Prospects on extensions of the Standard Model with vector-like quarks

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From the Planck scale to the Electroweak scale

Based on 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,

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

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

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

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

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

Mass diagonalisation (1)

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

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

The usual bidiagonalisation is

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

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

Mass diagonalisation (2)

Through quark rotations

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

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

Fermion couplings to gauge fields (1)

- Charged currents

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

$$J_W^{+\mu} = \bar{u}_{L\mathbf{i}}\ \gamma^\mu\ d_L^{\mathbf{i}}$$

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

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

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)

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

with

$$J^\mu_Z = \bar{u}_{L\mathbf{i}}\ \gamma^\mu\ u^{\mathbf{i}}_L - \bar{d}_{L\mathbf{i}}\ \gamma^\mu\ d^{\mathbf{i}}_L - 2s^2_w\ J^\mu_{em}$$

gives, in the mass basis,

$$J^\mu_Z = \bar{u}_{La}\ \gamma^\mu (VV^\dagger)^a{}_b\ u^b_L - \bar{d}_{Lc}\ \gamma^\mu\ d^c_L - 2s^2_w\ J^\mu_{em}$$

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

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

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

Summary of this (biased) pocket 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
- 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. . .
Nevertheless, recent times had brought interesting news

- Time-dependent, mixing induced, CP violation in $B_s \to J/\Psi\Phi$ measured at the Tevatron experiments,
- Same sign dimuon asymmetry $\mathcal{A}$ in B decays measured at the Tevatron experiments too,
- (Hints from $b \to s$ penguin transitions.)
- (D^0–$\bar{D}^0$ mixing at B factories,)

Can we expect some help from vector-like quarks?

- New contributions to $M_{12}^{B_s}$ (quarks T running in the box) to address 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.
- New contributions to loop processes (rare decays)
- (Short distance contributions to D^0–$\bar{D}^0$ mixing)

…maybe something else

- rare top decays $t \to c\,Z$ observable at the LHC ?
- enhanced rare decays $B_s \to \mu\,\bar{\mu}$?

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

Constraints – Shopping list

- Agreement with purely tree level observables constraining V

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

Constraints – Shopping list

Agreement with the following observables potentially sensitive to New Physics

- Mixing induced, time dependent, CP-violating asymmetry in $B_d^0 \to J/\Psi K_S$
- 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 $\Delta\Gamma_d/\Gamma_d$, $\Delta\Gamma_s$, $\Delta\Gamma_s^{CP}$ of the eigenstates of the mentioned effective Hamiltonians, related to $\text{Re}\left(\Gamma_{12}^{B_q}/M_{12}^{B_q}\right)$, $q = d, s$
- Charge/semileptonic asymmetries $\mathcal{A}$, A_{sl}^d, A_{sl}^s, controlled by $\text{Im}\left(\Gamma_{12}^{B_q}/M_{12}^{B_q}\right)$, $q = d, s$

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

Constraints – Shopping list

- 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

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

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

. . . , . . .

Constraints – Shopping list

- Electroweak oblique parameter T, which encodes violation of weak isospin; the S and U parameters play no relevant rôle here.

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

Beside experimentally based constraints, agreement is also required for every parameter entering the calculation of the observables: QCD corrections, lattice-QCD bag factors, etc.

Constraints – The experimental values

Observable	Exp. Value	Observable	Exp. Value
$\lvert V_{ud}\rvert$	0.97377 ± 0.00027	$\lvert V_{us}\rvert$	0.2257 ± 0.0021
$\lvert V_{cd}\rvert$	0.230 ± 0.011	$\lvert V_{cs}\rvert$	0.957 ± 0.095
$\lvert V_{ub}\rvert$	0.00431 ± 0.00030	$\lvert V_{cb}\rvert$	0.0416 ± 0.0006
γ	$(77 \pm 14)^\circ$		
$A_{J/\psi K_S}$	0.673 ± 0.023	$A_{J/\Psi\Phi}$	0.540 ± 0.27
$\Delta M_{B_d}(\times\ \text{ps})$	0.508 ± 0.004	$\Delta M_{B_s}\ (\times\ \text{ps})$	17.78 ± 0.12
x_D	0.0097 ± 0.0029	ΔT	0.13 ± 0.10
$\epsilon_K(\times 10^3)$	2.232 ± 0.007	$\epsilon'/\epsilon_K(\times 10^3)$	1.67 ± 0.16
$\text{Br}(K^+ \to \pi^+\nu\bar{\nu})$	$(1.73\ ^{+1.15}_{-1.05}) \times 10^{-10}$	$\text{Br}(K_L \to \mu\bar{\mu})_{SD}$	$< 2.5 \times 10^{-9}$
$\text{Br}(B \to X_s\ell^+\ell^-)$	$(1.60 \pm 0.51) \times 10^{-6}$	$\text{Br}(B \to X_s\gamma)$	$(3.56 \pm 0.25) \times 10^{-4}$
$\text{Br}(t \to cZ)$	$< 4 \times 10^{-2}$	$\text{Br}(t \to uZ)$	$< 4 \times 10^{-2}$
$\Delta\Gamma_s\ (\times\ \text{ps})$	0.075 ± 0.036	$\Delta\Gamma_s^{CP}\ (\times\ \text{ps})$	0.15 ± 0.11
$\Delta\Gamma_d/\Gamma_d$	-0.011 ± 0.037	$\mathcal{A}$	-0.0096 ± 0.0029
A_{sl}^d	-0.0047 ± 0.0046	A_{sl}^s	-0.0017 ± 0.0091

Table: Experimental values of observables.

Constraints – Summary

- Tree level

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

- Kaon physics

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

Constraints – Summary

- 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

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

Constraints – Summary

- 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

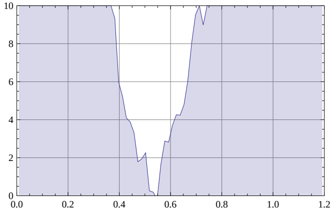
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} & U_{14} \\ V_{cd} & V_{cs} & V_{cb} & U_{24} \\ V_{td} & V_{ts} & V_{tb} & U_{34} \\ V_{Td} & V_{Ts} & V_{Tb} & U_{44} \end{pmatrix}$$

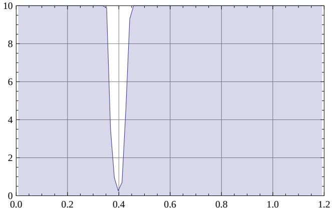
Method

- Likelihood function of model parameters and constraints
- Use likelihood to conduct an exploration of the parameter space

Preliminary plots: the phase β

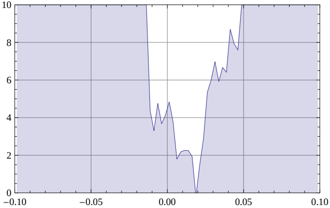
$-2\ln(\mathcal{L})$, Vector-like quark model vs. Standard Model

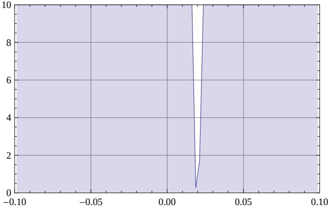




Preliminary plots: the phase β_s

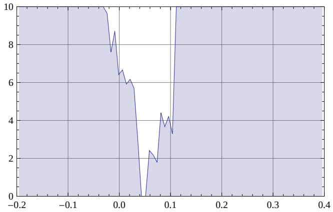
$-2\ln(\mathcal{L})$, Vector-like quark model vs. Standard Model

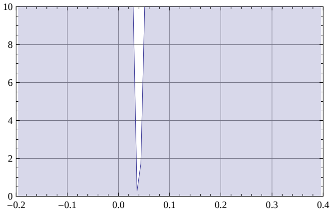




Preliminary plots: the asymmetry $A_{J/\Psi\Phi}$

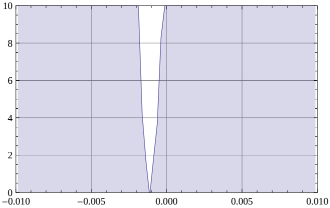
$-2\ln(\mathcal{L})$, Vector-like quark model vs. Standard Model

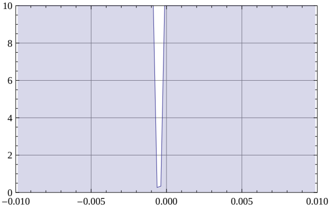




Preliminary plots: the semileptonic asymmetry A_{sl}^d

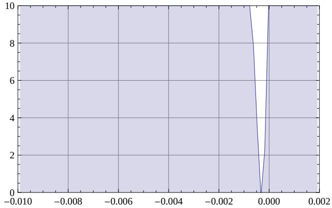
$-2\ln(\mathcal{L})$, Vector-like quark model vs. Standard Model

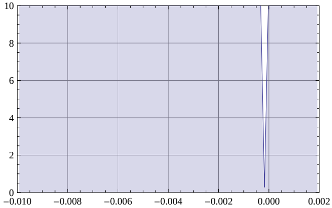




Preliminary plots: the dimuon charge asymmetry $\mathcal{A}$

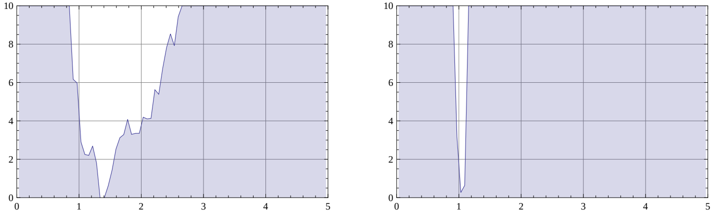
$-2\ln(\mathcal{L})$, Vector-like quark model vs. Standard Model





Preliminary plots: the enhancement in $B_s \to \mu\bar{\mu}$

$-2\ln(\mathcal{L})$, Vector-like quark model vs. Standard 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.
- However, if one tries *too hard* to accommodate these differences, the model may start to run into problems, other observables may suffer ...
- ... those are preliminary results, many parameters and more than 30 observables are involved, a complete and more detailed version of this analysis is necessary (and is in progress),
- ... and new experimental results are necessary too!

Thank you!