Vector-like quarks and New Physics at the LHC

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Multi-lepton final states in search of New Physics at the LHC

Based on work done in collaboration with **F.J. Botella** & **G.C. Branco**,
. . . and previous work done in collaboration with
J.A. Aguilar-Saavedra, **F.J. Botella** & **G.C. Branco**.

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

$$T_L^i,\ T_R^i \sim (3, 1, 4/3) \qquad B_L^j,\ B_R^j \sim (3, 1, -2/3)$$

- 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

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

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

Mass diagonalisation (2)

Through quark rotations

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

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

Fermion couplings to gauge fields (1)

- Charged currents

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

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

in the mass basis

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

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)

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

with

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

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

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

Summary of this reminder on 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, despite violation of Glashow & Weinberg's "Natural Flavor Conservation" in Z couplings

S.Glashow, S.Weinberg, *Phys. Rev.* **D15**, 1958 (1977)

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,

  CDF Collaboration, *Phys. Rev. Lett.* **100**, 161802 (2008), arXiv:0712.2397

  DØ Collaboration, *Phys. Rev. Lett.* **101**, 241801 (2008), arXiv:0802.2255

- Hints from $b \to s$ penguin transitions.

  M. Artuso *et al.*, *Eur. Phys. J. C* **57**, 309-492 (2008), arXiv:0801.1833

- D^0–$\bar{D}^0$ mixing at B factories,

  Babar Collaboration, *Phys. Rev. Lett.* **98**, 211802 (2007), hep-ex/0703020

  Belle Collaboration, *Phys. Rev. Lett.* **98**, 211803 (2007), hep-ex/0703036

  Belle Collaboration, *Phys. Rev. Lett.* **99**, 131803 (2007), arXiv:0704.1000

Guess what...

- Goal: tackle those issues
- Framework: one non-SM ingredient,

$$\boxed{\text{one new } Q = 2/3 \text{ isosinglet quark } T}$$

F. del Aguila, M. Bowick, *Nucl. Phys.* **B224**, 107 (1983)

G.C. Branco, L. Lavoura, *Nucl. Phys.* **B278**, 738 (1986)

. . . . . .

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

Implications of (small) violations of 3×3 unitarity

- Potentially large β_s to address the B_s^0–$\bar{B}_s^0$ mixing phase
- Rare top decays
- Short distance contributions to D^0–$\bar{D}^0$ mixing

Obtaining a large β_s

- Orthogonality of the s and b columns of V gives:

$$\sin\beta_s = \frac{|V_{ub}|\,|V_{us}|}{|V_{cb}|\,|V_{cs}|}\sin(\gamma-\beta_s+\chi') + \frac{|V_{Tb}|\,|V_{Ts}|}{|V_{cb}|\,|V_{cs}|}\sin(\sigma-\beta_s)$$

$$\sigma \equiv \arg(V_{Ts}V_{cb}V^*_{Tb}V^*_{cs})$$

  - In the SM, $\sin\beta_s = \mathcal{O}(\lambda^2)$ [N.B. $\lambda \simeq 0.22$]
  - If instead we want to obtain β_s of order λ,
    play with the couplings of T and look for $|V_{Tb}V_{Ts}| \sim \mathcal{O}(\lambda^3)$
    for example $V_{Tb} \approx \mathcal{O}(\lambda)$, $V_{Ts} \approx \mathcal{O}(\lambda^2)$

From large β_s to ...

- Orthogonality of the c and t rows of U gives:

$$\sin\beta_s = \frac{|V_{cd}|\,|V_{td}|}{|V_{cs}|\,|V_{ts}|}\sin\beta + \frac{|U_{24}|\,|U_{34}|}{|V_{cs}|\,|V_{ts}|}\sin\omega$$

$$\omega = \arg(V_{tb}^{*}U_{24}^{*}V_{cb}U_{34})$$

To have β_s of order λ,
$|U_{24}U_{34}|$ of order λ^3 is required,
for example $|U_{24}| \approx \mathcal{O}(\lambda^2)$, $|U_{34}| \approx \mathcal{O}(\lambda)$

Rare top decays

- We have just seen that $\beta_s \approx \mathcal{O}(\lambda)$ requires $|U_{24}U_{34}| \approx \mathcal{O}(\lambda^3)$
- ... but this is just what we have in the tcZ coupling

$$\frac{g}{2\cos\theta_W} U_{24}U_{34}^* \, \bar{c}_L \gamma^\mu t_L \, Z_\mu$$

- ... which leads to rare top decays $t \to cZ$ (at rates observable at the LHC)

That is,

$$\boxed{\text{a large value of } \beta_s \text{ implies rare top decays } t \to cZ}$$

D^0–$\bar{D}^0$ mixing

- We have tree level FCNC couplings

$$\frac{g}{2\cos\theta_W} U_{14} U_{24}^* \, \bar{u}_L \gamma^\mu c_L \, Z_\mu$$

- 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 with $|U_{24}| \approx \mathcal{O}(\lambda^2)$, $|U_{14}| \approx \mathcal{O}(\lambda^3)$
- However, $|U_{14}|$ has just an upper bound and this short-distance contribution to D^0–$\bar{D}^0$ mixing could be switched off (and thus long-distance contributions required)

Constraints – Shopping list

- Sizeable mixing induced, time dependent, CP-violating asymmetry in $B_s^0 \to J/\Psi\Phi$ (for the CP-even part of the final state)
$$A_{J/\Psi\Phi} \equiv \sin 2\beta_s^{\text{eff}}, \qquad 2\beta_s^{\text{eff}} = -\arg M_{12}^{B_s}$$
- The short-distance contribution to $x_D(\to \Delta M_D/\Gamma_D)$ in D^0–$\bar{D}^0$ from tree level FCNC could account for the observed value. As long-distance contributions might be important, smaller short-distance contributions to x_D are also considered.
- 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 Re $\left(\Gamma_{12}^{B_q}/M_{12}^{B_q}\right)$, $q = d, s$
- Charge/semileptonic asymmetries $\mathcal{A}$, A_{sl}^d, 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

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 $K^+ \to \pi^+\nu\bar{\nu}$, $(K_L \to \mu\bar{\mu})_{SD}$ 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

$\cdots,\cdots$

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
$\|V_{ud}\|$	0.97408 ± 0.00026	$\|V_{us}\|$	0.2253 ± 0.0009
$\|V_{cd}\|$	0.230 ± 0.011	$\|V_{cs}\|$	0.957 ± 0.095
$\|V_{ub}\|$	0.00431 ± 0.00030	$\|V_{cb}\|$	0.0416 ± 0.0006
γ	$(76 \pm 23)^\circ$		
$A_{J/\psi K_S}$	0.675 ± 0.026	$A_{J/\Psi\Phi}$	0.540 ± 0.225
$\Delta M_{B_d} (\times \text{ ps})$	0.507 ± 0.005	$\Delta M_{B_s}\ (\times \text{ ps})$	17.77 ± 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
$\text{Br}(K^+ \to \pi^+ \nu\bar{\nu})$	$(1.5\,^{+1.3}_{-0.9}) \times 10^{-10}$	$\text{Br}(K_L \to \mu\bar{\mu})_{SD}$	$< 2.5 \times 10^{-9}$
$\text{Br}(B \to X_s \ell^+ \ell^-)$	$(1.60 \pm 0.51) \times 10^{-6}$		
$\text{Br}(t \to cZ)$	$< 4 \times 10^{-2}$	$\text{Br}(t \to uZ)$	$< 4 \times 10^{-2}$
$\Delta\Gamma_s\ (\times \text{ ps})$	0.19 ± 0.07	$\Delta\Gamma_s^{CP}\ (\times \text{ ps})$	0.15 ± 0.11
$\Delta\Gamma_d/\Gamma_d$	0.009 ± 0.037		
A_{sl}^d	-0.003 ± 0.0078	$\mathcal{A}$	-0.0028 ± 0.0016

Table: Experimental values of observables.

Constraints – ΔM_{B_d}

- CKM elements: $V_{td}^* V_{tb}$, $V_{Td}^* V_{Tb}$
- 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 $2|M_{12}^{B_d}| = \Delta M_{B_d}$

$$
\begin{aligned}
M_{12}^{B_d} \propto {} & S_0(x_t)(V_{td}^* V_{tb})^2 \\
& + 2S_0(x_t, x_T)(V_{td}^* V_{tb} V_{Td}^* V_{Tb}) + S_0(x_T)(V_{Td}^* V_{Tb})^2
\end{aligned}
$$

Constraints – $A_{J/\psi K_S}$

$A_{J/\psi K_S}$: 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 $\sin(\arg M_{12}^{B_d}) = A_{J/\psi K_S}$

$$M_{12}^{B_d} \propto S_0(x_t)(V_{td}^* V_{tb})^2 + 2S_0(x_t, x_T)(V_{td}^* V_{tb} V_{Td}^* V_{Tb}) + S_0(x_T)(V_{Td}^* V_{Tb})^2$$

Constraints – ΔM_{B_s}

Analogous to ΔM_{B_d} with $d \to s$

- CKM elements: $V_{ts}^* V_{tb}$, $V_{Ts}^* V_{Tb}$
- Same loop functions $S_0(x_t), S_0(x_t, x_T), S_0(x_T)$
- Sensitivity to $2|M_{12}^{B_s}| = \Delta M_{B_s}$

$$M_{12}^{B_s} \propto S_0(x_t)(V_{ts}^* V_{tb})^2 + 2S_0(x_t, x_T)(V_{ts}^* V_{tb} V_{Ts}^* V_{Tb}) + S_0(x_T)(V_{Ts}^* V_{Tb})^2$$

Constraints – $A_{J/\Psi\Phi}$

Analogous to $A_{J/\psi K_S}$ with $d \to s$

- Sensitivity to $\sin(-\arg M_{12}^{B_s}) = A_{J/\Psi\Phi}$

$$M_{12}^{B_s} \propto S_0(x_t)(V_{ts}^* V_{tb})^2 + 2S_0(x_t, x_T)(V_{ts}^* V_{tb} V_{Ts}^* V_{Tb}) + S_0(x_T)(V_{Ts}^* V_{Tb})^2$$

Constraints – $\Delta\Gamma_d/\Gamma_d$ and A_{sl}^d

- CKM elements: $V_{ud}^*V_{ub}$, $V_{cd}^*V_{cb}$
- Sensitivity to real, imaginary parts of $\Gamma_{12}^{B_d}$

$$\Gamma_{12}^{B_d} \propto C_{uu}(V_{ud}^*V_{ub})^2 + C_{uc}(V_{ud}^*V_{ub}V_{cd}^*V_{cb}) + C_{cc}(V_{cd}^*V_{cb})^2$$

Constraints – $\Delta\Gamma_s$, $\Delta\Gamma_s^{CP}$ and $\mathcal{A}$

Analogous to $\Delta\Gamma_d$ and A_{sl}^d with $d \to s$

- CKM elements: $V_{us}^* V_{ub}$, $V_{cs}^* V_{cb}$
- Sensitivity to real, imaginary parts of $\Gamma_{12}^{B_s}$

$$\Gamma_{12}^{B_s} \propto C_{uu}(V_{us}^* V_{ub})^2 + C_{uc}(V_{us}^* V_{ub} V_{cs}^* V_{cb}) + C_{cc}(V_{cs}^* V_{cb})^2$$

Constraints – $\mathrm{Br}(B \to X_s \ell^+ \ell^-)$

- 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 $V_{ts}^* V_{tb} f_{C_i}(x_t) + V_{Ts}^* V_{Tb} f_{C_i}(x_T)$

Constraints – 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 $\epsilon_K \propto \mathrm{Im}\left[M_{12}^K\right]$

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

Constraints – 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 $\epsilon'/\epsilon_K \propto \mathrm{Im}\,[V_{td}V_{ts}^*]f(x_t) + \mathrm{Im}\,[V_{Td}V_{Ts}^*]f(x_T)$

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

Constraints – $\mathrm{Br}(K^+ \to \pi^+ \nu \bar{\nu})$

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

Constraints – $\mathrm{Br}(K_L \to \mu\bar{\mu})_{SD}$

- 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

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

Constraints – 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

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

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

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

Finding interesting examples

- Likelihood function of model parameters and constraints
- Eventual modifications to bias the search towards interesting regions of parameter space
- Input that to drive an exploration of the parameter space

A few examples

- Example 1: $m_T = 300$ GeV, large x_D
- Example 2: $m_T = 300$ GeV, x_D not large
- Example 3: $m_T = 450$ GeV, large x_D
- Example 4: $m_T = 450$ GeV, x_D not large

Example 1, $m_T = 300$ GeV and large x_D

Moduli

$$|U| = \left(\begin{array}{ccc|c} 0.974186 & 0.225642 & 0.003984 & 0.005530 \\ 0.225559 & 0.972463 & 0.041676 & 0.041252 \\ 0.009002 & 0.047563 & 0.948582 & 0.312809 \\ 0.001666 & 0.033749 & 0.313759 & 0.948904 \end{array}\right)$$

Phases

$$\arg U = \left(\begin{array}{ccc|c} 0 & 0.000530 & -1.055339 & 1.071901 \\ \pi & 0 & 0 & 0.947622 \\ -0.472544 & \pi - 0.208060 & 0 & 0 \\ 1.795665 & -1.266410 & 0 & \pi + 0.004752 \end{array}\right)$$

Example 1, $m_T = 300$ GeV and large x_D

Observable	Value	Observable	Value
γ	60.5°	β_s	-11.9°
ΔM_{B_d}	0.507 ps^{-1}	ΔM_{B_s}	17.77 ps^{-1}
$A_{J/\psi K_S}$	0.692	$A_{J/\Psi\Phi}$	0.288
ϵ_K	2.232×10^{-3}	ϵ'/ϵ_K	1.63×10^{-3}
x_D	0.0085	ΔT	0.16
$\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu})$	1.3×10^{-10}	$\mathrm{Br}(K_L \to \mu\bar{\mu})_{SD}$	1.86×10^{-9}
$\mathrm{Br}(t \to cZ)$	1.4×10^{-4}	$\mathrm{Br}(t \to uZ)$	2.5×10^{-6}
$\mathrm{Br}(B \to X_s e^+ e^-)$	1.63×10^{-6}	$\mathrm{Br}(B \to X_s \mu^+ \mu^-)$	1.58×10^{-6}
$\Delta\Gamma_d/\Gamma_d$	0.0042		
$\Delta\Gamma_s$	0.098 ps^{-1}	$\Delta\Gamma_s^{CP}$	0.094 ps^{-1}
A_{sl}^d	-0.0010	$\mathcal{A}$	-0.0006

Table: Observables for example 1 [Exp. Values 0]

Example 2, $m_T = 300$ GeV and x_D not large

Moduli

$$|U| = \left(\begin{array}{ccc|c} 0.974195 & 0.225663 & 0.004137 & 0.002015 \\ 0.225482 & 0.972938 & 0.041548 & 0.028688 \\ 0.009721 & 0.042034 & 0.945531 & 0.322660 \\ 0.002889 & 0.026471 & 0.322842 & 0.946078 \end{array}\right)$$

Phases

$$\arg U = \left(\begin{array}{ccc|c} 0 & 0.000569 & -1.204546 & 1.928448 \\ \pi & 0 & 0 & 1.267846 \\ -0.536152 & \pi - 0.189787 & 0 & 0 \\ 1.545539 & -1.774240 & 0 & \pi + 0.003725 \end{array}\right)$$

Example 2, $m_T = 300$ GeV and x_D not large

Observable	Value	Observable	Value
γ	69.0°	β_s	-10.9°
ΔM_{B_d}	$0.507\ \text{ps}^{-1}$	ΔM_{B_s}	$17.77\ \text{ps}^{-1}$
$A_{J/\psi K_S}$	0.686	$A_{J/\Psi\Phi}$	0.250
ϵ_K	2.232×10^{-3}	ϵ'/ϵ_K	1.66×10^{-3}
x_D	0.0005	ΔT	0.17
$\text{Br}(K^+ \to \pi^+\nu\bar{\nu})$	1.2×10^{-10}	$\text{Br}(K_L \to \mu\bar{\mu})_{SD}$	1.99×10^{-9}
$\text{Br}(t \to cZ)$	0.72×10^{-4}	$\text{Br}(t \to uZ)$	3.5×10^{-7}
$\text{Br}(B \to X_s e^+ e^-)$	1.92×10^{-6}	$\text{Br}(B \to X_s \mu^+ \mu^-)$	1.86×10^{-6}
$\Delta\Gamma_d/\Gamma_d$	0.0042		
$\Delta\Gamma_s$	$0.088\ \text{ps}^{-1}$	$\Delta\Gamma_s^{CP}$	$0.085\ \text{ps}^{-1}$
A_{sl}^d	-0.0013	$\mathcal{A}$	-0.0006

Table: Observables for example 2 [Exp. Values 0]

Example 3, $m_T = 450$ GeV and large x_D

Moduli

$$|U| = \left(\begin{array}{ccc|c} 0.974179 & 0.225657 & 0.004031 & 0.006073 \\ 0.225619 & 0.972525 & 0.041766 & 0.039324 \\ 0.008330 & 0.047219 & 0.966377 & 0.252620 \\ 0.001136 & 0.032304 & 0.253683 & 0.966747 \end{array}\right)$$

Phases

$$\arg U = \left(\begin{array}{ccc|c} 0 & 0.000570 & -0.957178 & 0.868831 \\ \pi & 0 & 0 & 0.816488 \\ -0.447359 & \pi - 0.140403 & 0 & 0 \\ 1.908192 & -1.055192 & 0 & \pi + 0.004977 \end{array}\right)$$

Example 3, $m_T = 450$ GeV and large x_D

Observable	Value	Observable	Value
γ	$54.8°$	β_s	$-8.0°$
ΔM_{B_d}	$0.507\ \text{ps}^{-1}$	ΔM_{B_s}	$17.77\ \text{ps}^{-1}$
$A_{J/\psi K_S}$	0.693	$A_{J/\Psi\Phi}$	0.317
ϵ_K	2.232×10^{-3}	ϵ'/ϵ_K	1.63×10^{-3}
x_D	0.0092	ΔT	0.20
$\text{Br}(K^+ \to \pi^+\nu\bar{\nu})$	1.0×10^{-10}	$\text{Br}(K_L \to \mu\bar{\mu})_{SD}$	1.87×10^{-9}
$\text{Br}(t \to cZ)$	0.80×10^{-4}	$\text{Br}(t \to uZ)$	1.88×10^{-6}
$\text{Br}(B \to X_s e^+e^-)$	1.60×10^{-6}	$\text{Br}(B \to X_s\mu^+\mu^-)$	1.55×10^{-6}
$\Delta\Gamma_d/\Gamma_d$	0.0041		
$\Delta\Gamma_s$	$0.110\ \text{ps}^{-1}$	$\Delta\Gamma_s^{CP}$	$0.104\ \text{ps}^{-1}$
A_{sl}^d	-0.0010	$\mathcal{A}$	-0.0007

Table: Observables for example 3 [Exp. Values 0]

Example 4, $m_T = 450$ GeV and x_D not large

Moduli

$$|U| = \left(\begin{array}{ccc|c} 0.974192 & 0.225675 & 0.004015 & 0.002260 \\ 0.225535 & 0.972984 & 0.041642 & 0.026487 \\ 0.009033 & 0.044207 & 0.961556 & 0.270876 \\ 0.001741 & 0.020444 & 0.271403 & 0.962247 \end{array}\right)$$

Phases

$$\arg U = \left(\begin{array}{ccc|c} 0 & 0.000622 & -1.092316 & 1.085654 \\ \pi & 0 & 0 & 0.885746 \\ -0.467721 & \pi - 0.108029 & 0 & 0 \\ 1.920727 & -1.329417 & 0 & \pi + 0.003299 \end{array}\right)$$

Example 4, $m_T = 450$ GeV and x_D not large

Observable	Value	Observable	Value
γ	62.6°	β_s	-6.2°
ΔM_{B_d}	$0.507\ \text{ps}^{-1}$	ΔM_{B_s}	$17.77\ \text{ps}^{-1}$
$A_{J/\psi K_S}$	0.688	$A_{J/\Psi\Phi}$	0.265
ϵ_K	2.232×10^{-3}	ϵ'/ϵ_K	1.66×10^{-3}
x_D	0.0006	ΔT	0.23
$\text{Br}(K^+ \to \pi^+ \nu\bar{\nu})$	1.0×10^{-10}	$\text{Br}(K_L \to \mu\bar{\mu})_{SD}$	2.10×10^{-9}
$\text{Br}(t \to cZ)$	0.42×10^{-5}	$\text{Br}(t \to uZ)$	3.0×10^{-7}
$\text{Br}(B \to X_s e^+ e^-)$	1.75×10^{-6}	$\text{Br}(B \to X_s \mu^+ \mu^-)$	1.70×10^{-6}
$\Delta\Gamma_d/\Gamma_d$	0.0043		
$\Delta\Gamma_s$	$0.098\ \text{ps}^{-1}$	$\Delta\Gamma_s^{CP}$	$0.094\ \text{ps}^{-1}$
A_{sl}^d	-0.0012	$\mathcal{A}$	-0.0006

Table: Observables for example 4 [Exp. Values 0]

B_s^0–$\bar{B}_s^0$ mixing phase

- Remember $A_{J/\Psi\Phi}$ *is not* $\sin 2\beta_s$ *but* $\sin 2\beta_s^{\text{eff}}$
- Values of $A_{J/\Psi\Phi}$ ranging up to [0.25;0.32], *significantly* larger than the SM expectation 0.04, are obtained
- However, the model does not allow for much larger values of $A_{J/\Psi\Phi}$, even if larger values of m_T are considered: difficulties with non-decoupling contributions to rare decays arise

D^0–$\bar{D}^0$ mixing

- The model can "account" for x_D just through the short-distance contributions available in this framework (tree level Z-mediated)
- ... or not, it is not compulsory
- The crucial test to disentangle the origin of D^0–$\bar{D}^0$ mixing, short or large distance, could come from CP violation; the present model produces new CP-violating phases

Observable $t \to cZ$ decays at the LHC and $|V_{tb}| \neq 1$

- The branching ratio of $t \to cZ$ decays has, in the examples, values $10^{-4} - 10^{-5}$
- ...typically within reach of the LHC detectability expectations
- $t \to uZ$ decays are also of potential interest but the resulting branching ratio is much smaller, typically $\mathcal{O}(10^{-6})$
- $|V_{tb}|$ is sizeably different from unity (potentially observable too)

Conclusions

- Through a new isosinglet $Q = 2/3$ quark and associated small violations of 3×3 unitarity, we can accommodate a large ($\mathcal{O}(\lambda)$) value of β_s^{eff}, partially accounting for the observed CP violation in $B_s \to J/\Psi\Phi$
- The mass of the T quark should not exceed ~ 500 GeV
- Potential explanation for the observed D^0–$\bar{D}^0$ mixing
- Interesting features concerning top quark physics ($t \to cZ$, $|V_{tb}| \neq 1$ for example)

Thank you!