Littlest Higgs Models Confronting the Data on ΔM_s,CP-Violation and $B \rightarrow X_s \gamma$

Andrzej J. Buras and Cecilia Tarantino

Technical University Munich

Flavour in the Era of the LHC

Third Workshop on the Interplay of Flavour and Collider Physics

CERN, May 15-17 2006

Our Goals for the Next 25 Min

1. Overture:
   Looking Desperately for Deviations from the SM and MFV

2. Signals of non-MFV Interactions?

3. LH Models without and with T-Parity

4. Problems of LH without T-Parity

5. LH with T-Parity: the Rescue from Mirror Fermions

6. Conclusions and Outlook

The recent measurements of ΔM_s by CDF and D0 offer an important model-independent test of Minimal Flavour Violation

Definition of Constrained-MFV and (General) MFV

CMFV: [AJB, Gambino, Jager, Silvestrini]

1. Flavour and CP-violation exclusively governed by the CKM matrix
2. The same operators as in the SM

(General) MFV: [D´Ambrosio, Giudice, Isidori, Strumia]

1. Only CKM matrix as in CMFV
2. New operators admitted

MFV, especially CMFV, implies strong correlations between observables in K, B_d and B_s systems

Universal vs. Reference Unitarity Triangle

Two possible sets of parameters to construct the CKM matrix

Set 1: from tree-level decays only ⇨ Reference-UT

$$|V_{us}| \equiv \lambda, \qquad |V_{cb}|, \qquad R_b, \qquad \gamma$$

R_b → from semileptonic B-decays

γ → from $B \to D^{(*)} K$

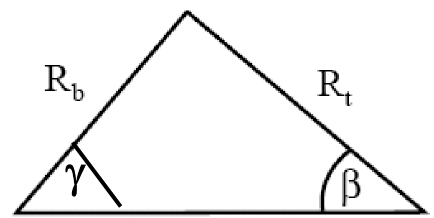
Set 2: from loop-induced processes ⇨ Universal-UT

$$|V_{us}| \equiv \lambda, \qquad |V_{cb}|, \qquad R_t, \qquad \beta$$

β → $\sin 2\beta = S_{\psi K_S}$ valid in MFV

$$R_t = \frac{\xi}{\lambda}\sqrt{\frac{\Delta M_d}{\Delta M_s}}\sqrt{\frac{m_{B_s}}{m_{B_d}}}$$

valid in CMFV only



Thanks to the recent first measurements

$$\Delta M_s = (17.33^{+0.42}_{-0.21} \pm 0.07)/\mathrm{ps} \qquad \text{CDF}$$

$$17/\mathrm{ps} \le \Delta M_s \le 21/\mathrm{ps} \quad (90\%\,\mathrm{C.L.}) \qquad \text{D0}$$

…other model independent relations:

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

(CMFV)

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

(CMFV)

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

(MFV)

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

First direct tests and surprises

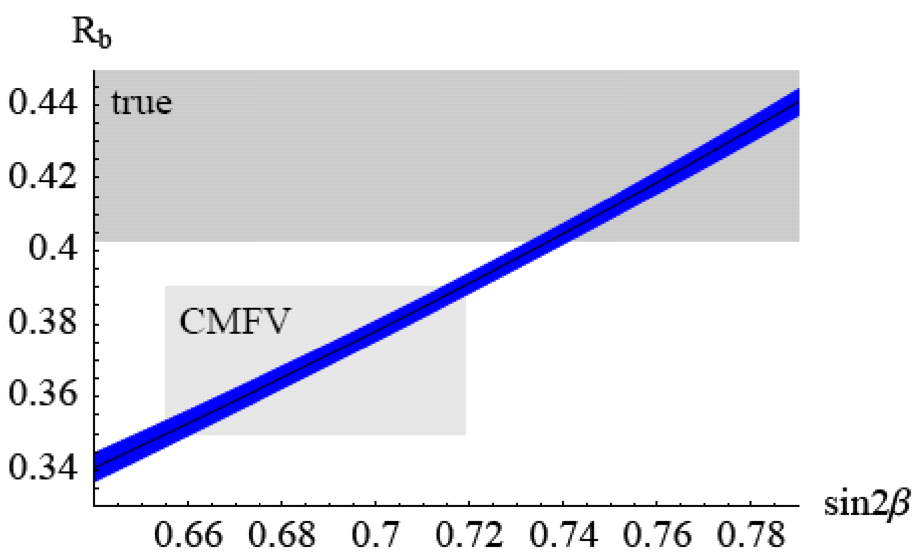
[M. Blanke, AJB, D. Guadagnoli and CT, hep-ph/0604057]

From CKM unitarity: $R_b = \sqrt{1 + R_t^2 - 2R_t \cos\beta}, \qquad \cot\gamma = \frac{1 - R_t \cos\beta}{R_t \sin\beta},$

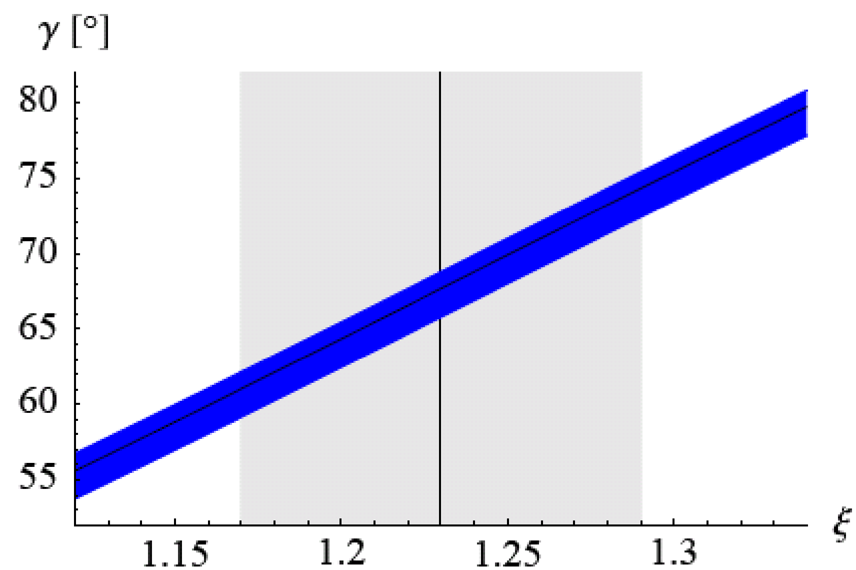
Comparison between RUT and UUT

$$(R_b)_{\rm true} = 0.440 \pm 0.037, \qquad \gamma_{\rm true} = (71 \pm 16)^\circ$$

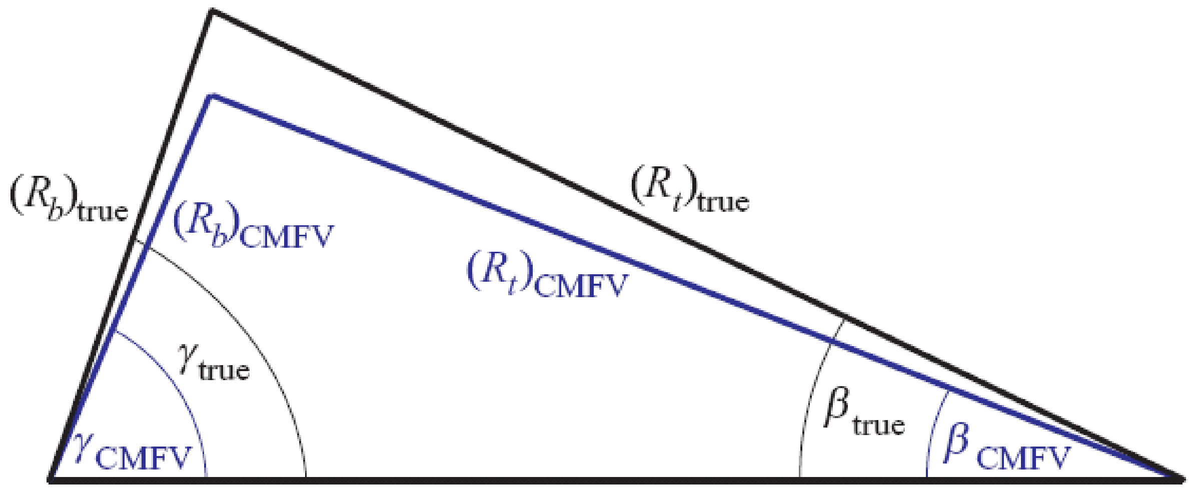
$$(R_b)_{\rm CMFV} = 0.370 \pm 0.020, \qquad \gamma_{\rm CMFV} = (67.4 \pm 6.8)^\circ$$



Tension between R_b and sin2β at 1.7σ



Main uncertainty from ξ in $\Delta M_s/\Delta M_d$



The differences between RUT and UUT are within present uncertainties

Importance of:

- **reducing theoretical non-perturbative uncertainties**
- **new experimental measurements to test the CMFV ``magic numbers´´**

$$\frac{Br(B\to X_s\nu\bar\nu)}{Br(B\to X_d\nu\bar\nu)}=\frac{|V_{ts}|^2}{|V_{td}|^2}=\frac{m_{B_d}}{m_{B_s}}\frac{1}{\xi^2}\frac{\Delta M_s}{\Delta M_d}=22.3\pm 2.2 \Rightarrow \frac{|V_{td}|}{|V_{ts}|}=0.212\pm 0.011$$

(consistent with B->Vγ [Ball, Zwicky], UTfit and CKMfitters)

$$\frac{Br(B_s\to\mu^+\mu^-)}{Br(B_d\to\mu^+\mu^-)}=\frac{\hat B_{B_d}}{\hat B_{B_s}}\frac{\tau(B_s)}{\tau(B_d)}\frac{\Delta M_s}{\Delta M_d}=32.4\pm 1.9$$

Further consequence of the recent measurements:
ΔM_s is surprisingly small

CDF

$$\Delta M_s = (17.33^{+0.42}_{-0.21} \pm 0.07)/\mathrm{ps}$$

D0

$$17/\mathrm{ps} \leq \Delta M_s \leq 21/\mathrm{ps}\ (90\%\ \ \mathrm{C.L.})$$

SM predictions from other constraints

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

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

- **ΔM_s seems smaller than the SM prediction**

- **Most MFV models predict higher values than the SM one (MSSM with MFV and large tanβ is an exception)**
[AJB, Chankowski, Rosiek, Slawianowska]

From direct calculation in the SM

$$(\Delta M_s)^{\rm SM}_{\rm direct} = \frac{G_F^2}{6\pi^2}\eta_B m_{B_s}\left(\hat{B}_{B_s}F_{B_s}^2\right)M_W^2 S(x_t)|V_{ts}|^2 = (17.8 \pm 4.8)/{\rm ps}$$

•with $F_{B_s}\sqrt{\hat{B}_{B_s}} = 262(35)\,{\rm MeV}$

from Wilson(JLQCD)+staggered(HPQCD) lattice fermions

A more accurate comparison is certainly desired

Lattice uncertainties need to be reduced (5% in 2010)

New possible routes to answer this question

(Very general) Model Independent Parametrization

$$M_{12}^{i}=\left(M_{12}^{i}\right)_{SM}+\left(M_{12}^{i}\right)_{new}=\left(M_{12}^{i}\right)_{SM}C_i e^{2i\varphi_i}$$

Such modifications can be studied introducing effective one-loop functions

$$(S_i)^{eff}=S_0 C_i e^{2i\varphi_i}, \qquad i=K,B_d,B_s$$

In CMFV:

$$C_K=C_{B_d}=C_{B_s},$$
$$\varphi_K=\varphi_{B_d}=\varphi_{B_s}=0$$

Mass differences and CP-asymmetries in B-systems

$$\Delta M_q=2\left|M_{12}^{q}\right|=(\Delta M_q)_{SM}C_{B_q}$$

Our aim:
determining C_{Bs} in a theoretically clean way!

$$S_{\psi K_s}=\sin(2\beta+2\varphi_{B_d}),$$
$$S_{\psi\phi}=\sin(2|\beta_s|-2\varphi_{B_s})$$

- Coefficients of $\sin(\Delta M_q\, t)$ in
  $A_{CP}^{mix}(B_d\to\psi K_S),\ A_{CP}^{mix}(B_s\to\psi\phi),$
- Attention to the relative sign!

New Idea: let us consider the semileptonic CP-asymmetry

[B.B.G.T.]

$$A^s_{\rm SL} = \frac{\Gamma(\bar{B}^0_s \to l^+ X) - \Gamma(B^0_s \to l^- X)}{\Gamma(\bar{B}^0_s \to l^+ X) + \Gamma(B^0_s \to l^- X)} = {\rm Im}\left(\frac{\Gamma^s_{12}}{M^s_{12}}\right)$$

$$A^s_{\rm SL} = {\rm Im}\left(\frac{\Gamma^s_{12}}{M^s_{12}}\right)^{\rm SM} \frac{\cos 2\varphi_{B_s}}{C_{B_s}} - {\rm Re}\left(\frac{\Gamma^s_{12}}{M^s_{12}}\right)^{\rm SM} \frac{\sin 2\varphi_{B_s}}{C_{B_s}}$$

$$\approx -{\rm Re}\left(\frac{\Gamma^s_{12}}{M^s_{12}}\right)^{\rm SM} \frac{\sin 2\varphi_{B_s}}{C_{B_s}} \approx -\left|{\rm Re}\left(\frac{\Gamma^s_{12}}{M^s_{12}}\right)^{\rm SM}\right| \frac{1}{C_{B_s}} S_{\psi\phi}$$

$$|{\rm Re}(\Gamma^s_{12}/M^s_{12})^{\rm SM}| = (2.6 \pm 1.0)\cdot 10^{-3}$$

$$\frac{\Delta M_s}{(\Delta M_s)^{\rm SM}} = -\left|{\rm Re}\left(\frac{\Gamma^s_{12}}{M^s_{12}}\right)^{\rm SM}\right| \frac{S_{\psi\phi}}{A^s_{\rm SL}}$$

- **Wilson coefficients at the NLO and O(1/m_b^4)**
  [Ciuchini, Franco, Lubicz, Mescia, CT]
  [Beneke, Buchalla, Greub, Lenz, Nierste]
- **B-parameters from LatticeQCD +VSA**
  [SPQ$_{cd}$R,JLQCD,UKQCD]

Theoretically:

- **free from the F_{B_s} uncertainties**
- **but dimension-seven operators**

Experimentally:

$S_{\psi\phi}$ and A^s_{SL} have to be measured

Advantage and Limit of the model-independent analysis:
``New Physics is knocking on our door but
we have no idea what it is´´

We focus now on
The Littlest Higgs Model without and with T-Parity

Main goals:

1. **In the MFV limit: is** $(\Delta M_s)_{LH} < (\Delta M_s)_{SM}$ **possible?**

2. **With new flavour and CP-violating interactions from mirror fermions:**

- **Can** $(\Delta M_s)_{LH} < (\Delta M_s)_{SM}$ **and** $\varphi_{B_d} < 0$ **?**
- **Are large values of** $A_{CP}(B \to X_s \gamma),\ \ A_{CP}(B_s \to \psi\phi),\ \ A_{SL}^s$ **, consistent with all other constraints, possible?**

Littlest Higgs Models

Non-linear Sigma-Models

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

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

LH

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

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

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

(g_1) (g'_1) (g_2) (g'_2)

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

LHT

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

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

Littlest Higgs Models without and with T-Parity

New particles: (with O(f) masses)

LH

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

Fermions: T

Scalars: $\Phi^{\pm}$,…

LHT

T-even Sector

SM Particles + T_{+}

T-odd Sector

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

Fermions: T_{-}, Mirror Fermions

Scalars: $\Phi^{\pm}$,…

The World of Mirror Fermions

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

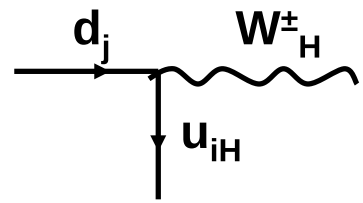
$$\begin{pmatrix} u_{1H} \\ d_{1H} \end{pmatrix} \quad \begin{pmatrix} u_{2H} \\ d_{2H} \end{pmatrix} \quad \begin{pmatrix} u_{3H} \\ d_{3H} \end{pmatrix}$$

Vectorial couplings under $SU(2)_L$

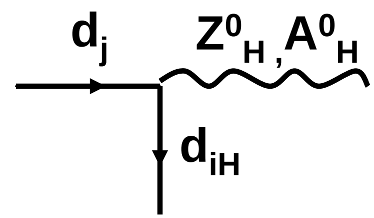
Similarly for Leptons

$m^u_{Hi} = m^d_{Hi}$ $\quad$ $i=1,2,3$
to first order in v/f

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



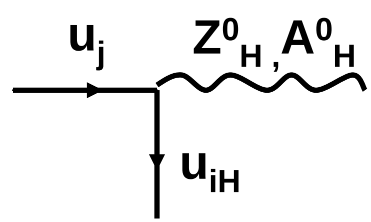
$\sim \ (V_{Hd})_{ij}\, \gamma_\mu\, (1-\gamma_5)$

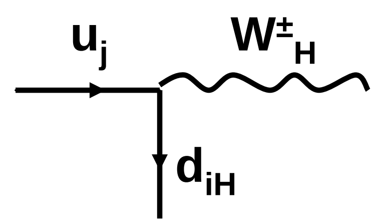


$\sim \ (V_{Hd})_{ij}\, \gamma_\mu\, (1-\gamma_5)$

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

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





Determination of the LHT Parameters at the LHC

Discovery of $W^{\pm}_H$, Z^0_H, A^0_H → f

Discovery of $T_{\pm}$ → x_L

Discovery of Mirror Fermions → m_{H1}, m_{H2}, m_{H3}

- FCNC Processes
- CP-Asymmetries

→ $\hat{s}_{12}$, $\hat{s}_{23}$, $\hat{s}_{13}$ and $\hat{\delta}$

General Structure of the Amplitudes

LH (CMFV Model)

Non-perturbative factors

Real functions

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

LHT

Real functions

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

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

Problems of LH without T-Parity

1.

Custodial SU(2) Symmetry violated at tree level ⇒ **$f \geq 2$ TeV** ⇒ **Effects in FCNC small**

[AJB,Poschenrieder,Uhlig]
(hep-ph/0410309)
[Choudhury et al.]

$$\frac{M_W^2}{M_Z^2} = \cos^2\theta_W\left(1 + O\left(\frac{v^2}{f^2}\right)\right)$$

2. **$\sin(2\beta)$ – R_b Problem not solved**

3. **$(\Delta M_s)_{LH} > (\Delta M_s)_{SM}$**

Go to LHT!

Virtues of LHT

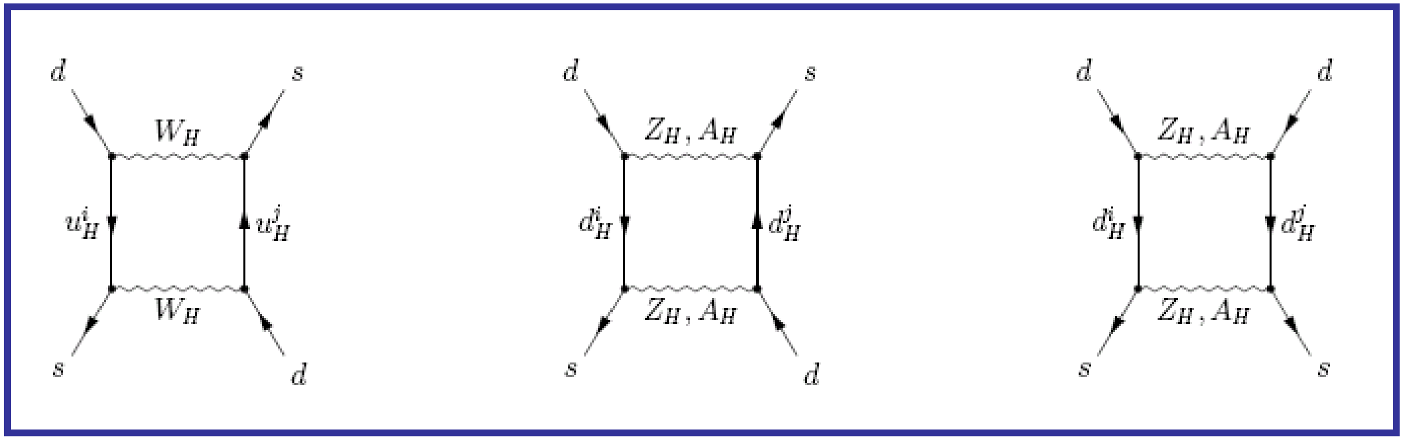
1. **Custodial SU(2) Symmetry unbroken at tree level** ⇒ **$f \geq 500$ GeV** ⇒ **Effects in FCNC can be larger**
[Blanke,AJB,Poschenrieder, CT,Uhlig,Weiler]
[Hubisz et al.]

2. **New Flavour Violating Interactions in the Mirror fermion Sector**

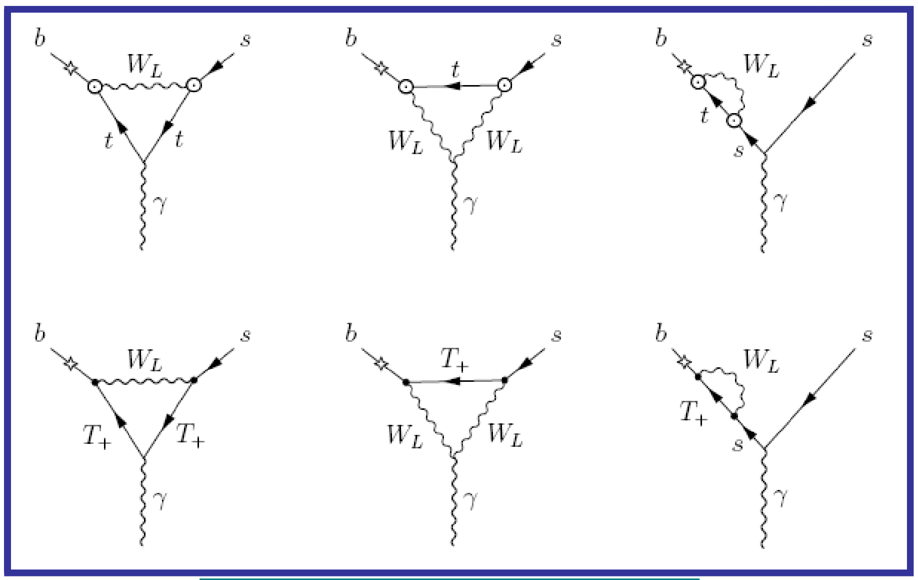
3. **All existing $\Delta F=2$ Problems can be solved** + **A^s_{SL}, $S_{\psi\phi}$ can be by an order of magnitude larger than in the SM**

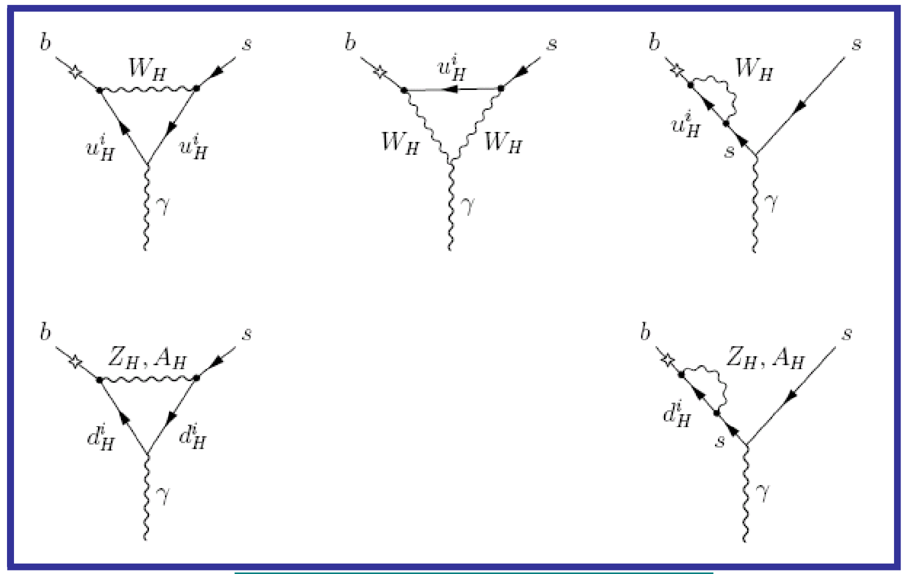
Feynman Diagrams for:

Particle-Antiparticle Mixing



$B \to X_s \gamma$





T-even contribution

T-odd contribution

Benchmark Scenarios in LHT

$f \equiv 1000$ TeV

1. Degenerate Mirror Fermion Spectrum → CMFV

2. Non-degenerate Mirror Fermion Spectrum + $V_{Hd} = V_{CKM}$ → Approximate CMFV

3. m_{H1} =350 GeV, m_{H2} =400 GeV, m_{H3}=450 GeV + $V_{Hd} \neq V_{CKM}$

4. $m_{H1} \approx m_{H2}$ =500 GeV, m_{H3}=1000 GeV + V_{Hd} hierarchy different from the V_{CKM} one

   Favourite scenario (large effects in B_s!)

5. γ_{tree}= - (109 ± 16)° (forbidden in the SM, MFV)

   Can Mirror Fermions rescue it? (large effects in B_d!)

Results in Scenarios: 1 - 3

1. and **2.** (uninteresting) — **No Problems solved** — $(\Delta M_s) > (\Delta M_s)_{SM}$

3. — **$\sin(2\beta) - R_b$ Problem solved** — **but** — $(\Delta M_s) > (\Delta M_s)_{SM}$

and

~~CP~~ effetcs in $B^0_s - \overline{B}^0_s$ remain tiny

Non-degenerate m_{H1} and m_{H2} force through ΔM_K and ε_K $\hat{V}^{32}_{Hd}$ to be almost real

4. Favourite "B_s" Scenario

V_{CKM}

V_{Hd} + Degeneracy of Mirror Fermions in the first two generations

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

$$\begin{pmatrix} \hat{c}_{12} & \hat{s}_{12} & \hat{s}_{13}e^{-i\hat{\delta}} \\ -\hat{s}_{12} & \hat{c}_{12} & \hat{s}_{23} \\ -\hat{c}_{12}\hat{s}_{13}e^{i\hat{\delta}} & -\hat{s}_{12}\hat{s}_{13}e^{i\hat{\delta}} & 1 \end{pmatrix}$$

Large $\not{CP}$ in $B^0_d - \bar{B}^0_d$
Tiny $\not{CP}$ in $B^0_s - \bar{B}^0_s$

Large $\not{CP}$ in $B^0_s - \bar{B}^0_s$
Small $\not{CP}$ in $B^0_d - \bar{B}^0_d$

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

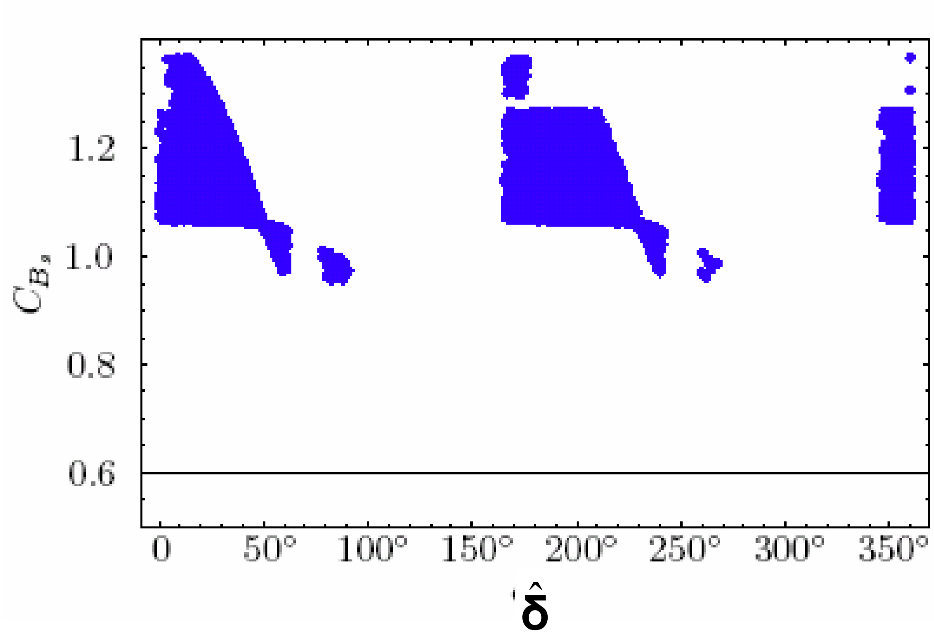
$(4\cdot10^{-3})$ $(4\cdot10^{-2})$ (0.2)

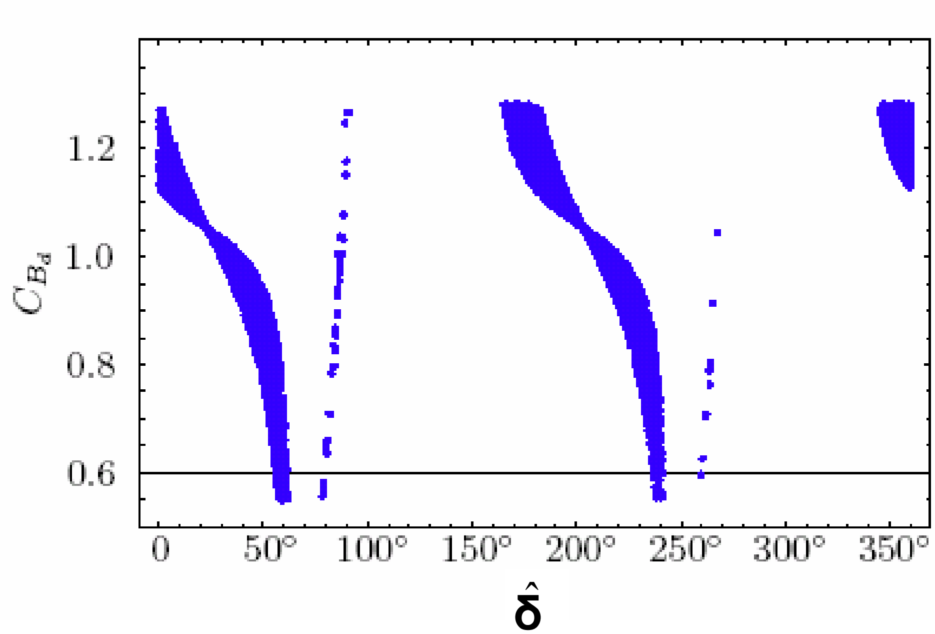
$\hat{s}_{23} << \hat{s}_{13} << \hat{s}_{12}$

$(4\cdot10^{-4})$ $(8\cdot10^{-2})$ (0.90)

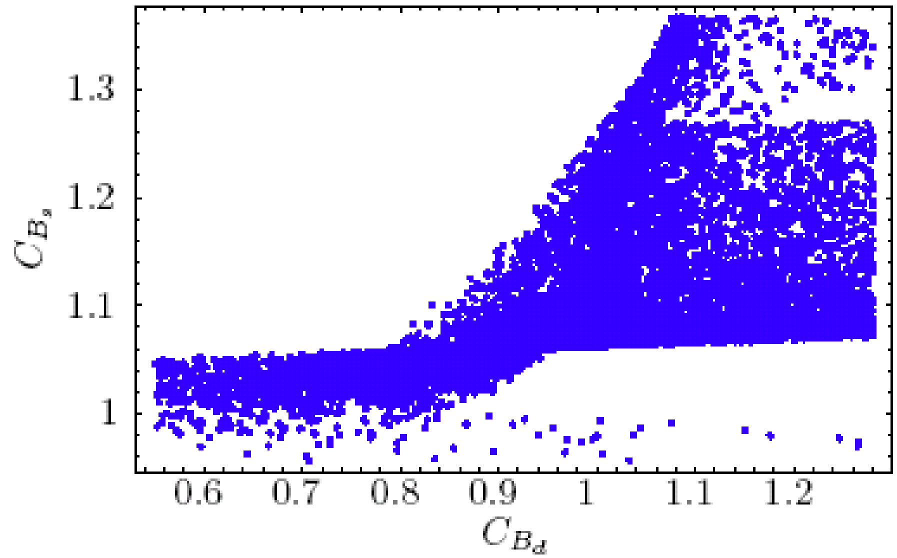
Results in Scenario 4

``favourite!´´





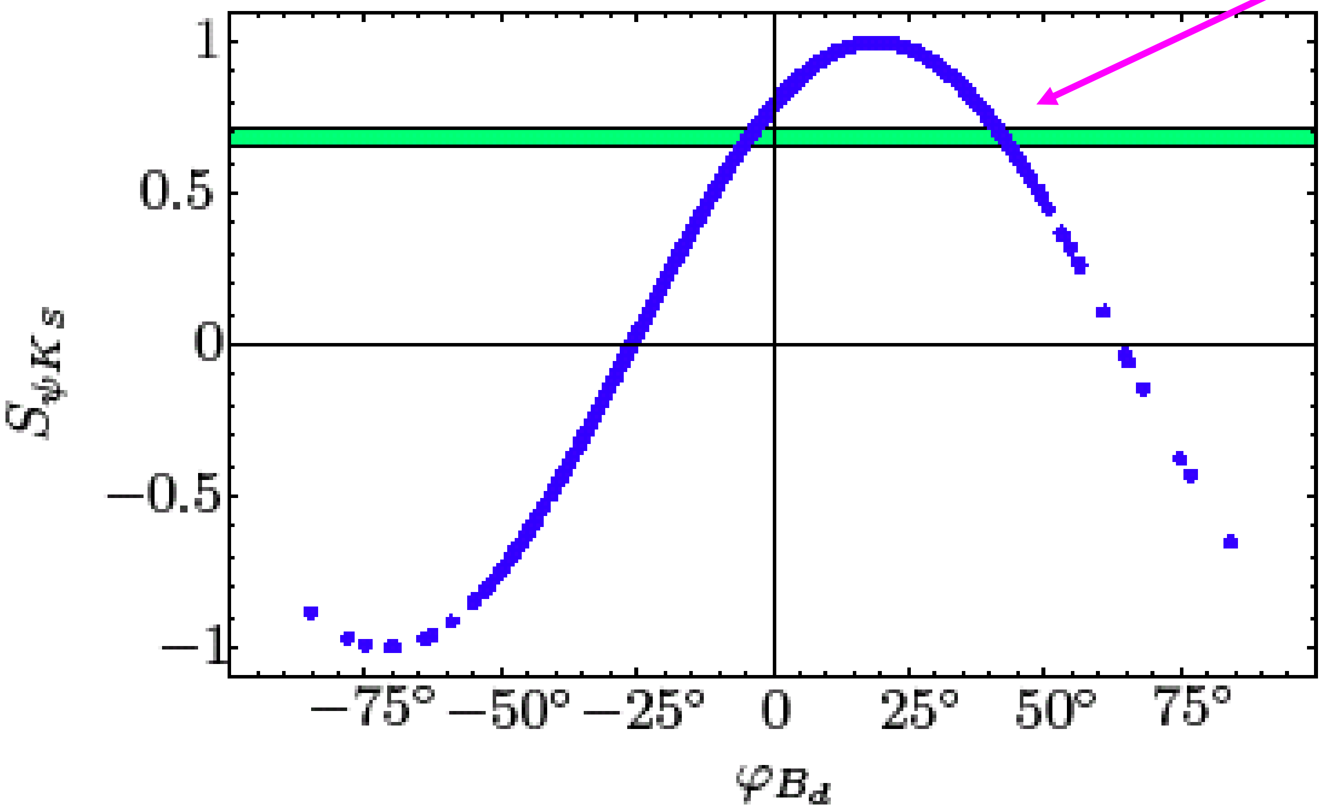
$C_{Bs} \geq 0.93$



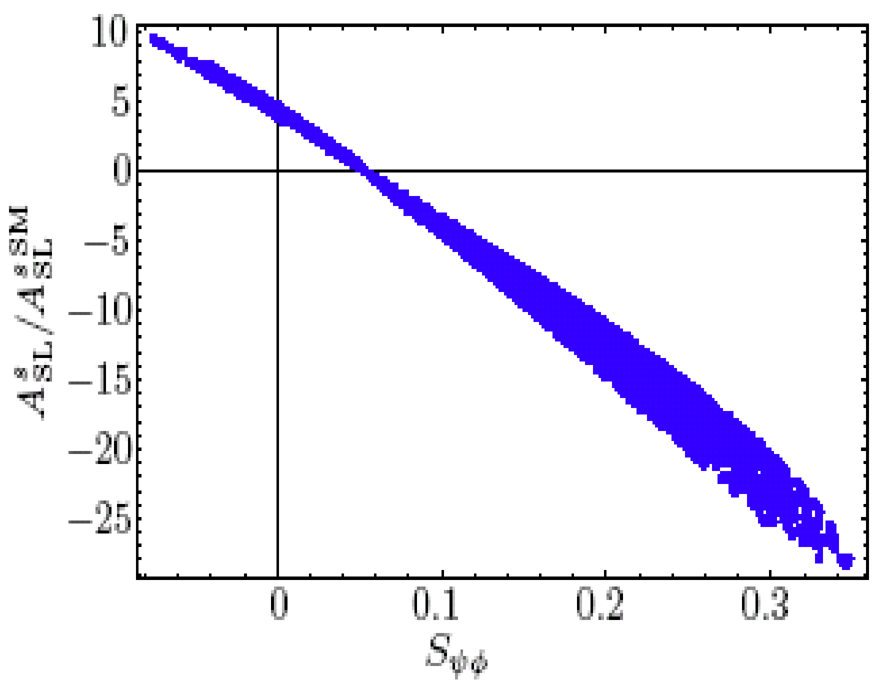
$(\Delta M_s) < (\Delta M_s)_{SM}$
possible,
but more difficult than
$(\Delta M_d) < (\Delta M_d)_{SM}$

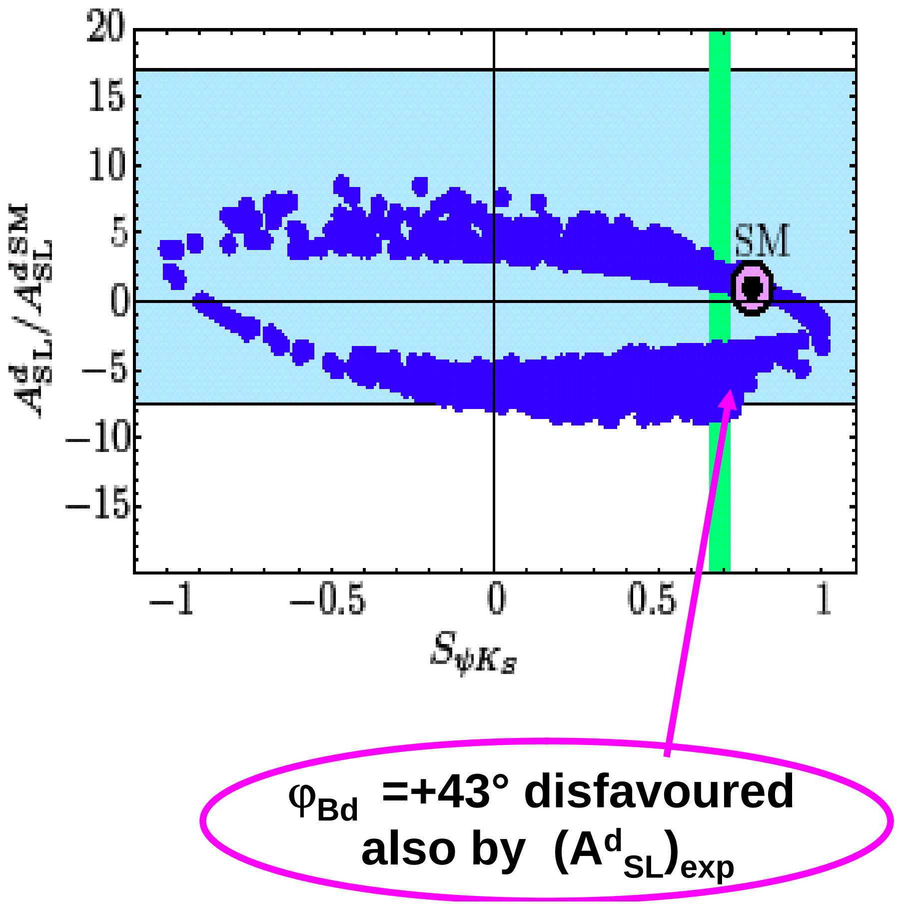
$\sin(2\beta)$ – R_b Problem solved ⇒ **$\varphi_{B_d} \approx$ - 3°, +43°**

strongly disfavoured by $\cos(2\beta+2\varphi_{B_d})^{exp}$



- A^s_{SL} **enhanced** by 10-20, A^d_{SL} by ~3
- $S_{\psi\Phi}$ can be as high as **+0.3**
- $B \to X_s\,\gamma$ and $A_{CP}(B \to X_s\,\gamma)$ **consistent** with the data





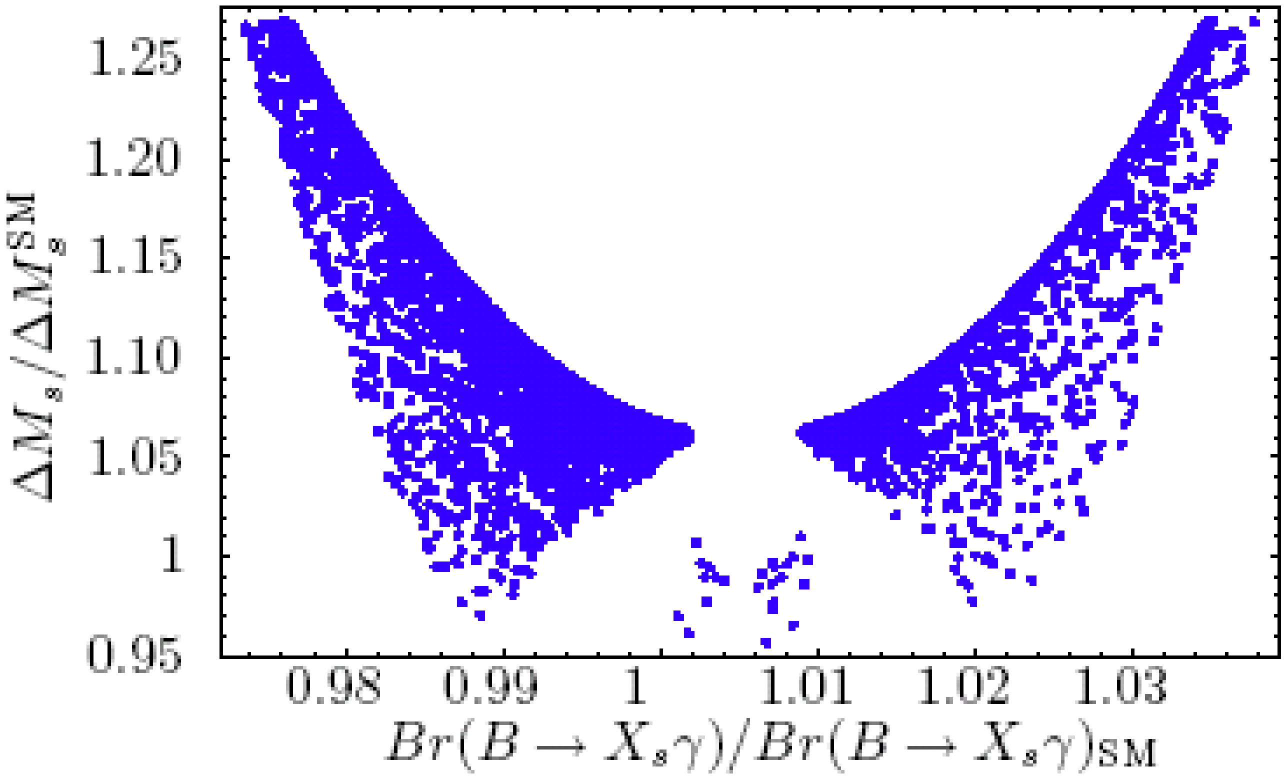
Model-independent correlation [Ligeti et al.], more efficient in the specific LHT Model

$Br(B\to X_s\,\gamma)$

At most ±4% effects in the LHT Model

Good agreement with data

Small effects also in $A_{CP}(B\to X_s\,\gamma)$



5. The $\gamma_{tree} \approx -109°$ (``B_d´´) Scenario

m_{H1} =500 GeV, m_{H2} =450 GeV
m_{H3}=1000 GeV

$\hat{s}_{12} << \hat{s}_{23} << \hat{s}_{13}$

Within the SM:

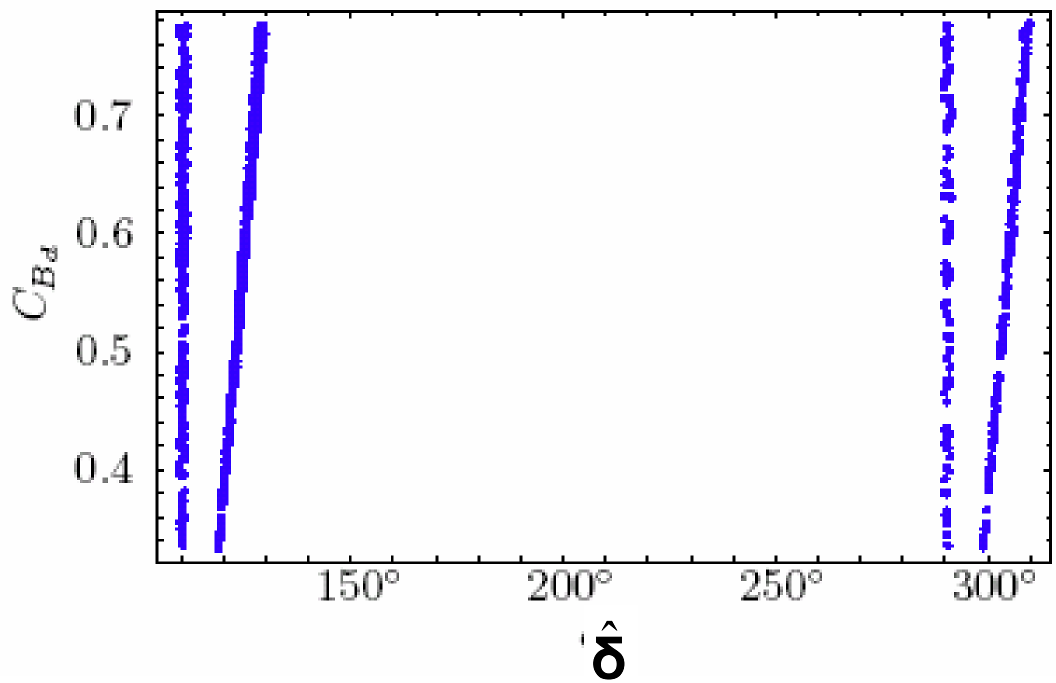
$$(R_t)_{true} \approx 1.22 \qquad \beta_{true} = -20°$$

$$S_{\psi K_S} = -0.64 \qquad \varepsilon_K = -3.7 \cdot 10^{-3} \cdot e^{i\pi/4}$$

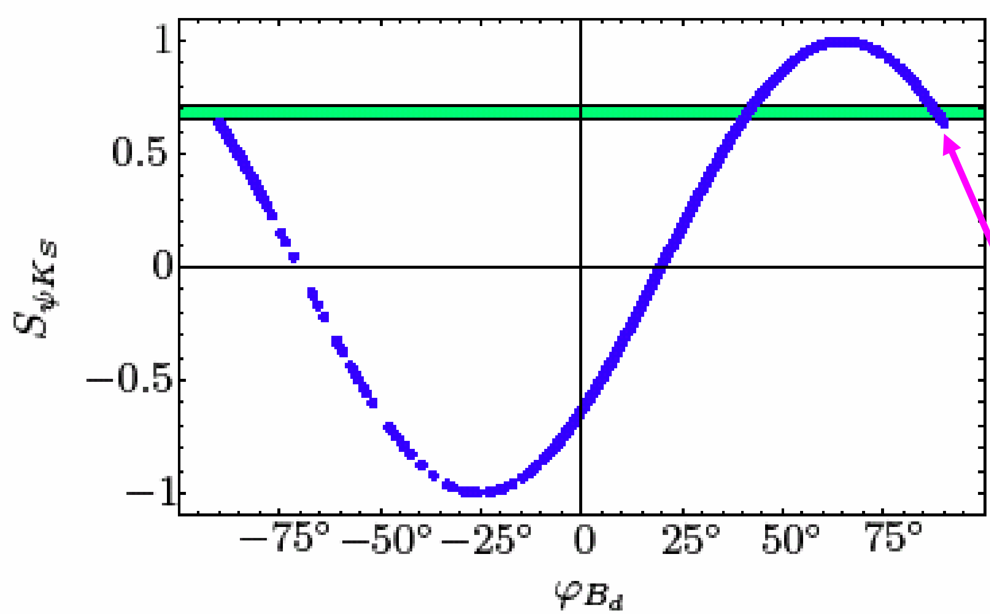
$$\Delta M_d = 0.90/ps$$

Hard Work for Mirror Fermions:

- Reversing signs of ε_K and $S_{\psi K_S} = \sin(2\beta_{true} + 2\varphi_{B_d})$: $\varphi_{Bd} \approx$ + 42°, +88°!
- Descreasing ΔM_d: C_{Bd} <1!
- Can they still give large ~~CP~~ effects in $B^0_s - \bar{B}^0_s$ and $\Delta M_s < (\Delta M_s)_{SM}$?



C_{Bd} < 1
is indeed possible

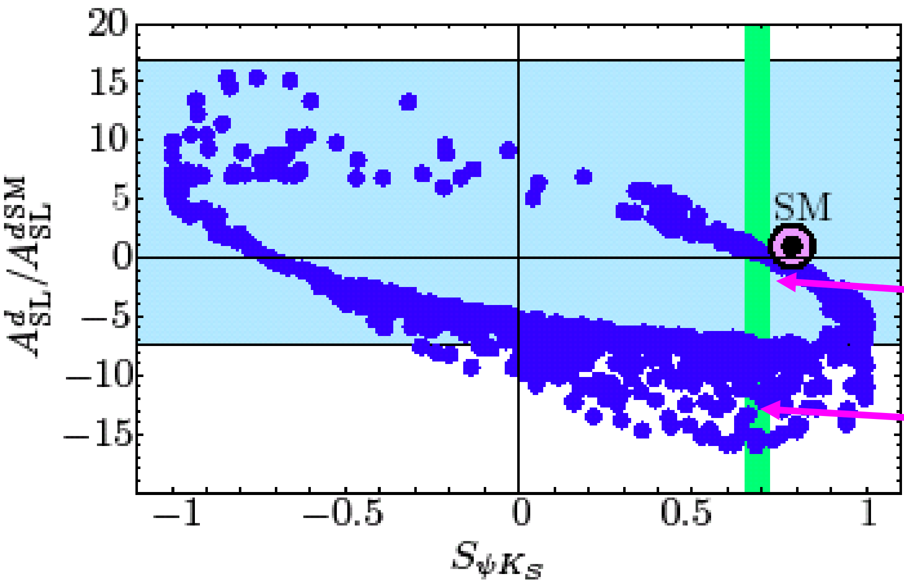


2 large values for φ_{Bd}
(+42°, +88°)
are pointed out by data

strongly disfavoured by $\cos(2\beta+2\varphi_{Bd})^{exp}$

$A_{SL}^{d} / (A_{SL}^{d})_{SM}$

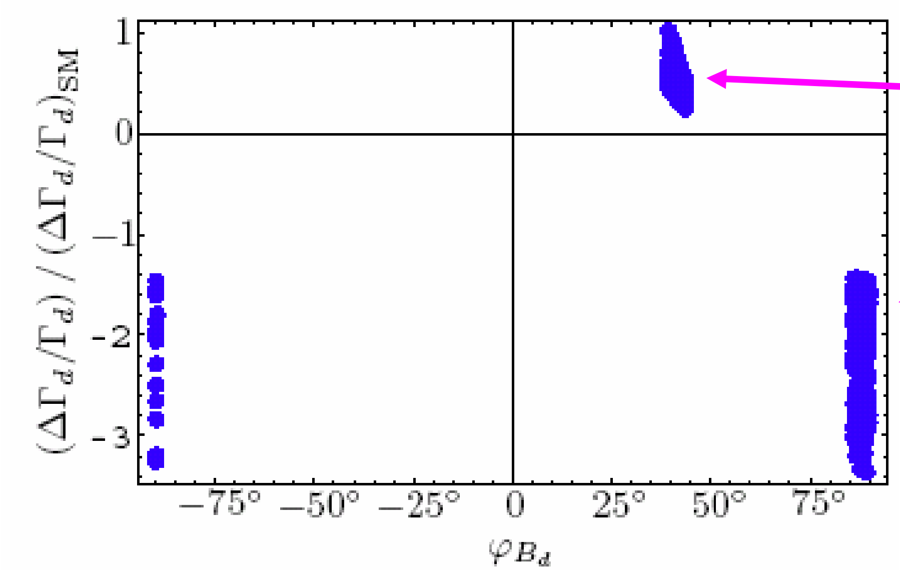
Reversed sign w.r.t. the γ=71° case



φ_{Bd} =+88°

φ_{Bd} =+42°

$\Delta\Gamma_d / (\Delta\Gamma_d)_{SM}$



φ_{Bd} =+42°

φ_{Bd} =+88°

γ=-109° Scenario still survives

- Importance to reduce the experimental uncertainties

Main Messages from
Blanke, AJB, Poschenrieder, CT, Uhlig, Weiler

- The **LHT** Model offers a **useful playground** for studying **non-MFV** interactions
- All the existing ``Problems´´ can be **solved**
- Large $\not{CP}$-effects in $B^0_s - \bar{B}^0_s$ are allowed
- Mirror Fermions rescue the γ=-109° solution

The analysis of

$$B_{s,d} \to \mu^+\mu^-,\ B \to X_{s,d}\nu\bar{\nu},\ B \to X_{s,d}l^+l^-$$

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

is coming soon !