FCNC Processes in the LHC Era

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CERN, 28th of March, 2007

TH-Finale:
Allegro Vivace

Overture

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 ★

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**

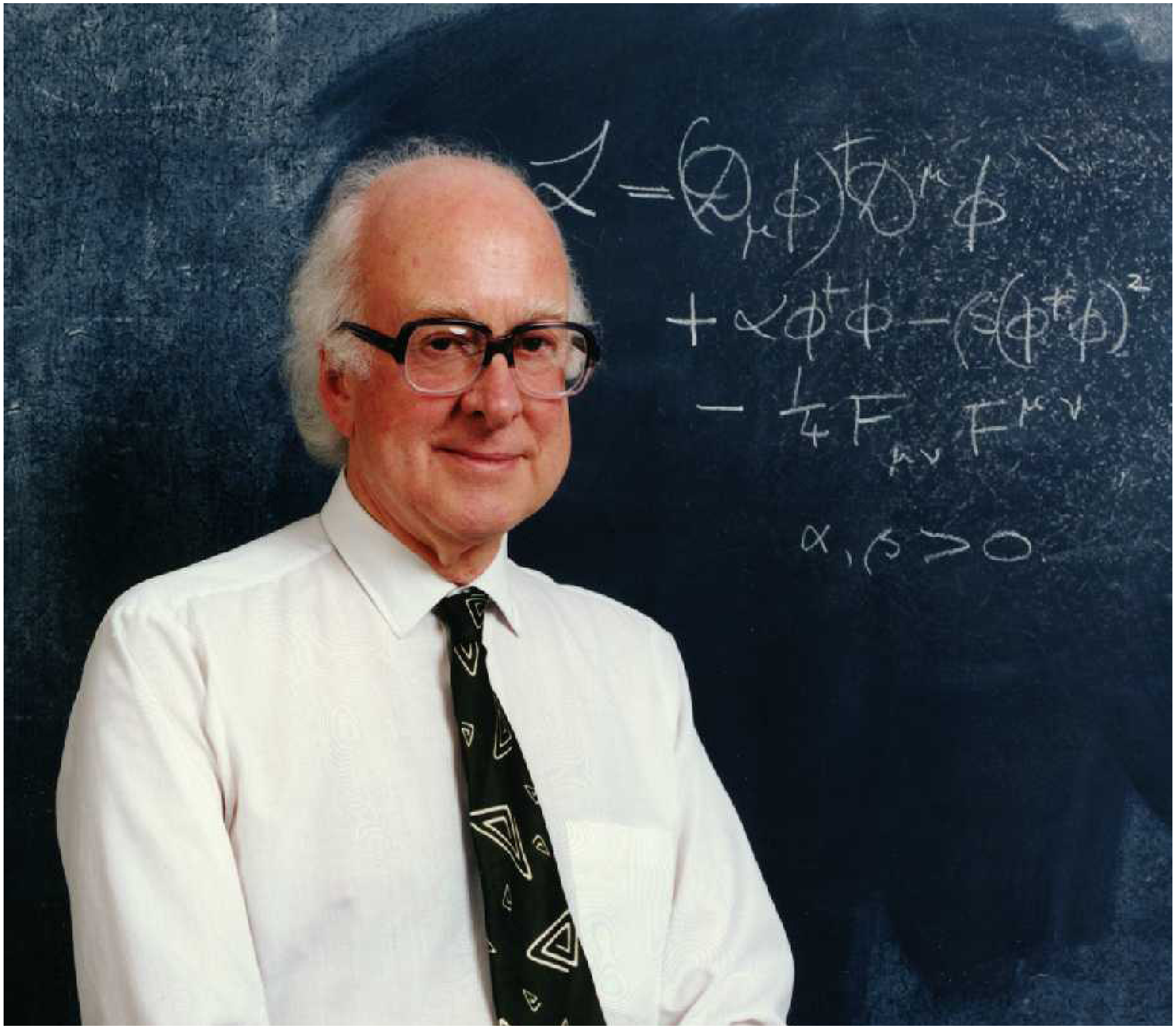
4. $B \to X_s \gamma$, $B \to X_s l^+ l^-$ OK

~~CP~~ in B_s?

5. Very very highly suppressed transitions also consistent with experiment: (not seen)

Standard Model	Exp Upper Bound
$Br(B_s \to \mu^+\mu^-) \cong 3 \cdot 10^{-9}$	$\sim 10^{-7}$
$Br(K_L \to \pi^0 \nu\bar{\nu}) \cong 3 \cdot 10^{-11}$	$\sim 10^{-7}$
$Br(K_L \to \mu e) \cong 10^{-40}$	$\sim 10^{-12}$
$Br(\mu \to e\gamma) \approx 10^{-54}$	$\sim 10^{-11}$
$d_n \approx 10^{-32}$ ecm	$\sim 10^{-26}$ ecm

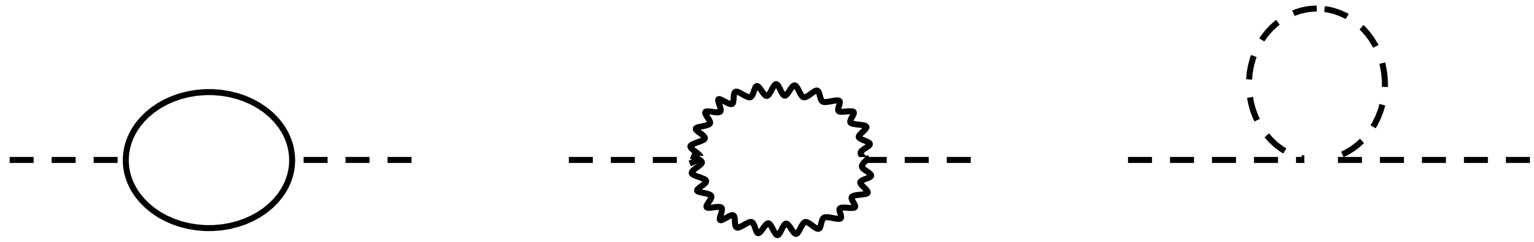
The only Higgs found : Peter Higgs



Hierarchy (Naturalness) Problem

(Quadratic divergences in the Higgs mass)

$m_H^2 \sim \Lambda_{cut\text{-}off}^2$ **through radiative effects**



Disaster for $\Lambda_{cut\text{-}off} >> 1$ **TeV** $\Lambda_{cut\text{-}off} \approx \Lambda_{Planck}$

Must fine tune parameters to 34 decimal places to keep $m_H \approx 0$ (v_{SM})

or postulate New Physics at scales 0 (1 TeV)

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**

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

(Higgs = <u>Pseudogoldstone</u> Boson of a new spontaneously broken global symmetry)

(New strong force at 10 – 20 TeV)

3. **Technicolour**

Higgs = Bound State of Techniquarks } (New strong force at 1 TeV)

4. **Extra Dimensions**

(Gauge-Higgs-Unification)

Higgs = 5th component of a Gauge Field in D = 5 dimensions

(+ many other ideas)

(Higgsless models)

Collider Signatures of these Proposals

New Particles with masses 500 – 2000 GeV

1. Supersymmetry

Superpartners: squarks, sleptons, gluinos, charginos, neutralinos

(R-Parity) ⟶ (Dark matter candidate)

2. Little Higgs

New heavy Gauge Bosons: W_H, Z_H, A_H

New heavy Fermions: Mirror Fermions

(Scalars)

(T-Parity) ⟶ New heavy Fermions; ⟶ (Dark matter candidate)

3. Technicolour

New Resonances
Pseudogoldstone Bosons (Scalars)

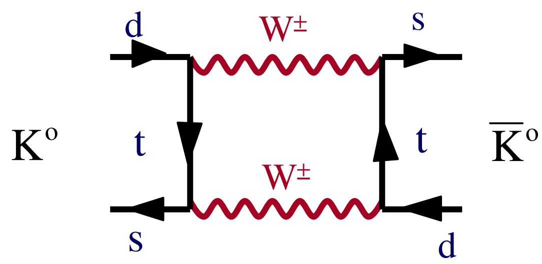
} Analogy to QCD

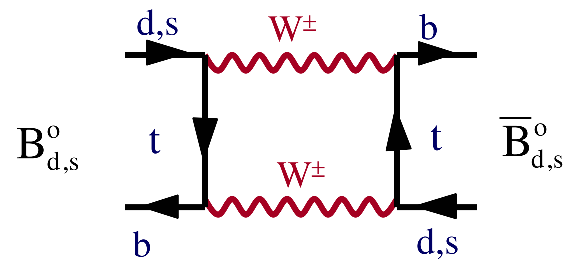
4. Extra Dimensions

Kaluza-Klein Particles

(KK-Parity) ⟶ (Dark matter candidate)

Impact through Quantum Fluctuations





★ ~~CP~~ ε_K-Parameter
ΔM (K_L-K_S)

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

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

(CDF, DØ)

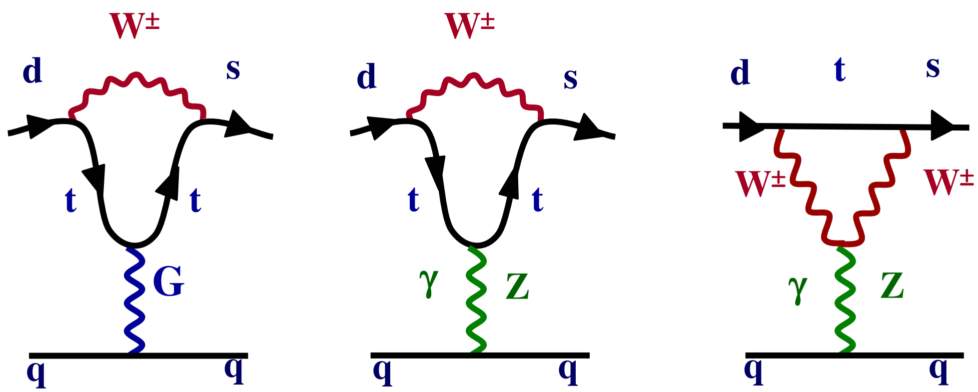
<u>CP-Asymmetries</u>

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

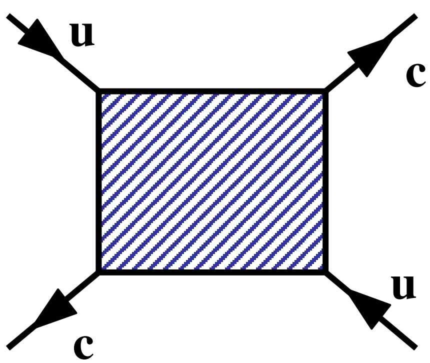
$$S_{\psi\varphi} = \sin\left(2|\beta_s| - 2\varphi_s^{new}\right) \qquad \textbf{(LHC)}$$

Impact through Quantum Fluctuations

★ ε'



(NA48, KTEV)

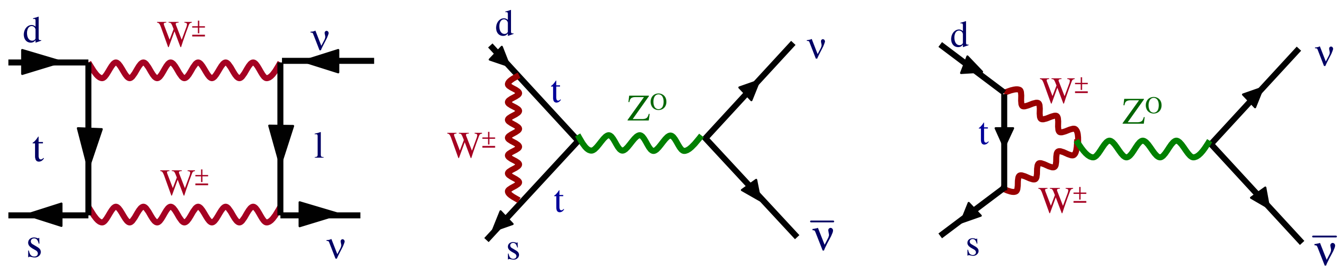


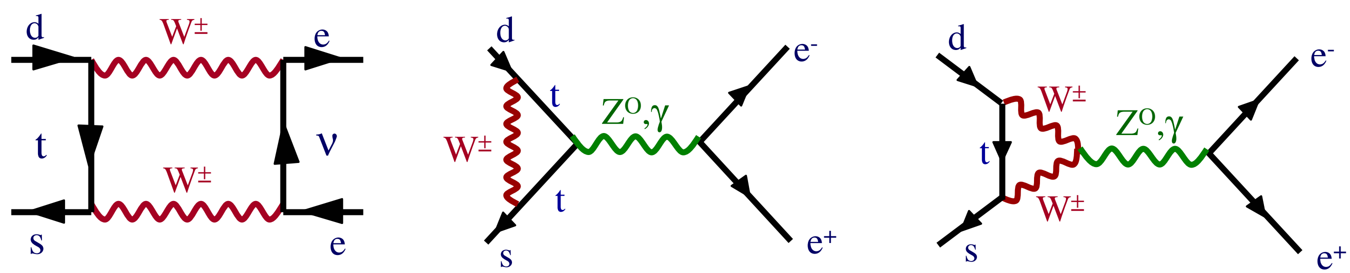
$D^0 - \overline{D}^0$ **Mixing** ★

(BaBar, Belle)

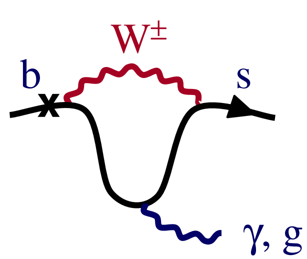
Impact through Quantum Fluctuations

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





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



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

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

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

Different Roles of EWP-Tests and Flavour Physics

EWPT :

Possible signals of NP in EWP-observables have to be very small (1%). Experiments (LEP, SLC) reached already high precision. Can be used mainly to bound parameters of a given extension of SM.

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

Goals for the Next 37 Min

1. **Theoretical Framework**
2. **Puzzles in Flavour Physics (SM)**
3. **CMFV and MFV**
4. **Going beyond MFV**
5. **Finals**

Goals for the Next 37 Min

1. Theoretical Framework
2. Puzzles in Flavour Physics (SM)
3. CMFV and MFV
4. Going beyond MFV
5. Finals

Main Goal : **Collection of 31 Goals for the LHC Era**

1.

Theoretical Framework

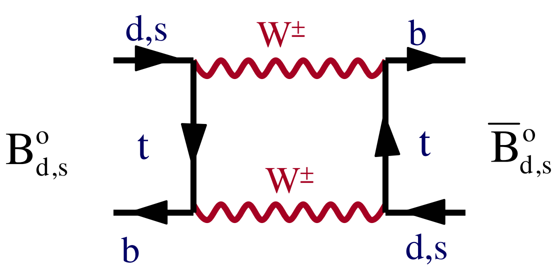
Starting Point :

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

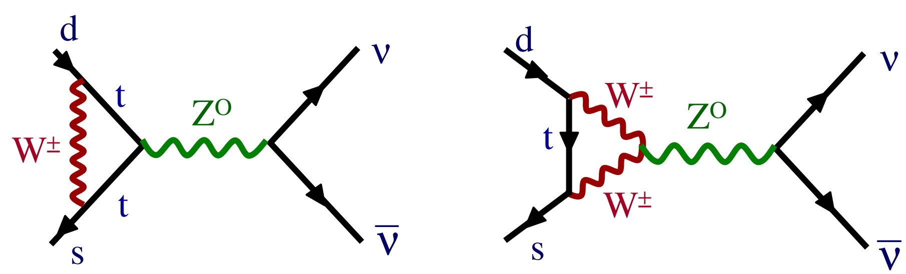
Goal :

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



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

+ 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 $\log(\mu_{SD} / \mu_{LD})$

Master Formula for Weak Decays

AJB (2001)
hep-ph/0101336
hep-ph/0109197

Non-Perturbative Factors in the SM	QCD RG Factors	Short Distance Loop Functions (Penguins, Boxes)	New Flavour-Changing Parameters

Represent different Dirac and Colour Stuctures

$$A(\text{Decay}) = B_i \; \eta^i_{QCD} \; V^i_{CKM} \left[F^i_{SM} + F^i_{New} \right] + B^{New}_i \left[\eta^i_{QCD} \right]^{New} V^i_{New} \left[G^i_{New} \right]$$

(Summation over i)

Non-Perturbative Factors beyond SM	Short Distance Loop Functions Penguins, Boxes

$\text{New} \equiv \text{NP}$

$F^i_{SM}, \; F^i_{New}, \; G^i_{New}$: **Fully calculable in Perturbation Theory**

$\eta^i_{QCD}, \; \left[\eta^i_{QCD} \right]^{New}$: **Fully calculable in RG improved Perturbation Theory**

$B_i, \; B^{New}_i$: **Require Non-Perturbative Methods or can be extracted from leading decays**

$\left(\text{represent } \langle Q_i \rangle \right)$

Fully calculable in the SM

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

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

AJB, Misiak, Urban, Jäger

New

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, 4^{th} generation	**D** beyond GMFV MSSM with $(\delta_{ij})_{AB} \neq 0$ LR Models	

More on the 2 x 2 Flavour Matrix

(1,1) = CMFV (Y_t)

Gabrielli, Giudice
AJB, Gambino, Gorbahn, Jäger, Silvestrini
Ali, London; Laplace, Ligeti, Nir, Perez
Blanke, AJB, Guadagnoli, Tarantino

(1,1) + (1,2) ≡ MFV (Y_t, Y_d) D`Ambrosio, Giudice, Isidori, Strumia

(Spurions and Flavour Symmetries)

(2,1) = New Phases in CMFV

Enhanced Z^0-penguins (Munich + Rome, BFRS)
NMFV (Agashe, Papucci, Perez, Pirjol)
Z´ (Promberger, Schatt, Schwab)

} New Physics coupling dominantly to third generation

LHT (Hubisz et al; Blanke et al) } New Sector of FV-Interactions (Mirror Fermions)

(2,1) + (2,2) ≡ nMFV (Y_t, Y_d, Y_R, Z_L, ...)
(Feldmann + Mannel)

("Spurion-Symphony")

Essential Ingredients in the Master Formula

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

(Progress still has to be made)

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)
- ★ $K^+ \to \pi^+ \nu\bar{\nu}$ (AJB, Gorbahn, Haisch, Nierste)
- ★ Non-Leptonic + Semi-Leptonic (Gorbahn, Haisch) 3 Loop $\hat{\gamma}_{anom}$

Magnificent 17

M. Misiak, H.M. Asatrian, K. Bieri, M. Czakon, A. Czarnecki, T. Ewerth, A. Ferroglia, P. Gambino, M. Gorbahn, C. Greub, U. Haisch, A.Hovhannisyan, T. Hurth, A. Mitov, B.V. Poghosyan, M. Ślusarczyk, M. Steinhauser

$B \rightarrow X_s \gamma$ at NNLO

Magnificent 17

M. Misiak, H.M. Asatrian, K. Bieri, M. Czakon, A. Czarnecki, T. Ewerth, A. Ferroglia, P. Gambino, M. Gorbahn, C. Greub, U. Haisch, A. Hovhannisyan, T. Hurth, A. Mitov, A.V. Poghosyan, M. Ślusarczyk, M. Steinhauser

$B \to X_s \gamma$ at NNLO

Mount Everest Expedition

3. Calculation of short distance loop functions

Best studied: **SM** **MSSM** **UED**

LH **LHT** **Z´-Models**

2.

Puzzles in Flavour Physics (SM)

UTfit Collaboration

Thank You !

**M. Bona, M. Ciuchini, E. Franco, V. Lubicz
G. Martinelli, F. Parodi, M. Pierini, P. Roudeau
C. Schiavi, L. Silvestrini, V. Sordini, A. Stocchi
V. Vangoni**

CKMfit Collaboration

Thank You !

**T. Charles, A. Höcker, H. Lacker,
F.R. Le Diberder, S. T´Jampens**

10 important Goals around the SM

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. Resolution of the first "sin2β-Problem" → $UUT \overset{?}{\neq} RUT$ $\varphi_{B_d}^{new} \overset{?}{\neq} 0$

$(\sin 2\beta)_{\psi K_s} < (\sin 2\beta)_{RUT}$

3. Resolution of the second "sin2β-Problem" → $(\sin 2\beta)_{eff} < (\sin 2\beta)_{\psi K_s}$

Reference Unitarity Triangle and UUT (CMFV)

$$(R_b)_{CMFV} = 0.363 \pm 0.016$$

$$(R_b)_{true} = 0.428 \pm 0.027$$

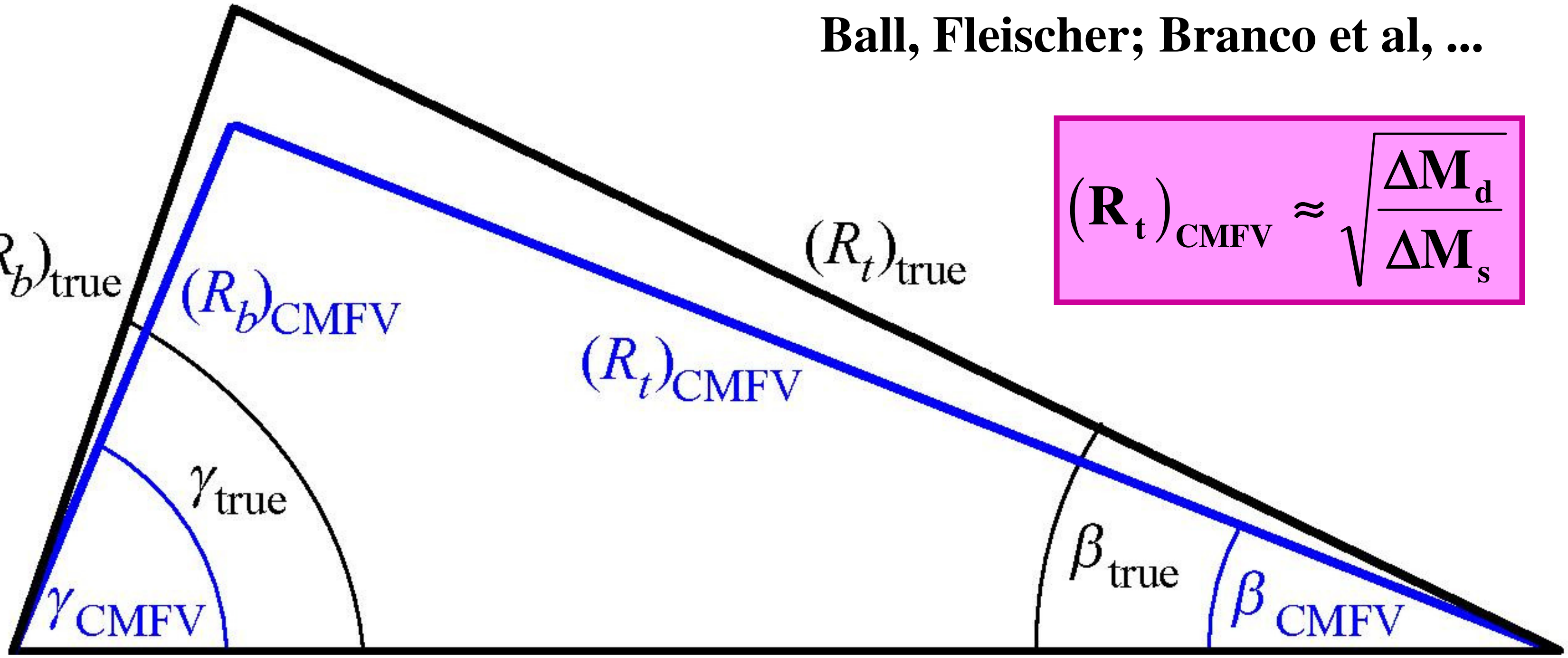
$$\gamma_{true} = (82 \pm 20)^{o}$$

$$\sin 2\beta_{CMFV} = 0.675 \pm 0.026$$

$$\sin 2\beta_{true} = 0.749 \pm 0.063$$ "true"= RUT

Blanke, AJB, Guadagnoli, Tarantino
Utfit, CKMfit
Ball, Fleischer; Branco et al, ...

$$(R_t)_{CMFV} \approx \sqrt{\frac{\Delta M_d}{\Delta M_s}}$$



$$\beta_{CMFV} = \beta_{\psi K_s}$$

First Sign of a new Phase φ_{B_d} in $B_d^0 - \overline{B}_d^0$?

$$(\sin 2\beta)_{true} = 0.749 \pm 0.063$$

$$(\sin 2\beta)_{\psi K_s} = 0.675 \pm 0.026$$

$S_{\psi K_s}$

0.759 ± 0.037

↑ (Utfit)

sides added

$$\gamma_{true} = (80 \pm 20)^o$$

$$S_{\psi K_s} = \sin(2\beta_{true} + 2\varphi_{B_d})$$

"$\sin 2\beta$ Problem"

Is this a $|V_{ub}|$ Problem?

$$\varphi_{B_d} = -(2.9 \pm 3.3)^o$$ (pure tree)

$$\varphi_{B_d} = -(3.5 \pm 1.9)^o$$ sides added

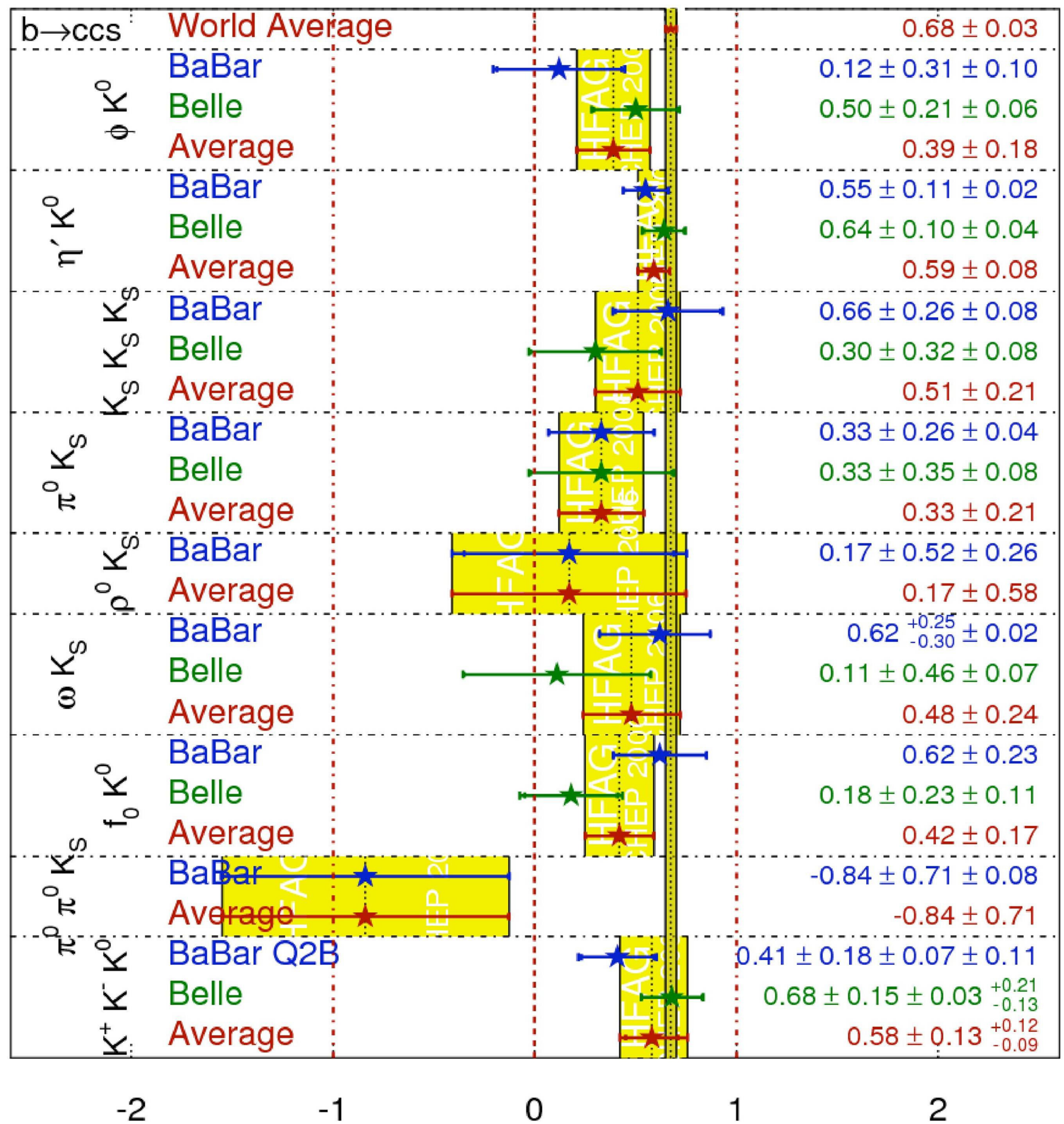
Preliminary

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

HFAG
ICHEP 2006
PRELIMINARY

second

"sin2β Problem"



4.

Precise calculations of

$\hat{B}_d F_{B_d}^2,\ \hat{B}_s F_{B_s}^2,\ \xi$

→

?

$(\Delta M_{d,s})_{exp} = (\Delta M_{d,s})_{SM}$

Important for CMFV, MSSM and LHT

5.

Precise calculation of

$\hat{B}_K$

→

Does the SM really describe $(\varepsilon)_{exp}$?

(indirect $\not{C}\not{P}$)

6.

Precise calculation of

B_6 and B_8

(hadronic matrix elements in $\Delta S = 1$ Hamiltonian)

→

Does the SM really describe $(\varepsilon'/\varepsilon)_{exp}$ $\left(\begin{matrix}\text{direct}\\ \not{C}\not{P}\end{matrix}\right)$?

7.

Resolution of the
$B \to X_s\gamma$ problem

$$\left(B \to X_s\gamma\right)_{SM} < \left(B \to X_s\gamma\right)_{exp}$$

8.

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

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

9.

$B \to \pi K, \pi^+\pi^-$
Puzzles

Some "Puzzles" softened
Other remained (CP-asymmetries)
Are new phases necessary to fit
the two body data ?

10.

Did we see
direct ~~CP~~ in $B_d^0 \to \pi^+\pi^-$?

$$\left[A_{CP}^{dir}\left(\pi^+\pi^-\right)\right]_{Belle} = -0.55 \pm 0.08 \pm 0.05$$

$$\left[A_{CP}^{dir}\left(\pi^+\pi^-\right)\right]_{Babar} = -0.16 \pm 0.11 \pm 0.03$$

$B \to X_s \gamma$ Puzzle (2007)

$$Br(B \to X_s\gamma)_{exp} = (3.55 \pm 0.24 \pm 0.10 \pm 0.03) \cdot 10^{-4}$$

(BaBar, Belle) (HFAG)

$$Br(B \to X_s\gamma)_{SM} = (2.98 \pm 0.26) \cdot 10^{-4}$$

(Misiak + 16 Magnificent) (Becher, Neubert)

1.4 σ lower

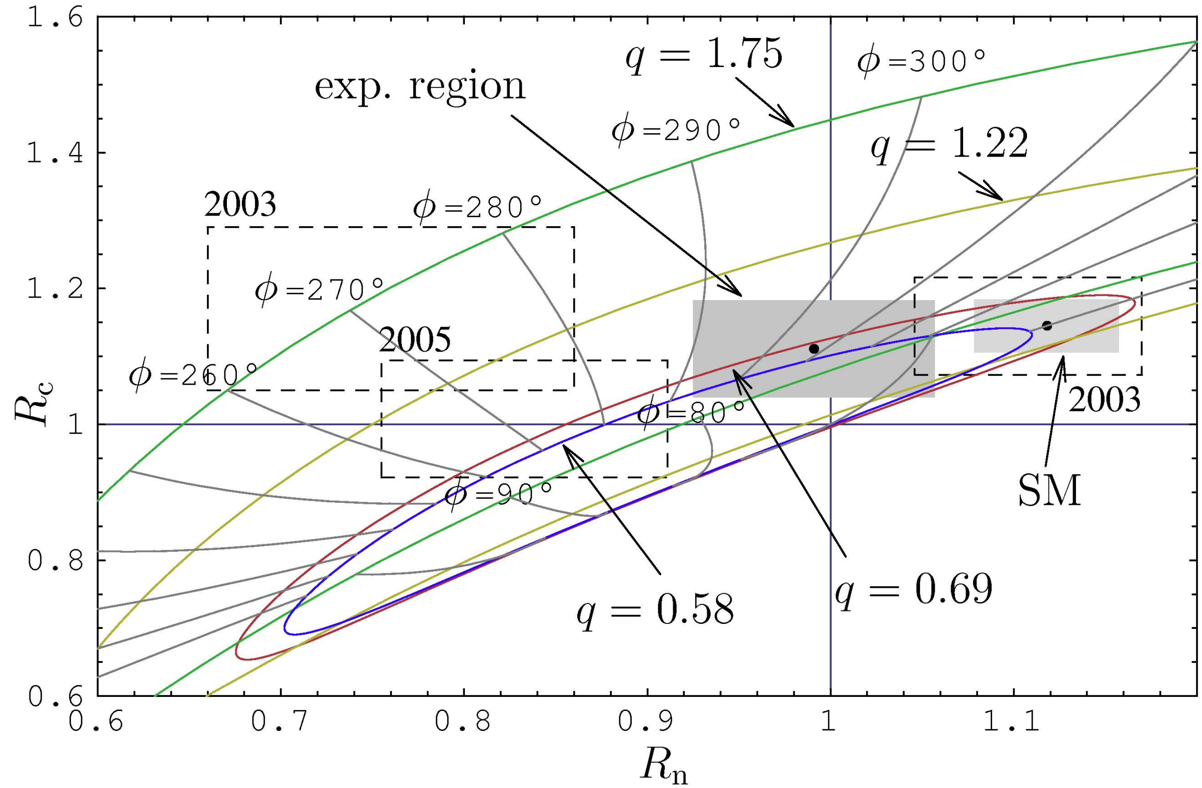
Really not a puzzle but models with $Br(B \to X_s\gamma) < Br(B \to X_s\gamma)_{SM}$ disfavoured

B→ππ, πK Puzzles (2007)

AJB, Fleischer (2000)
Yoshikawa (2003)
Gronau, Rosner (2003)
Beneke, Neubert (2003)
BFRS (2003)

(EWP with new complex phases at work ?)

AJB
Fleischer
Recksiegel
Schwab



FRS (0702275)

Messages from Fleischer, Recksiegel, Schwab

hep-ph 0702275

1.

BFRS strategy
+
$A_{CP}^{dir}(B_d \to \pi^\pm K^\pm)$
(Belle + BaBar)

$\Rightarrow$ $A_{CP}^{dir}(B_d \to \pi^+\pi^-) = -0.24 \pm 0.04$

in favour of BaBar

2.

$R_n \neq R_c$ softened but CP-puzzle remains

$$A_{CP}^{mix}(B_d \to \pi^0 K_s)_{SM} = -0.81 \pm 0.03$$

$$A_{CP}^{mix}(B_d \to \pi^0 K_s)_{exp} = -0.33 \pm 0.21$$

possibly related to $(\sin 2\beta)_{eff} < (\sin 2\beta)_{\psi K_s}$

3.

$$A_{CP}^{dir}(B^\pm \to \pi^0 K^\pm) - A_{CP}^{dir}(B_d \to \pi^\mp K^\pm) \overset{exp}{=} -0.140 \pm 0.030$$

likely generated through hadronic effects

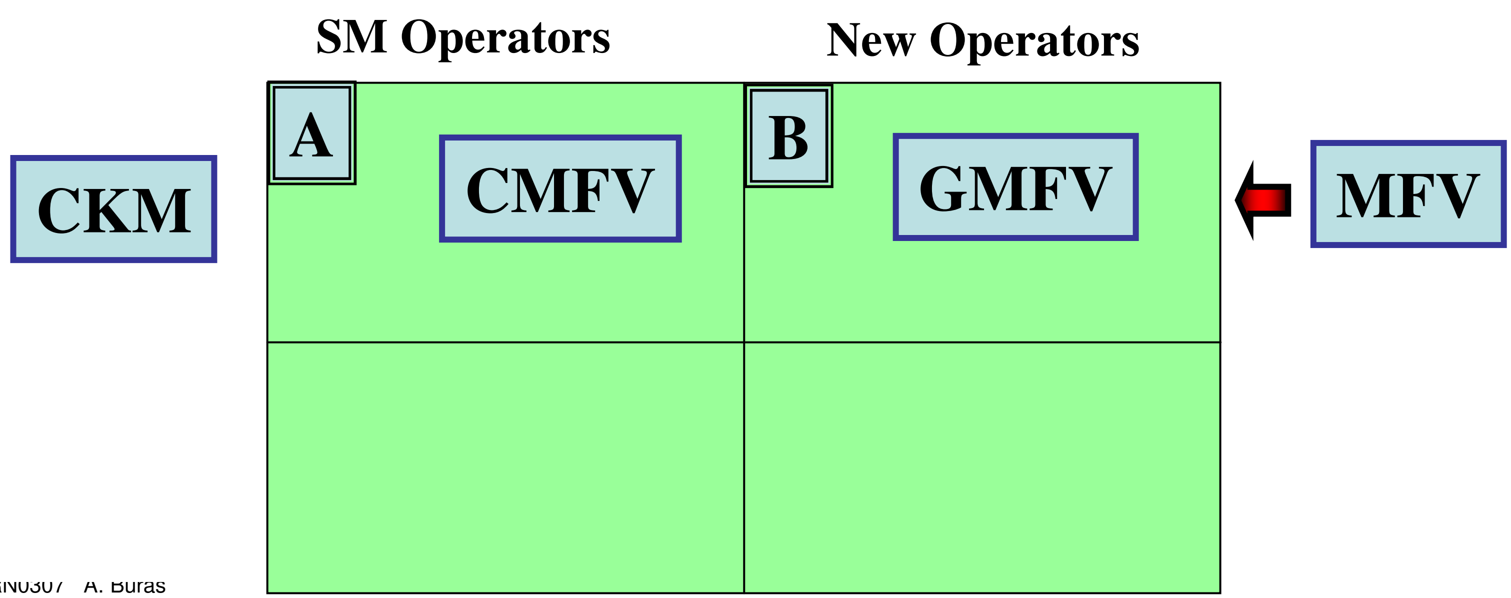
4.

$$\gamma = \left(70.0^{+3.8}_{-4.3}\right)^{o} \pm TH$$

in agreement with UT-fits

3.

CMFV and MFV



Upper Bounds on Rare K and B Decays from CMFV

Bobeth, Bona, AJB, Ewerth, Pierini, Silvestrini, Weiler hep-ph/0505110

Branching Ratios	CMFV (95%)	SM (95%)	SM (68%)	Exp
$Br(K^+ \to \pi^+ \nu\bar{\nu}) \cdot 10^{11}$	<11.9	<10.9	8.3±1.2	$14.7^{+13.0}_{-8.9}$
$Br(K_L \to \pi^0 \nu\bar{\nu}) \cdot 10^{11}$	<4.6	<4.2	3.1±0.6	$<5.9 \cdot 10^4$
$Br(B \to X_s \nu\bar{\nu}) \cdot 10^5$	<5.2	<4.1	3.7±0.2	<64
$Br(B_s \to \mu^+\mu^-) \cdot 10^9$	<7.4	<5.9	3.7±1.0	$<5.0 \cdot 10^2$
$Br(B_d \to \mu^+\mu^-) \cdot 10^{10}$	<2.2	<1.8	1.1±0.4	$<1.6 \cdot 10^3$

Improved Bounds (2007)

Including Impact from R_b^0, A_b, $A_{FB}^{0,b}$

Haisch Weiler (2007)

The sign of Z-penguin Amplitude in CMFV is SM like

Branching Ratios	CMFV (95%)	SM (95%)	Exp
$Br(K^+ \to \pi^+ \nu\bar{\nu}) \cdot 10^{11}$	3.9-10.7	5.5-9.5	$14.7^{+13.0}_{-8.9}$
$Br(K_L \to \pi^0 \nu\bar{\nu}) \cdot 10^{11}$	1.2-4.5	2.3-3.6	$<2.1 \cdot 10^4$
$Br(B \to X_s \nu\bar{\nu}) \cdot 10^5$	1.5-4.7	3.0-3.6	<64
$Br(B_s \to \mu^+\mu^-) \cdot 10^9$	0.8-6.1	2.9-4.2	$<1.0 \cdot 10^2$
$Br(B_d \to \mu^+\mu^-) \cdot 10^{10}$	0.2-1.5	0.9-1.3	$<3.0 \cdot 10^2$

Golden Relations of CMFV and MFV:

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

Buchalla, AJB (94)
AJB, Fleischer (01)

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

(MFV)

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

$\Delta M_{s,d}$ (2007)

$$(\Delta M_s) = (17.77 \pm 0.10 \pm 0.07)/\text{ps}$$ (CDF, DØ)

(before measurements):

$$(\Delta M_s)^{SM}_{UTfit} = (21.5 \pm 2.6)/\text{ps}$$

$$(\Delta M_s)^{SM}_{CKMfitter} = \left(21.7 \pm {}^{5.9}_{4.2}\right)/\text{ps}$$

(2007):

$$(\Delta M_s)^{SM}_{UTfit} = (18.4 \pm 2.2)/\text{ps}$$

$$(\Delta M_s)^{SM}_{CKMfitter} = \left(18.9 \pm {}^{5.7}_{2.8}\right)/\text{ps}$$

Implications of ΔM_s Measurement for Rare Decays

BBGT (2006)

(Model independent "magic numbers" of CMFV)

$$\frac{Br(B_s \to \mu^+\mu^-)}{Br(B_d \to \mu^+\mu^-)} = 33.0 \pm 1.9$$

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.210 \pm 0.010$$

(Blanke, AJB, Guadagnoli, Tarantino)

(update)

$$\frac{Br(B \to X_s \nu\bar{\nu})}{Br(B \to X_d \nu\bar{\nu})} = 22.7 \pm 2.2$$

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

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

$$> 1 \cdot 10^{-7}$$

$$> 3 \cdot 10^{-8}$$

CDF (95% C.L.)

DØ

Is $(\Delta M_s)_{CMFV} > (\Delta M_s)_{SM}$?

M. Blanke, AJB (06) : **(Diagramatic analysis)**

Indeed it is, with two possible exceptions:

Negative contributions from :

- **U(1) neutral gauge bosons in box diagrams (no tree)**
- **Majorana Fermions in box diagrams (for certain values of the parameters of a given theory)**

} **Could still be cancelled by other positive contributions in a given theory.**

New

MSSM with MFV and low tanβ

Altmannshofer, AJB, Guadagnoli (07)

0703200

Explicit Execution of D´Ambrosio, Giudice, Isidori, Strumia (02)

Proposal : Expression of all soft terms through Yukawa couplings Y_t and Y_d

Very significant increase of predictivity

⇓

Correct MFV Limit of MSSM

Messages

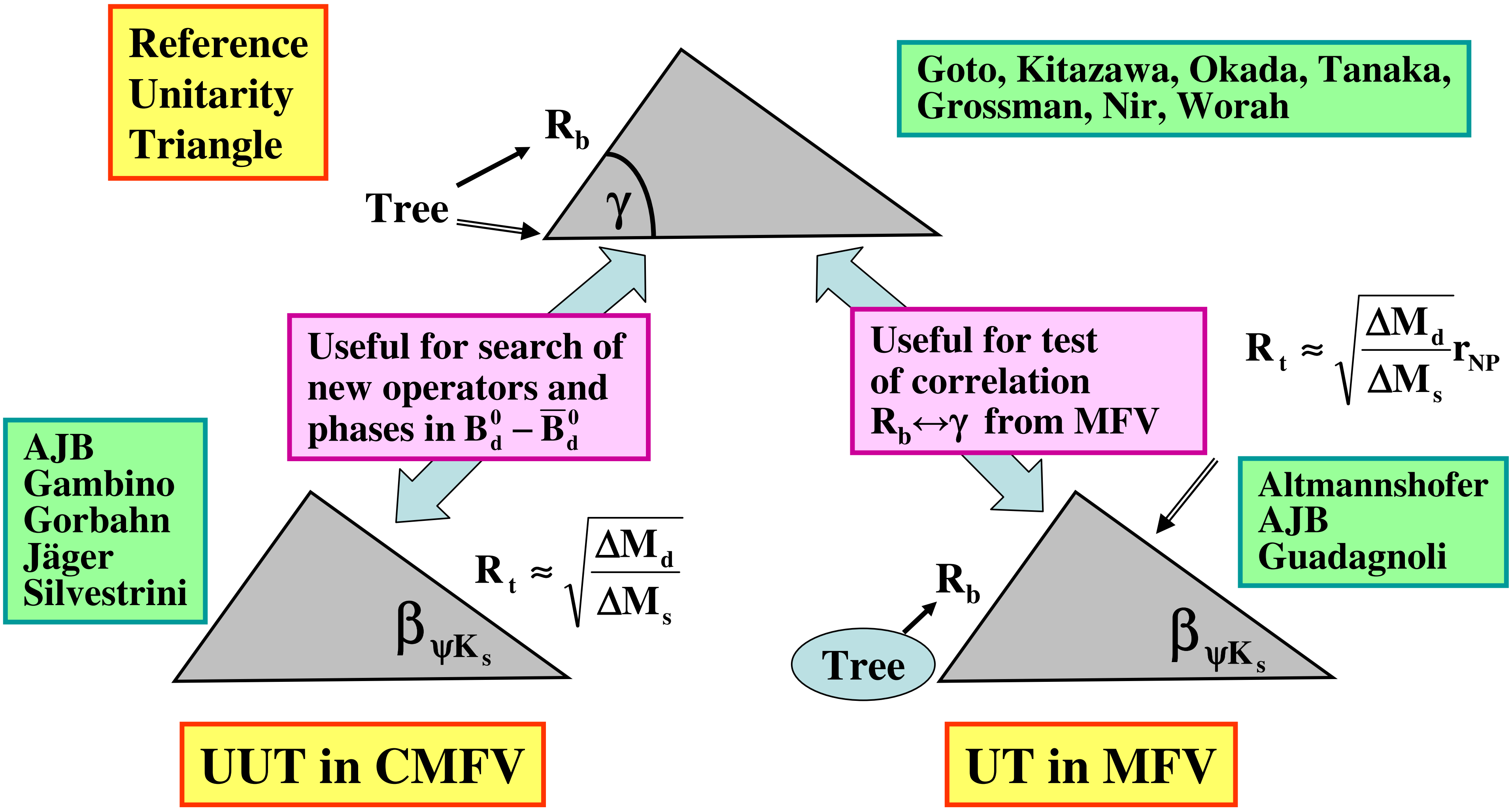
1. $$(\Delta M_s)_{\substack{\text{MSSM}\\(\text{low}\tan\beta)}} > (\Delta M_s)_{\text{SM}}$$

Interesting interplay of charginos and gluinos

2. **MSSM at low tanβ ≠ CMFV** ★

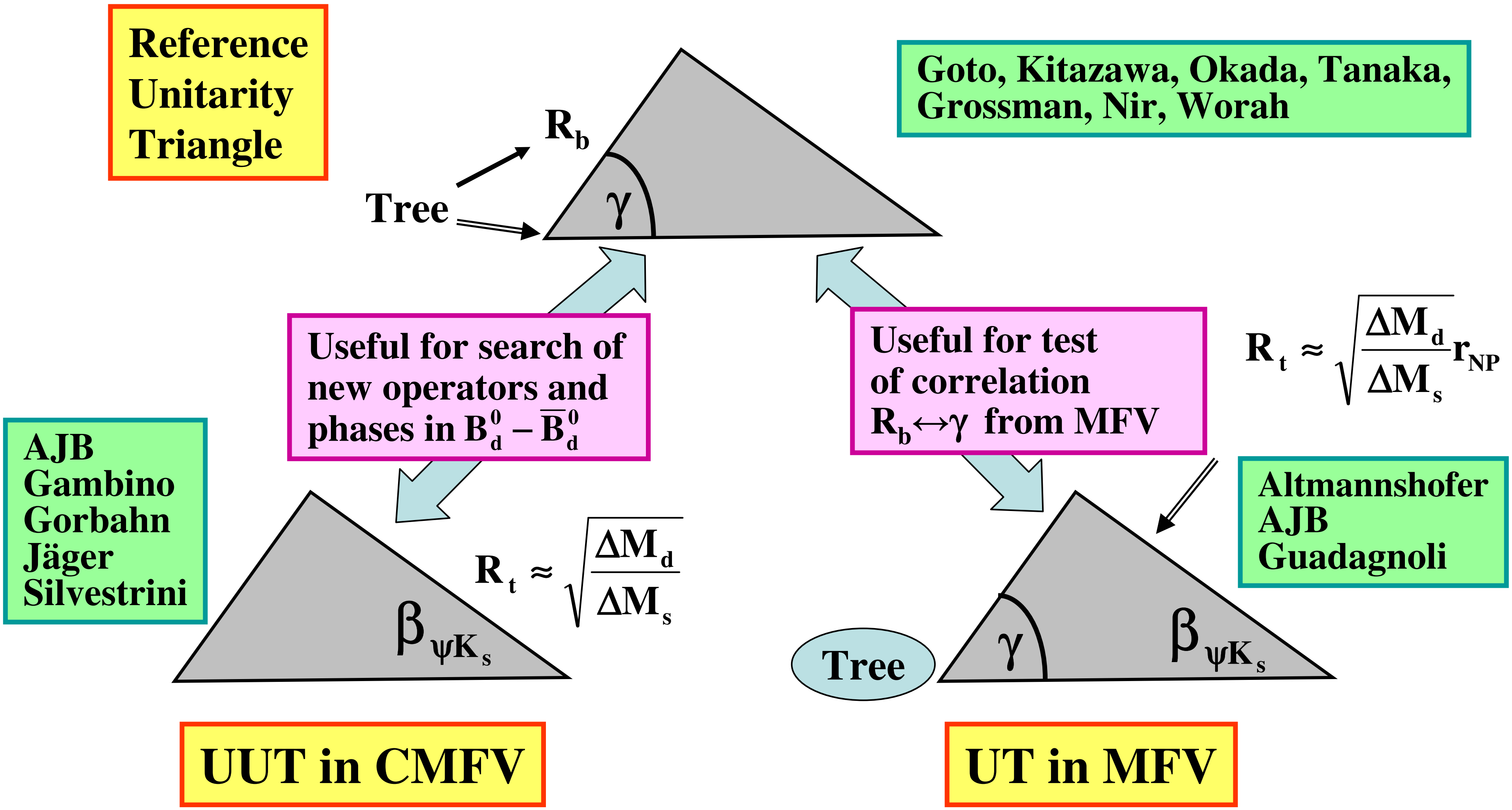
(mainly because of gluino contributions at large μ, which imply NEW OPERATORS)

Three Unitarity (B_d) Triangles



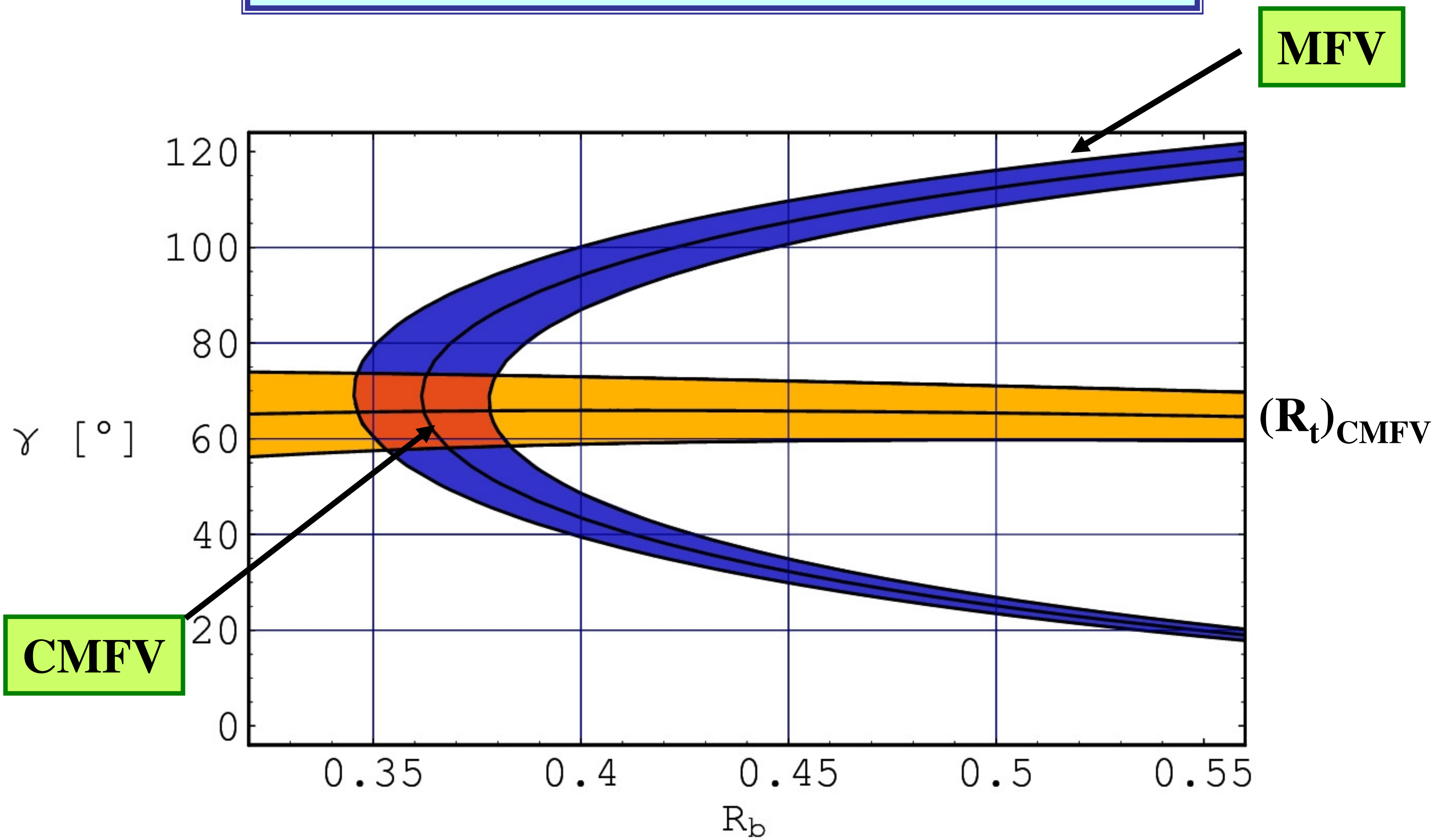
Need improved Non-Pert. + SFF(SB) to distinguish them

Three Unitarity (B_d) Triangles



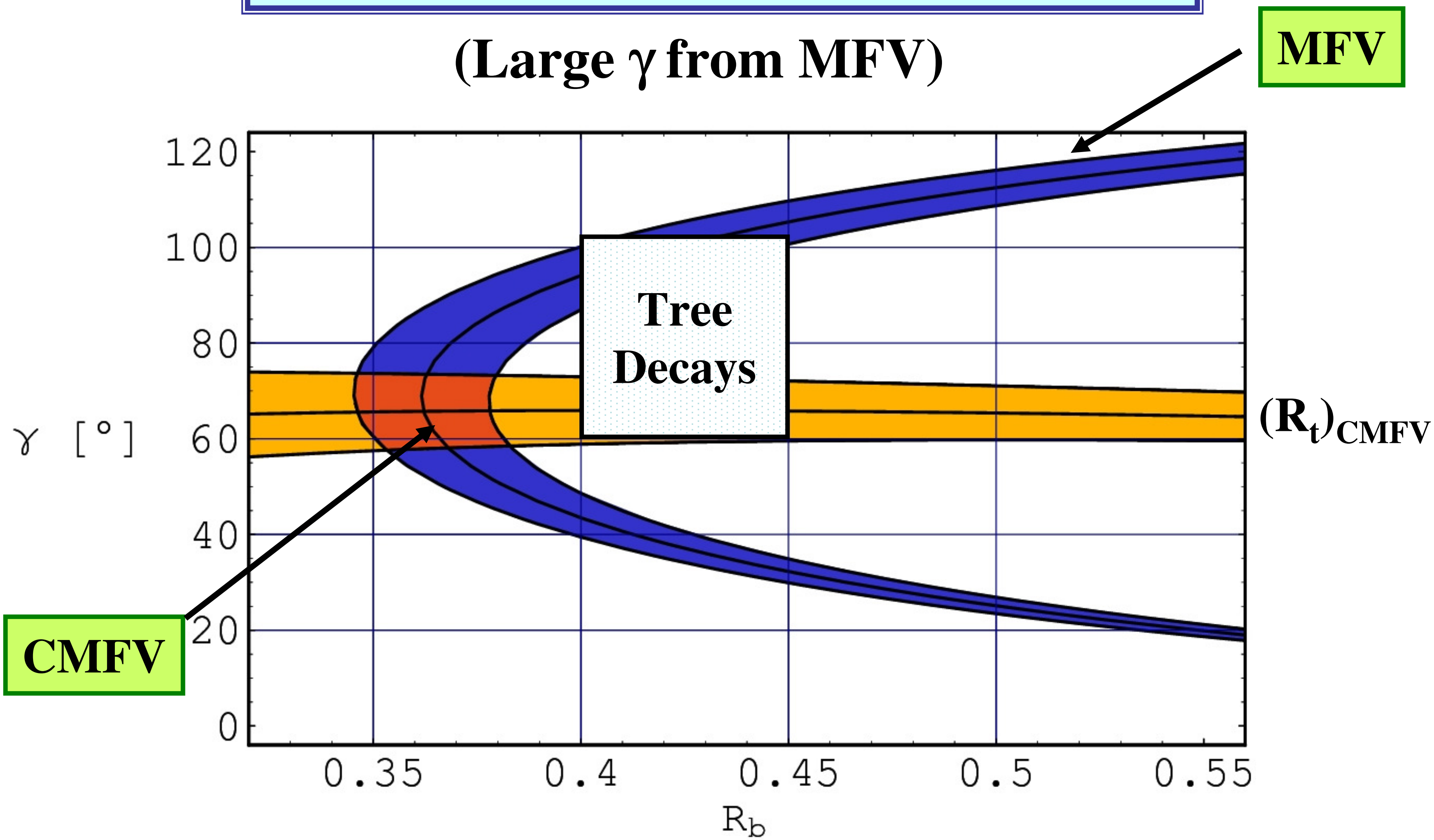
Need improved Non-Pert. + SFF(SB) to distinguish them

A closer Look at CMFV and MFV : $R_b \leftrightarrow \gamma$ Correlation



A closer Look at CMFV and MFV : $R_b \leftrightarrow \gamma$ Correlation

(Large γ from MFV)



Conjecture

$|V_{ub}|_{incl}$ **correct**

(R_b)

First "sin2β problem" is not a problem of MFV but a problem of CMFV

MFV

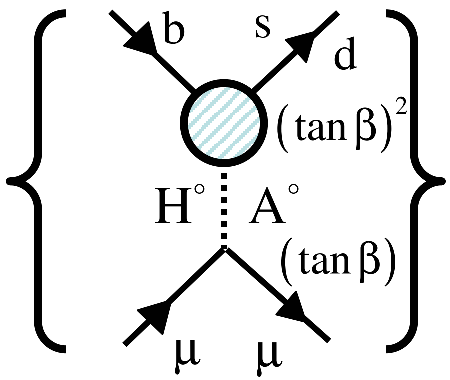
$\gamma_{true} \gtrsim 80^o$

Larger than SM UT-fits but could be OK in the presence of NP

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

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

Strong Enhancement



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

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

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

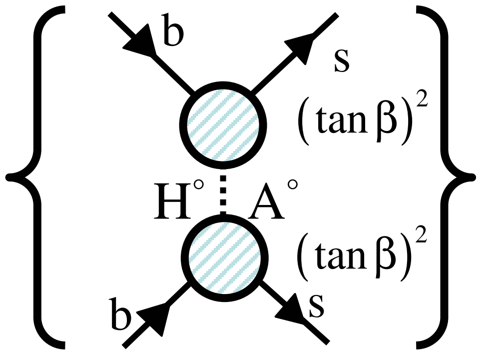
Babu, Kolda
Chankowski, Slawianowska
Bobeth, Ewerth, Krüger, Urban
Huang, Liao, Yan, Zhu
Isidori, Retico
Dedes, Dreiner, Nierste
Dedes, Pilaftis
Chankowski, Rosiek
Foster, Okumura, Roszkowski
Carena et al.
Isidori, Paradisi

$\mathbf{Br}\left(\mathbf{B_s} \to \mu\bar{\mu}\right) < \mathbf{1 \cdot 10^{-7}}$ 95% C.L (CDF, DØ)

$\mathbf{Br}\left(\mathbf{B_d} \to \mu\bar{\mu}\right) < \mathbf{3 \cdot 10^{-8}}$ 95% C.L.

$\Delta M_{s,d}$ in MSSM with MFV and large tanβ

Suppression



$$\Delta M_s \approx (\Delta M_s)^{SM} - c(\tan\beta)^4$$

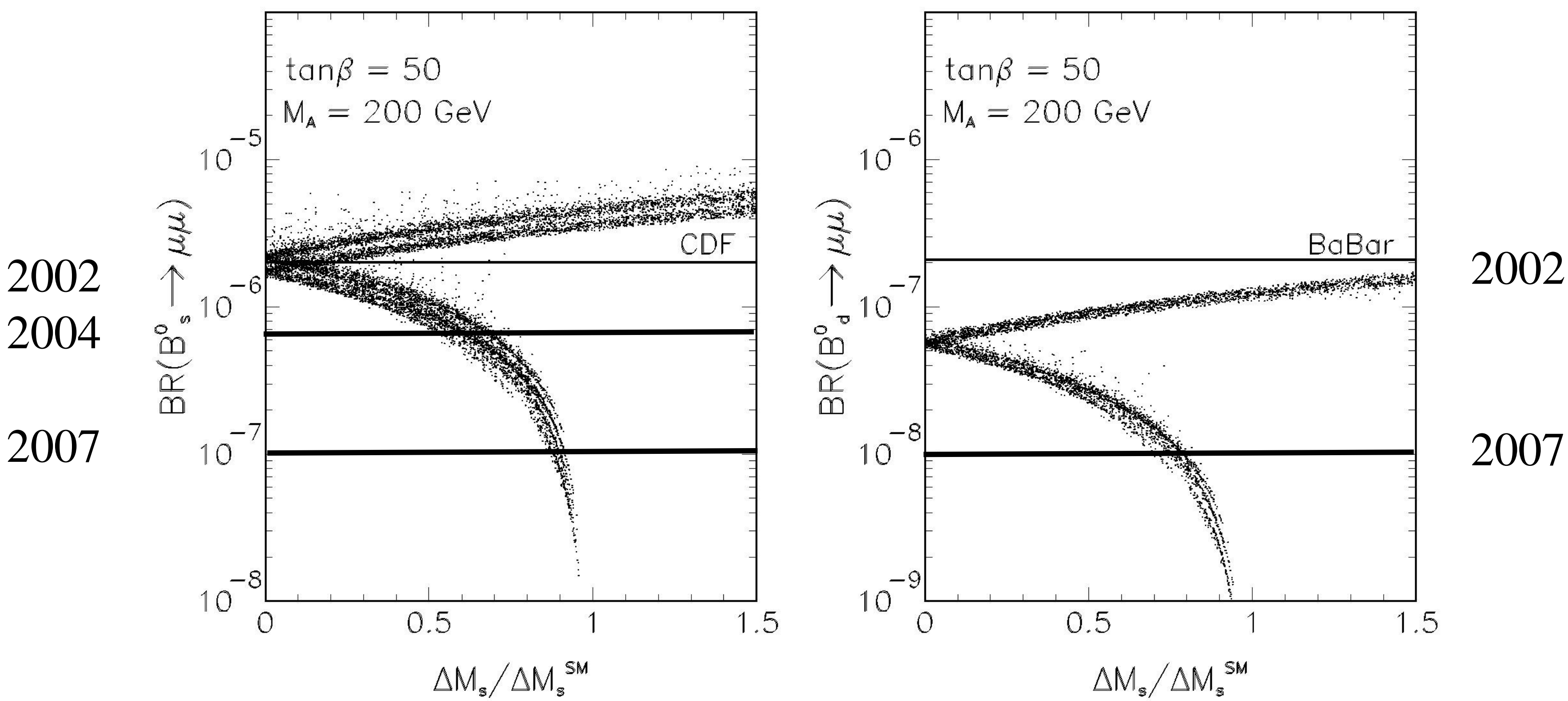
AJB, Chankowski, Rosiek
Slawianowska (2001, 2002)

Correlation between
SUSY effects in
$Br(B_{s,d} \to \mu\bar{\mu})$ and ΔM_s

<u>Subsequent analyses</u>: D'Ambrosio, Giudice, Isidori, Stumia
Dedes, Pilaftis; Carena et al

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

AJB, Chankowski, Rosiek, Slawianowska, hep-ph/0207241



The Virtue of ΔM_s

$$(\Delta M_s)_{CMFV} > (\Delta M_s)_{SM}$$

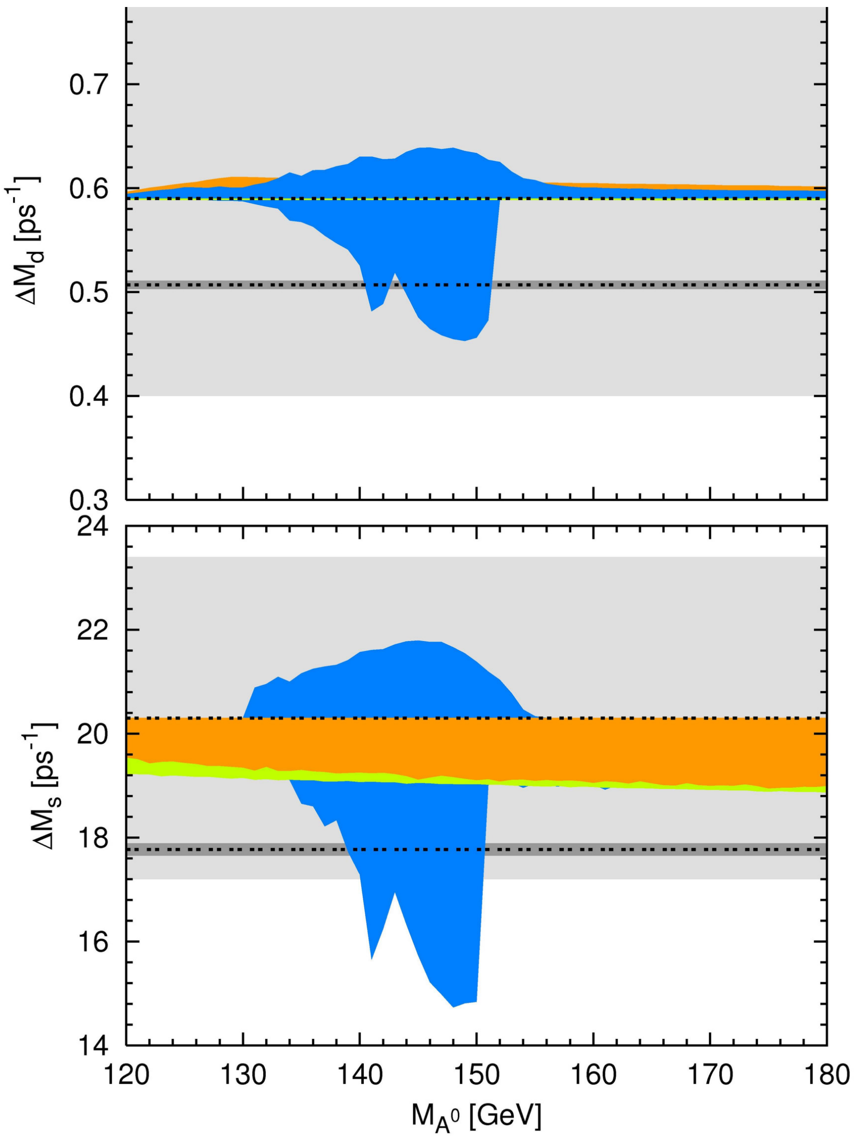
$$(\Delta M_s)_{\substack{MSSM \\ (Low\ \tan\beta)}} > (\Delta M_s)_{SM}$$

$$(\Delta M_s)_{\substack{MSSM \\ (Large\ \tan\beta)}} < (\Delta M_s)_{SM}$$

Answering $(\Delta M_s)_{exp} \leftrightarrow (\Delta M_s)_{SM}$ could rule out certain scenarios independently of specific parameters of a given model

New Analysis of $\Delta M_{s,d}$ at large tanβ

(MSSM) with **MFV**



A. Freitas
E. Gasser
U. Haisch

(hep-ph/0702267)

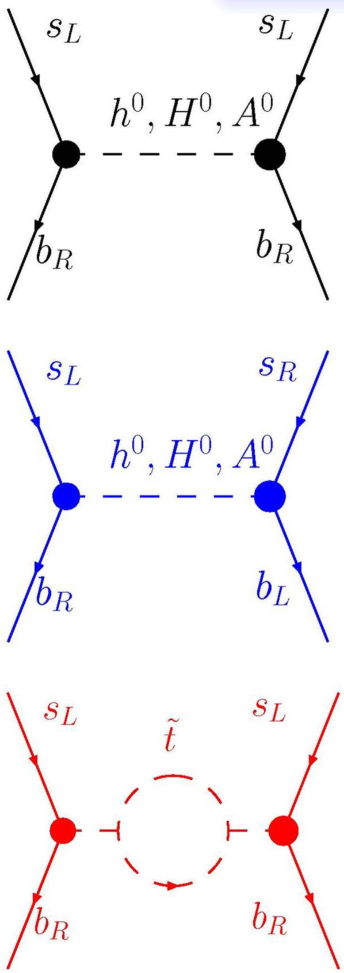
Inclusion of three loop corrections

$$(\Delta M_s)_{MSSM} > (\Delta M)_{SM}$$

at large tanβ

Possible (?)

Message from Gorbahn, Jäger, Nierste, Trine 2007



- "Tree-level" contribution vanishes [Babu, Kolda '99]
- All subleading effects have to be studied:
  m_s/m_b, loops, $1/\tan\beta$, $v_{\rm EW}/M_{\rm SUSY}$
- $\mathcal{O}(\frac{m_s}{m_b})$: Significantly suppress ΔM_{B_s}.
  [AJB, Chankowski, Rosiek, Slawianowska '02]
- Loop induced Higgs interactions:
  Moderately enhance ΔM_{B_s} and ΔM_{B_d}.

Sparticle Loops and $\mathcal{O}(m_s/m_b)$:

$(\Delta M_s)_{\rm MSSM} < (\Delta M_s)_{\rm SM}$
$(\Delta M_d)_{\rm MSSM} > (\Delta M_d)_{\rm SM}$

Impact on UT fit

Large tanβ

Messages from Universal Extra Dimensions

ACD Model in D=5

CMFV

1. $\mathrm{Br}(B \to X_s\gamma)_{\mathrm{UED}} < \mathrm{Br}(B \to X_s\gamma)_{\mathrm{SM}}$

Agashe, Deshpande, Wu

AJB, Poschenrieder, Spranger, Weiler

2. $(\hat{s}_o)_{\mathrm{UED}} < (\hat{s}_o)_{\mathrm{SM}}$ $\quad A_{FB}(B \to X_s l^+ l^-)$

BPSW

correlated with the suppression of $\mathrm{Br}(B \to X_s\gamma)$

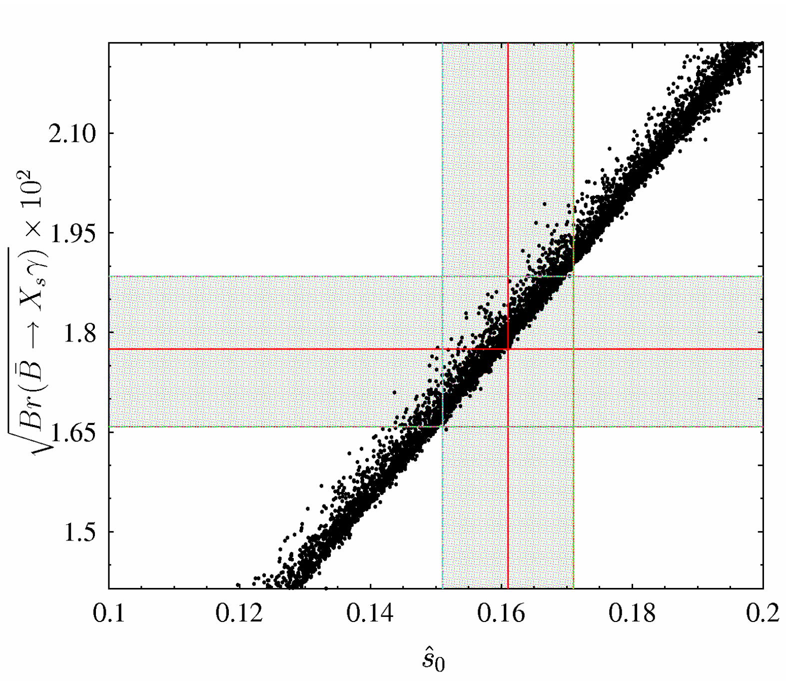
3. Similar suppression in $A_{FB}(B \to K^* l^+ l^-)$

(Colangelo, De Fazio, Ferrandes, Pham)

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

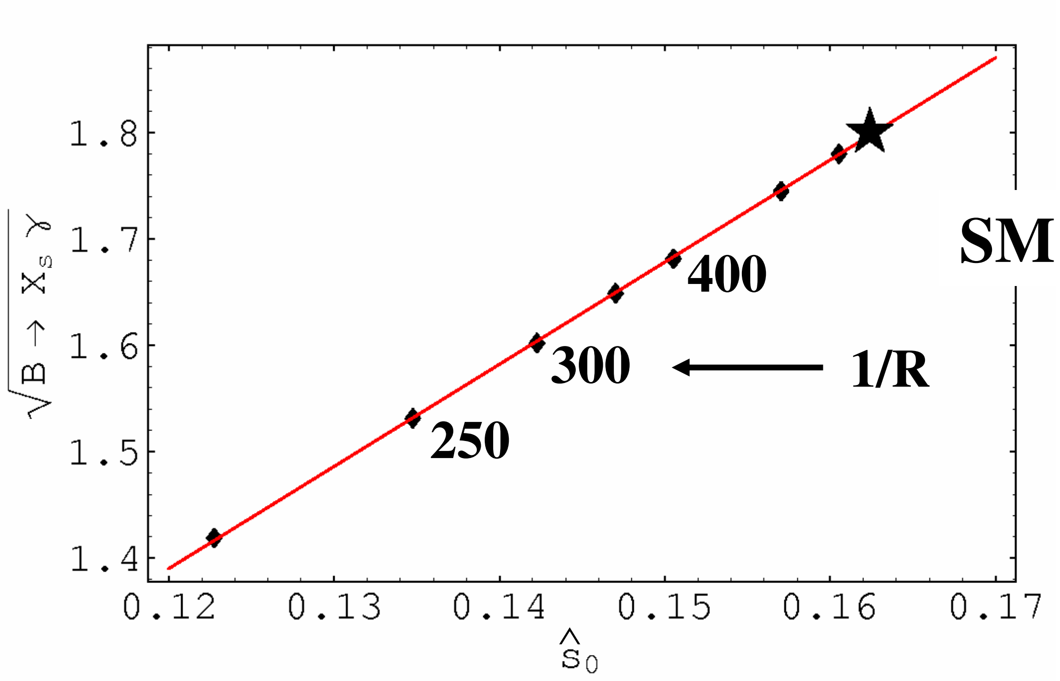
MSSM (MFV)

(Bobeth, AJB, Ewerth)



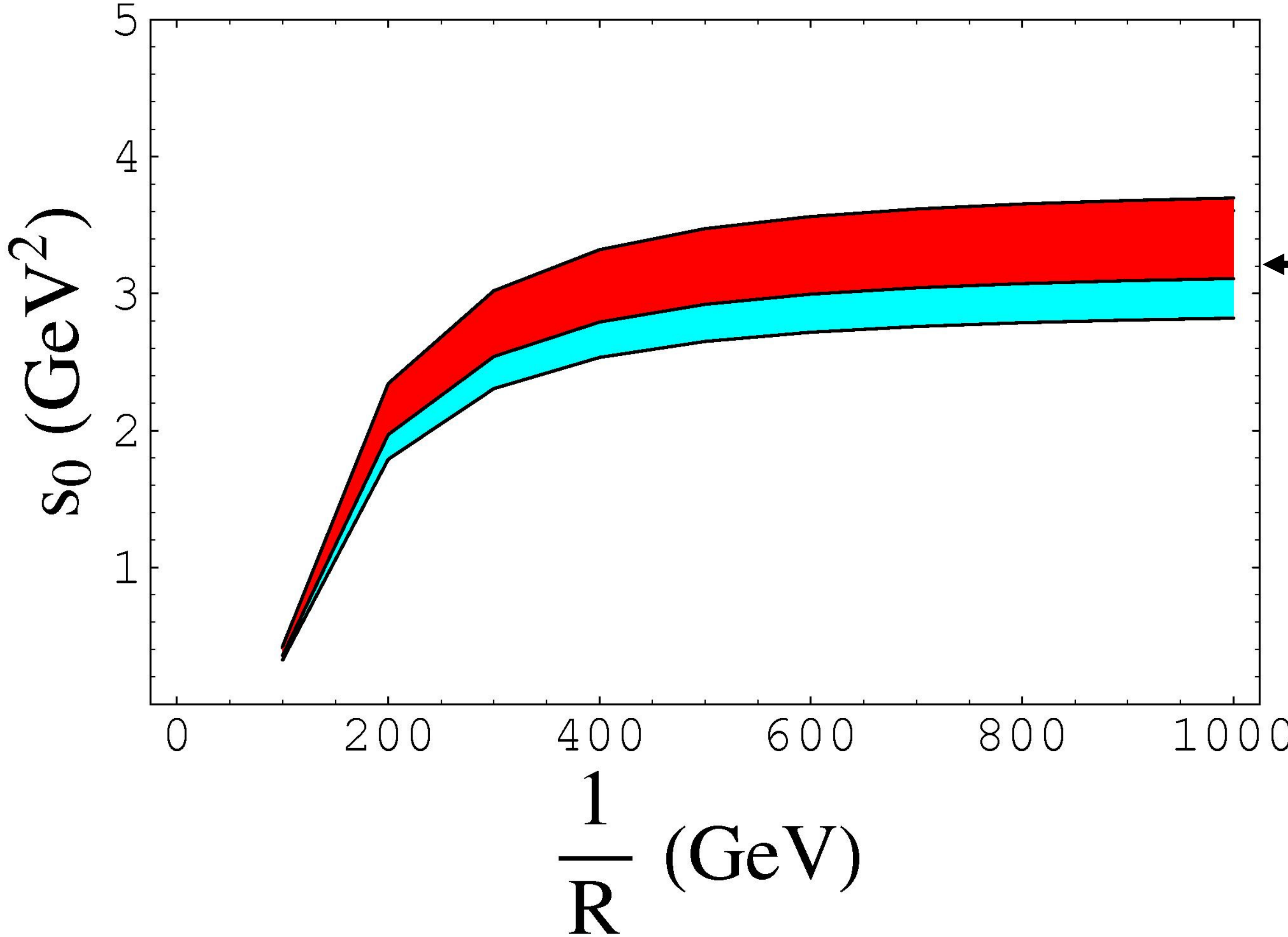
Universal Extra Dimensions

(AJB, Poschenrieder, Spranger, Weiler)



UED and $B \to K^* l^+ l^-$

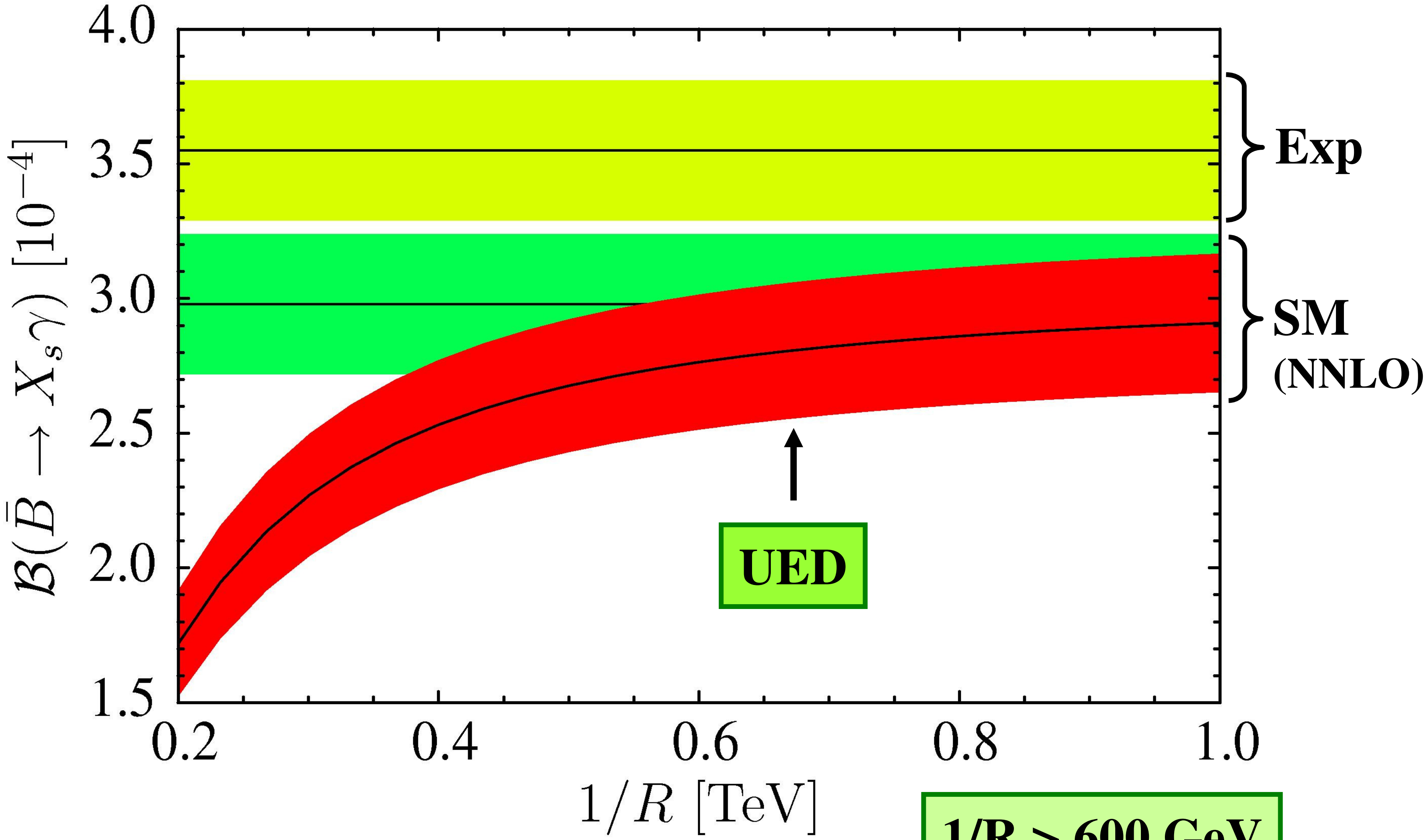
Colangelo
De Fazio
Ferrandes
Pham



← Formfactor dependence

$B \to X_s\gamma$ in Universal Extra Dimensions

Haisch, Weiler (2007)



1/R > 600 GeV

11. Tests of CMFV bounds on rare decays and $\Delta M_{d,s}$. **In particular UED** $(\hat{s}_o)$

12. Test of $Br(B_{s,d} \to \mu^+\mu^-) \xleftrightarrow{\text{CMFV}} \Delta M_{d,s}$

13. Measurement of β through $K \to \pi\nu\bar{\nu}$ system

14. Test of MSSM correlation at large $\tan\beta$

$$Br(B_{s,d} \to \mu^+\mu^-) \xleftrightarrow[\text{MFV}]{\text{MSSM}} \Delta M_{d,s}$$

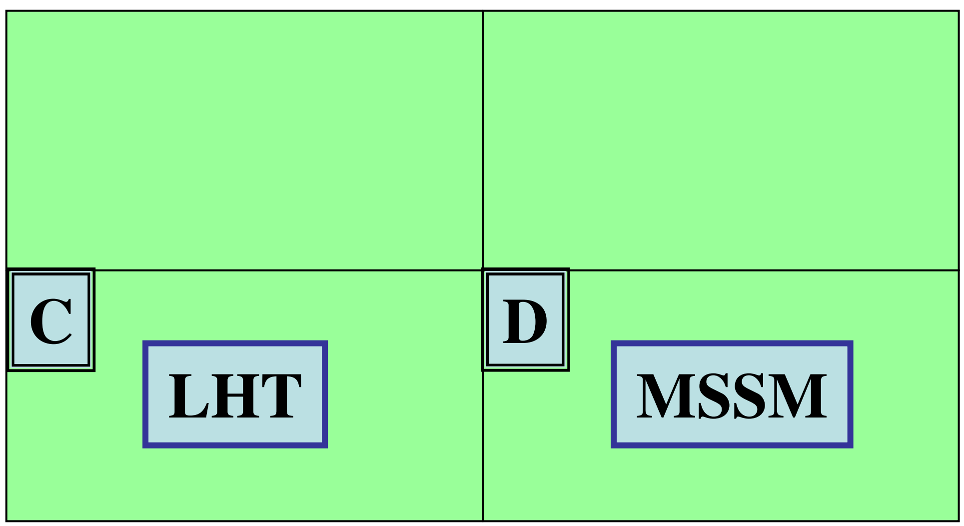
15. Exploration of the $R_b \leftrightarrow \gamma$ Plot

4.

Beyond MFV

SM Operators   New Operators

New sources of Flavour (CP) Violation



Next Hopes for new Phases : $B_s^0 - \overline{B}_s^0$ System

$$\left(S_{\psi\varphi}\right)_{SM} = \sin\left(2\left|\beta_s\right|\right) \approx 0.035$$

$$V_{ts} = -\left|V_{ts}\right| e^{-i\beta_s}$$

$$\beta_s = -1^o$$

But if there is a new phase $\varphi_{B_s} \neq 0$

$$\left(S_{\psi\varphi}\right) = \sin\left(2\left|\beta_s\right| - 2\varphi_{B_s}\right) \approx 0.30$$

$$\left(\varphi_{B_s} \approx -8^o\right)$$

One order of magnitude enhancement

Can be also tested in semi-leptonic CP-Asymmetry

$$A_{SL}^s = -\left|\mathrm{Re}\left(\frac{\Gamma_{12}}{M_{12}}\right)^{SM}\right| \frac{S_{\psi\varphi}}{C_{B_s}}$$

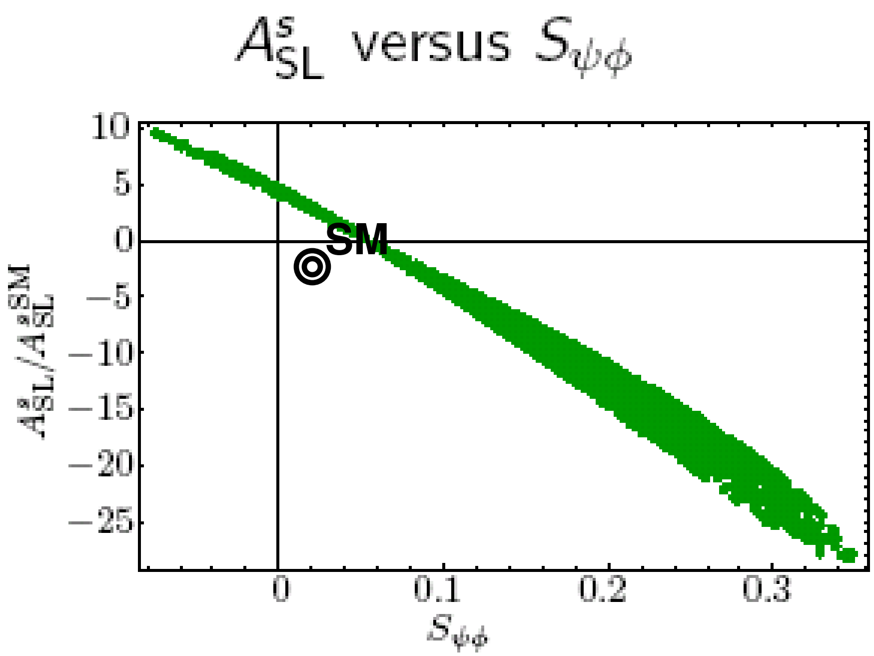
$$C_{B_s} = \frac{\Delta M_s}{\left(\Delta M_s\right)_{SM}}$$

could be measured this way (BBGT)

From Lattice (cleaner than ΔM_s)

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

Ligeti
Papucci
Perez (06)



Example from LHT (Blanke et al)

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

The Magnificent Six

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

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

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

$K_L \to \pi^0 \mu^+ \mu^-$ ★

$B_s \to \mu^+ \mu^-$ ★

$B_d \to \mu^+ \mu^-$ ★

★ **sensitive to helicity suppressed operators (scalar operators)**

Golden Relations of CMFV and MFV:

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

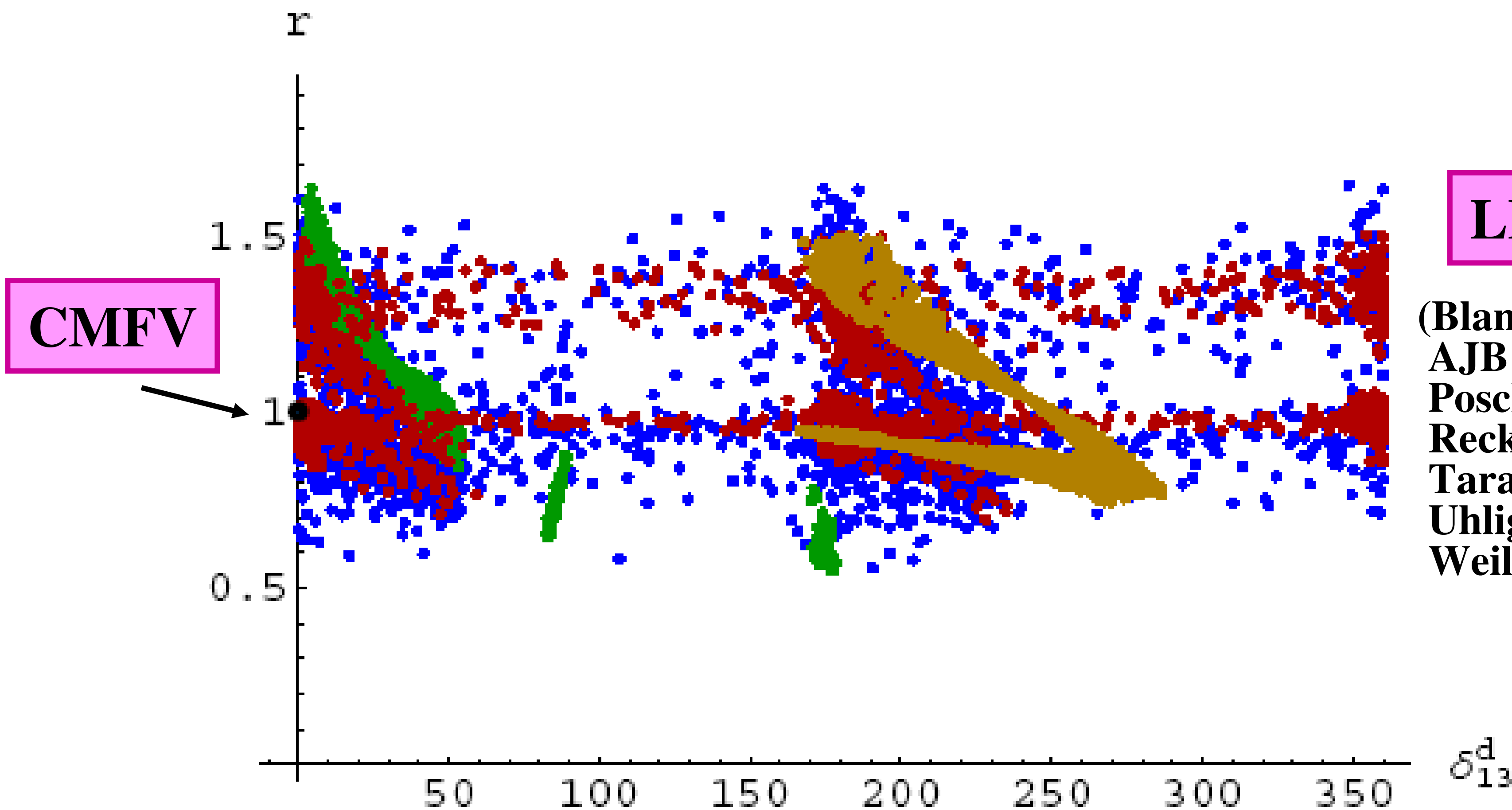
Buchalla, AJB (94)
AJB, Fleischer (01)

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

(MFV)

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

Violation of the Golden Relation



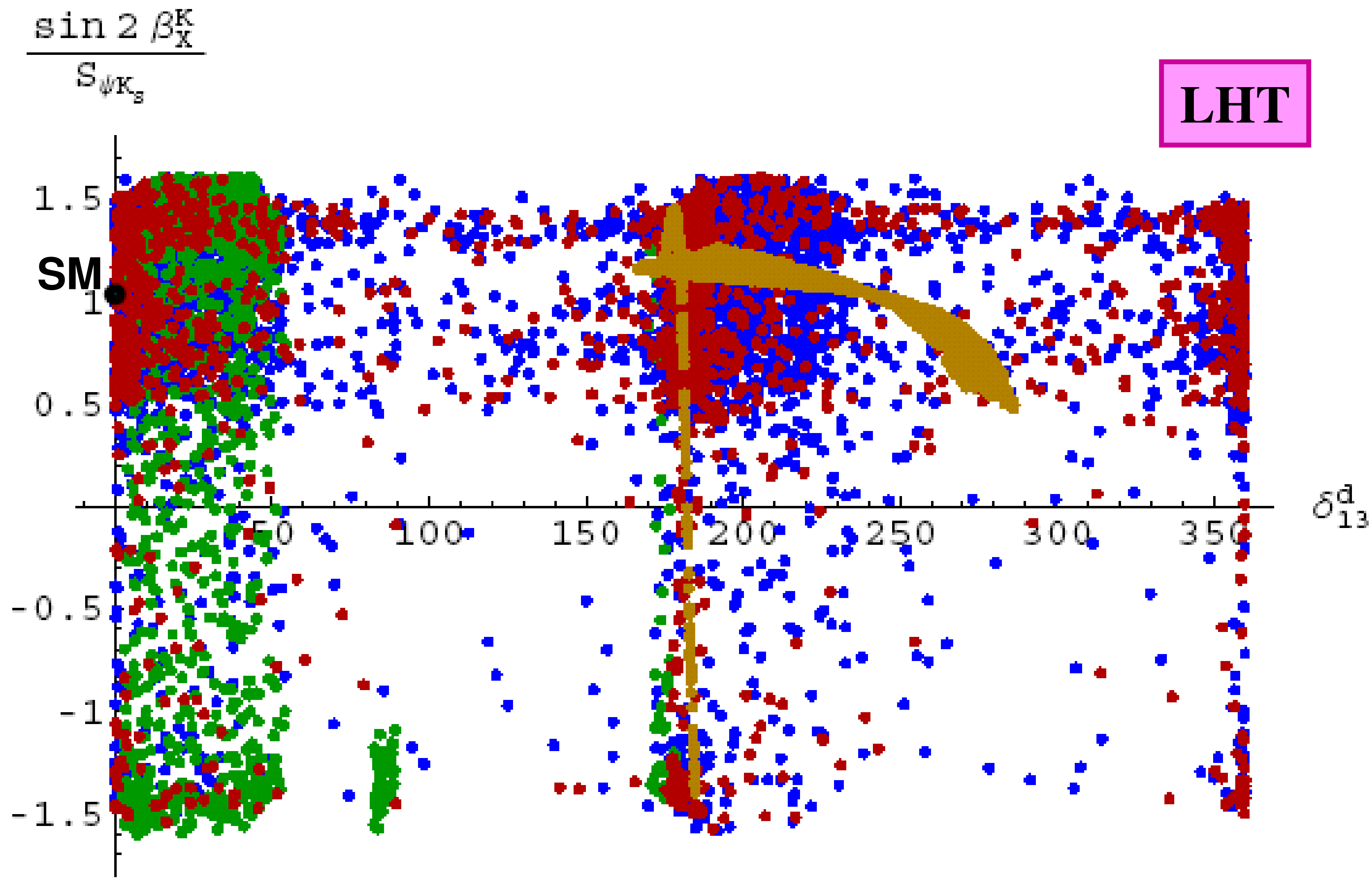
(Blanke AJB Poschenrieder Recksiegel Tarantino Uhlig Weiler)

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

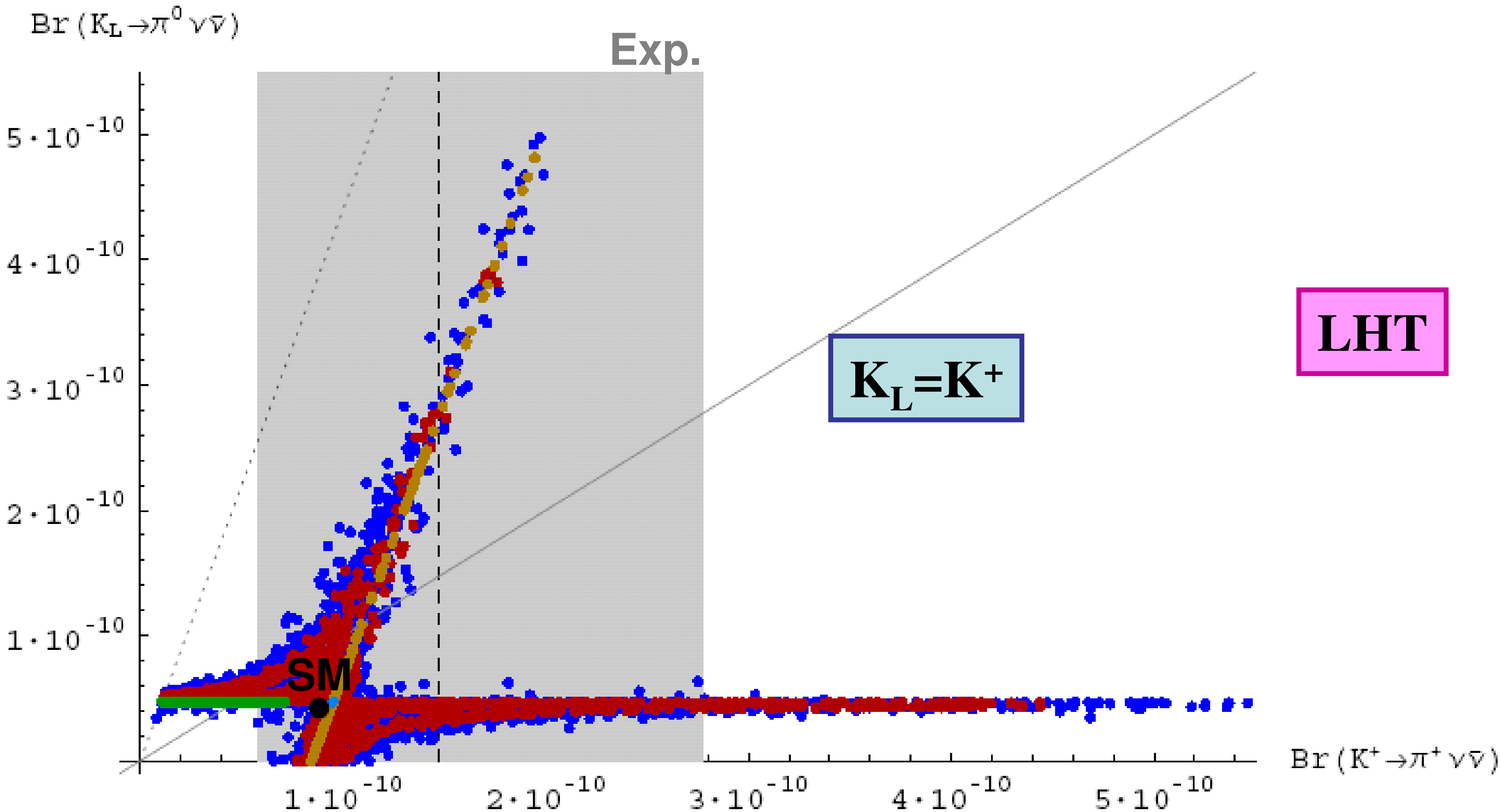
An evident Consequence of Universality Breakdown

The MFV identity between β from $B \to \psi K_S$ and $K_L \to \pi^0 \nu \bar{\nu}$ can be strongly violated

LHT



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



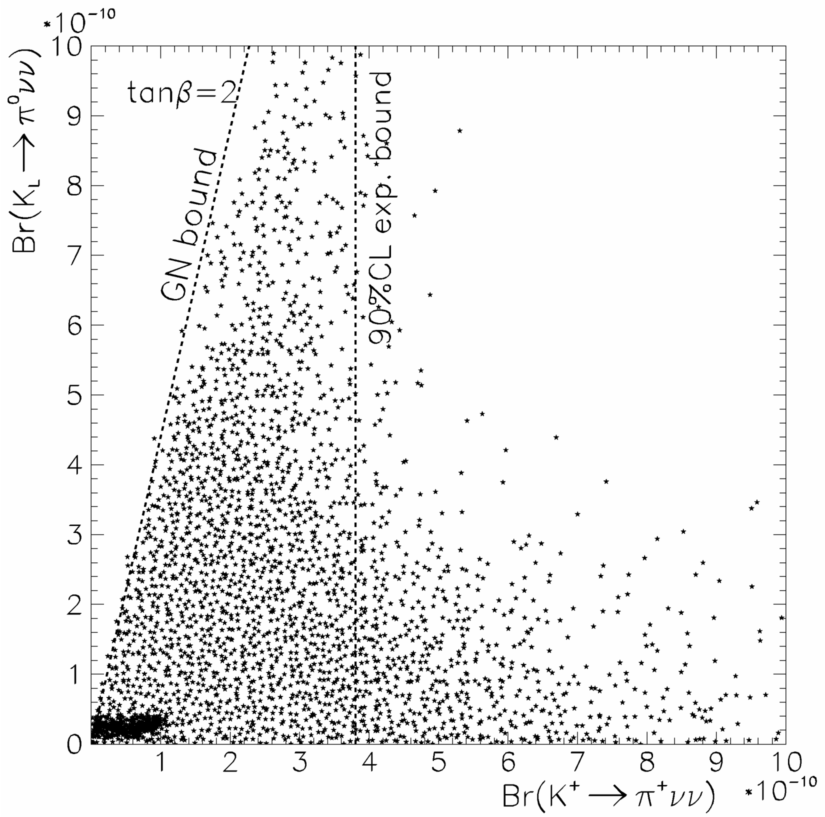
Two distinguished branches appear!

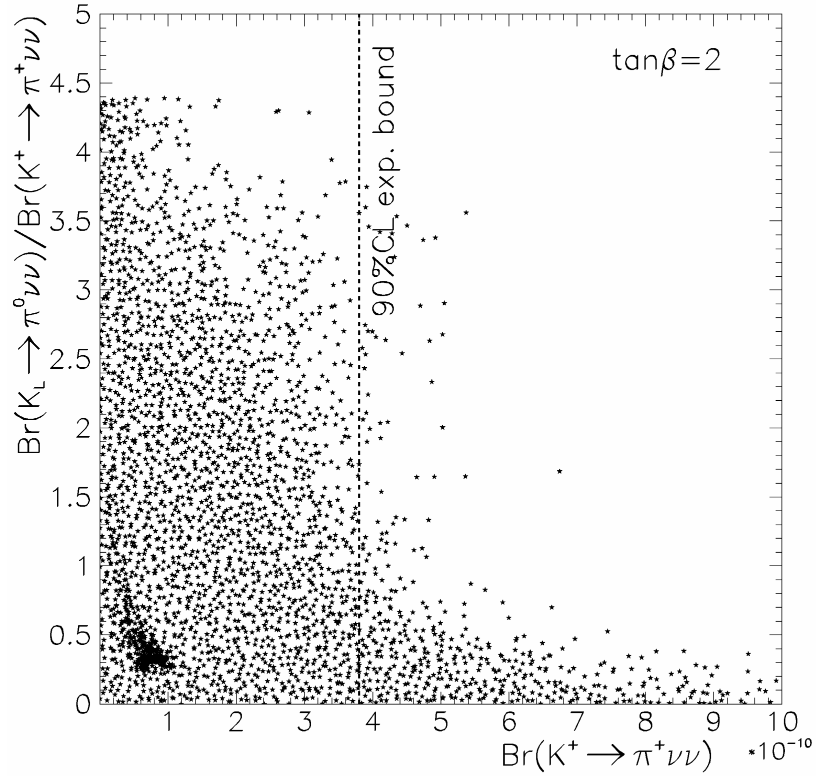
~10 times enhancement in $K_L \to \pi^0 \nu\bar{\nu}$

~5 times enhancement in $K^+ \to \pi^+ \nu\bar{\nu}$

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

AJB, Ewerth, Jäger, Rosiek (04)

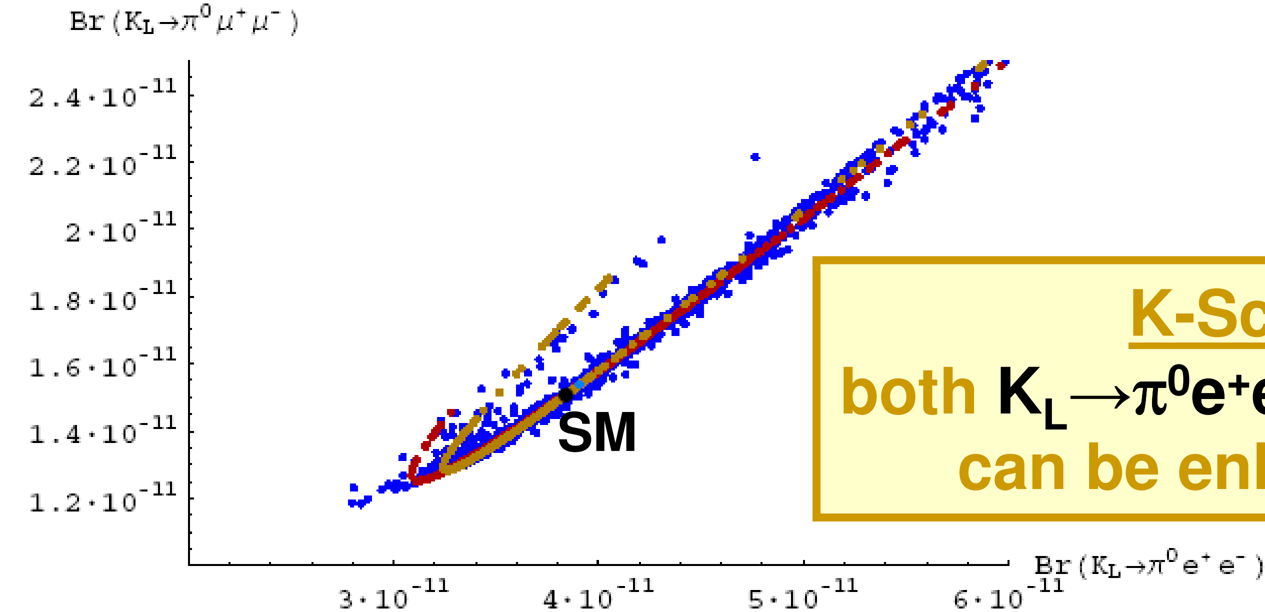




see also (Isidori, Mescia, Paradisi, Smith, Trine)

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

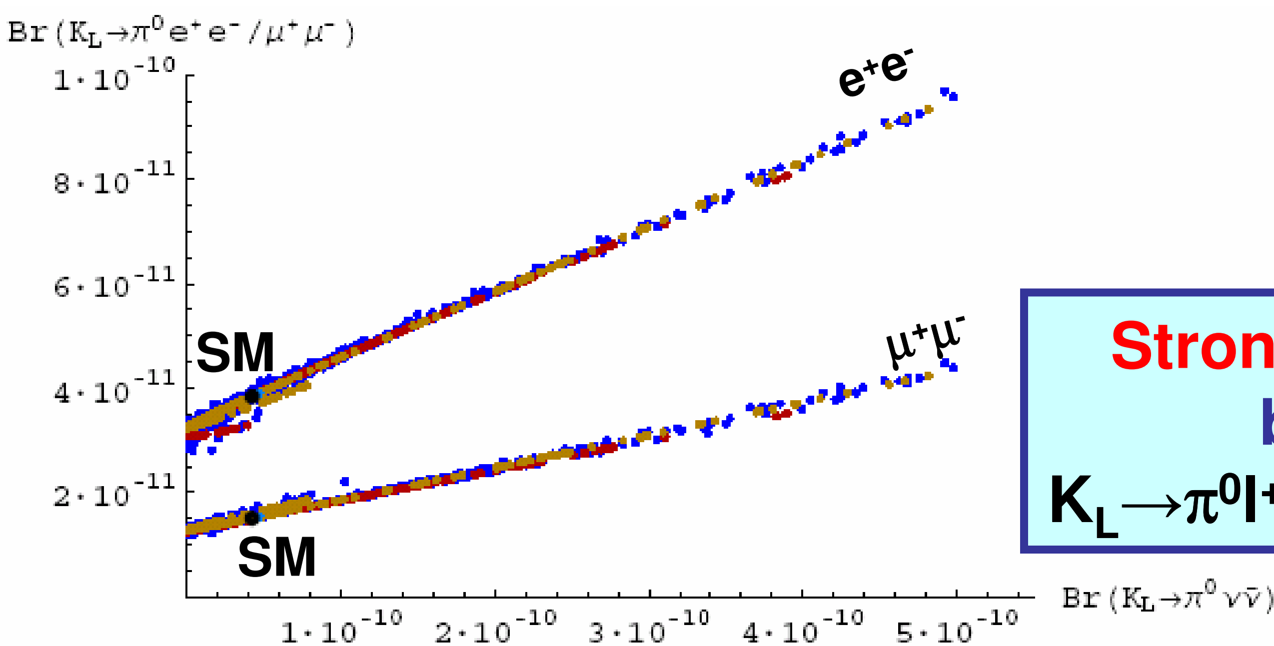
(2,1)



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

K-Scenario:
both $K_L \to \pi^0 e^+e^-$ and $K_L \to \pi^0 \mu^+\mu^-$
can be enhanced by ~2

LHT

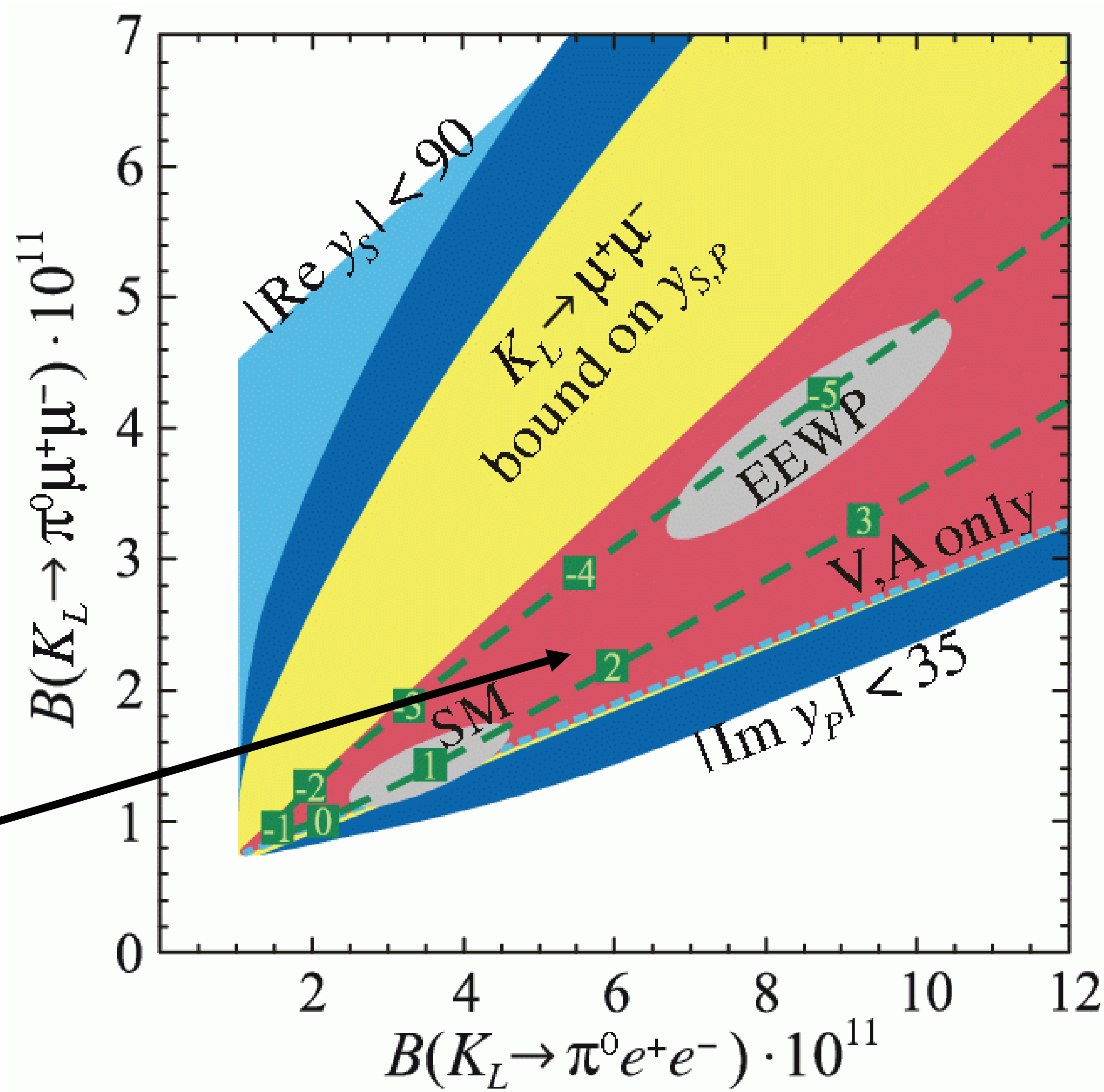


BBPRTUW (06)

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

Correlations in various NP Scenarios

Mescia, Smith, Trine (06)



LHT

NP with new Operators

(2,2)

Important Constraint

$$\frac{\varepsilon'}{\varepsilon} = (16.7 \pm 1.6) \cdot 10^{-4}$$

(NA48)
(KTeV)

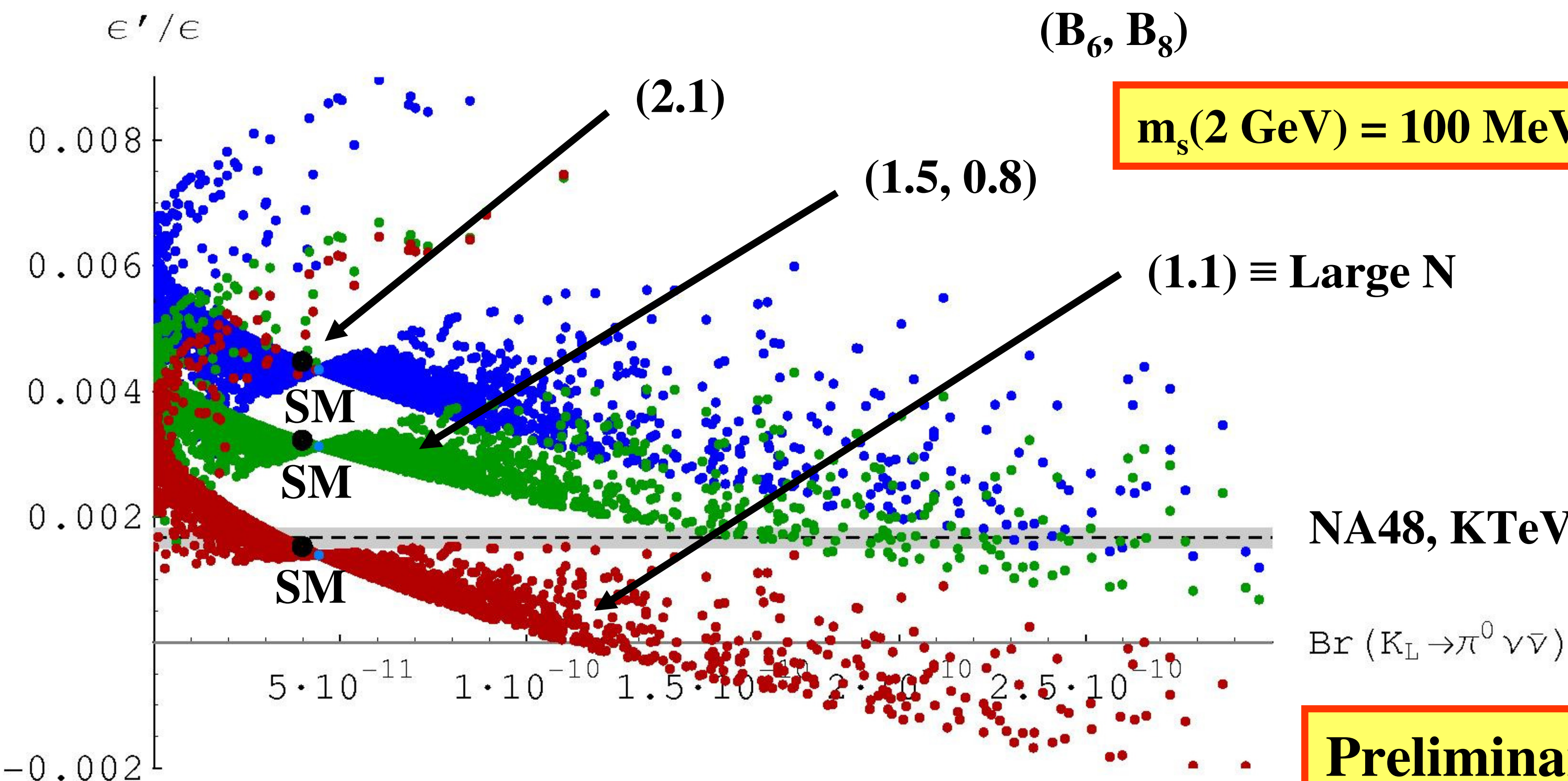
AJB + Silvestrini (99)
AJB + Colangelo, Isidori, Romanino, Silvestrini (99)

Could have considerable impact on possible enhancements of rare K Decays provided hadronic matrix elements (B_6 , B_8) under control.

Correlation between ε´/ε and Rare K Decays

M. Blanke, AJB, S. Recksiegel, C. Tarantino, S. Uhlig (0704xxx)

LHT



Preliminary

$D^0 - \overline{D}^0$ Mixing (2007)

$$\Delta M_D = (14.5 \pm 5.6) \cdot 10^{-3} \, / \, ps$$

(BaBar)
(Belle)

First implications:

Ciuchini, Franco, Guadagnoli, Lubicz Pierini, Porretti, Silvestrini

(Impact on MSSM)

(hep-ph/0703204)

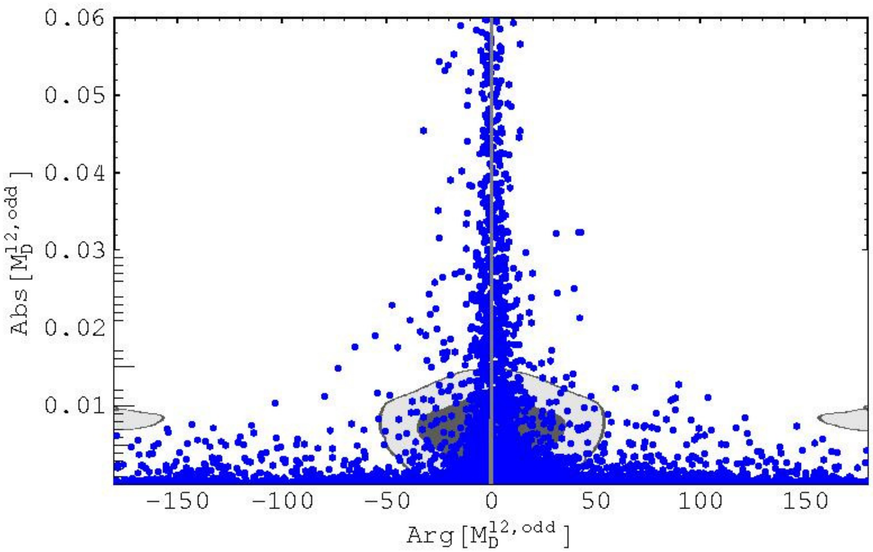
see also Nir
(0703235)

LHT confronts new data on $D^0 - \overline{D}^0$ Mixing

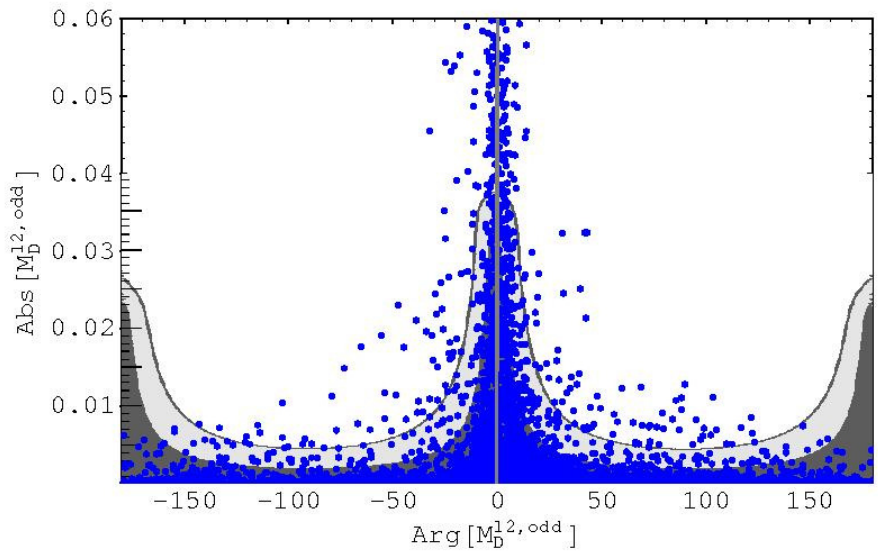
M. Blanke, AJB, S. Recksiegel, C. Tarantino, S. Uhlig (0703254)

LHT

$(\Delta M_D)^{SM} = 0$

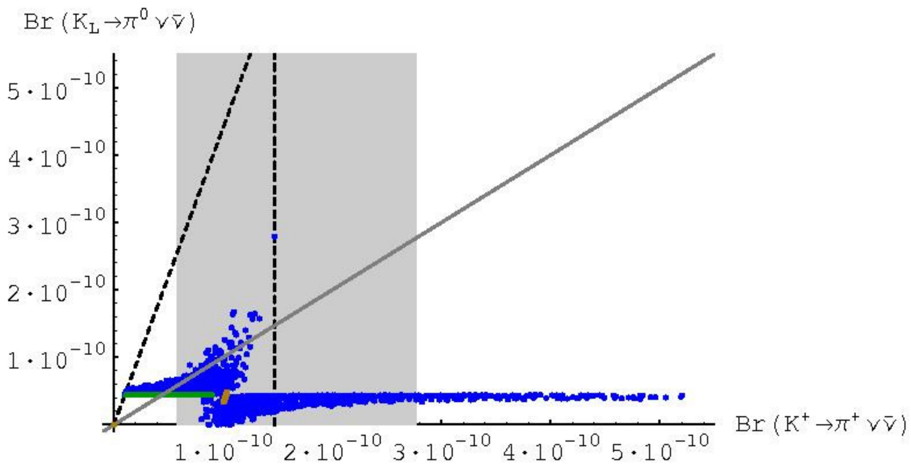


$(\Delta M_D)^{SM} \neq 0$

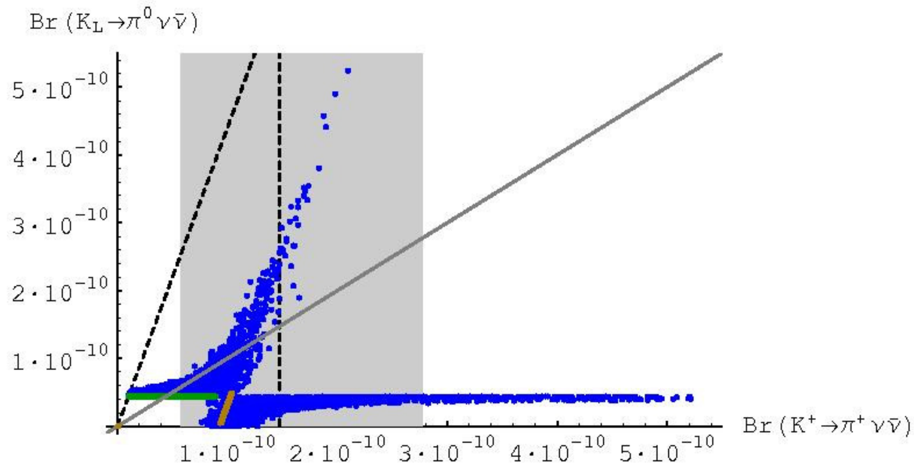


Impact on $K \to \pi\nu\bar{\nu}$

$(\Delta M_D)^{SM} = 0$



$(\Delta M_D)^{SM} \neq 0$



16. Measurements of $S_{\psi\varphi}$ and $A_{SL}^{s,d}$

17. Test of $K_L \to \pi^0 \nu\bar{\nu} \leftrightarrow K^+ \to \pi^+ \nu\bar{\nu}$ correlation

18. Test of $K_L \to \pi^0 e^+ e^- \leftrightarrow K^+ \to \pi^0 \mu^+ \mu^-$ correlation

19. Test of $K_L \to \pi^0 \nu\bar{\nu} \leftrightarrow K_L \to \pi^0 l^+ l^-$ correlations

20. $D^0 - \bar{D}^0$ Mixing and $\not{C}\!\!\not{P}$

21. Transverse muon polarisation in $K^+ \to \pi^0 \mu^+ \nu$ (T)

22. $B \to X_{s,d} \nu\bar{\nu}$ and $B \to K^*(\rho) \nu\bar{\nu}$

What about
Lepton Flavour Violation ?

$\mu \to e\gamma$: 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 $\sim 10^{-13}$ by MEG in 2007

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

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]

Symphony of LFV Decays

$\mu \to e\gamma$
$\tau \to \mu\gamma$
$\tau \to e\gamma$

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

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

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)

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

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

$(g-2)_\mu$

Correlations between LFV Processes

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

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

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

LHT : **Dipole Operator Irrelevance (Z-penguins, Boxes dominate)**
(Blanke, AJB, Duling, Poschenrieder, Tarantino)

Symphony of Correlations

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

$$\frac{R(\mu T_i \to e T_i)}{Br(\mu \to e\gamma)} \approx 5 \cdot 10^{-3}$$

LHT: $10^{-2} - 10^{2}$

"μ ↔ e Symmetry" and its Violation (BBDPT)

	μ ↔ e Symmetry	MSSM	LHT
$\dfrac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau^- \to \mu^- \mu^+ \mu^-)} \quad \dfrac{Br(\tau^- \to \mu^- e^+ e^-)}{Br(\tau^- \to e^- \mu^+ \mu^-)}$	**1**	**21**	**1.0 ± 0.2**
$\dfrac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau^- \to \mu^- \mu^+ \mu^-)} \quad \dfrac{Br(\tau^- \to \mu^- \gamma)}{Br(\tau^- \to e^- \gamma)}$	**1**	**4.6**	**1.0 ± 0.2**
$\dfrac{Br(\tau^- \to e^- \mu^+ \mu^-)}{Br(\tau^- \to \mu^- e^+ e^-)} \quad \dfrac{Br(\tau^- \to \mu^- \gamma)}{Br(\tau^- \to e^- \gamma)}$	**1**	**0.2**	**1.0 ± 0.2**

23. **$\not{CP}$ in neutrino oscillations**

24. θ_{13}

25. $\mu \to e\gamma,\ \tau \to e\gamma,\ \tau \to \mu\gamma$

26. $\mu \to 3e,\ \tau \to 3e,\ \tau \to 3\mu,\ \mu \to e$ **Conversion**

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

28. $K_L \to \mu e,\ K_L \to \pi^0 \mu e$

29. d_n, d_e, d_μ

30. **Leptogenesis $\Leftrightarrow$ LFV**

5.

Finals

(Allegro Vivace)

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

Comparison of MSSM with LHT

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

$K_L \to \pi^0 e^+ e^-,\ K_L \to \pi^0 \mu^+ \mu^-$ ⟵ **Pattern could distinguish MSSM from LHT**

All LFV decays

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

FCNC Goals for the LHC Era (2007)

1	2	3	4	5
6	7	8	9	10
11	12	13	14	15
16	17	18	19	20
21	22	23	24	25
26	27	28	29	30

FCNC Goals for the LHC Era (2009)

	2	3	4	5
6		8		10
	12		14	15
16	17			20
21		23	24	25
26	27	28		

FCNC Goals for the LHC Era (2011)

	2		4	5
6		8		
				15
16				
		23	24	25
26	27			

FCNC Goals for the LHC Era (2013)

1	2	3	4	5
6	7	8	9	10
11	12	13	14	15
16	17	18	19	20
21	22	23	24	25
26	27	28	29	30

31

A new very high energy collider (100 TeV) before

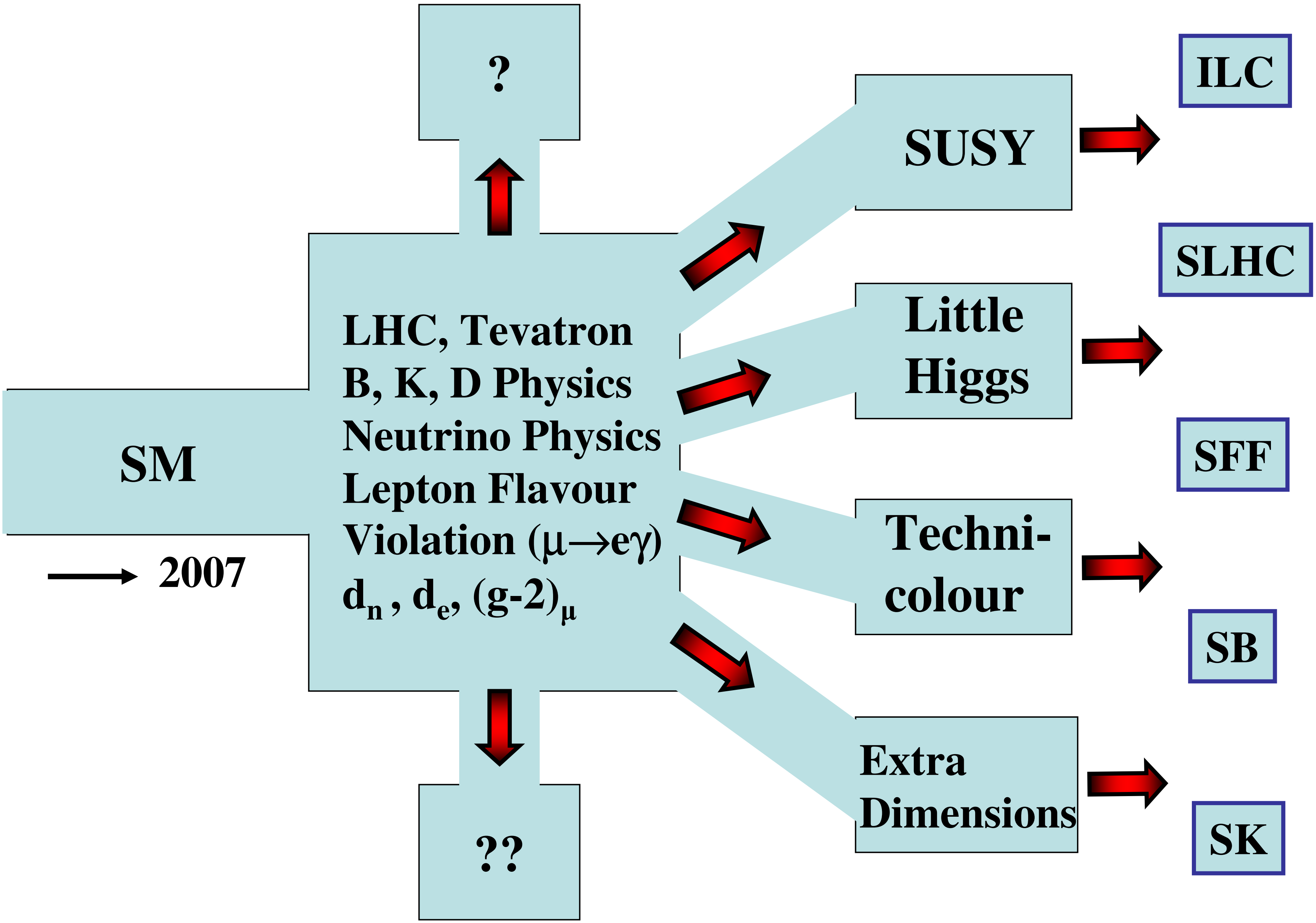
2046

31

A new very high energy collider (100 TeV) before

2046

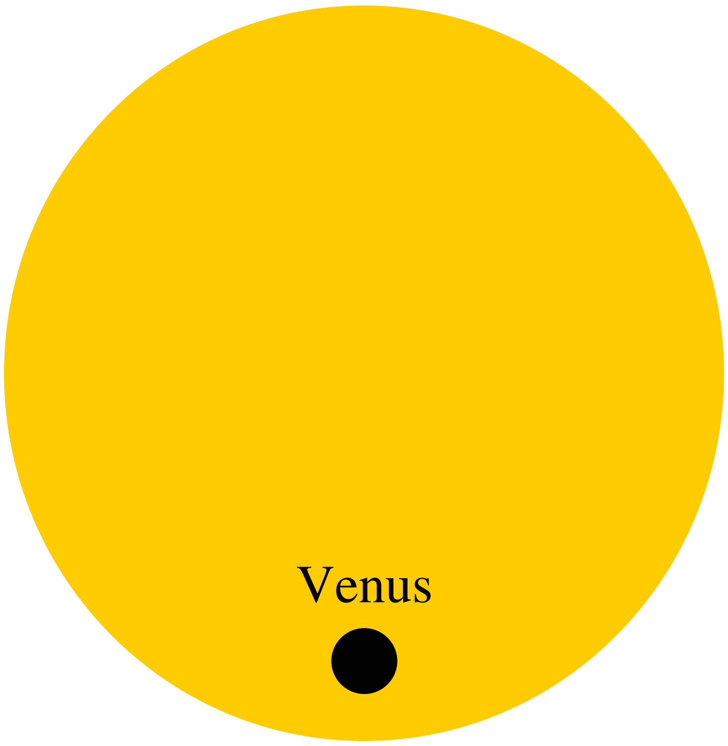
Very important for John Ellis and me !


?
SM
→ 2007
LHC, Tevatron
B, K, D Physics
Neutrino Physics
Lepton Flavour
Violation (μ→eγ)
d_n , d_e, $(g-2)_\mu$
??
SUSY
Little Higgs
Techni-colour
Extra Dimensions
ILC
SLHC
SFF
SB
SK

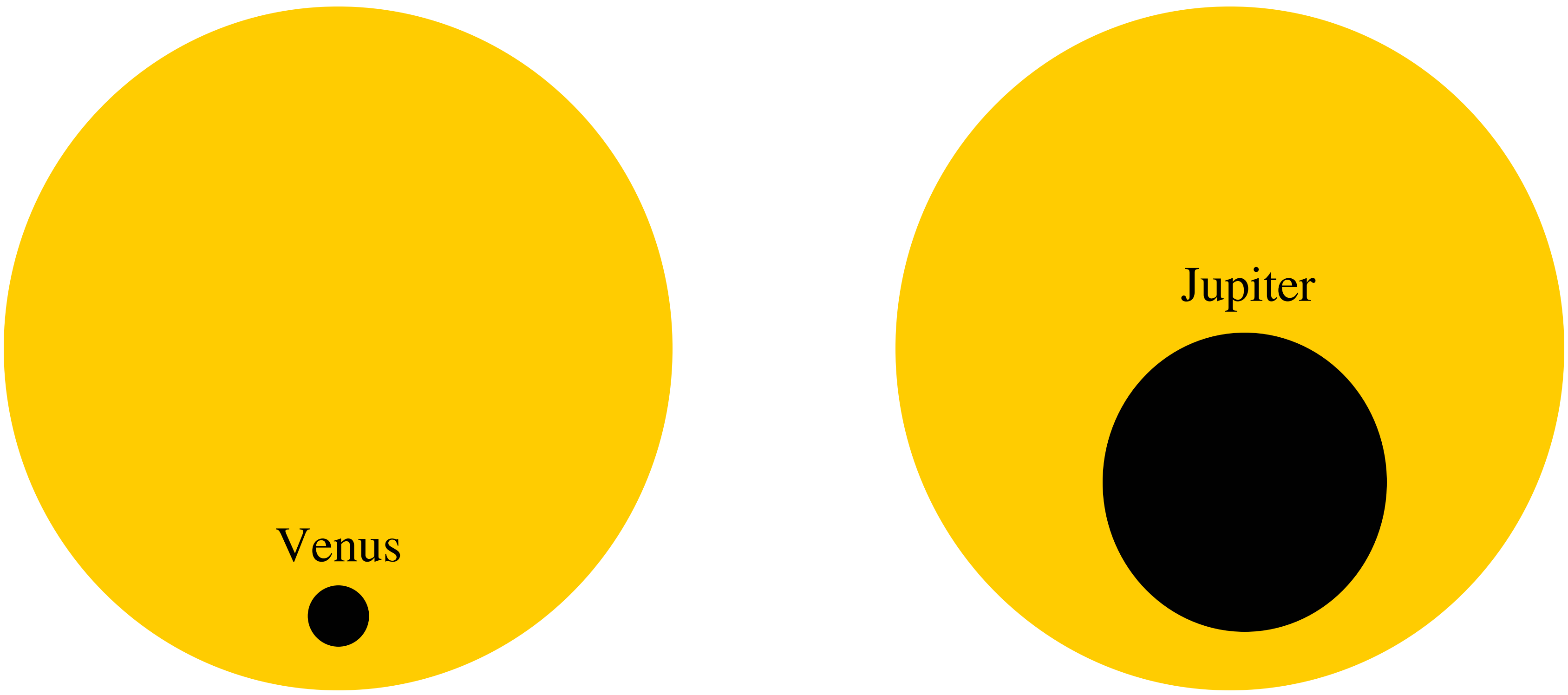
from **The European Strategy for Particle Physics**

CERN Courier, Sept. 2006

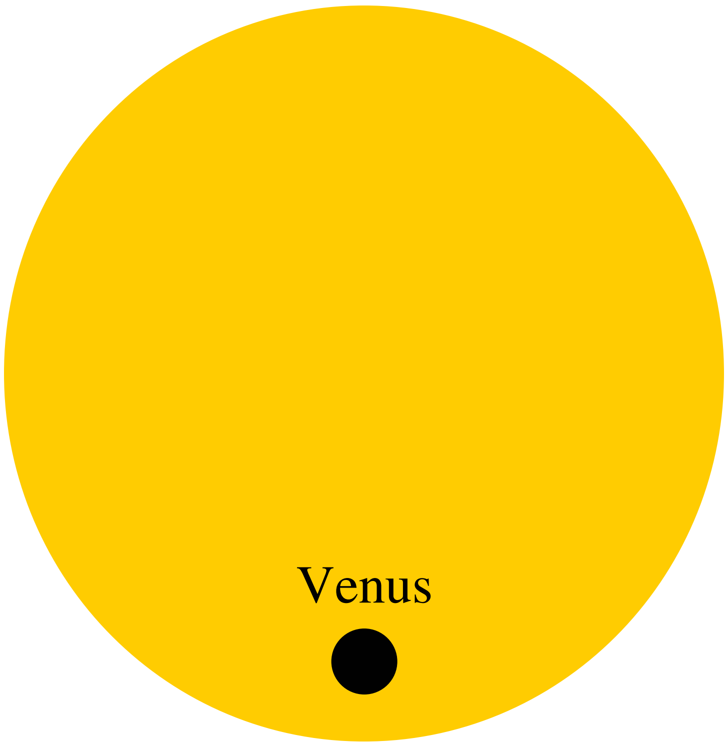
″Particle Physics stands on the threshold of a new and exciting era of discovery. The next generation of experiments will explore new domains and probe the deep structure of space-time. They will measure the properties of the elementary constituents of matter and their interactions with unprecedented accuracy, and they will uncover new phenomena such as the Higgs boson or new forms of matter. Long-standing puzzles such as the origin of mass, the matter-antimatter asymmetry of the universe and the mysterious dark matter and energy that permeate the cosmos will soon benefit from the insights that new measurements will bring. Together, the results will have a profound impact on the way we see our universe.″


Venus

Profound Impact on the Way we see our Universe



Standard Model



A clear Signal of New Physics