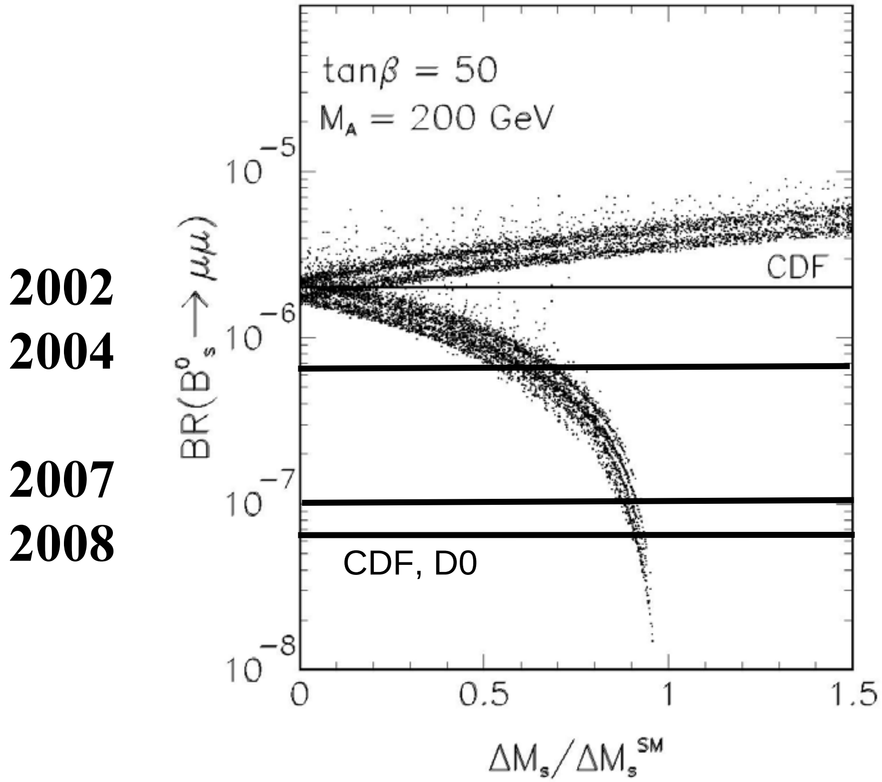
95% C.L
(CDF, DØ)

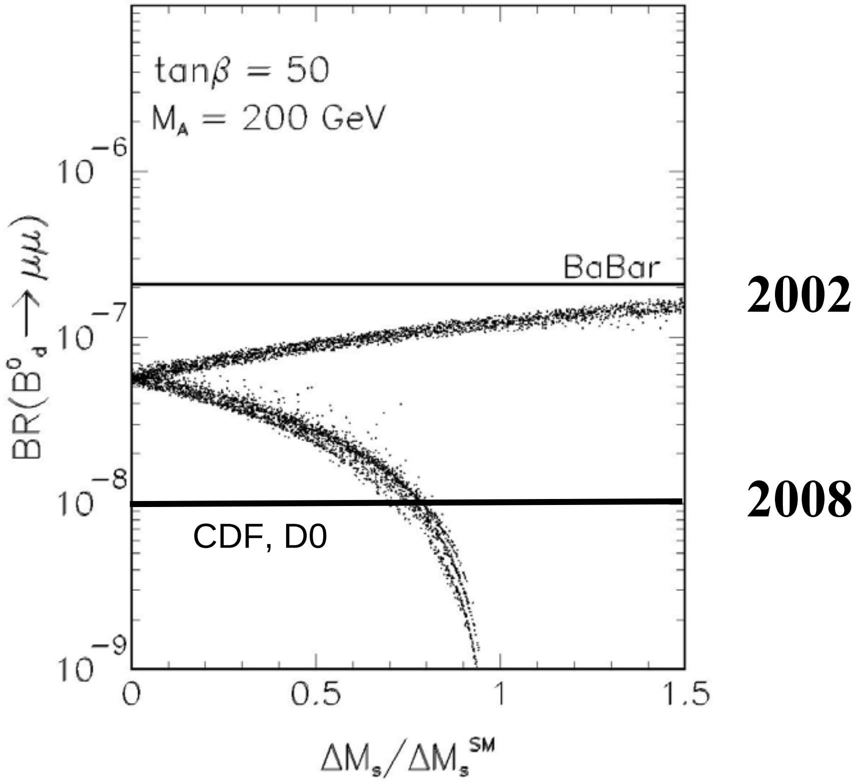
$$\mathbf{Br\left(B_d \to \mu\bar{\mu}\right) < 2 \cdot 10^{-8}}$$

95% C.L.

$Br\left(B_{s,d} \to \mu^+\mu^-\right)$ vs $\left(\Delta M_s\right)^{exp} / \left(\Delta M_s\right)^{SM}$ in SUSY at Large $\tan\beta$

AJB, Chankowski, Rosiek, Slawianowska (2002)
Gorbahn, Jäger, Nierste, Trine (2008)
Could be modified by Non-MFV (Chankowski; Dedes, Pilaftsis)





10. $B^+ \to \tau^+\nu,\ K^+ \to l^+\nu$

(LFV effects in B and K Physics)

Sensitivity to NP

A.

$$\frac{Br\left(B^+ \to \mu^+\nu\right)}{Br\left(B^+ \to \tau^+\nu\right)}$$

(test of $\mu \leftrightarrow \tau$ universitality)

Isidori - Paradisi (2006)

B.

$$\frac{\Gamma\left(K^+ \to \mu^+\nu\right)}{\Gamma\left(K^+ \to e^+\nu\right)}$$

(test of $\mu \leftrightarrow e$ universitality)

Masiero, Paradisi, Petronzio (2005)

Very accurate precision test

Tested soon at CERN to 0.5%

TH: ± 0.1%

11.

$B^+ \to \tau^+ \nu$ $(\mu^+ \nu)$

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

(Belle, BaBar)

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

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

(Hou)
(Akeroyd, Recksiegel)
(Isidori, Paradisi)

Tree-Level
H^+ exchange

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

Altmannshofer, AJB, Guadagnoli, Wick (07)

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

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

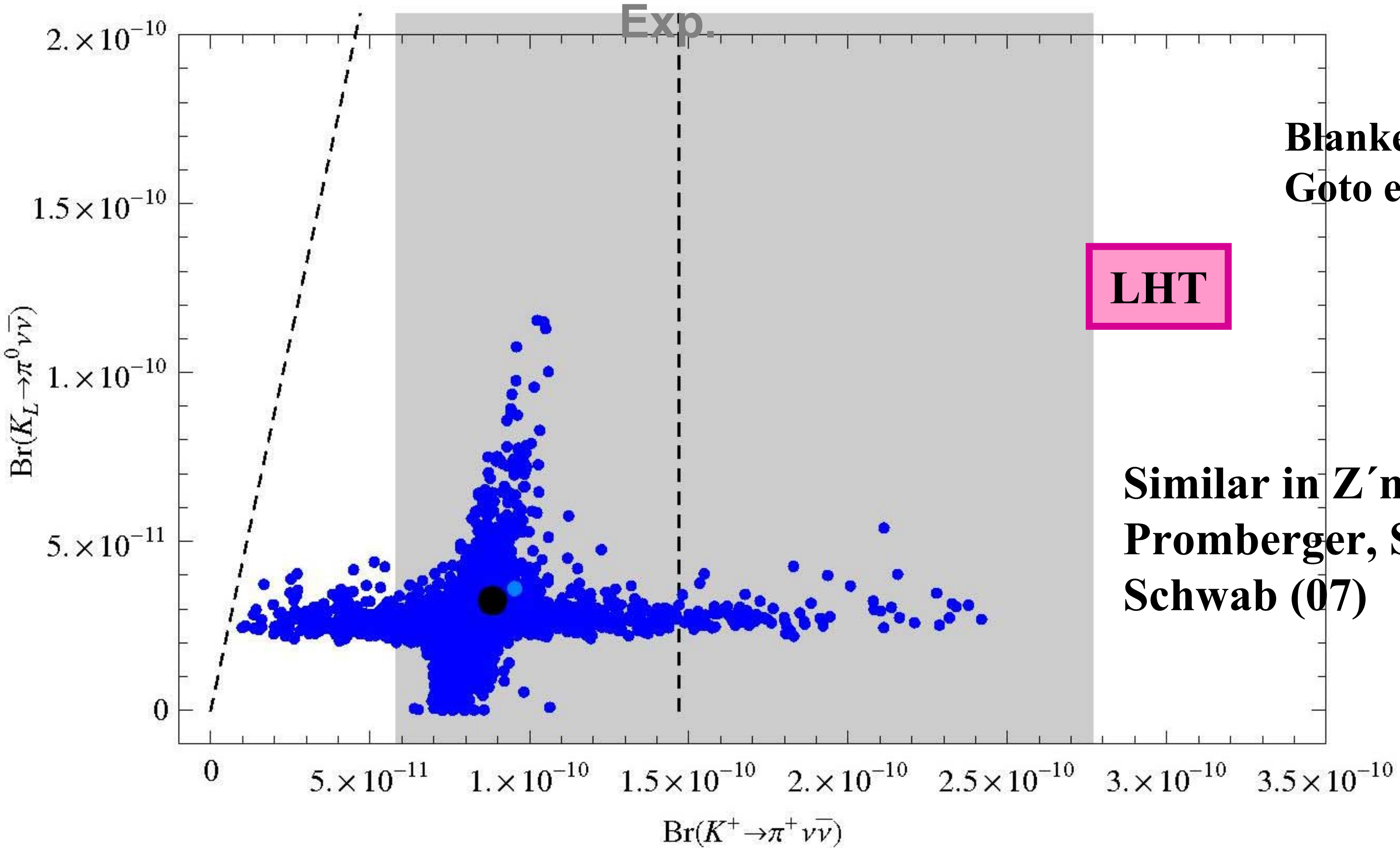
Some recent solutions: Altmannshofer et al.

12. $K^+ \to \pi^+ \nu\bar{\nu},\ K_L \to \pi^0 \nu\bar{\nu},\ K_L \to \pi^0 l^+ l^-,\ B \to K(K^*)$ ★

Z^0 - Penguin dominated Decays

Decay	SM	Exp	TH
$K^+ \to \pi^+ \nu\bar{\nu}$	$(8.5\pm0.7)\cdot10^{-11}$	$(17.3^{+11.5}_{-10.5})\cdot10^{-11}$ (BNL)	±2-3%
$K_L \to \pi^0 \nu\bar{\nu}$	$(2.6\pm0.3)\cdot10^{-11}$	$< 6.7\cdot10^{-8}$ (KEK)	±1-2%
$K_L \to \pi^0 e^+ e^-$	$(3.5\pm1.0)\cdot10^{-11}$	$< 28\cdot10^{-11}$ (KTeV)	±15%
$K_L \to \pi^0 \mu^+ \mu^-$	$(1.4\pm0.3)\cdot10^{-11}$	$< 38\cdot10^{-11}$ (KTeV)	±15%
$B \to K^+ \nu\bar{\nu}$	$(4.5\pm0.7)\cdot10^{-6}$	$< 14\cdot10^{-6}$ (Belle)	±15%
$B \to K^* \nu\bar{\nu}$	$(6.8\pm1.1)\cdot10^{-6}$	$< 80\cdot10^{-6}$ (BABAR)	±15%
$B \to X_S \nu\bar{\nu}$	$(2.7\pm0.2)\cdot10^{-5}$	$< 64\cdot10^{-5}$ (ALEPH)	±3%

K-system: $K_L \to \pi^0 \nu\bar{\nu}$ vs $K^+ \to \pi^+ \nu\bar{\nu}$



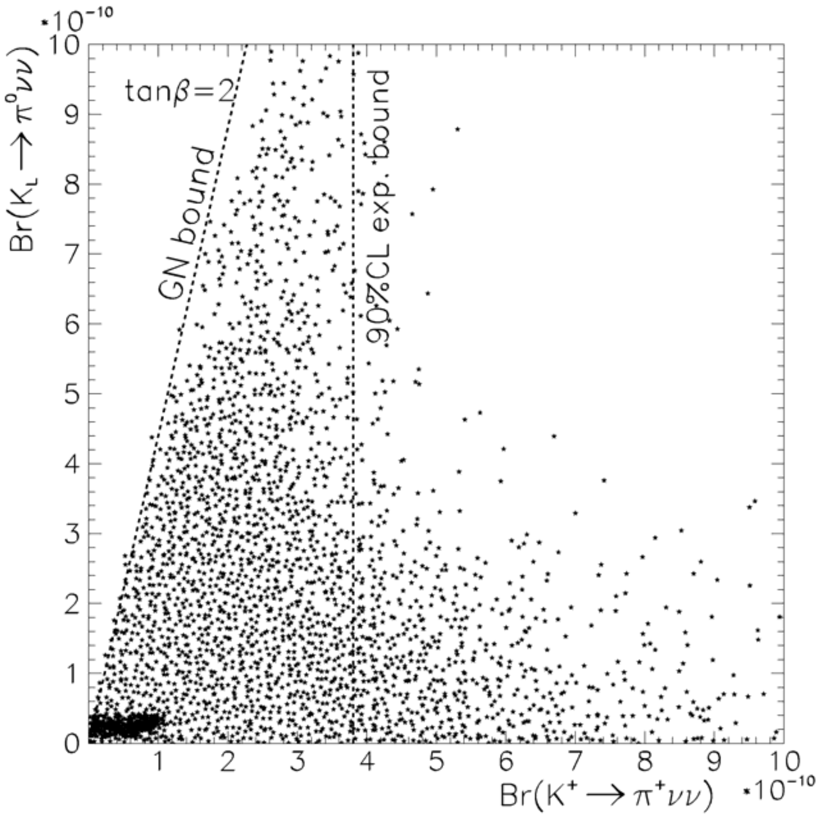
Blanke et al. (06)
Goto et al. (08)

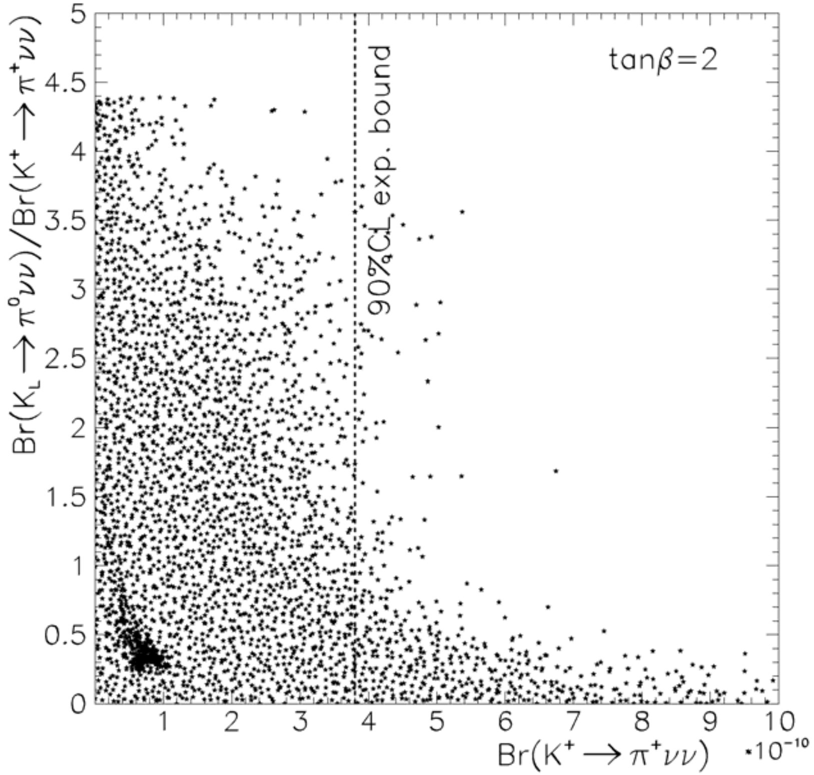
Similar in Z' models:
Promberger, Schatt, Schwab (07)

Two distinguished branches appear!
~5 times enhancement in $K_L \to \pi^0 \nu\bar{\nu}$
~3 times enhancement in $K^+ \to \pi^+ \nu\bar{\nu}$

$K_L \to \pi^0\nu\bar{\nu}$ and $K^+ \to \pi^0\nu\bar{\nu}$ from a general MSSM

AJB, Ewerth, Jäger, Rosiek (04)





see also (Isidori, Mescia, Paradisi, Smith, Trine)

13. Lepton Flavour Violaton

★

A $\mu \to e\gamma,\ \tau \to e\gamma,\ \tau \to \mu\gamma$

B $\mu \to 3e,\ \tau \to 3e,\ \tau \to 3\mu,\ \mu \to e$ **Conversion**

C $\tau^- \to \mu^- e^+ e^-,\ \tau^- \to e^- \mu^+ \mu^-,\ \tau \to \mu(e)P$

$\mu \to e\gamma$: 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]

Correlations between LFV Processes

MSSM : **Dipole Operator Dominance**
(Ellis, Hisano, Raidal, Shimizu; Arganda, Herrero; Paradisi)
(Brignole, Rossi)

$$\frac{Br\left(l_i^- \to l_j^- l_j^+ l_j^-\right)}{Br\left(l_i^- \to l_j^- \gamma\right)} \cong \frac{\alpha}{3\pi}\left(\log\frac{m_{l_i}^2}{m_{l_j}^2} - 2.7\right)$$

$$\frac{Br\left(l_i^- \to l_j^- l_K^+ l_K^-\right)}{Br\left(l_i^- \to l_j^- \gamma\right)} \cong \frac{\alpha}{3\pi}\left(\log\frac{m_{l_i}^2}{m_{l_K}^2} - 2.7\right)$$

LHT : **Dipole Operator Irrelevance (Z-penguins, Boxes dominate)**
(Blanke, AJB, Duling, Poschenrieder, Tarantino) (2007)
del Aguila, Illana, Jenkins (2008)

Spectacular Distinction between MSSM and LHT

Paradisi et al | **Blanke et al**

MSSM | **LHT**

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

LHT: $0.4 - 2.5$

$$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau^- \to e^- \gamma)} \cong \frac{Br(\tau^- \to \mu^- e^+ e^-)}{Br(\tau^- \to \mu^- \gamma)} \approx \frac{1}{95}$$

LHT: $0.4 - 2.3$, $0.3 - 1.6$

$$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau^- \to \mu^- \gamma)} \cong \frac{Br(\tau^- \to e^- \mu^+ \mu^-)}{Br(\tau^- \to e^- \gamma)} \approx \frac{1}{435}$$

LHT: $0.4 - 2.3$, $0.3 - 1.6$

14. Search for $\not{CP}$ in Lepton Sector

A $\not{CP}$ in neutrino oscillations

B θ_{13}

15. $(g-2)_\mu$ and EDM's

Flavour Conserving ★

A $(g-2)_\mu$: Flavour and CP conserving

Resolution of the $(g-2)_\mu$ problem

$$\left[(g-2)_\mu\right]_{SM} \neq \left[(g-2)_\mu\right]_{exp}$$

$$a_\mu^{exp} = 11659\,2080\ (63)\ 10^{-11}$$

$$a_\mu^{SM} = 11659\,1785\ (51)\ 10^{-11}$$

3.6 σ discrepancy

MSSM
~~LHT~~

→ But e^+e^- from BaBar → 0.9 σ

(?)

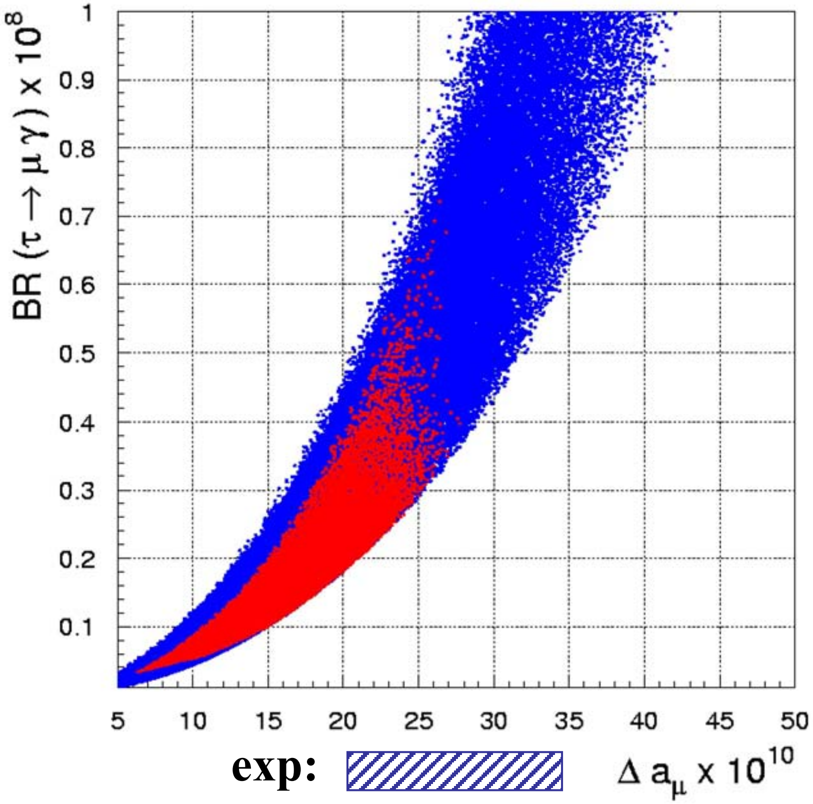
B EDM´s Flavour conserving but ~~CP~~

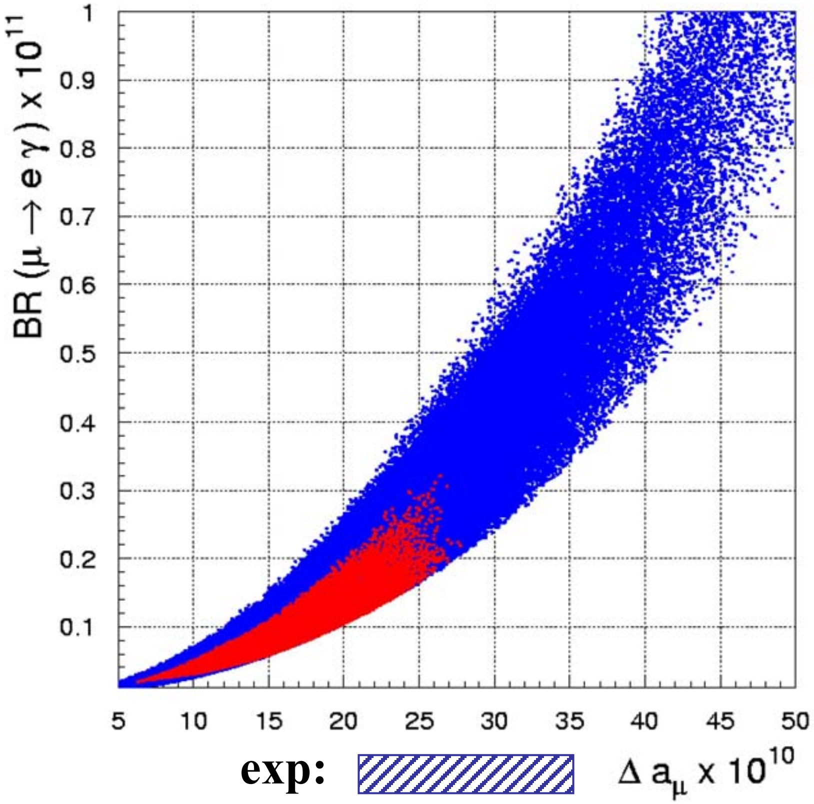
MSSM, ~~LHT~~, WED

Correlation between LFV and $(g\text{-}2)_\mu$

MSSM
large tanβ

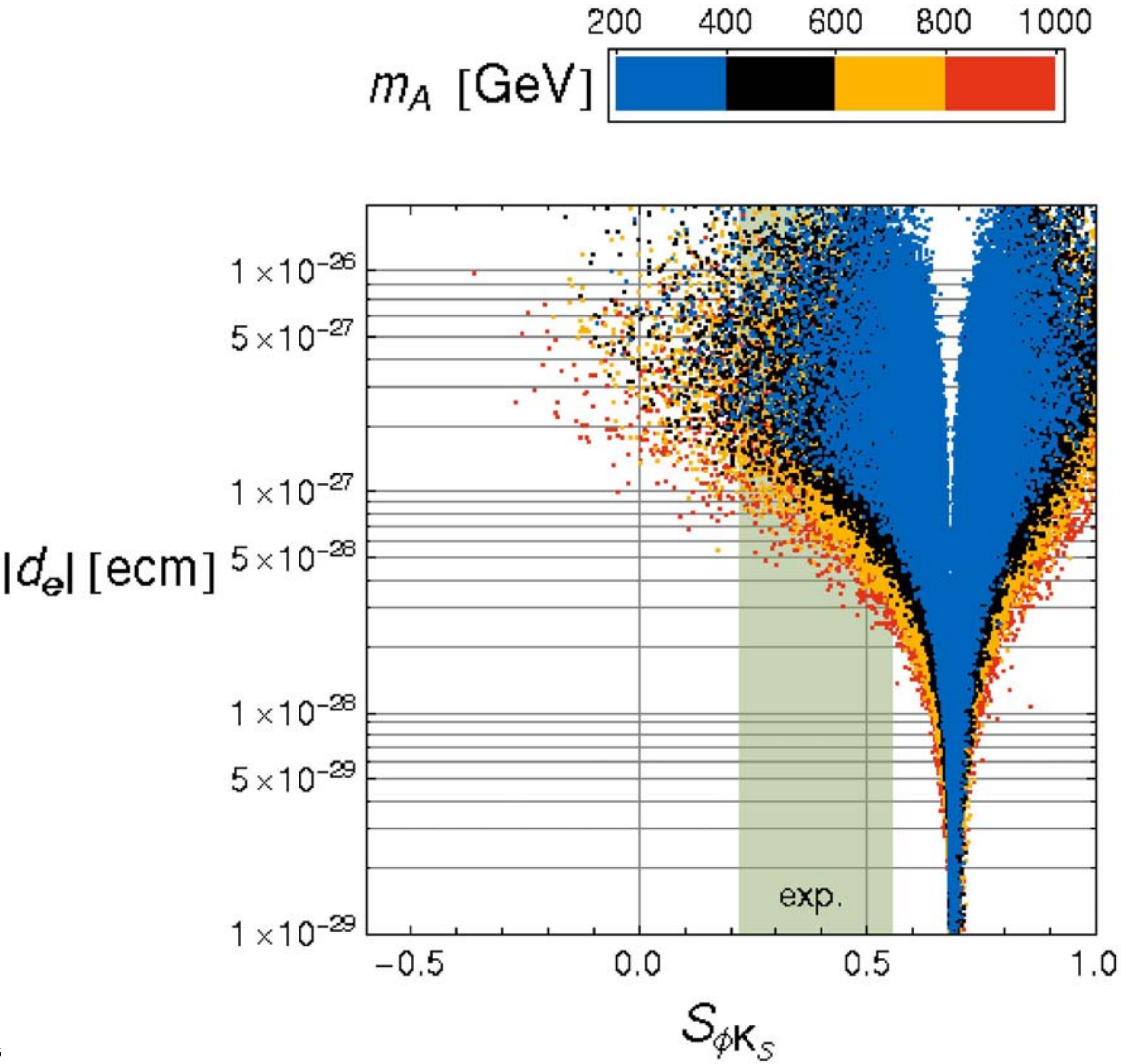
Isidori, Mescia, Paradisi, Temes (2007)





Correlation between d_n and $S_{\varphi K_s}$ in Flavour Blind MSSM

Altmannshofer, AJB, Paradisi (2008)



Desire to explain

$$\left(S_{\varphi K_s}\right)_{exp} < \left(S_{\varphi K}\right)_{SM}$$

d_e by several orders of magnitude larger than $(d_e)_{SM}$

16.

Precise Calculation of B_6 and B_8 (hadronic matrix elements in $\Delta S = 1$ Hamiltonian)

⇒

Does the SM really describe $(\varepsilon'/\varepsilon)_{exp}$ [Direct ~~CP~~]

$$\varepsilon'/\varepsilon = (16.6 \pm 1.7) \cdot 10^{-3}$$

NA48
KTeV

Very sensitive probe of electroweak penguins

(more sensitive than most B-decays)

Large error in B_6 precludes very efficient tests at present

17. Charm Decays

(Messages from Ikaros Bigi)

Main Targets:

a. $D^+ \to \mu^+\nu,\ D^+ \to \tau^+\nu,\ D_s \to \tau\nu$
with higher exp. and lattice accuracy (H^+ physics)

b. $(x_D, y_D) \neq (0,0)$ (time-dependent $\not{C}\not{P}$)

c. Dedicated CP studies in D decays

18. Non-Perturbative Perspectives

Several observables have significant hadronic uncertainties

★ They should be decreased below 5%

Present progress on the lattice gives us hope that this should be possible by

2016

19. Main Theoretical Goal in Flavour Physics

19. Main Theoretical Goal in Flavour Physics

Construction of a

New Standard Model (NSM)

that is **predictive**, consistent with all data and giving

explanation of hierarchies in fermion masses and mixing angles.

20. Main Experimental Goals

in Flavour Physics

20. Main Experimental Goals

in Flavour Physics

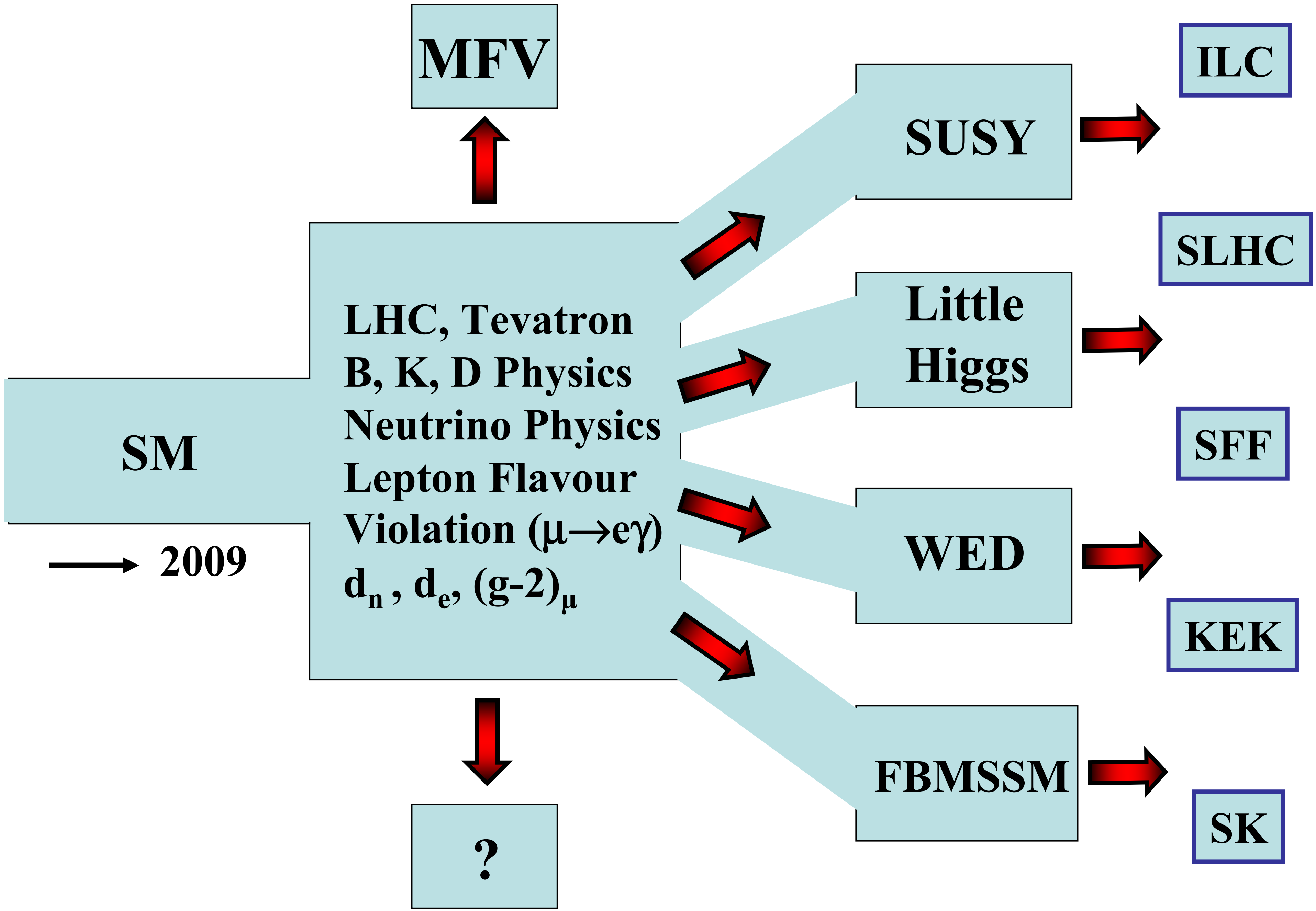
LHC, Super-KEK, SFF
Super-K, LFV machines

to

give hints for NSM
and test NSM

3.

Final Messages


MFV
SM
2009
LHC, Tevatron
B, K, D Physics
Neutrino Physics
Lepton Flavour
Violation (μ→eγ)
d_n , d_e, $(g-2)_\mu$
?
SUSY
Little
Higgs
WED
FBMSSM
ILC
SLHC
SFF
KEK
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

Great discoveries are ahead of us !

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**

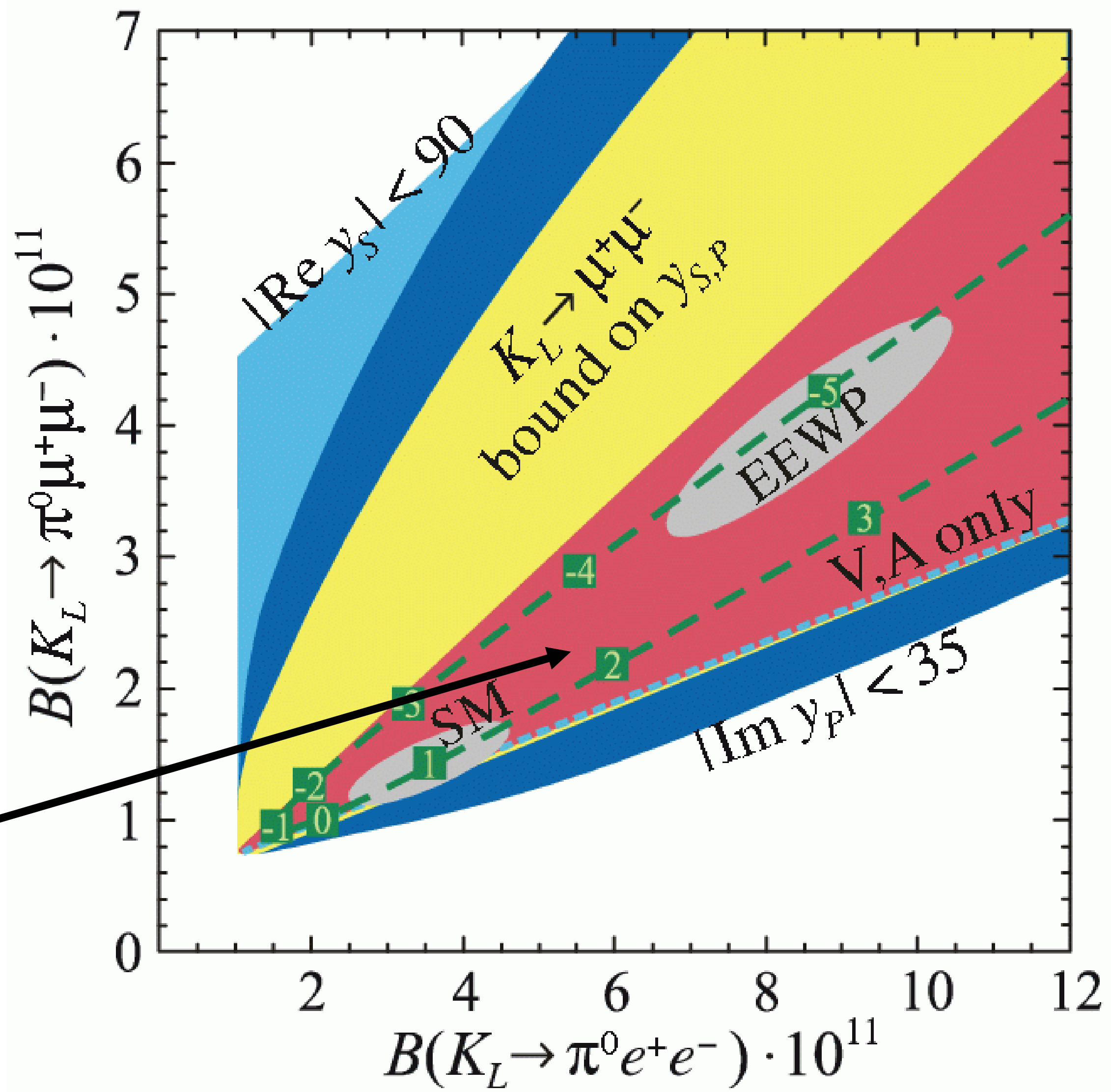
Great discoveries are ahead of us !

Thank You !

Backup

Correlations in various NP Scenarios

Mescia, Smith, Trine (06)



LHT

NP with new Operators

(2,2)

2 x 2 Flavour Matrix

	SM Operators	+ New Operators
CKM	**A** SM-like CMFV-Correlations and Golden Relations between K and B	**B** Large Enhancements of $B_{s,d} \to \mu^+\mu^-$ Departures from CMFV Relations ← **MFV**
+ New Sources of Flavour Violation	**C** Large Enhancements of $\not{CP}$ Observables $\left(S_{\psi\varphi},\ K_L \to \pi^0 \nu\bar{\nu}, K_L \to \pi^0 l^+ l^-\right)$ but moderate change in $B_{s,d} \to \mu^+\mu^-$	**D** Simultaneous Signatures of B + C

Little Hierarchy Problem

Stabilization of the Higgs mass requires New Physics at scales 0 (1 TeV)

but

Electroweak Precision Tests and Flavour Physics Experiments imply that New Physics shifted to scales 0 (10 TeV) or higher

Solution : **Protective Symmetries that suppress NP effects in EWP-tests and Flavour Physics in spite of NP Scales 0 (1 TeV)**

Custodial Symmetry; GIM Mechanism; Minimal Flavour Violation (MFV)
T-Parity, RS-GIM, P_{LR}

Comparison of MSSM with LHT

Very large departures from SM in both models : $S_{\psi\varphi}$, $K_L \to \pi^0 \nu\bar{\nu}$, $K^+ \to \pi^+ \nu\bar{\nu}$
$K_L \to \pi^0 e^+ e^-$, $K_L \to \pi^0 \mu^+ \mu^-$
All LFV decays

Pattern could distinguish MSSM from LHT

Very large or significant departures only in MSSM : $B_{s,d} \to \mu^+\mu^-$, $(g-2)_\mu$
d_n, d_e

Correlations in LFV very different in both models :

$$\frac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu \to e\gamma)} \approx \begin{cases} 0(10^{-2}) & \text{MSSM} \\ 0(1) & \text{LHT} \end{cases}$$

Approximate "$\mu \leftrightarrow e$" Symmetry: ~~MSSM~~ LHT

Messages from the Nature

	$S_{\psi K_S}$	ε_K	ΔM_s	ΔM_d	ΔM_K
TH:	$\pm 1\%$	$\pm 15\%$	$\pm 25\%$	$\pm 25\%$	$\pm 35\%$

	$B \to X_s \gamma$ (branching ratio)	$B \to X_s l^+ l^-$ (branching ratio)	$B \to K^* \gamma$ (branching ratio)
TH:	$\pm 10\%$	$\pm 15\%$	$\pm 25\%$

All Loop induced in the SM

All these observables turned out to be close to SM expectations ⇒ They put important constraints on New Physics

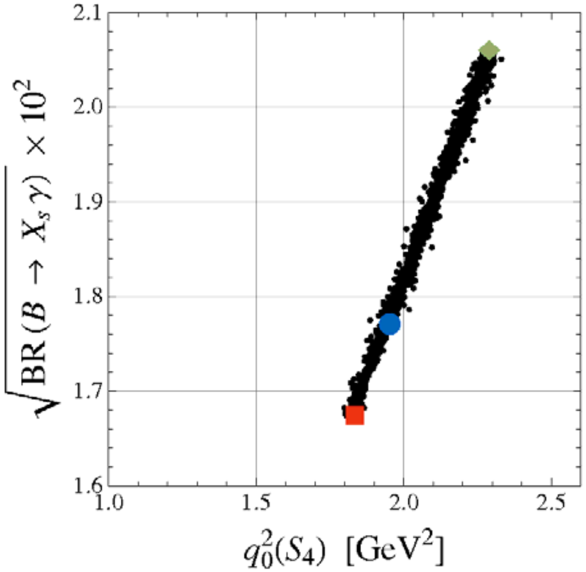
⇓

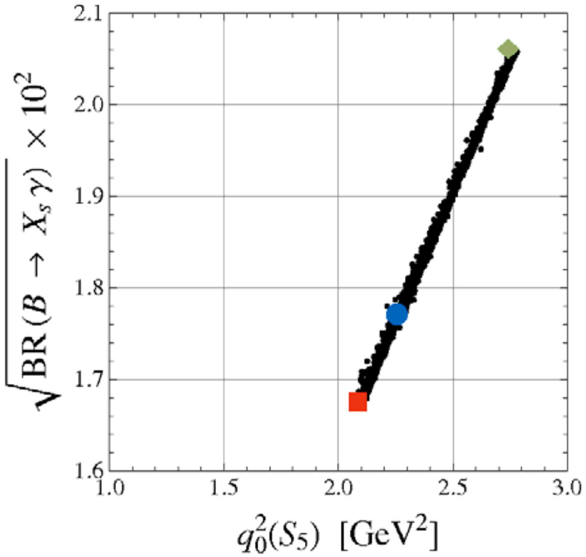
Obviously, no spectacular effects from NP are allowed here

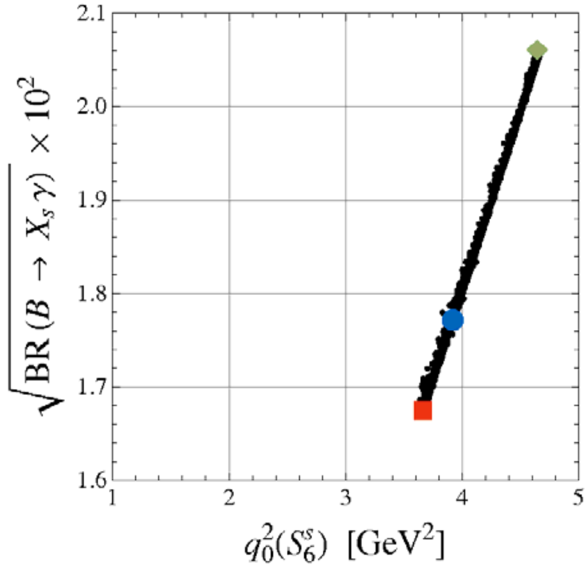
These constraints will improve with improved data and TH

Three S_i in MFV MSSM

ABBBSW (08)

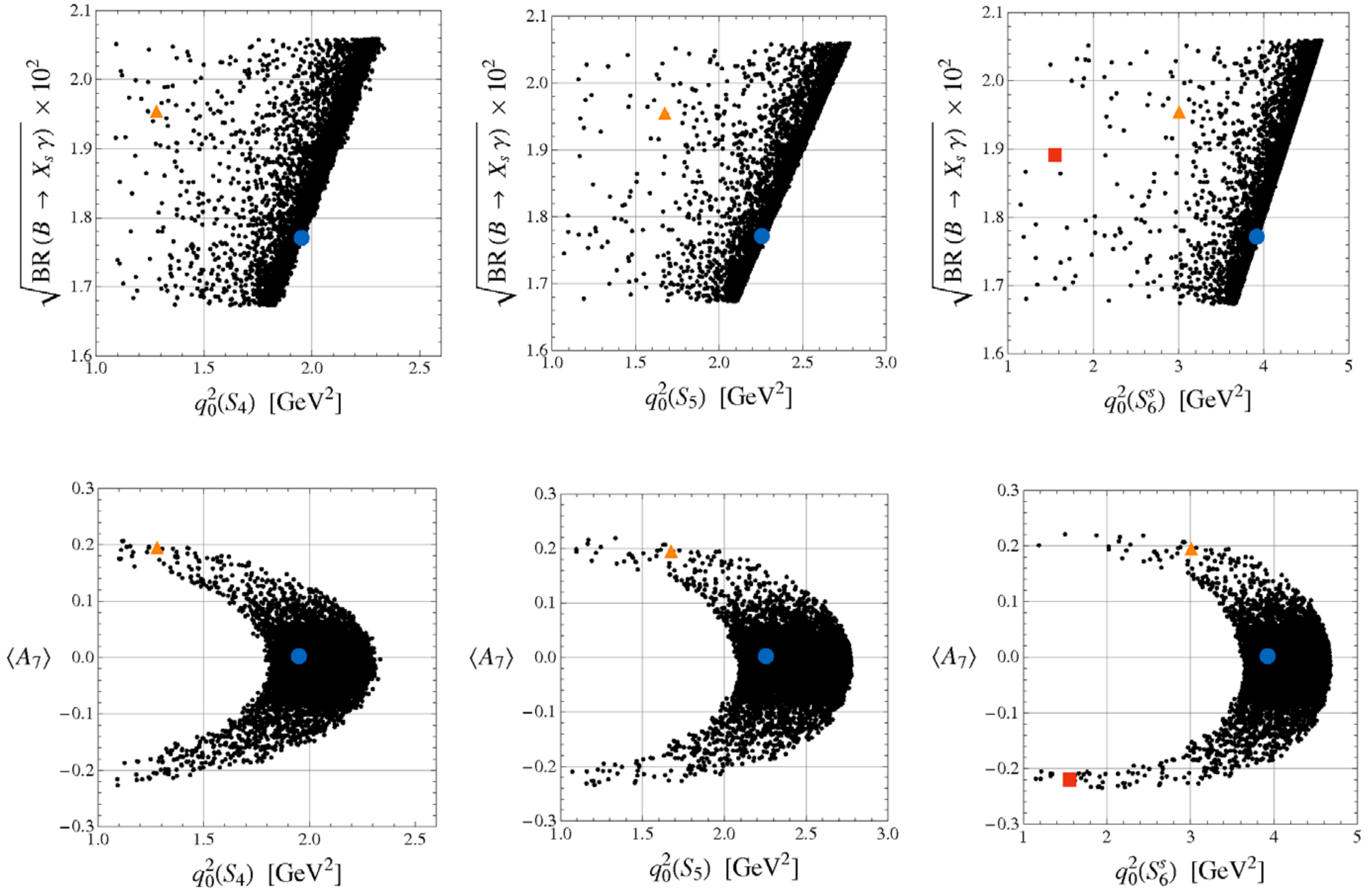






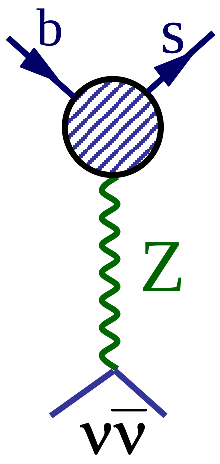
FB MSSM

ABBBSW (08)



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

(Buchalla, Hiller, Isidori, 00)



$$c_L \bar{b}_L \gamma_\mu s_L + c_R \bar{b}_R \gamma_\mu s_L \qquad (c_R)_{SM} = 0$$

$B \to K\nu\bar{\nu}$ ⟶ $|c_L + c_R|$

$B \to K^*\nu\bar{\nu}$ ⟶ $|c_L + c_R|$ and $|c_L - c_R|$

$B \to X_s\nu\bar{\nu}$ ⟶ $|c_L|^2 + |c_R|^2$

No dipole operators

Z-penguins better seen than in $b \to s\, l^+ l^-$

SM

$$Br(B \to K\nu\bar{\nu}) \approx 4 \cdot 10^{-6}$$

$$Br(B \to K^*\nu\bar{\nu}) \approx 1.3 \cdot 10^{-5}$$

$$Br(B \to X_s\nu\bar{\nu}) \approx 3.5 \cdot 10^{-5}$$

Could be enhanced by even an order of magnitude over SM through NP

Has to be considered together with $B \to \tau\nu$

ALEPH

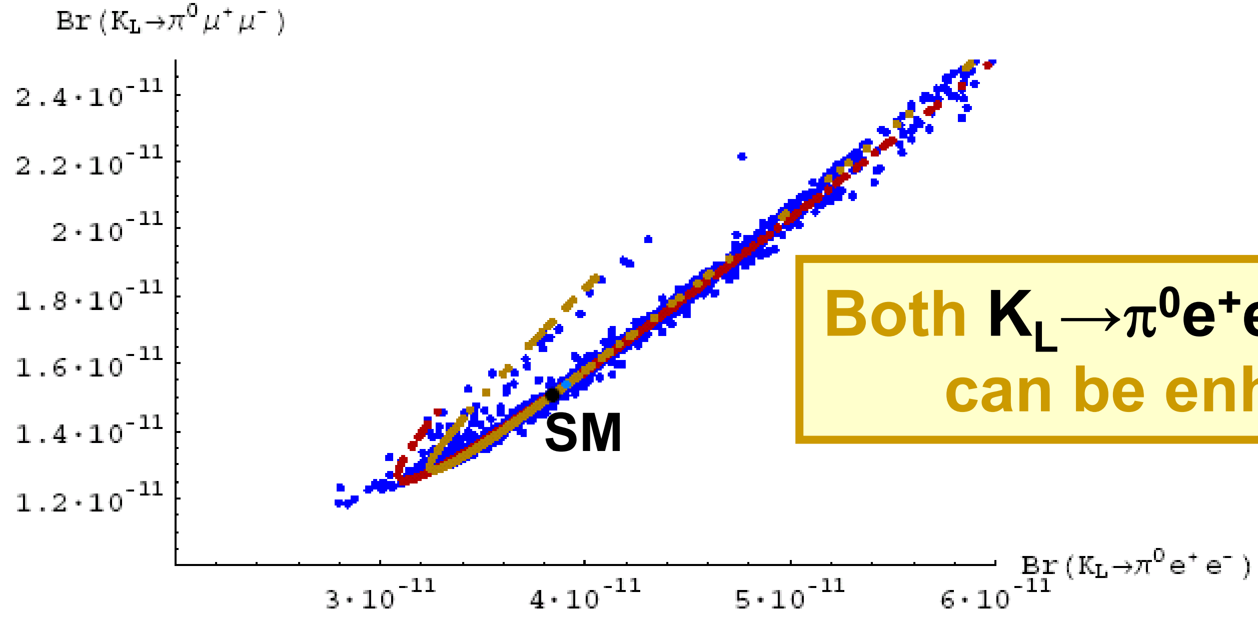
$$Br(B \to X_s\nu\bar{\nu}) \le 7.7 \cdot 10^{-4}$$

$$Br(B \to K\nu\bar{\nu}) \le 14 \cdot 10^{-6}$$

(Belle)

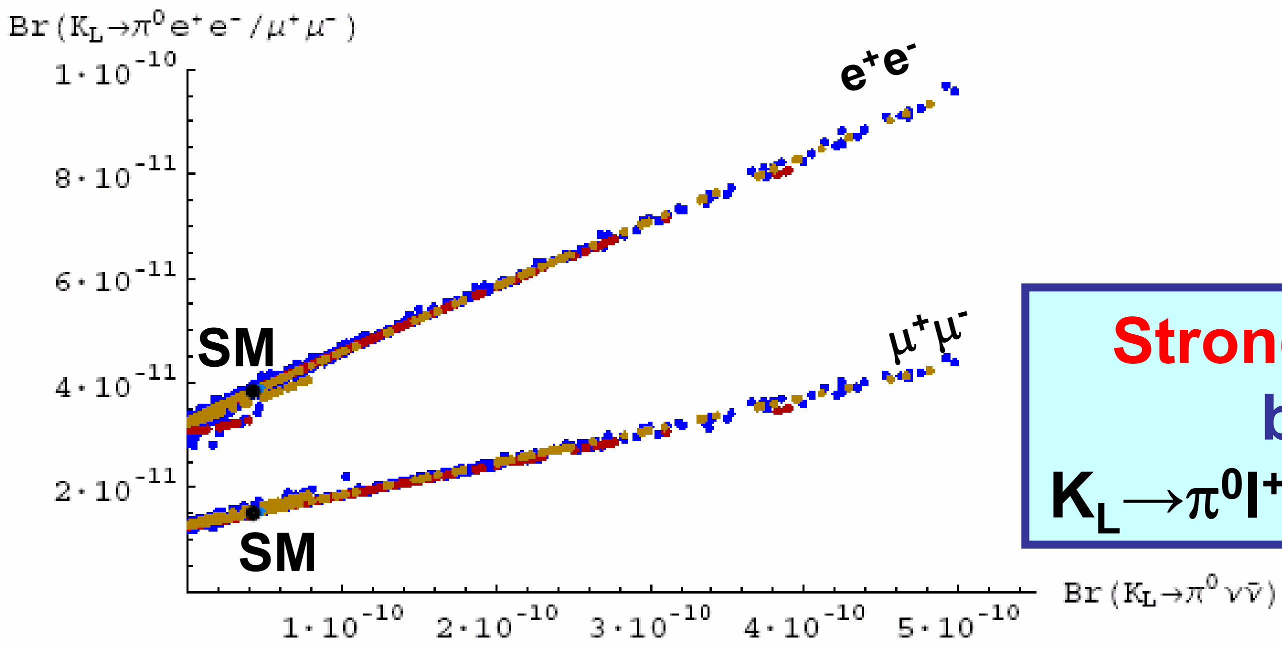
K-system: $K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \mu^+ \mu^-$

(2,1)



Friot, Greynat, de Rafael (04)
General correlation:
Isidori, Smith, Unterdorfer (04)
Mescia, Smith, Trine (06) ★

Both $K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \mu^+ \mu^-$ can be enhanced by ~2



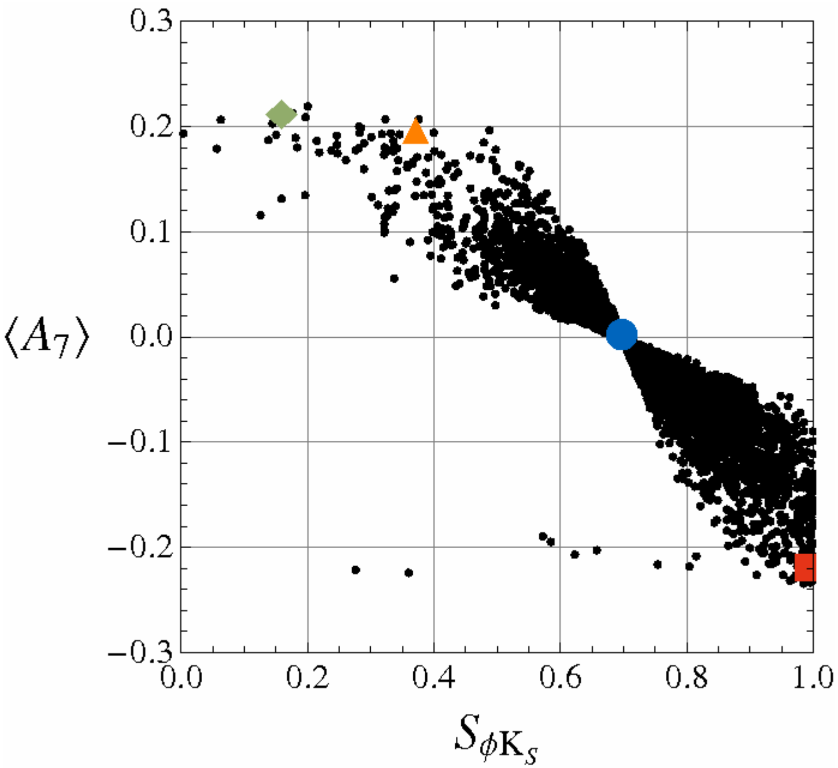
LHT

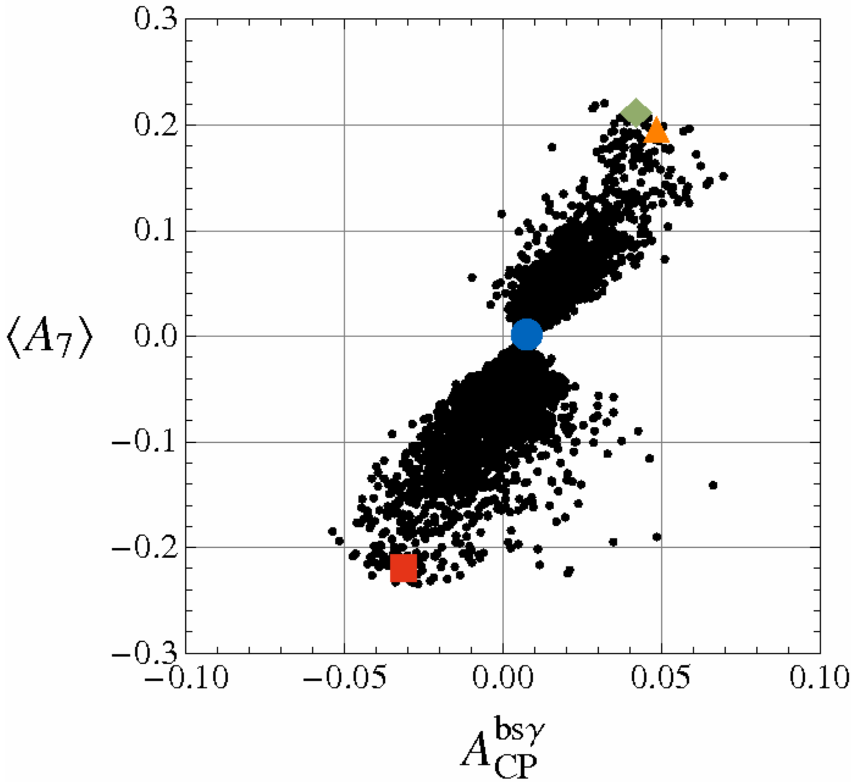
Blanke et al.

Strong correlation between $K_L \to \pi^0 l^+ l^-$ and $K_L \to \pi^0 \nu \bar{\nu}$

FBMSSM

ABBBSW (08)





Flavour Blind MSSM

Altmannshofer, AJB, Paradisi (2008)

Baek, Ko (98)
Bartl, Lunghi,
Masiero, Vives et al (2001)

a CKM - the only source of flavour violation (universal squark masses and diagonal A_i)

→ No gluino contributions to FCNCs

b Parameters of FBMSSM

$\tan\beta$, $M_{H^\pm}$

μ

Gaugino masses M_1, M_2, M_3

Squark masses m^2_Q, m^2_U, m^2_D

trilinear couplings : A_d, A_s, A_b, A_u, A_c, A_t

μ, M_i, A_i can be complex

c Main role played by one complex parameter combination μA_t

→ Interesting correlations between

$S_{\varphi K_s}, \; d_n, \; A_{CP}(b \to s\gamma), \dots$

New flavour conserving phases

Essential Ingredients in the Master Formula

1. **Hadronic Matrix Elements** $(\hat{B}_i)$

(Progress still has to be made) Recent progress: $\hat{B}_K$

2. **QCD and QED RG-Effects for $\mu < m_t$** (η_i^{QCD})

1990´s - era of NLO calculations
2000´s - era of NNLO calculations

- ★ $B \to X_s l^+ l^-$ (Greub et al; Isidori et al, Beneke et al
- ★ $B \to X_s \gamma$ (Misiak et al) Bobeth et al)
- ★ $K^+ \to \pi^+ \nu\bar{\nu}$ (AJB, Gorbahn, Haisch, Nierste)
- ★ Non-Leptonic (Buchalla; Beneke, Jäger,…)
  + Semi-Leptonic (Gorbahn, Haisch)
  3 Loop $\hat{\gamma}_{anom}$

3. Calculation of short distance loop functions

Best studied: SM | MSSM | UED | WED

LH | LHT | Z´-Models

4th Generation | FBMSSM

Flavour Physics in Warped Extra Dimensions

Hierarchies in Quark and Lepton Masses and their mixings "explained" through different position in WED → Non-universal (in flavour) Gauge couplings of KK-gauge Bosons and Z → Tree Level contributions to FCNC Processes from KK and Z

Many free parameters ★

Most recent studies:

Csaki, Falkowski, Weiler : ε_K → $M_{KK} \geq 20\text{TeV}$ No fine tuning

Blanke, AJB, Duling, Gori, Weiler : ε_K → $M_{KK} \geq 2\text{TeV}$ With modest fine tuning

★ Large $S_{\psi\varphi}$

Blanke, AJB, Duling, Gemmler, Gori :

Albrecht, Blanke, AJB, Duling, Gemmler

(TH framework)

Protective custodial symmetry suppresses contributions to rare K and B $\Delta F = 1$ transitions

soon to appear

($\leq$ 100% Effects)

(Patterns different from LHT) ★