Hunting for New Physics with Vector-like Quarks

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Based on work done in collaboration with:
G.C. Branco (Lisbon) & F.J. Botella (Valencia),
in progress & `arXiv:1207.4440` [JHEP 1212 (2012) 040]

Motivation

Vector-like quarks appear in several extensions of the SM:

- Little Higgs models
- Composite models
- Extra-dimensional models
- Unification models
- ...

Several possibilities, we concentrate on a very simple setup

- An enlarged matter content through the inclusion of weak isospin singlet fermions

$$T_L^i,\ T_R^i \sim (3, 1, 4/3)$$

New terms

- In addition to the usual Yukawa terms[1],

$$\mathscr{L}_Y = -\bar{q}_{0L\mathbf{i}}\ \tilde{\Phi}\ {Y_u}^{\mathbf{i}}{}_{\mathbf{j}}\ u^{\mathbf{j}}_{0R} - \bar{q}_{0L\mathbf{i}}\ \Phi\ {Y_d}^{\mathbf{i}}{}_{\mathbf{j}}\ d^{\mathbf{j}}_{0R} + \text{h.c.}$$

  for an up vector-like quark, we have additional terms:

$$\mathscr{L}_T = -\bar{q}_{0L\mathbf{i}}\ \tilde{\Phi}\ Y_T^{\mathbf{i}}\ T_{0R} - \bar{T}_{0L}\ \mu_{T\mathbf{i}}\ u^{\mathbf{i}}_{0R} - M_{0T}\ \bar{T}_{0L}\ T_{0R} + \text{h.c.}$$

- With SSB $\langle\Phi\rangle = \left(\begin{smallmatrix} 0 \\ \hat{v} \end{smallmatrix}\right)$,

$$\mathscr{L}_M = -\left(\bar{u}_{0L\mathbf{i}}\ \bar{T}_{0L}\right) \underbrace{\begin{pmatrix} \hat{v}{Y_u}^{\mathbf{i}}{}_{\mathbf{j}} & \hat{v}Y_T^{\mathbf{i}} \\ \mu_{\mathbf{j}} & M_0 \end{pmatrix}}_{\hat{M}_u} \begin{pmatrix} u^{\mathbf{j}}_{0R} \\ T_{0R} \end{pmatrix} - \bar{d}_{0L\mathbf{i}}\ \underbrace{\hat{v}{Y_d}^{\mathbf{i}}{}_{\mathbf{j}}}_{\hat{M}_d}\ d^{\mathbf{j}}_{0R} + \text{h.c.}$$

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[1] Subindex 0 labels *weak* eigenstates.

Mass diagonalisation (1)

The usual bidiagonalisation is

$$\left.\begin{array}{l}\mathcal{U}_L^{u\dagger}\hat{M}_u\hat{M}_u^\dagger\,\mathcal{U}_L^u=\mathrm{Diag}_u{}^2\\ \mathcal{U}_R^{u\dagger}\hat{M}_u^\dagger\hat{M}_u\,\mathcal{U}_R^u=\mathrm{Diag}_u{}^2\end{array}\right\}\longrightarrow\mathcal{U}_L^{u\dagger}\hat{M}_u\,\mathcal{U}_R^u=\mathrm{Diag}_u=\begin{pmatrix}m_u&&&\\&m_c&&\\&&m_t&\\&&&m_T\end{pmatrix}$$

$$\left.\begin{array}{l}\mathcal{U}_L^{d\dagger}\hat{M}_d\hat{M}_d^\dagger\,\mathcal{U}_L^d=\mathrm{Diag}_d{}^2\\ \mathcal{U}_R^{d\dagger}\hat{M}_d^\dagger\hat{M}_d\,\mathcal{U}_R^d=\mathrm{Diag}_d{}^2\end{array}\right\}\longrightarrow\mathcal{U}_L^{d\dagger}\hat{M}_d\,\mathcal{U}_R^d=\mathrm{Diag}_d=\begin{pmatrix}m_d&&\\&m_s&\\&&m_b\end{pmatrix}$$

Mass diagonalisation (2)

With quark rotations

$$\begin{pmatrix} u^{\mathbf{i}}_{0R} \\ T_{0R} \end{pmatrix} = \mathcal{U}^u_R \begin{pmatrix} u_R \\ c_R \\ t_R \\ T_R \end{pmatrix} \quad ; \quad \begin{pmatrix} u^{\mathbf{i}}_{0L} \\ T_{0L} \end{pmatrix} = \mathcal{U}^u_L \begin{pmatrix} u_L \\ c_L \\ t_L \\ T_L \end{pmatrix} \qquad \mathcal{U}^u_L, \mathcal{U}^u_R \quad 4 \times 4 \text{ unitary}$$

$$\left(d^{\mathbf{i}}_{0R} \right) = \mathcal{U}^d_R \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix} \quad ; \quad \left(d^{\mathbf{i}}_{0L} \right) = \mathcal{U}^d_L \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} \qquad \mathcal{U}^d_L, \mathcal{U}^d_R \quad 3 \times 3 \text{ unitary}$$

Fermion couplings to gauge fields (1)

- Charged currents

$$\mathscr{L}_{CC} = \frac{g}{\sqrt{2}}(W_\mu^\dagger J_W^\mu + \text{h.c.})$$

$$J_W^\mu = \bar{u}_{0L\mathbf{i}}\ \gamma^\mu\ d_{0L}^{\mathbf{i}}$$

in the mass basis

$$J_W^\mu = \bar{u}_{La}\ \gamma^\mu\ V^a{}_b\ d_L^b, \quad a = 1,2,3,4;\ b = 1,2,3$$

- The CKM matrix is

$$V^a{}_b = (\mathcal{U}_L^{u\dagger})^a{}_{\mathbf{j}}(\mathcal{U}_L^d)^{\mathbf{j}}{}_b, \quad \mathbf{j} = 1,2,3$$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \\ V_{Td} & V_{Ts} & V_{Tb} \end{pmatrix}$$

It has orthonormal columns

The CKM matrix

- $V^a{}_b = (\mathcal{U}_L^{u\dagger})^a{}_{\mathbf{j}} (\mathcal{U}_L^d)^{\mathbf{j}}{}_b, \quad \mathbf{j} = 1, 2, 3$
- Explicitely, the mixing matrix is embedded in a unitary matrix $V \hookrightarrow U$

$$U = \mathcal{U}_L^{u\dagger} \begin{pmatrix} \mathcal{U}_L^d & 0 \\ 0 & 1 \end{pmatrix} = \left(\begin{array}{ccc|c} V_{ud} & V_{us} & V_{ub} & U_{u4} \\ V_{cd} & V_{cs} & V_{cb} & U_{c4} \\ V_{td} & V_{ts} & V_{tb} & U_{t4} \\ V_{Td} & V_{Ts} & V_{Tb} & U_{T4} \end{array}\right) \qquad 4 \times 4 \text{ unitary}$$

- From unitarity of U

$$(VV^\dagger)^\alpha{}_\beta = V^\alpha{}_a V^{\dagger a}{}_\beta = \delta^\alpha_\beta - U_{\alpha 4} U^*_{\beta 4}$$

$$(V^\dagger V)^a{}_b = V^{\dagger a}{}_\alpha V^\alpha{}_b = \delta^a_b$$

Fermion couplings to gauge fields (2)

- Neutral currents (A)

$$\mathscr{L}_{em} = e\ A_\mu\ J^\mu_{em}$$

with

$$J^\mu_{em} = \frac{2}{3}\,\bar{u}_{0L\mathbf{i}}\ \gamma^\mu\ u^{\mathbf{i}}_{0L} + \frac{2}{3}\,\bar{u}_{0R\mathbf{i}}\ \gamma^\mu\ u^{\mathbf{i}}_{0R} + \\ -\frac{1}{3}\,\bar{d}_{0L\mathbf{i}}\ \gamma^\mu\ d^{\mathbf{i}}_{0L} - \frac{1}{3}\,\bar{d}_{0R\mathbf{i}}\ \gamma^\mu\ d^{\mathbf{i}}_{0R} + \\ \frac{2}{3}\,\bar{T}_{0L}\ \gamma^\mu\ T_{0L} + \frac{2}{3}\,\bar{T}_{0R}\ \gamma^\mu\ T_{0R}$$

remains diagonal, as it should, in the mass basis

$$J^\mu_{em} = \frac{2}{3}\ \bar{u}_a\ \gamma^\mu\ u^a - \frac{1}{3}\ \bar{d}_b\ \gamma^\mu\ d^b, \qquad a = 1,2,3,4;\ \ b = 1,2,3$$

Fermion couplings to gauge fields (3)

- Neutral currents (Z)

$$\mathscr{L}_{NC} = \frac{g}{2c_w}\ Z_\mu\ J_Z^\mu$$

with

$$J_Z^\mu = \bar{u}_{0L\mathbf{i}}\ \gamma^\mu\ u_{0L}^{\mathbf{i}} - \bar{d}_{0L\mathbf{i}}\ \gamma^\mu\ d_{0L}^{\mathbf{i}} - 2s_w^2\ J_{em}^\mu$$

gives, in the mass basis,

$$J_Z^\mu = \bar{u}_{La}\ \gamma^\mu (VV^\dagger)^a{}_b\ u_L^b - \bar{d}_{Li}\ \gamma^\mu\ d_L^i - 2s_w^2\ J_{em}^\mu$$

$$a, b = 1, 2, 3, 4;\ i = 1, 2, 3$$

- There are FCNC couplings controlled by $(VV^\dagger)_{ij} = \delta_{ij} - U_{i4}U_{j4}^*$
- For example, the tcZ coupling is

$$\frac{g}{2c_w}\left[\bar{c}_L\gamma^\mu(-U_{c4}U_{t4}^*)t_L + \bar{t}_L\gamma^\mu(-U_{t4}U_{c4}^*)c_L\right] Z_\mu \subset \mathscr{L}_{NC}$$

while the ttZ coupling is

$$\frac{g}{c_w}\bar{t}_L\gamma^\mu(1 - |U_{t4}|^2)t_L\ Z_\mu \subset \mathscr{L}_{NC}$$

Modifications (Summary)

Most salient features of models with (just one) up vector-like quark:

- New mass eigenstate (eigenvalue m_T),
- Enlarged mixing matrix $V_{u_i d_j}$, $u_i = u, c, t, T$ and $d_j = d, s, b$ controlling charged current interactions, no 3×3 unitarity anymore,
- Couplings to the Z are modified in the up sector
  - Tree level flavour changing terms
  - Reduced flavour diagonal terms

Phase convention/Notation

With no loss of generality one can rephase

$$\arg U = \begin{pmatrix} 0 & \chi' & -\gamma & \cdots \\ \pi & 0 & 0 & \cdots \\ -\beta & \pi+\beta_s & 0 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

where

$$\beta \equiv \arg(-V_{cd}V_{cb}^{*}V_{td}^{*}V_{tb}) \qquad \gamma \equiv \arg(-V_{ud}V_{ub}^{*}V_{cd}^{*}V_{cb})$$

$$\beta_s \equiv \arg(-V_{ts}V_{tb}^{*}V_{cs}^{*}V_{cb}) \qquad \chi' \equiv \arg(-V_{cd}V_{cs}^{*}V_{ud}^{*}V_{us})$$

G.C.Branco, L.Lavoura *Phys. Lett.* **B208**, 123 (1988)

R.Aleksan, B.Kayser, D.London, *Phys. Rev. Lett.* **73**, 18 (1994), hep-ph/9403341

Observables – Shopping list (1)

- Moduli of V

$$|V_{ud}|, |V_{us}|, |V_{ub}|, |V_{cd}|, |V_{cs}|, |V_{cb}|.$$

(+ $|V_{tb}|$ from single top production)

- Tree level phase γ.

Observables – Shopping list (2)

- Mixing induced, time dependent, CP-violating asymmetries in B meson systems, $A_{J/\psi K_S} = \sin(2\bar{\beta})$ in $B_d^0 \to J/\Psi K_S$ and $A_{J/\Psi\Phi} = \sin(2\bar{\beta}_s)$ in $B_s^0 \to J/\Psi\Phi|_{CP}$.
- Additional asymmetries involving mixing and decay, like $\sin(2\bar{\alpha})$ from $B \to \pi\pi$ and $\sin(2\bar{\beta}+\gamma)$ from $B \to D\pi(\rho)$.
- Mass differences ΔM_{B_d}, ΔM_{B_s}, of the eigenstates of the effective Hamiltonians controlling B_d^0–$\bar{B}_d^0$ and B_s^0–$\bar{B}_s^0$ mixings.
- Width differences $\Delta\Gamma_d/\Gamma_d$, $\Delta\Gamma_s$, of the eigenstates of the mentioned effective Hamiltonians, related to Re $\left(\Gamma_{12}^{B_q}/M_{12}^{B_q}\right)$, $q = d, s$.
- Charge/semileptonic asymmetries A_{SL}^b, A_{SL}^d, A_{SL}^s, controlled by Im $\left(\Gamma_{12}^{B_q}/M_{12}^{B_q}\right)$, $q = d, s$

A. Lenz, U. Nierste *JHEP* **0706**, 072 (2007), hep-ph/0612167

Observables – Shopping list (3)

- Neutral kaon CP-violating parameters ϵ_K and ϵ'/ϵ_K

E. Pallante, A. Pich, *Phys. Rev. Lett.* **84**, 2568 (2000), hep-ph/9911233

Nucl. Phys. **B617**, 441 (2001), hep-ph/0105011

A. Buras, M. Jamin, *JHEP* **01**, 048 (2004), hep-ph/0306217

A. Buras, D. Guadagnoli, *Phys. Rev.* **78**, 033005 (2008), hep-ph/0805.3887

A. Buras, D. Guadagnoli, G. Isidori *Phys. Lett.* **688**, 309 (2010), arXiv:1002.3612

- Branching ratios of representative rare K and B decays such as $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$, $(K_L \to \mu\bar{\mu})_{SD}$, $B \to X_s\gamma$, $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$

V. Cirigliano, G. Ecker et al. *Rev. Mod. Phys.* **84**, 399 (2012), arXiv:1107.6001

FlaviaNet WG on Kaon Decays, arXiv:0801.1817

A. Buras, M. Gorbahn, U. Haisch, U. Nierste, *Phys. Rev. Lett.* **95**, 261805 (2005),

F. Mescia, C. Smith, *Phys. Rev.* **D76**, 034017 (2007), arXiv:0705.2025

… ,…

Observables – Shopping list (4)

- Electroweak oblique parameter T, S (secondary rôle)

L. Lavoura, J.P. Silva, *Phys. Rev.* **D47**, 1117 (1993)

...

J. Alwall *et al.*, *Eur. Phys. J. C* **C49**, 791 (2007), hep-ph/0607115

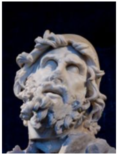
I.Picek, B.Radovcic, *Phys. Rev.* **D78**, 015014 (2008), arXiv:0804.2216

- Tree level Z-mediated rare top decays $t \to cZ$, $t \to uZ$.
- Tree level Z-mediated D^0–$\bar{D}^0$.

Observables – Summary & values

Observable	Exp. Value	Observable	Exp. Value
$\lvert V_{ud}\rvert$	0.97425 ± 0.00022	$\lvert V_{us}\rvert$	0.2252 ± 0.0009
$\lvert V_{cd}\rvert$	0.230 ± 0.011	$\lvert V_{cs}\rvert$	1.023 ± 0.036
$\lvert V_{ub}\rvert$	0.00375 ± 0.00040	$\lvert V_{cb}\rvert$	0.041 ± 0.001
$A_{J/\psi K_S} = \sin 2\bar{\beta}$	0.68 ± 0.02	$\Delta M_{B_d} (\times \text{ ps})$	0.508 ± 0.004
$A_{J/\Psi\Phi} = \sin 2\beta_s$	0.01 ± 0.07	$\Delta M_{B_s} (\times \text{ ps})$	17.725 ± 0.049
γ	$(68 \pm 8)^\circ \mod 180^\circ$	$\sin(2\bar{\alpha})$	0.00 ± 0.15
$\sin(2\beta + \gamma)$	1.00 ± 0.16	$\cos(2\beta)$	0.87 ± 0.13
$\Delta\Gamma_s$ (ps)	0.091 ± 0.008	$\Delta\Gamma_d$ (ps)	-0.011 ± 0.014
A^d_{SL}	0.0003 ± 0.0023	A^s_{SL}	-0.0032 ± 0.0052
A^b_{SL}	-0.00496 ± 0.00169		
$\epsilon_K (\times 10^3)$	2.228 ± 0.011	$\epsilon'/\epsilon_K (\times 10^3)$	1.67 ± 0.16
x_D	$0.0041\,^{+0.0015}$		
$\text{Br}(K^+ \to \pi^+ \nu\bar{\nu})$	$(1.73\,^{+1.15}_{-1.05}) \times 10^{-10}$	$\text{Br}(K_L \to \mu\bar{\mu})$	$(6.84 \pm 0.11) \times 10^{-9}$
$\text{Br}(K_L \to \pi^0 \nu\bar{\nu})$	$< 2.6 \times 10^{-8}$	$\text{Br}(B \to X_s\gamma)$	$(3.56 \pm 0.25) \times 10^{-4}$
$\text{Br}(B_s \to \mu^+\mu^-)$	$(2.8 \pm 0.7) \times 10^{-9}$	$\text{Br}(B_d \to \mu^+\mu^-)$	$(3.90 \pm 1.5) \times 10^{-10}$
$\text{Br}(t \to cZ)$	$< 10^{-3}$	$\text{Br}(t \to uZ)$	$< 10^{-3}$
ΔT	0.05 ± 0.12	ΔS	0.02 ± 0.11

Flavour?



Odysseus (Ulysses)

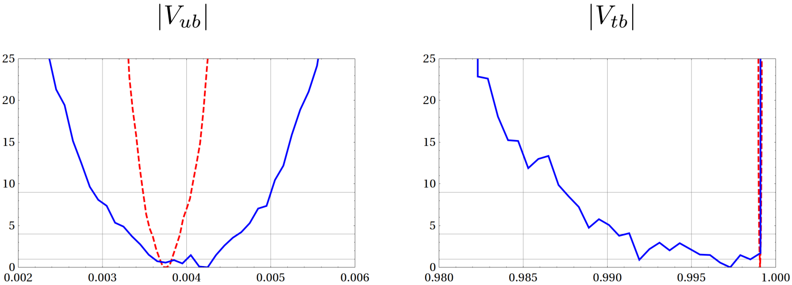
- The Iliad
- The Odyssey

New Physics siren songs

Claim the (BSM) “Physics Kingdom”

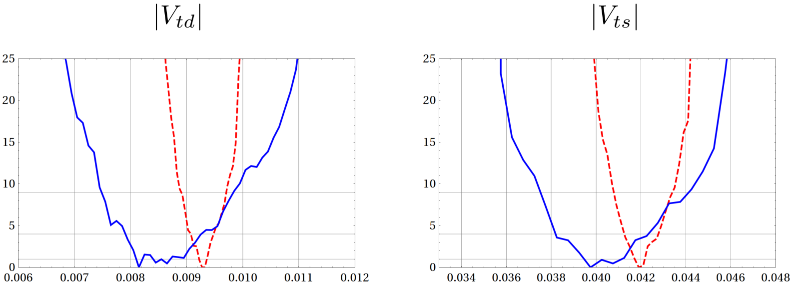
DISCLAIMER: preliminary plots

CKM – Moduli (1)



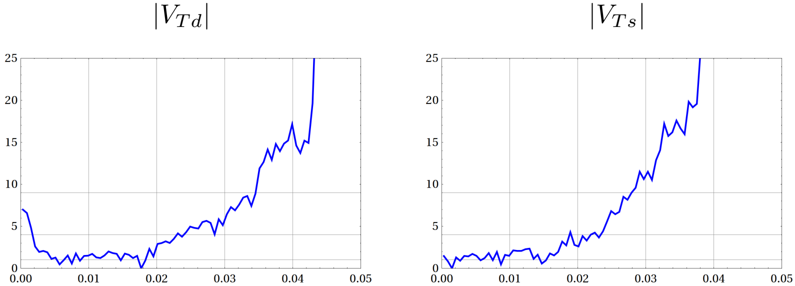
$\Delta\chi^2$ profile, – UpVL, – SM

CKM – Moduli (2)



$\Delta\chi^2$ profile, – UpVL, – SM

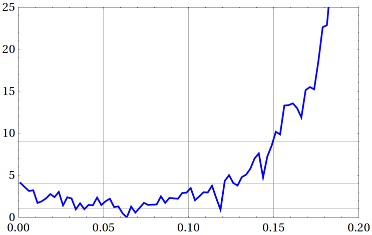
CKM – Moduli (3)



$\Delta\chi^2$ profile, – UpVL

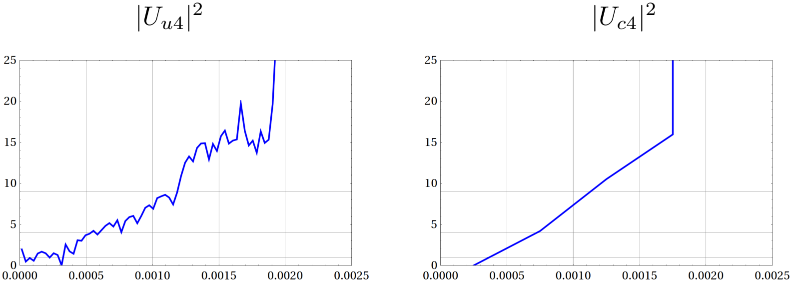
CKM – Moduli (4)

$|V_{Tb}|$



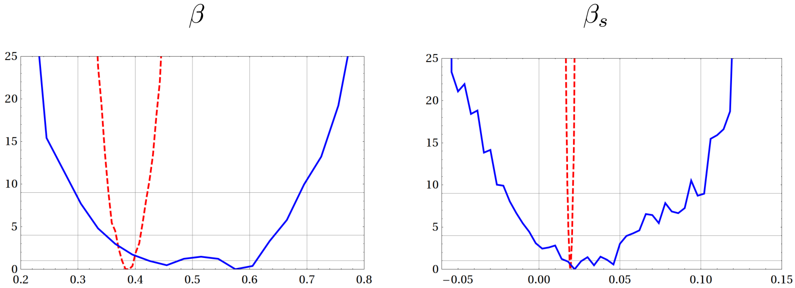
$\Delta\chi^2$ profile, – UpVL

3×3 unitarity deviations



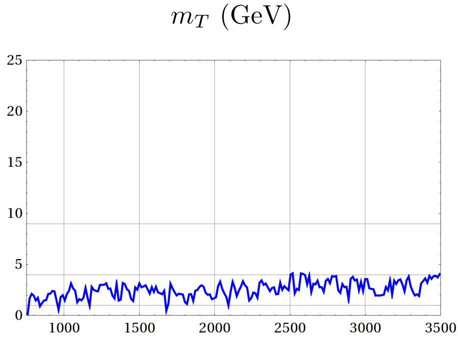
$\Delta\chi^2$ profile, – UpVL

CKM – Phases



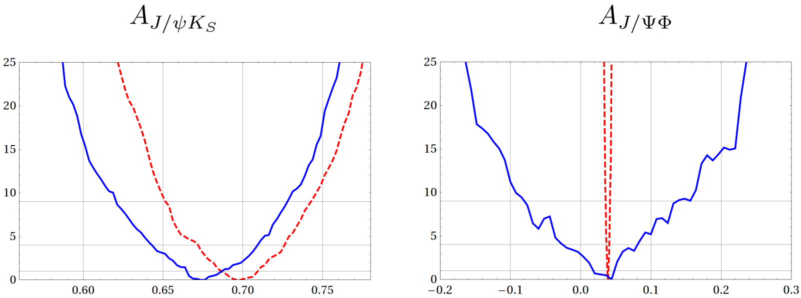
$\Delta\chi^2$ profile, – UpVL, – SM

Mass of the new quark



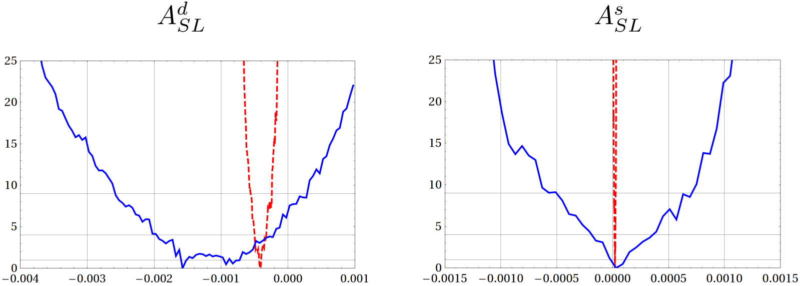
$\Delta\chi^2$ profile, – UpVL

CP Asymmetries



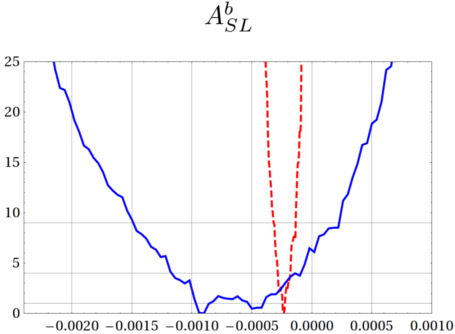
$\Delta\chi^2$ profile, – UpVL, – SM

Semileptonic asymmetries (1)



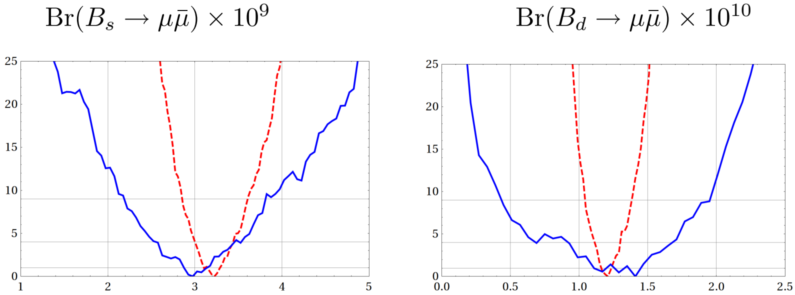
$\Delta\chi^2$ profile, – UpVL, – SM

Semileptonic asymmetries (2)



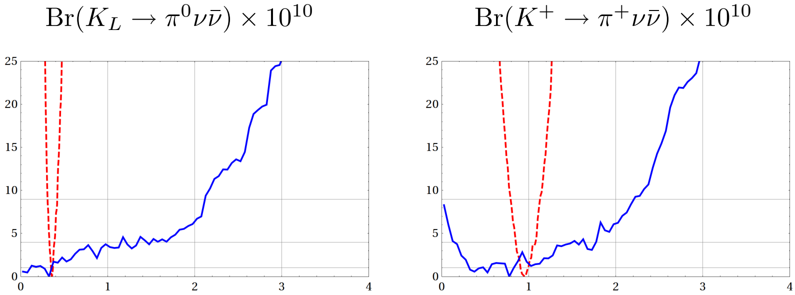
$\Delta\chi^2$ profile, – UpVL, – SM

Rare B decays



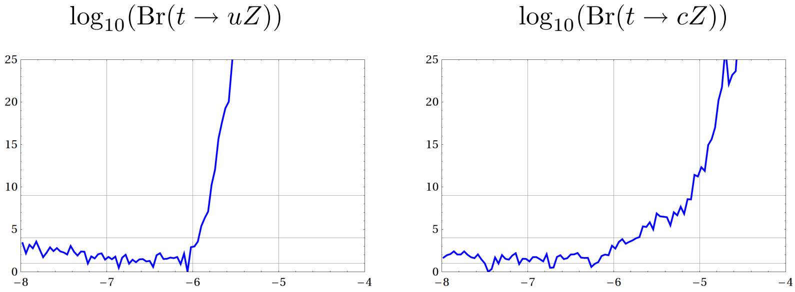
$\Delta\chi^2$ profile, – UpVL, – SM

Rare kaon decays



$\Delta\chi^2$ profile, – UpVL, – SM

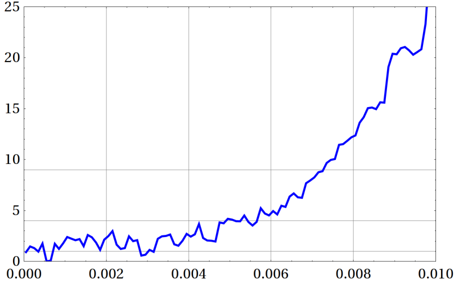
Rare top decays



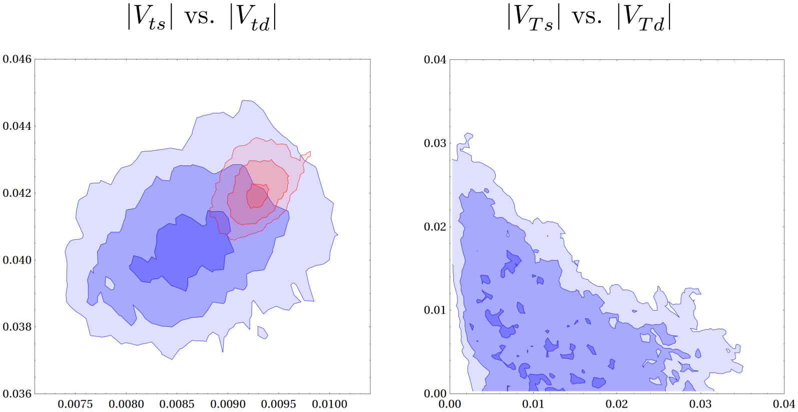
$\Delta\chi^2$ profile, – UpVL

Charm mixing

D^0–$\bar{D}^0$ mixing, x_D

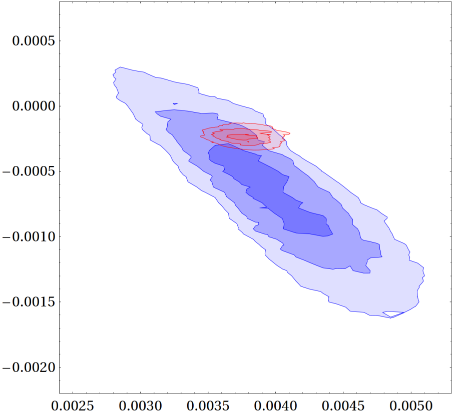


$\Delta\chi^2$ profile, – UpVL



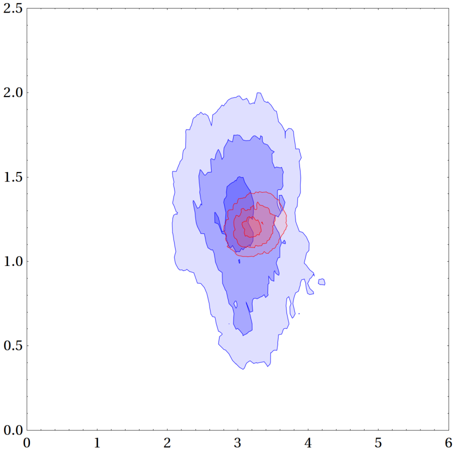
$\Delta\chi^2$ profile (regions), – UpVL, – SM

A^b_{SL} vs. $|V_{ub}|$



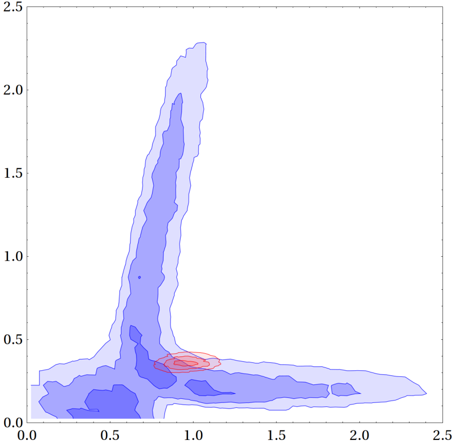
$\Delta\chi^2$ profile (regions), – UpVL, – SM

$\text{Br}(B_d \to \mu\bar{\mu}) \cdot 10^{10}$ vs. $\text{Br}(B_s \to \mu\bar{\mu}) \cdot 10^{9}$



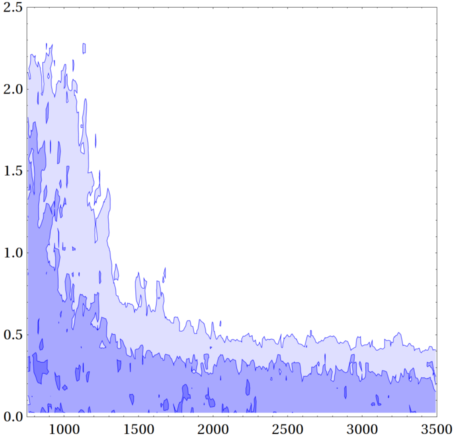
$\Delta\chi^2$ profile (regions), – UpVL, – SM

$\mathrm{Br}(K_L \to \pi^0 \nu \bar{\nu}) \cdot 10^{10}$ vs. $\mathrm{Br}(K^+ \to \pi^+ \nu \bar{\nu}) \cdot 10^{10}$



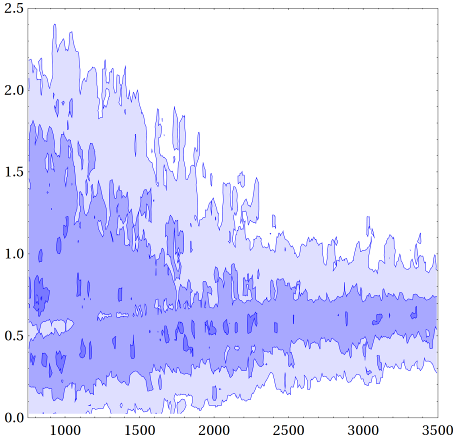
$\Delta\chi^2$ profile (regions), – UpVL, – SM

$$\mathrm{Br}(K_L \to \pi^0 \nu\bar{\nu}) \cdot 10^{10} \text{ vs. } m_T$$

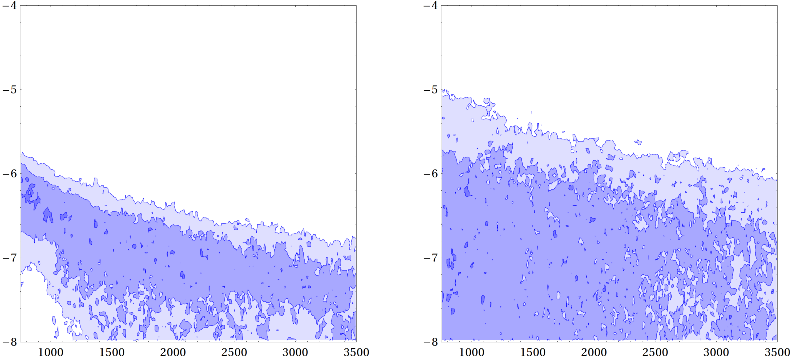


$\Delta\chi^2$ profile (regions), – UpVL

$\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu}) \cdot 10^{10}$ vs. m_T



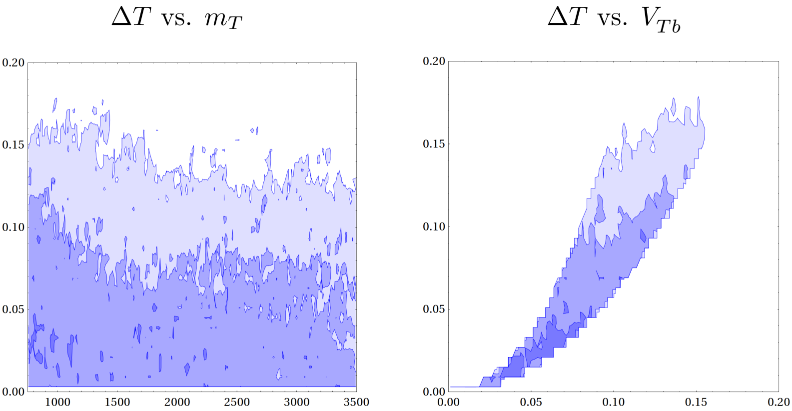
$\Delta\chi^2$ profile (regions), – UpVL



$\log_{10}(\mathrm{Br}(t \to uZ))$ vs. m_T

$\log_{10}(\mathrm{Br}(t \to cZ))$ vs. m_T

$\Delta\chi^2$ profile (regions), – UpVL

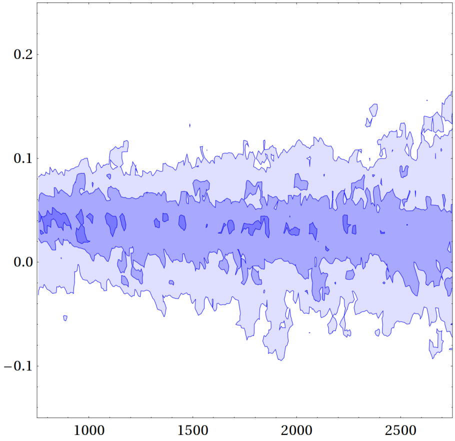


ΔT vs. m_T

ΔT vs. V_{Tb}

$\Delta\chi^2$ profile (regions), – UpVL

$A_{J/\Psi\Phi}$ vs. m_T



$\Delta\chi^2$ profile (regions), – UpVL

Conclusions

- Rich phenomenology
- Room from deviations from SM expectations, within experimental reach
- Importance of correlations
- (Decoupling regime)

Remember…

&

Direct searches + patterns of SM deviations