Updated Phenomenology of Vector-Like Quark models: preliminary results

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Based on ongoing work done in collaboration with:
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Outline of the talk

The basic framework

Extensions of the Standard Model with

- The same gauge group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$,
- An enlarged matter content through the inclusion of weak isospin singlet fermions

$$T^i_L,\ T^i_R \sim (3, 1, 4/3) \qquad B^j_L,\ B^j_R \sim (3, 1, -2/3)$$

- N.B. Although leptons can be included too, we only consider quarks in the following

New terms in $\mathscr{L}$

In addition to the usual Yukawa terms,

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

- if we add an up vectorlike quark, additional terms:

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

- if we add a down vectorlike quark, additional terms:

$$\mathscr{L}_B = -\bar{q}_{0L\mathbf{i}}\ \Phi\ Y^{\mathbf{i}}_B\ B_{0R} - \bar{B}_{0L}\ y_{B\mathbf{i}}\ d^{\mathbf{i}}_{0R} - M_B\ \bar{B}_{0L}\ B_{0R} + \text{h.c.}$$

Mass diagonalisation (1)

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

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

The usual bidiagonalisation is

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

$$\left.\begin{matrix}\mathcal{U}_L^{d\dagger}M_dM_d^\dagger\,\mathcal{U}_L^d = {\text{Diag}_d}^2\\ \mathcal{U}_R^{d\dagger}M_d^\dagger M_d\,\mathcal{U}_R^d = {\text{Diag}_d}^2\end{matrix}\right\}\longrightarrow \mathcal{U}_L^{d\dagger}M_d\,\mathcal{U}_R^d = \text{Diag}_d = \begin{pmatrix}m_d & & \\ & m_s & \\ & & m_b\end{pmatrix}$$

Mass diagonalisation (2)

Through quark rotations

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

$\mathcal{U}^u_L, \mathcal{U}^u_R$ 4×4 unitary

$$\begin{pmatrix} d^{\mathbf{i}}_{0R} \end{pmatrix} = \mathcal{U}^d_R \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix} \quad ; \quad \begin{pmatrix} d^{\mathbf{i}}_{0L} \end{pmatrix} = \mathcal{U}^d_L \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

$\mathcal{U}^d_L, \mathcal{U}^d_R$ 3×3 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

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

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

Fermion couplings to gauge fields (2)

- Neutral currents (A)

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

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)

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

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,

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

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

Fermion couplings to gauge fields (4)

Explicitely, the mixing matrix is embedded in a unitary matrix $V \hookrightarrow U$

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

The FCNC couplings are thus controlled by

$$(VV^\dagger)_{ij} = \delta_{ij} - U_{i4}U^*_{j4}$$

For example, the tcZ coupling is

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

while the ttZ coupling is

$$\frac{g}{\cos\theta_W}\bar{t}_L\gamma^\mu(1-|U_{t4}|^2)t_L \; Z_\mu \subset \mathscr{L}_{\psi\psi Z}$$

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

Summary of this (micro) introduction to models with (up) vectorlike quarks:

- 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,
- Additional contributions to loop amplitudes involving **up** quarks,
- Presence of tree level FCNC only in the up sector, naturally suppressed if we think in terms of "Mixing $\sim \frac{m_q}{M}$", seesaw-like.

Motivations

The Standard Model shows an outstanding consistency for an impressive list of flavour-related observables, in terms of a reduced number of parameters. . .
nevertheless, the last few years have brought exciting news with different "lifetimes"

- Tensions in the bd sector,
- Time-dependent, mixing induced, CP violation in $B_s \to J/\Psi\Phi$, large value measured at the Tevatron experiments, small value measured at LHCb with smaller uncertainty,
- Same sign dimuon asymmetry A_{sl}^{b} in B decays measured at Tevatron (D0), around the 3σ level for SM expectations,
- D^0–$\bar{D}^0$ mixing at B factories, recent charm excitment,
- Hints from $b \to s$ penguin transitions.

Expectations

Can we expect some help from (up) vector-like quarks?

- Relaxing the tensions in the *bd* sector,
- The new contributions to $M_{12}^{B_s}$ (quarks T running in the box) may modify the B_s^0–$\bar{B}_s^0$ mixing phase,
- Deviations from 3×3 unitarity to modify $\Gamma_{12}^{B_q}$ and address the dimuon asymmetry,
- Rare decays,
- (Short distance contributions to D^0–$\bar{D}^0$ mixing)

Observables – Shopping list (1)

- Moduli of V

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

- Tree level phase γ.
- Suppressed tree level decay $B^+ \to \tau^+\nu$.

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 $\mathrm{Re}\left(\Gamma_{12}^{B_q}/M_{12}^{B_q}\right)$, $q = d, s$.
- Charge/semileptonic asymmetries A_{sl}^b, A_{sl}^d, A_{sl}^s, controlled by $\mathrm{Im}\left(\Gamma_{12}^{B_q}/M_{12}^{B_q}\right)$, $q = d, s$

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 $K^+ \to \pi^+ \nu\bar{\nu}$, $K^0 \to \pi^0 \nu\bar{\nu}$, $K_L \to \mu^+\mu^-$, $B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$ and $B_s \to \mu^+\mu^-$

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

$\ldots, \ldots$

Observables – Shopping list (4)

- Electroweak oblique parameter T, which encodes violation of weak isospin; the S parameter plays no significant rôle, the U parameter is completely irrelevant.

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

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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 – The experimental 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
$\lvert V_{ub}\rvert$	0.00389 ± 0.00044	$\lvert V_{cb}\rvert$	0.0406 ± 0.0013
$A_{J/\psi K_S}(= \sin 2\beta)$	0.68 ± 0.02	$\Delta M_{B_d}(\times \text{ ps})$	0.508 ± 0.004
$A_{J/\Psi\Phi}(= \sin 2\beta_s)$	-0.03 ± 0.175	$\Delta M_{B_s}\ (\times \text{ ps})$	17.725 ± 0.049
γ	$(77 \pm 14)^\circ$ mod 180°	$\sin(2\bar{\alpha})$	0.00 ± 0.15
$\sin(2\beta + \gamma)$	1.00 ± 0.16	$\cos(2\beta)$	1.35 ± 0.34
ΔT	0.13 ± 0.10	ΔS	0.07 ± 0.10
x_D	0.008 ± 0.002		
$\epsilon_K(\times 10^3)$	2.228 ± 0.011	$\epsilon'/\epsilon_K(\times 10^3)$	1.67 ± 0.16
$\text{Br}(K^+ \to \pi^+\nu\bar{\nu})$	$(1.73\,^{+1.15}_{-1.05}) \times 10^{-10}$	$\text{Br}(K_L \to \mu\bar{\mu})$	$(6.84 \pm 0.11) \times 10^{-9}$
$\text{Br}(B \to X_s\ell^+\ell^-)$	$(1.60 \pm 0.51) \times 10^{-6}$	$\text{Br}(B \to X_s\gamma)$	$(3.56 \pm 0.25) \times 10^{-4}$
$\text{Br}(t \to cZ)$	$< 4 \times 10^{-2}$	$\text{Br}(t \to uZ)$	$< 4 \times 10^{-2}$
$\Delta\Gamma_s\ (\times \text{ ps})$	0.123 ± 0.030	$\Delta\Gamma_d/\Gamma_d$	-0.017 ± 0.021
A^d_{sl}	-0.0030 ± 0.0078	A^s_{sl}	-0.0017 ± 0.0091
A^b_{sl}	-0.00787 ± 0.00196	$\text{Br}(B^+ \to \tau^+\nu)$	$(16.8 \pm 3.1) \times 10^{-5}$

Table: Experimental values of observables.

Observables – A closer look – ΔM_{B_d}, ΔM_{B_s} (1)

- CKM elements: $V_{tq}^* V_{tb}$, $V_{Tq}^* V_{Tb}$
- Loop functions $S_0(x_t), S_0(x_t, x_T), S_0(x_T)$ $(x_q \equiv m_q^2/M_W^2)$:

$$
\begin{aligned}
S_0(x) &= \frac{x^3 - 11x^2 + 4x}{4(1-x)^2} - \frac{3\; x^3 \ln x}{2(1-x)^3} \\
S_0(x,y) &= -\frac{3\; x\; y}{4(1-x)(1-y)} \\
&\quad + x\; y\; \frac{x^2 - 8x + 4}{4(x-1)^2(x-y)} \ln x + \; x\; y\; \frac{y^2 - 8y + 4}{4(y-1)^2(y-x)} \ln y
\end{aligned}
$$

- Sensitivity to $2|M_{12}^{B_q}| = \Delta M_{B_q}$

$$
\begin{aligned}
M_{12}^{B_q} \propto\; & S_0(x_t)(V_{tq}^* V_{tb})^2 \\
& + 2S_0(x_t, x_T)(V_{tq}^* V_{tb} V_{Tq}^* V_{Tb}) + S_0(x_T)(V_{Tq}^* V_{Tb})^2
\end{aligned}
$$

Observables – A closer look – ΔM_{B_d}, ΔM_{B_s} (2)

- Loop function: $S_0(x_t) \sim 2.34$
- CKM elements, SM:

$$|V_{td}^* V_{tb}| \sim 8.74 \times 10^{-3}\,,$$

$$|V_{ts}^* V_{tb}| \sim 4.09 \times 10^{-2}\,,$$

- New loop functions

$$S_0(x_T) \in [11.15; 40.16]\,, \quad S_0(x_T, x_t) \in [4.34; 5.92]\,,$$

for $m_T \in [450; 950]\,\mathrm{GeV}$.

Observables – A closer look – $A_{J/\psi K_S}$, $A_{J/\Psi\Phi}$

$A_{J/\psi K_S}$: the mixing induced, time dependent, CP-violating asymmetry in $B_d^0 \to J/\Psi K_S$

- Same CKM elements and loop functions as ΔM_{B_d} but…
- …sensitivity to $\sin(\arg M_{12}^{B_d}) = A_{J/\psi K_S}$

$A_{J/\Psi\Phi}$: the mixing induced, time dependent, CP-violating asymmetry in $B_s^0 \to J/\Psi\Phi|_{CP}$

- Same CKM elements and loop functions as ΔM_{B_s} but…
- …sensitivity to $\sin(-\arg M_{12}^{B_s}) = A_{J/\Psi\Phi}$

Observables – A closer look – $\Gamma_{12}^{B_q}$, $\Delta\Gamma_q$ and A_{sl}^q (1)

- CKM elements: $V_{uq}^* V_{ub}$, $V_{cq}^* V_{cb}$
- Sensitivity to real, imaginary parts of $\Gamma_{12}^{B_q}$

$$\frac{\Gamma_{12}^{B_q}}{M_{12}^{B_q}} = \frac{(\mathrm{Const})_q}{M_{12}^{B_q}} \times \left[C_{uu}(V_{uq}^* V_{ub})^2 + C_{uc}(V_{uq}^* V_{ub} V_{cq}^* V_{cb}) + C_{cc}(V_{cq}^* V_{cb})^2\right]$$

$$\text{with} \quad (\mathrm{Const})_q = \frac{G_F^2 M_W^2 B_{B_q} f_{B_q}^2 m_{B_q} \eta_B S_0(x_t)}{12\pi^2}$$

$$A_{sl}^q = \mathrm{Im}\left[\frac{\Gamma_{12}^{B_q}}{M_{12}^{B_q}}\right], \qquad \Delta\Gamma_q = -\Delta M_{B_q}\,\mathrm{Re}\left[\frac{\Gamma_{12}^{B_q}}{M_{12}^{B_q}}\right].$$

Observables – A closer look – $\Gamma_{12}^{B_q}$, $\Delta\Gamma_q$ and A_{sl}^q (2)

- Could be rewritten using experimental information on $M_{12}^{B_q}$
- For example, $M_{12}^{B_d} = \frac{1}{2}\Delta M_{B_d}\, e^{i2\bar{\beta}}$ an so

$$\frac{\Gamma_{12}^{B_q}}{M_{12}^{B_q}} = \frac{2(\mathrm{Const})_q}{\Delta M_{B_d}} \times$$
$$[C_{uu}|V_{uq}^* V_{ub}|^2 e^{-i(\gamma+\bar{\beta})} + C_{uc}|V_{uq}^* V_{ub} V_{cq}^* V_{cb}| e^{-i(2\bar{\beta}+\gamma)} +$$
$$C_{cc}|V_{cq}^* V_{cb}|^2 e^{-i2\bar{\beta}}]$$

Observables – A closer look – $\Gamma_{12}^{B_q}$, $\Delta\Gamma_q$ and A_{sl}^q (3)

- The constants:

$$C_{uu} \sim -52\,,\;\; C_{uc} \sim 92\,,\;\; C_{cc} \sim -40$$

$$|C_{uu} + C_{uc} + C_{cc}| \ll |C_{uu}|, |C_{uc}|, |C_{cc}|$$

- In the SM (3×3 unitary mixing),
  - Significant cancellations for $q = d$ because both terms, $V_{ud}^* V_{ub}$ and $V_{cd}^* V_{cb}$, are of order λ^3 (the usual unitarity triangle)
  - $\Rightarrow$ small A_{sl}^d, $\Delta\Gamma_d$.
  - For $q = s$, $V_{us}^* V_{ub}$ is $\mathcal{O}(\lambda^4)$ while $V_{cs}^* V_{cb}$ is $\mathcal{O}(\lambda^2)$ (squashed $\mathcal{O}(\lambda^2)$, $\mathcal{O}(\lambda^2)$, $\mathcal{O}(\lambda^4)$ unitarity triangle)
  - $\Rightarrow$ “not so small” $\Delta\Gamma_s$ but small A_{sl}^s because $\arg(V_{cs}^* V_{cb}/(V_{ts}^* V_{tb}))$ is $\mathcal{O}(\lambda^2)$.
- Potential room to change the picture!

Observables – A closer look – ϵ_K

- CKM elements: $V_{cd}^{*}V_{cs}$, $V_{td}^{*}V_{ts}$, $V_{Td}^{*}V_{Ts}$
- Loop functions: $S_0(x_c)$, $S_0(x_c,x_t)$, $S_0(x_c,x_T)$, $S_0(x_t)$, $S_0(x_t,x_T)$, $S_0(x_T)$
- Sensitivity to $\epsilon_K \propto \mathrm{Im}\left[M_{12}^{K}\right]$

$$
\begin{aligned}
M_{12}^{K} \propto \eta_{cc}S_0(x_c)(V_{cd}^{*}V_{cs})^2 + \eta_{tt}S_0(x_t)(V_{td}^{*}V_{ts})^2 \\
+ 2\eta_{ct}S_0(x_c,x_t)(V_{cd}^{*}V_{cs}V_{td}^{*}V_{ts}) \\
+ 2\eta_{tT}S_0(x_t,x_T)(V_{td}^{*}V_{ts}V_{Td}^{*}V_{Ts}) \\
+ 2\eta_{cT}S_0(x_c,x_T)(V_{cd}^{*}V_{cs}V_{Td}^{*}V_{Ts}) \\
+ \eta_{TT}S_0(x_T)(V_{Td}^{*}V_{Ts})^2
\end{aligned}
$$

Observables – A closer look – ϵ'/ϵ_K

- CKM elements: $V_{td}V_{ts}^*$, $V_{Td}V_{Ts}^*$
- Loop functions: $X_0(x_t)$, $Y_0(x_t)$, $Z_0(x_t)$, $E_0(x_t)$, $X_0(x_T)$, $Y_0(x_T)$, $Z_0(x_T)$, $E_0(x_T)$
- Sensitivity to $\epsilon'/\epsilon_K \propto \mathrm{Im}\,[V_{td}V_{ts}^*]f(x_t) + \mathrm{Im}\,[V_{Td}V_{Ts}^*]f(x_T)$

$$\text{where} \quad f(x) = c_X X_0(x) + c_Y Y_0(x) + c_Z Z_0(x) + c_E E_0(x)$$

Observables – A closer look – $\mathrm{Br}(B^+ \to \tau^+\nu)$

- Sensitive to $|V_{ub}|$

$$\mathrm{Br}(B^+ \to \tau^+\nu) = \tau_{B^+} \frac{G_F^2 m_\tau^2 m_{B^+} f_{B_d}}{8\pi} \left(1 - \frac{m_\tau^2}{m_{B^+}^2}\right)^2 \times |V_{ub}|^2$$

Observables – A closer look – $\mathrm{Br}(K^+ \to \pi^+ \nu \bar{\nu})$

- CKM elements: $V_{td}V_{ts}^*$, $V_{Td}V_{Ts}^*$
- Loop functions: $X_0(x_t)$, $X_0(x_T)$

$$X_0(x) = \frac{x}{8}\left(-\frac{2+x}{1-x} + \frac{3x-6}{(1-x)^2}\ln x\right)$$

- Sensitivity to
  $\mathrm{Br} \propto |\text{Charm terms } + V_{td}V_{ts}^*\eta_t X_0(x_t) + V_{Td}V_{Ts}^*\eta_T X_0(x_T)|^2$

Observables – A closer look – $\mathrm{Br}(K^0 \to \pi^0 \nu\bar{\nu})$

- CKM elements: $V_{td}V_{ts}^*$, $V_{Td}V_{Ts}^*$
- Loop functions: $X_0(x_t)$, $X_0(x_T)$

$$X_0(x) = \frac{x}{8}\left(-\frac{2+x}{1-x} + \frac{3x-6}{(1-x)^2}\ln x\right)$$

- Sensitivity to
  $\mathrm{Br} \propto \left(\mathrm{Im}\left[\text{Charm terms } + V_{td}V_{ts}^*\eta_t X_0(x_t) + V_{Td}V_{Ts}^*\eta_T X_0(x_T)\right]\right)^2$

Observables – A closer look – $(K_L \to \mu\bar{\mu})_{SD}$

- CKM elements: $V_{td}V_{ts}^*$, $V_{Td}V_{Ts}^*$
- Loop functions: $Y_0(x_t)$, $Y_0(x_T)$

$$Y_0(x) = \frac{x}{8}\left(\frac{4-x}{1-x} + \frac{3x}{(1-x)^2}\ln x\right)$$

- Sensitivity to

$$\mathrm{Br}_{SD} \propto Y_0(x_t)\mathrm{Re}\left[V_{td}V_{ts}^*\right] + Y_0(x_T)\mathrm{Re}\left[V_{Td}V_{Ts}^*\right]$$

Observables – A closer look – $b \to s$ transitions

$\mathrm{Br}(B \to X_s \gamma)$ and $\mathrm{Br}(B \to X_s \ell^+ \ell^-)$

- CKM elements: $V_{ts}^* V_{tb}$, $V_{Ts}^* V_{Tb}$
- Several loop functions in different Wilson coefficients (C_7^{eff}, C_8^{eff}, C_9, C_{10})
- Sensitivity to combinations $V_{ts}^* V_{tb} f_{C_i}(x_t) + V_{Ts}^* V_{Tb} f_{C_i}(x_T)$

Observables – A closer look – $\mathrm{Br}(B_s^0 \to \mu^+\mu^-)$

- CKM elements: $V_{td}V_{ts}^*$, $V_{Td}V_{Ts}^*$
- Loop functions: $Y_0(x_t)$, $Y_0(x_T)$

$$Y_0(x) = \frac{x}{8}\left(\frac{4-x}{1-x} + \frac{3x}{(1-x)^2}\ln x\right)$$

- Sensitivity to $\mathrm{Br} \propto |V_{tb}V_{ts}^*\eta_{Y_t}Y_0(x_t) + V_{Tb}V_{Ts}^*\eta_{Y_T}Y_0(x_T)|^2$

Observables – A closer look – ΔT

- CKM elements: V_{tq}, V_{Tq} + U_{34}, U_{44}
- Loop function: $f_T(x,y)$

$$f_T(x,y) = x + y - 2\frac{xy}{x-y}\ln\frac{x}{y}$$

- Sensitivity to

$$\sum_{q_u,q_d} |V_{q_u q_d}|^2 f_T(x_{q_u}, x_{q_d}) - \sum_{i,j} |U_{i4}U_{j4}|^2 f_T(x_i, x_j)$$

Observables – D^0–$\bar{D}^0$ mixing

- We have tree level FCNC couplings

$$\mathscr{L}_{\psi\psi Z} \supset \frac{g}{2\cos\theta_W} U_{14} U_{24}^{*}\, \bar{u}_L \gamma^\mu c_L\, Z_\mu$$

- To account for the observed size of D^0–$\bar{D}^0$ without having to invoke long-distance contributions to the mixing,
  $|U_{14}U_{24}|$ has to be of order λ^5

  E.Golowich, J.Hewett, S.Pakvasa, A.A.Petrov *Phys. Rev.* **D76**, 095099 (2007), arXiv:0705.3650

- Achievable; however, this short-distance contribution to D^0–$\bar{D}^0$ mixing could be switched off (and thus long-distance contributions required)

Observables – Rare top decays

- Tree level FCNC couplings

$$\mathscr{L}_{\psi\psi Z} \supset \frac{g}{2\cos\theta_W}\left(U_{24}U_{34}^{*}\,\bar{c}_L\gamma^{\mu}t_L + U_{14}U_{34}^{*}\,\bar{u}_L\gamma^{\mu}t_L\right) Z_{\mu}\,,$$

- ... which potentially lead to rare top decays $t \to cZ$, $t \to uZ$ at rates observable at the LHC

Observables – A simple picture of tensions in *bd within the SM* (1)

N.B. $|V_{ub}|$ is $|V_{ub}| \times 10^3$ and $\mathrm{Br}(B^+ \to \tau^+\nu)$ is $\mathrm{Br}(B^+ \to \tau^+\nu) \times 10^5$

- Experimental inputs:

$$A_{J/\psi K_S} = 0.68 \pm 0.02\,,\ |V_{ub}| = 3.89 \pm 0.44\,,\ \mathrm{Br}(B^+ \to \tau^+\nu) = 16.8 \pm 3.1$$

- Values from a complete fit

$$A_{J/\psi K_S} = 0.695\,, \quad |V_{ub}| = 3.66\,, \quad \mathrm{Br}(B^+ \to \tau^+\nu) = 9.74$$

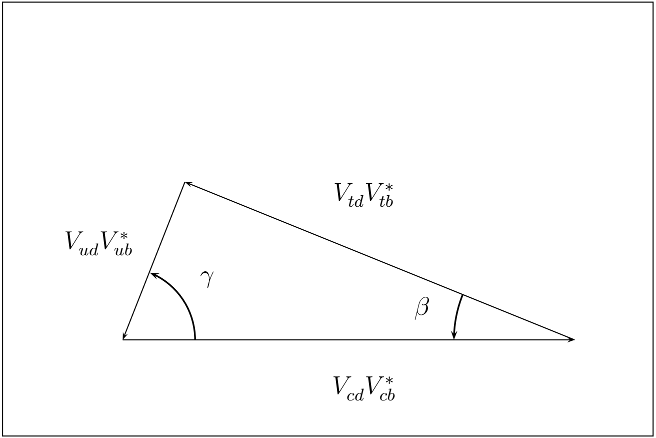
- Values from a complete fit with $A_{J/\psi K_S}$ left out

$$A_{J/\psi K_S} = 0.785\,, \quad |V_{ub}| = 4.17\,, \quad \mathrm{Br}(B^+ \to \tau^+\nu) = 12.5$$

- Values from a complete fit with $|V_{ub}|$ and $\mathrm{Br}(B^+ \to \tau^+\nu)$ left out

$$A_{J/\psi K_S} = 0.687\,, \quad |V_{ub}| = 3.61\,, \quad \mathrm{Br}(B^+ \to \tau^+\nu) = 8.93$$

Observables – A simple picture of tensions in *bd within the SM* (2)



Observables – Summary (1)

- Tree level

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} & U_{14} \\ V_{cd} & V_{cs} & V_{cb} & U_{24} \\ V_{td} & V_{ts} & V_{tb} & U_{34} \\ V_{Td} & V_{Ts} & V_{Tb} & U_{44} \end{pmatrix} \qquad + \qquad \gamma = \arg(-V_{ud}V_{ub}^{*}V_{cd}^{*}V_{cb})$$

- Kaon physics

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} & U_{14} \\ V_{cd} & V_{cs} & V_{cb} & U_{24} \\ V_{td} & V_{ts} & V_{tb} & U_{34} \\ V_{Td} & V_{Ts} & V_{Tb} & U_{44} \end{pmatrix}$$

Observables – Summary (2)

- B_d^0 physics

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} & U_{14} \\ V_{cd} & V_{cs} & V_{cb} & U_{24} \\ \color{red}{V_{td}} & V_{ts} & \color{red}{V_{tb}} & U_{34} \\ \color{red}{V_{Td}} & V_{Ts} & \color{red}{V_{Tb}} & U_{44} \end{pmatrix}$$

- B_s^0 physics

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} & U_{14} \\ V_{cd} & V_{cs} & V_{cb} & U_{24} \\ V_{td} & \color{red}{V_{ts}} & \color{red}{V_{tb}} & U_{34} \\ V_{Td} & \color{red}{V_{Ts}} & \color{red}{V_{Tb}} & U_{44} \end{pmatrix}$$

Observables – Summary (3)

- Electroweak precision (ΔT)

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} & U_{14} \\ V_{cd} & V_{cs} & V_{cb} & U_{24} \\ V_{td} & V_{ts} & V_{tb} & U_{34} \\ V_{Td} & V_{Ts} & V_{Tb} & U_{44} \end{pmatrix}$$

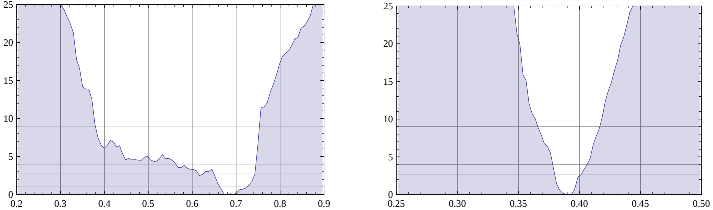
- D^0–$\bar{D}^0$ mixing, rare top decays

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} & U_{14} \\ V_{cd} & V_{cs} & V_{cb} & U_{24} \\ V_{td} & V_{ts} & V_{tb} & U_{34} \\ V_{Td} & V_{Ts} & V_{Tb} & U_{44} \end{pmatrix}$$

Method

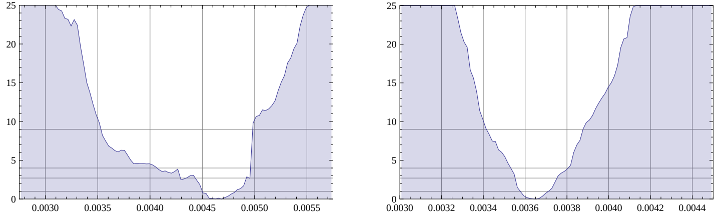
- Build a likelihood/probability function out of model parameters and constraints
- Use it to conduct an exploration of the parameter space
- Produce bayesian PDFs and likelihood profiles

Preliminary plots: the phase β



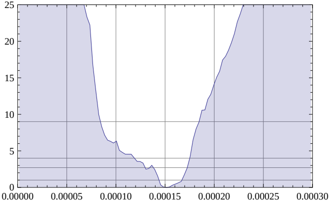
$-2\ln(\mathcal{L})$, Vector-like quark model vs. Standard Model

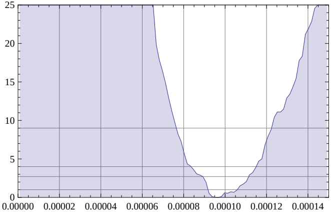
Preliminary plots: $|V_{ub}|$



$-2\ln(\mathcal{L})$, Vector-like quark model vs. Standard Model

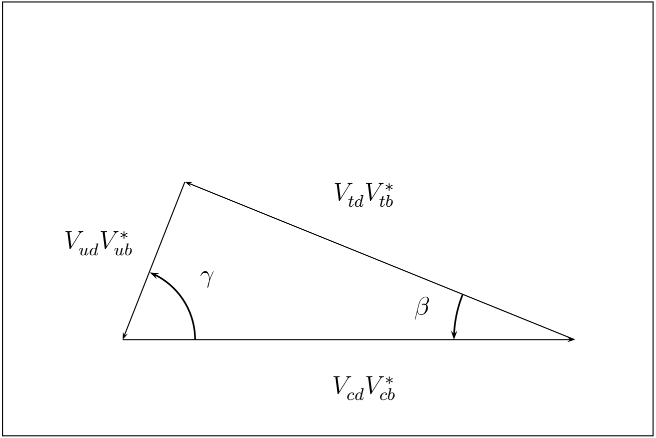
Preliminary plots: $\mathrm{Br}(B^+ \to \tau^+\nu)$



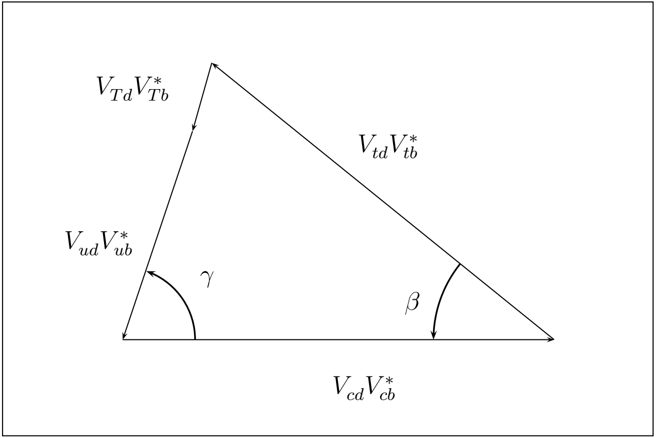


$-2\ln(\mathcal{L})$, Vector-like quark model vs. Standard Model

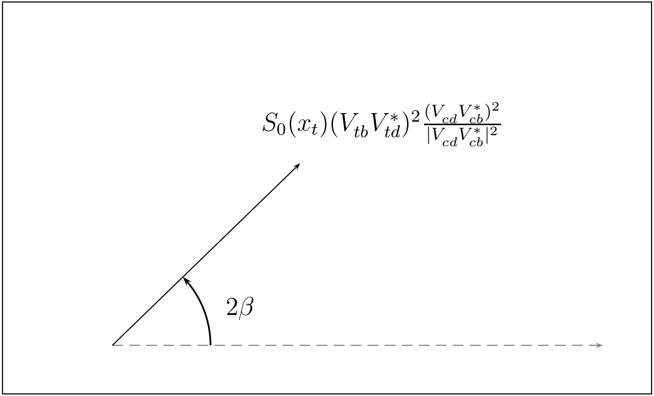
Interlude: relaxing the *bd* tensions (1)



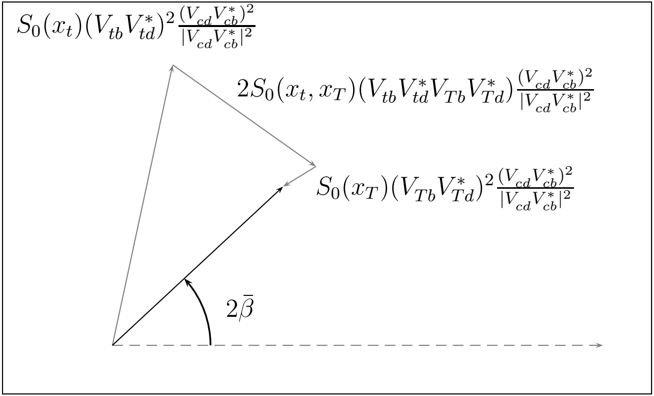
Interlude: relaxing the *bd* tensions (2)



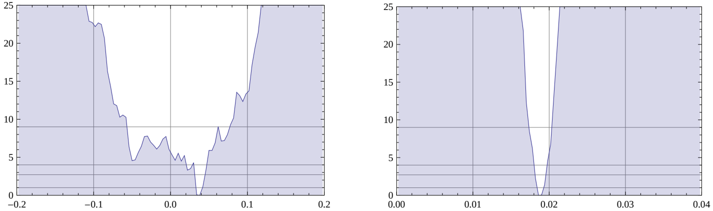
Interlude: relaxing the *bd* tensions (3)



Interlude: relaxing the *bd* tensions (4)

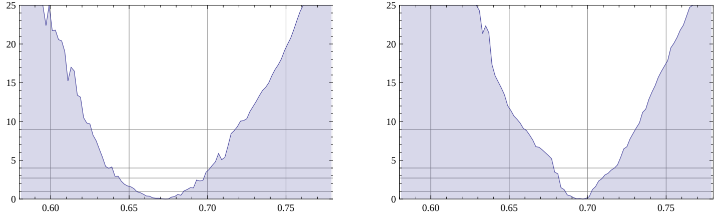


Preliminary plots: the phase β_s



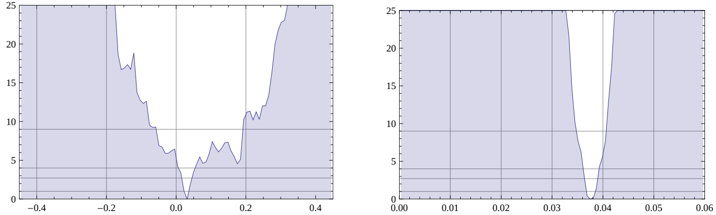
$-2\ln(\mathcal{L})$, Vector-like quark model vs. Standard Model

Preliminary plots: the asymmetry $A_{J/\psi K_S}$



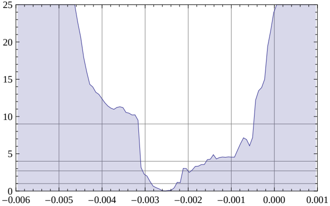
$-2\ln(\mathcal{L})$, Vector-like quark model vs. Standard Model

Preliminary plots: the asymmetry $A_{J/\Psi\Phi}$



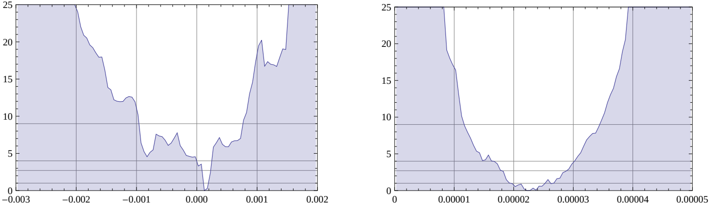
$-2\ln(\mathcal{L})$, Vector-like quark model vs. Standard Model

Preliminary plots: mixing asymmetry A_{sl}^d



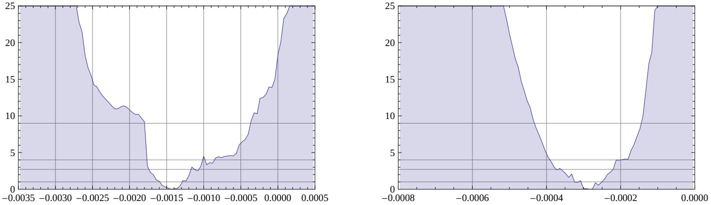
$-2\ln(\mathcal{L})$, Vector-like quark model vs. Standard Model

Preliminary plots: mixing asymmetry A_{sl}^s



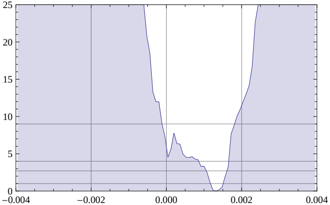
$-2\ln(\mathcal{L})$, Vector-like quark model vs. Standard Model

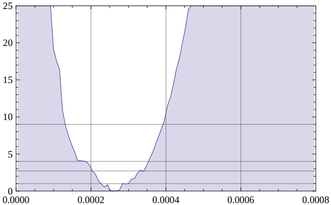
Preliminary plots: mixing asymmetry A_{sl}^b



$-2\ln(\mathcal{L})$, Vector-like quark model vs. Standard Model

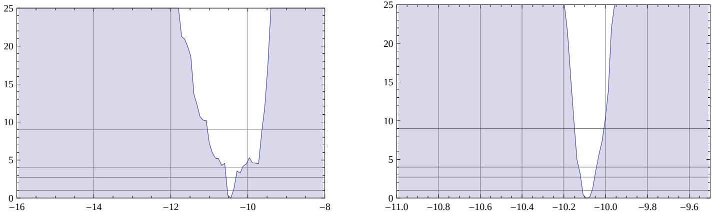
Preliminary plots: $(A_{sl}^s - A_{sl}^d)/2$





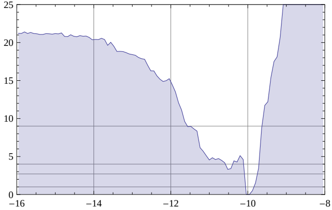
$-2\ln(\mathcal{L})$, Vector-like quark model vs. Standard Model

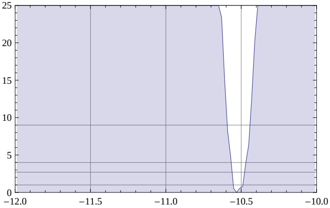
Preliminary plots: $\mathrm{Br}(K^+ \to \pi^+ \nu \bar{\nu})$



$-2\ln(\mathcal{L})$, Vector-like quark model vs. Standard Model

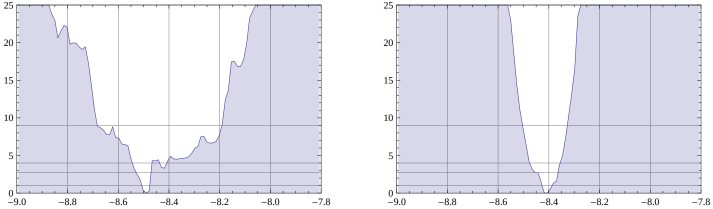
Preliminary plots: $\text{Br}(K^0 \to \pi^0 \nu\bar{\nu})$





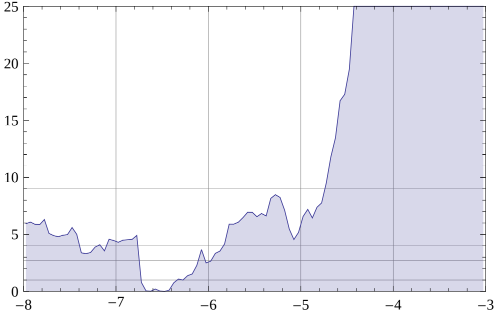
$-2\ln(\mathcal{L})$, Vector-like quark model vs. Standard Model

Preliminary plots: $\mathrm{Br}(B_s \to \mu^+\mu^-)$



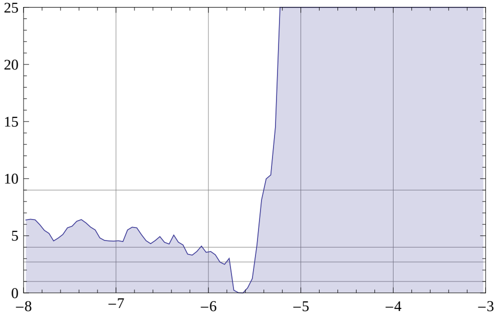
$-2\ln(\mathcal{L})$, Vector-like quark model vs. Standard Model

Preliminary plots: $\mathrm{Br}(t \to cZ)$



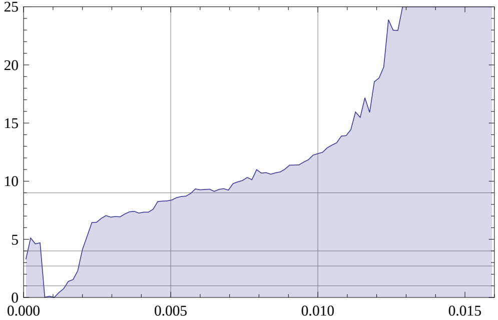
$-2\ln(\mathcal{L})$, Vector-like quark model

Preliminary plots: $\mathrm{Br}(t \to uZ)$



$-2\ln(\mathcal{L})$, Vector-like quark model

Preliminary plots: short distance x_D



$-2\ln(\mathcal{L})$, Vector-like quark model

Conclusions

- Through a new isosinglet $Q = 2/3$ quark and associated small violations of 3×3 unitarity, we can enhance some observables partially accounting for the differences with the SM expectations.
- ...and partially producing sizeable deviations in some places, potentially measurable.
- Not included: correlations, vast amount of information ($\mathcal{O}(10^3)$ plots!)

Thank you!