Flavour Physics in the Littlest Higgs Model with T-Parity: Effects in the K, $B_{d/s}$ and D systems

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- Blanke, Buras, Poschenrieder, S.R., Tarantino, Uhlig, Weiler, JHEP **0701**, 066 (2007), hep-ph/0610298 (LHT flavour basics, long)
- Blanke, Buras, S.R., Tarantino, Uhlig, Phys. Lett. B **657**, 81 (2007) ($D\bar{D}$ I)
- Bigi, Blanke, Buras, S.R., JHEP **07**, 097 (2009), arXiv:0904.1545 ($D\bar{D}$ II)
- Blanke, Buras, Duling, S.R., Tarantino, arXiv:0906.5454 (LHT flavour update)

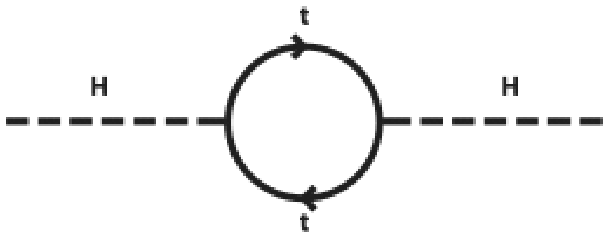
Introduction

Major problem in the SM: Gauge Hierarchy !

Top-loop corrections make Higgs mass unstable,

$\Delta m_H^2 = -\frac{|\lambda_t|^2}{8\pi^2}\left[\Lambda_{UV}^2 + \ldots\right]$

Expect $m_H \to m_{\text{Planck}}$ or incredible fine-tuning.



One possible solution:

E.g. SUSY, cancel top-loop with stop-loop,

$\Delta m_H^2 = 2\frac{|\lambda_s|^2}{16\pi^2}\left[\Lambda_{UV}^2 + \ldots\right]$

Or, lower the Planck mass with extra dimensions, or ...

Or: **Little Higgs !**

The Little Higgs Model(s)

Arkani-Hamed, Cohen, Georgi '01

Why little Higgs ? (Why not ?)

Interesting physics with very few (c.f. SUSY !) new parameters.

Give experimental physicists other signatures to look for.

Effects in some observables complementary to SUSY, UED, ...

Little Higgs idea:

Higgs Boson is pseudo-Goldstone boson of a spontaneously broken global symmetry. Gauge and Yukawa couplings break the symmetry explicitely, but every single coupling conserves enough of the symmetry to keep Higgs massless.

→ Radiative corrections only logarithmically divergent at one loop.

Common to all Little Higgs models:

New heavy weak gauge bosons, scalars, top partner T at TeV scale.

Similar phenomenology → most people study Little**st** Higgs Model

The Littlest Higgs Model

Arkani-Hamed, Cohen, Katz, Nelson '02

Higgs boson is pseudo-Goldstone boson from global symmetry breaking of a global $SU(5)$ to a global $SO(5)$ at scale $f \sim \mathcal{O}(\text{TeV})$.

Mechanism for symmetry breaking unspecified $\rightarrow$
Littlest Higgs model is an effective theory valid up to $\Lambda \sim 4\pi f$.

14 Nambu-Goldstone bosons from symmetry breaking: SM Higgs, new $W_H^\pm$, Z_H, A_H, scalar triplet Φ, also heavy partner for top, T.

In the original Littlest Higgs, custodial $SU(2)$ is broken already at tree level $\rightarrow$ electroweak precision observables demand $f \gtrsim 2{-}3\,\text{TeV}$.
$\Rightarrow$ Small (10–20%) effects in Flavour Physics.

More interesting: Littlest Higgs **with T parity (LHT)**.

The Littlest Higgs Model with T parity (LHT)

Cheng, Low '03

Littlest Higgs with a discrete symmetry ("T parity"):
All new particles (except T_+) are odd, all SM particles are even.

$\Rightarrow$ No contributions by T odd particles at tree level

(Cancellation of divergences still works: loop effect !)

$\Rightarrow f \sim 1\,\mathrm{TeV}$ (or even lower) OK!

This gives us:

- three doublets of "mirror quarks" (T odd, heavy)
- three doublets of "mirror leptons" (T odd, heavy)
- T odd T_- in addition to T even T_+.
- Potentially large effects in the Flavour sector ☺
  (Although *raison d'être* is gauge hierarchy, not flavour !)
- (Dark matter candidate)

Particle content of the LHT model

	T-even sector	**T-odd sector**
gauge bosons	$W_L^\pm$, Z_L, A_L	$W_H^\pm$, Z_H, A_H
	gluons	—
fermions	**SM quarks**	**mirror quarks**
	top partner T_+	T_-
	SM leptons	**mirror leptons**
scalars	Higgs doublet H	scalar triplet Φ

New parameters in LHT:

- f: NP scale ($\to M_{W_H}, \ldots$), x_L: $t{-}T$ mixing
- mirror quark masses: m_{H1}, m_{H2}, m_{H2} (MFV if degenerate !)
- mirror quark mixing matrix: V_{Hd} ($V_{Hu}^\dagger V_{Hd} = V_{CKM}$)
  $\to$ three angles and **three** phases
  (less phases to rotate away !)
- (9 mirror lepton parameters, c.f. mirror quarks)

"MFV" ?

Minimal Flavour Violation ↔ Non-MFV

Buras et al. 01, D'Ambrosio et al. 02

Models are MFV if there are no new sources of Flavour Violation (i.e. only SM-Yukawa).

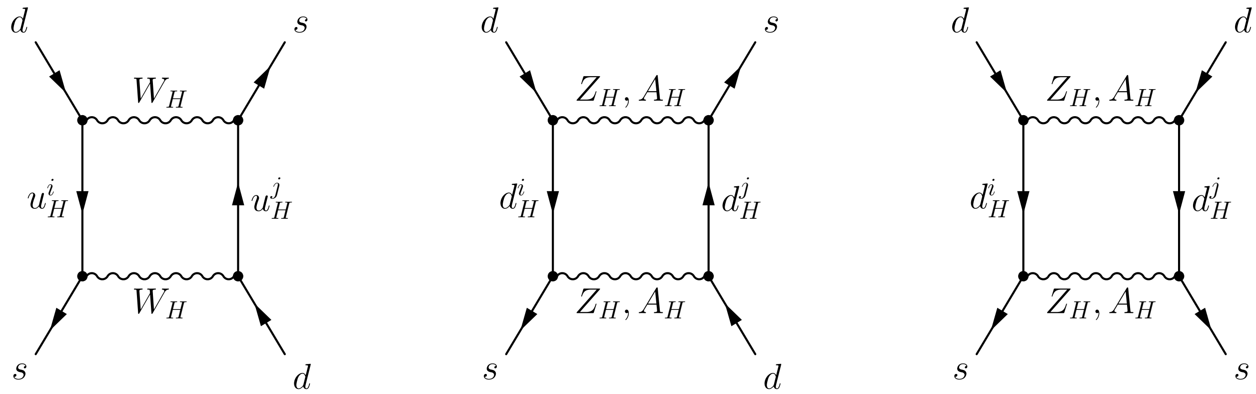
Examples of MFV:

- Universal extra dimensions (UED) (**A**ppelquist, **C**heng, **D**obrescu)
- SUSY with universal soft-scalar masses and trilinear soft terms proportional to Yukawa couplings (squark, quark masses aligned)
- Little Higgs without T parity

Examples of non-MFV:

- General SUSY (squark mass matrices not aligned with quarks)
- Littlest Higgs with T-parity

LHT is **not** MFV, new particles contribute to FCNC processes, e.g.



(contributing to $K\bar{K}$ mixing $\to \Delta M_K, \epsilon_K^{(\prime)}$)

LHT amplitudes (e.g. K sector) $\sim \sum_{i=u,c,t} \underbrace{\lambda_i^K F_i(m_i, m_{T+}, \ldots)}_{\text{T even}} + \underbrace{\xi_i^K G_i(m_H^i, M_{W_H}, \ldots)}_{\text{T odd}}$

(No new operators !)

$\to$ Inami-Lim: $X_K = X_{\rm SM} + X_{\rm even} + \xi_i^K / \lambda_t^K X_{\rm odd}$,

$\lambda_t^K = V_{ts}^* V_{td}$ (CKM), $\xi_i^K = V_{Hd}^{*is} V_{Hd}^{id}$ (mirror quark mixing)

CKM hierarchy: $1/\lambda_t^K \gg 1/\lambda_t^{B_d} \gg 1/\lambda_t^{B_s}$,

$\to$ expect largest effects in K physics,

but suitable ξ_i^j can produce large effects in B_d, B_s !

$\rightarrow$ Interesting phenomenology expected in LHT, but

need to check experimental FCNC constraints very carefully !

Constraints that we studied:

$K\bar{K}$ mixing: ΔM_K, $\not{C}\not{P}$: ϵ_K

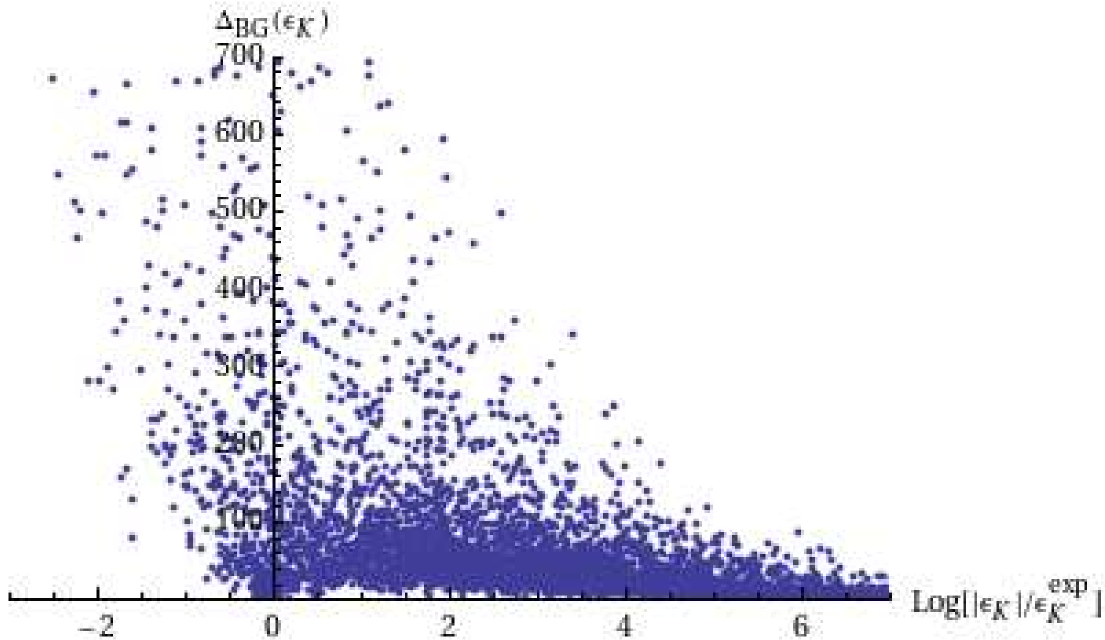
$B\bar{B}$ mixing: ΔM_{B_d}, ΔM_{B_s}, asymmetry: $S_{J/\psi K_S}$

($b \rightarrow s\gamma$ is not a problem, very moderate effects)

We generate random points in the LHT parameter space, check these constraints and keep only points that fulfill all constraints. Input parameters are evenly distributed over their 1σ ranges.

Fine tuning ?

For arbitrary model parameters, LHT tends to break experimental constraints, most strongly ϵ_K: (this plot: no ϵ_K constraint)



$$\Delta_{\rm BG}(O) = \max\{\Delta_{\rm BG}(O,p_j)\}\,,\ \Delta_{\rm BG}(O,p_j) = \left|\frac{p_j}{O}\frac{\partial O}{\partial p_j}\right| \quad \text{(Barbieri,Giudice '87)}$$

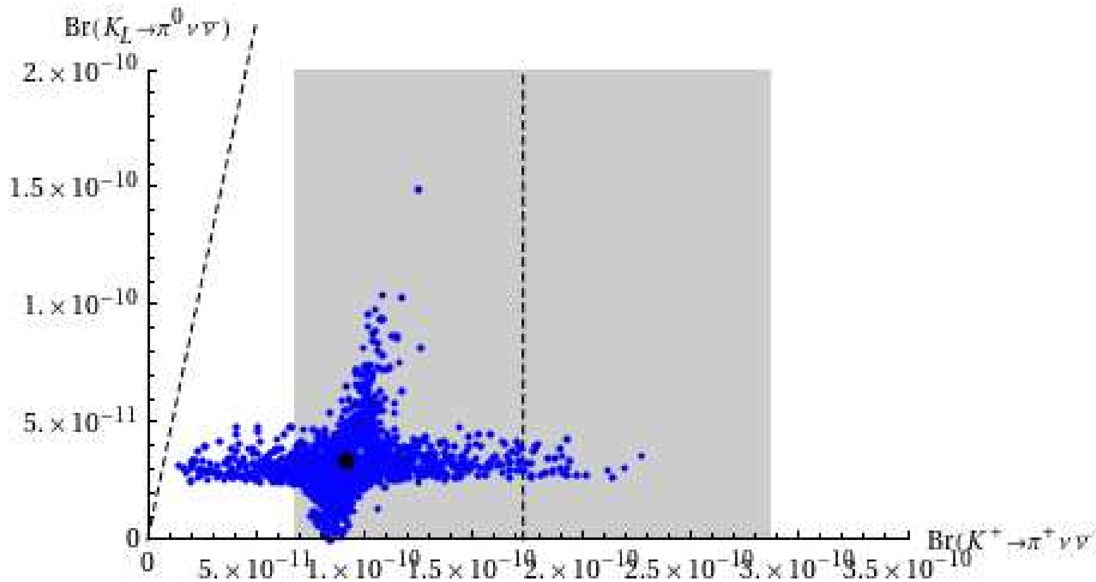
$\Rightarrow$ ϵ_K typically $\sim \mathcal{O}(10\text{–}100\,\epsilon_K^{\rm exp})$, but no real fine tuning required.

Some of the most spectacular points need no fine tuning at all.

General results from LHT flavour study

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

(Very clean, excellent measure of $\not{CP}$ in Kaon system)



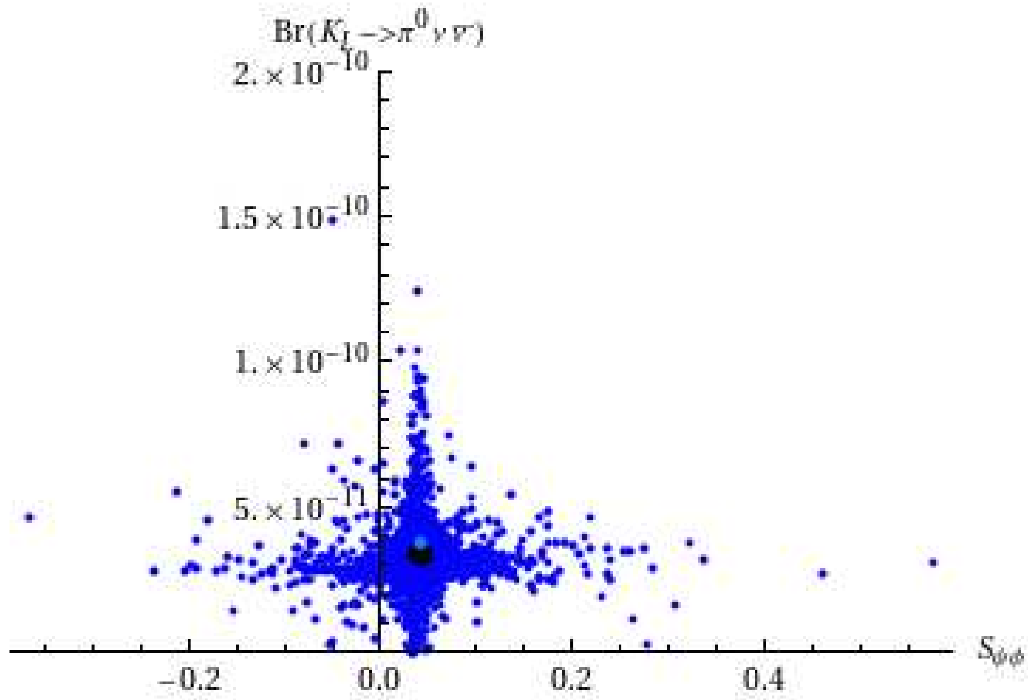
$K_L \to \pi^0 \nu \bar{\nu}$ can be enhanced significantly ! (SM: black dot)

Most data points lie on two axes: constant $K_L \to \pi^0 \nu \bar{\nu}$ and parallel to the Grossmann-Nir bound → operator structure

(Effects even larger before divergence cancellation found by Goto et al. '08)

CP-asymmetry $S_{\psi\phi}$ much smaller in SM than $S_{J/\psi K_S}$ ($\beta_s \leftrightarrow \beta$).

Large LHT effects possible:

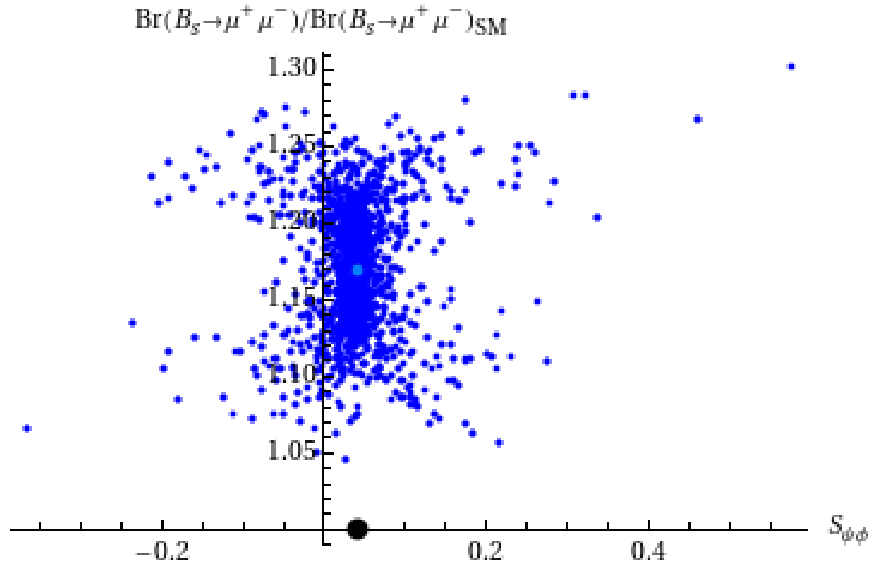


Simultaneous large effects in $K_L \to \pi^0 \nu\bar{\nu}$ and $S_{\psi\phi}$ possible, but unlikely.

Contrary to

$Br(B_s \to \mu^+\mu^-)$ and $S_{\psi\phi}$:

Here simultaneous significant effects are rather likely !

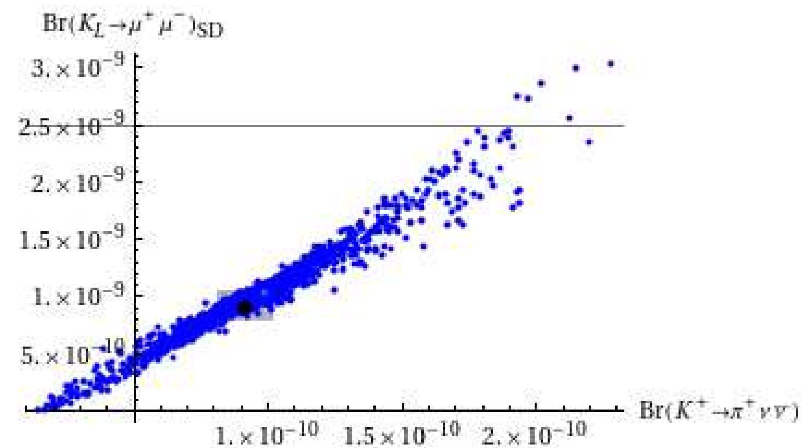


Another interesting signature:

Correlation between the Br's of

$K_L \to \mu^+\mu^-{}_{SD}$ and $K^+ \to \pi^+\nu\bar{\nu}$

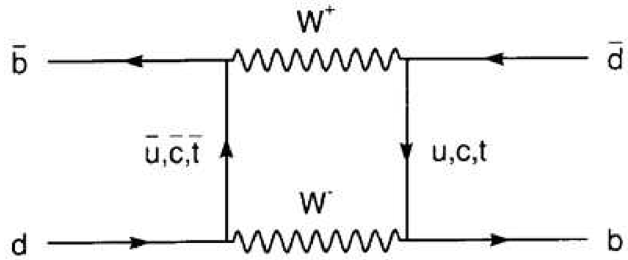
$\to$ complementary to RS model !



$\Rightarrow$ Test LHT signatures in experiment !

$D\bar{D}$ Oscillations (in the LHT model)

$D\bar{D}$ more complicated than $K\bar{K}$ and $B\bar{B}$:
$K\bar{K}$ and $B\bar{B}$ dominated by short-distance physics: charm/top loops



$D\bar{D}$ has almost no short-distance contribution:
Small CKM factors, down-type quarks in the loops too light
$\rightarrow$ SM: long-distance $\rightarrow$ difficult to estimate
$\rightarrow$ we vary SM contribution in reasonable range in our calculation

Significant contribution from LHT possible !

Need to be careful, $D\bar{D}$ is special, e.g.

$\Delta M_K = 2\,\mathrm{Re}(M_K^{12})$ because weak phase tiny

$\Delta M_B = 2 \quad \left|M_B^{12}\right|$ because $\Delta\Gamma_B \ll \Delta M_B$

No such approximation in the D system,

$$\Delta M_D = 2\,\mathrm{Re}\sqrt{\left|M_D^{12}\right|^2 - \frac{1}{4}\left|\Gamma_D^{12}\right|^2 - i\Gamma_D^{12} M_D^{12*}}$$

Some formalism

$D\bar{D}$ mixing:

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0 \\ \bar{D}^0 \end{pmatrix} = \begin{pmatrix} M_{11}^D - \frac{i}{2}\Gamma_{11}^D & M_{12}^D - \frac{i}{2}\Gamma_{12}^D \\ M_{12}^{D\,*} - \frac{i}{2}\Gamma_{12}^{D\,*} & M_{11}^D - \frac{i}{2}\Gamma_{11}^D \end{pmatrix}\begin{pmatrix} D^0 \\ \bar{D}^0 \end{pmatrix}$$

Flavour violation: Off-diagonal elements are non-zero, $M_{12}^D, \Gamma_{12}^D \neq 0$

Flavour eigenstates: $$|D_{1/2}\rangle = \frac{1}{\sqrt{|p|^2+|q|^2}}\left(p|D^0\rangle +/- \, q|\bar{D}^0\rangle\right)$$

Observables: normalised mass and width differences, also: $|q/p|$.

$$x_D \equiv \frac{\Delta M_D}{\overline{\Gamma}}\,, \qquad y_D \equiv \frac{\Delta\Gamma_D}{2\overline{\Gamma}}\,, \qquad \frac{q}{p} \equiv \sqrt{\frac{M_{12}^{D\,*} - \frac{i}{2}\Gamma_{12}^{D\,*}}{M_{12}^D - \frac{i}{2}\Gamma_{12}^D}}$$

BaBar / Belle / CDF 07

Rather recently: $x_D, y_D \neq 0$ measured $\to$ $D\bar{D}$ oscillations observed !

$$x_D = 0.0100^{+0.0024}_{-0.0026}\,, \qquad y_D = 0.0076^{+0.0017}_{-0.0018}\,, \qquad \left|\frac{q}{p}\right| = 0.86^{+0.17}_{-0.15}$$

(BaBar, arXiv:0908.0761: $y_D = 0.0112 \pm 0.0026 \pm 0.0022$)

CP violation not (yet) observed, $|q/p|$ consistent with 1 !

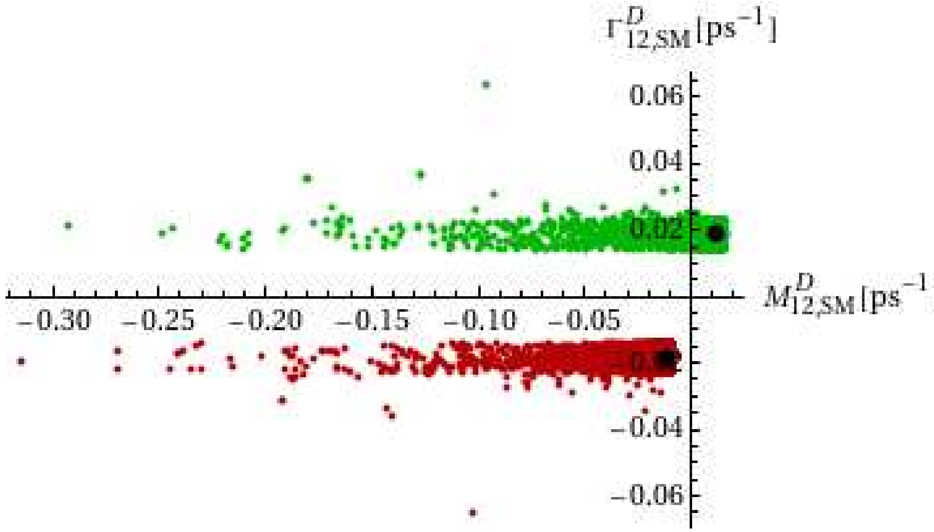
In the SM, no significant $\not{CP}$ expected. LHT ?

Our strategy:

We determine $(M_{12}^D)_{\rm SM}$ and $(\Gamma_{12}^D)_{\rm SM}$ so that together with the LHT contribution, x_D and y_D coincide with experiment.

Bigi, Uraltsev '01 / Falk, Grossman, Ligeti, Nir, Petrov '04

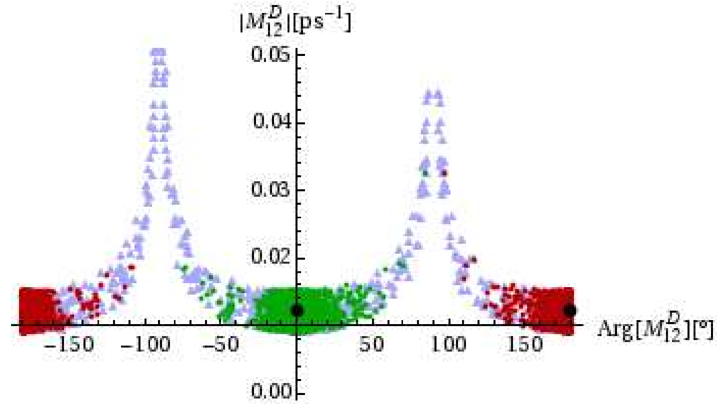
$(M_{12}^D)_{\rm SM}$ and $(\Gamma_{12}^D)_{\rm SM}$ are real, but the relative sign is not known (relative minus seems to be preferred). $\rightarrow$ Two solutions !



Essentially all LHT parameter points are consistent with expectations for magnitude of SM contributions.

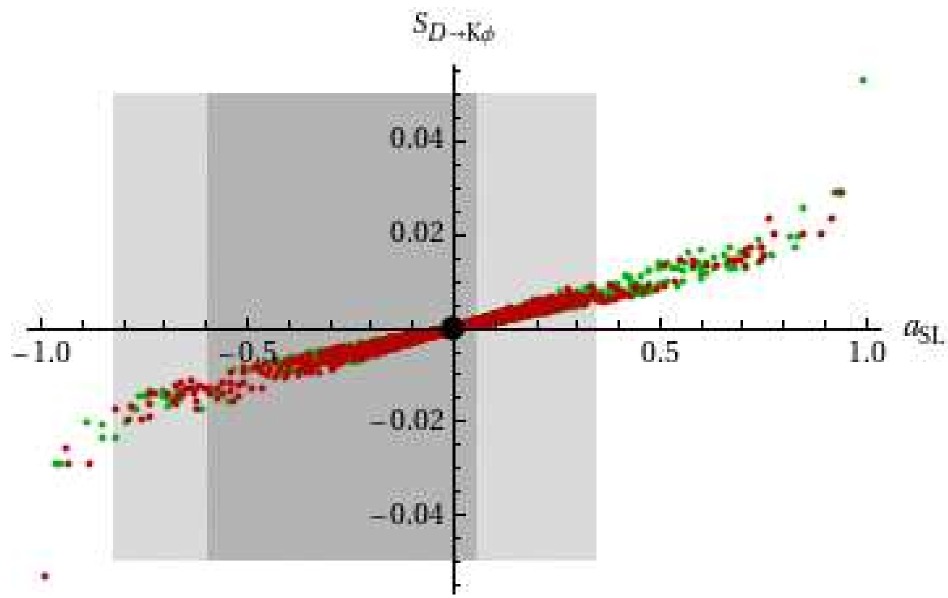
In some cases, $(M_{12}^D)_{\rm SM}$ / $(\Gamma_{12}^D)_{\rm SM}$ can be rather large, but these are not our most spectacular/interesting data points.

ϵ_K constraint cuts away very large results for $|M_{12}^D|$, (blue triangles: no ϵ_K constraint)

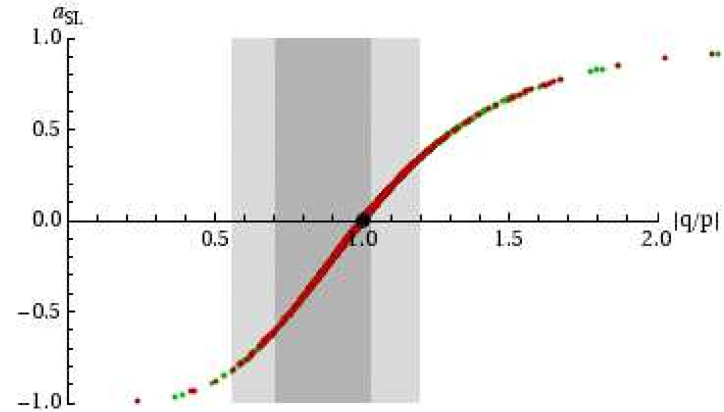


but very large (for D) CP asymmetries possible !

Why experimental bound on $a_{\rm SL}$? $\rightarrow |q/p|$!

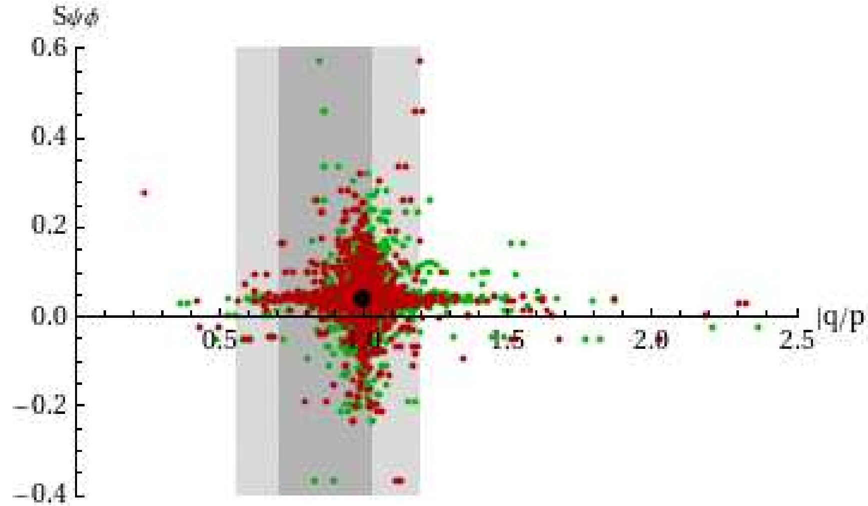


Semileptonic CP asymmetry $a_{SL}^{D^0}$ is closely related to $|q/p|$, and $|q/p|_{\text{exp}} = 0.86^{+0.17}_{-0.15}$



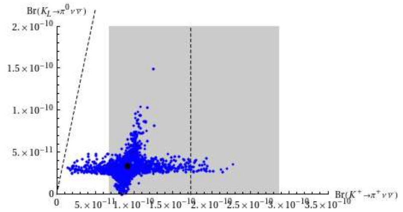
Correlation with $B_s\bar{B}_s$ mixing: Simultaneous large effects possible, but unlikely.

(c.f. (no) correlation
K system ↔ B system)

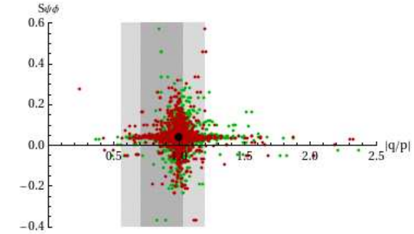


Conclusions

- The LHT model is an interesting, economical alternative to SUSY etc. in solving the little hierarchy problem
- Rather few parameters, hierarchy OK, EW precision tests OK
- Interesting, sometimes spectacular effects on Flavour observables



- Large CP violation in $D\bar{D}$ oscillations possible



- Wait for experimental veri-/falsification