Phenomenology of Vector-like quarks

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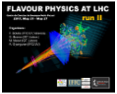


Flavour Physics at LHC run II

May 23$^{\mathrm{rd}}$ 2017

Never underestimate the joy people derive from hearing something they already know.

Enrico Fermi

(N.B. this quote itself counts)

Fermion content

$$\boldsymbol{Q_L} = \begin{pmatrix} \boldsymbol{P_L} \\ \boldsymbol{N_L} \end{pmatrix}, \quad \boldsymbol{p_L}, \quad \boldsymbol{n_L}, \quad \boldsymbol{Q_R} = \begin{pmatrix} \boldsymbol{P_R} \\ \boldsymbol{N_R} \end{pmatrix}, \quad \boldsymbol{p_R}, \quad \boldsymbol{n_R},$$

- $SU(2)_L$ doublets $\boldsymbol{Q_L}$ and $\boldsymbol{Q_R}$; $SU(2)_L$ singlets $\boldsymbol{p_L}, \boldsymbol{n_L}, \boldsymbol{p_R}, \boldsymbol{n_R}$.
- Number of fields:

  $$\#(\text{Left-handed fields}) = \#(\text{Right handed fields})$$

  Within doublets:

  $$\#(\boldsymbol{P_L}) = \#(\boldsymbol{N_L}) = \#(\boldsymbol{Q_L}), \quad \#(\boldsymbol{P_R}) = \#(\boldsymbol{N_R}) = \#(\boldsymbol{Q_R})$$

Yukawa couplings

$$\mathscr{L}_{\mathrm{Y}} = \left[-\bar{\boldsymbol{Q}}_{\boldsymbol{L}}\,\Phi\,\boldsymbol{Y_d}\,\boldsymbol{n_R} - \bar{\boldsymbol{Q}}_{\boldsymbol{L}}\,\tilde{\Phi}\,\boldsymbol{Y_u}\,\boldsymbol{p_R} - \bar{\boldsymbol{n}}_{\boldsymbol{L}}\,\Phi^{\dagger}\,\boldsymbol{\Gamma_d}\,\boldsymbol{Q_R} - \bar{\boldsymbol{p}}_{\boldsymbol{L}}\,\tilde{\Phi}^{\dagger}\,\boldsymbol{\Gamma_u}\,\boldsymbol{Q_R}\right] + \text{H.C.}$$

Bare mass terms

$$\mathscr{L}_{\mathrm{bM}} = \left[-\bar{\boldsymbol{n}}_{\boldsymbol{L}}\,\boldsymbol{\mu_d}\,\boldsymbol{n_R} - \bar{\boldsymbol{p}}_{\boldsymbol{L}}\,\boldsymbol{\mu_u}\,\boldsymbol{p_R} - \bar{\boldsymbol{Q}}_{\boldsymbol{L}}\,\boldsymbol{M_Q}\,\boldsymbol{Q_R}\right] + \text{H.C.}$$

Electroweak Spontaneous Symmetry Breaking

$$\langle\Phi\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

Mass terms

$$\mathscr{L}_{\text{M}} = \left[-\frac{v}{\sqrt{2}} \left(\bar{\boldsymbol{N}}_{\boldsymbol{L}}\, \boldsymbol{Y_d}\, \boldsymbol{n_R} + \bar{\boldsymbol{P}}_{\boldsymbol{L}}\, \boldsymbol{Y_u}\, \boldsymbol{p_R} + \bar{\boldsymbol{n}}_{\boldsymbol{L}}\, \boldsymbol{\Gamma_d}\, \boldsymbol{N_R} + \bar{\boldsymbol{p}}_{\boldsymbol{L}}\, \boldsymbol{\Gamma_u}\, \boldsymbol{P_R} \right) - \bar{\boldsymbol{n}}_{\boldsymbol{L}}\, \boldsymbol{\mu_d}\, \bar{\boldsymbol{n}}_{\boldsymbol{R}} - \bar{\boldsymbol{p}}_{\boldsymbol{L}}\, \boldsymbol{\mu_u}\, \boldsymbol{p_R} - \bar{\boldsymbol{P}}_{\boldsymbol{L}}\, \boldsymbol{M_Q}\, \bar{\boldsymbol{P}}_{\boldsymbol{R}} - \bar{\boldsymbol{N}}_{\boldsymbol{L}}\, \boldsymbol{M_Q}\, \boldsymbol{N_R} \right] + \text{H.C.}$$

Mass matrices

$$\mathscr{L}_{\text{M}} = -\begin{pmatrix} \bar{\boldsymbol{N}}_{\boldsymbol{L}} & \bar{\boldsymbol{n}}_{\boldsymbol{L}} \end{pmatrix} \mathscr{M}_d \begin{pmatrix} \boldsymbol{n_R} \\ \boldsymbol{N_R} \end{pmatrix} - \begin{pmatrix} \bar{\boldsymbol{P}}_{\boldsymbol{L}} & \bar{\boldsymbol{p}}_{\boldsymbol{L}} \end{pmatrix} \mathscr{M}_u \begin{pmatrix} \boldsymbol{p_R} \\ \boldsymbol{P_R} \end{pmatrix} + \text{H.C.}$$

$$\mathscr{M}_d = \begin{pmatrix} \boxed{\begin{matrix} v\mathbf{Y_d}/\sqrt{2} & \begin{matrix}\uparrow\\ \#(\boldsymbol{N_L})\\ \downarrow\end{matrix} \\ \leftarrow \;\; \#(\boldsymbol{n_R}) \;\; \rightarrow & \end{matrix}} & \boxed{\begin{matrix} \boldsymbol{M_Q} & \begin{matrix}\uparrow\\ \#(\boldsymbol{N_L})\\ \downarrow\end{matrix} \\ \leftarrow \;\; \#(\boldsymbol{N_R}) \;\; \rightarrow & \end{matrix}} \\ \boxed{\begin{matrix} \boldsymbol{\mu_d} & \begin{matrix}\uparrow\\ \#(\boldsymbol{n_L})\\ \downarrow\end{matrix} \\ \leftarrow \;\; \#(\boldsymbol{n_R}) \;\; \rightarrow & \end{matrix}} & \boxed{\begin{matrix} v\mathbf{\Gamma_d}/\sqrt{2} & \begin{matrix}\uparrow\\ \#(\boldsymbol{n_L})\\ \downarrow\end{matrix} \\ \leftarrow \;\; \#(\boldsymbol{N_R}) \;\; \rightarrow & \end{matrix}} \end{pmatrix}$$

$$\mathscr{M}_u = \begin{pmatrix} \boxed{\begin{array}{ccc} & v\boldsymbol{Y_u}/\sqrt{2} & \begin{array}{c}\uparrow\\ \#(\boldsymbol{P_L})\\ \downarrow\end{array} \\ \leftarrow & \#(\boldsymbol{p_R}) & \rightarrow \end{array}} & \boxed{\begin{array}{ccc} & \boldsymbol{M_Q} & \begin{array}{c}\uparrow\\ \#(\boldsymbol{P_L})\\ \downarrow\end{array} \\ \leftarrow & \#(\boldsymbol{P_R}) & \rightarrow \end{array}} \\ \boxed{\begin{array}{ccc} & \boldsymbol{\mu_u} & \begin{array}{c}\uparrow\\ \#(\boldsymbol{p_L})\\ \downarrow\end{array} \\ \leftarrow & \#(\boldsymbol{p_R}) & \rightarrow \end{array}} & \boxed{\begin{array}{ccc} & v\boldsymbol{\Gamma_u}/\sqrt{2} & \begin{array}{c}\uparrow\\ \#(\boldsymbol{p_L})\\ \downarrow\end{array} \\ \leftarrow & \#(\boldsymbol{P_R}) & \rightarrow \end{array}} \end{pmatrix}$$

No right-handed doublets

Repeat

$$\mathscr{L}_{\mathrm{Y}} = \left[-\bar{\boldsymbol{Q}}_{\boldsymbol{L}}\,\Phi\,\boldsymbol{Y_d}\,\boldsymbol{n_R} - \bar{\boldsymbol{Q}}_{\boldsymbol{L}}\,\tilde{\Phi}\,\boldsymbol{Y_u}\,\boldsymbol{p_R} - \bar{\boldsymbol{n}}_{\boldsymbol{L}}\,\boldsymbol{\mu_d}\,\boldsymbol{n_R} - \bar{\boldsymbol{p}}_{\boldsymbol{L}}\,\boldsymbol{\mu_u}\,\boldsymbol{p_R}\right] + \mathrm{H.C.}$$

$$\mathscr{L}_{\mathrm{M}} = \left[-\frac{v}{\sqrt{2}}\bar{\boldsymbol{N}}_{\boldsymbol{L}}\,\boldsymbol{Y_d}\,\boldsymbol{n_R} - \frac{v}{\sqrt{2}}\bar{\boldsymbol{P}}_{\boldsymbol{L}}\,\boldsymbol{Y_u}\,\boldsymbol{p_R} - \bar{\boldsymbol{n}}_{\boldsymbol{L}}\,\boldsymbol{\mu_d}\,\bar{\boldsymbol{n}}_{\boldsymbol{R}} - \bar{\boldsymbol{p}}_{\boldsymbol{L}}\,\boldsymbol{\mu_u}\,\boldsymbol{p_R}\right] + \mathrm{H.C.}$$

$$\mathscr{L}_{\mathrm{M}} = -\begin{pmatrix}\bar{\boldsymbol{N}}_{\boldsymbol{L}} & \bar{\boldsymbol{n}}_{\boldsymbol{L}}\end{pmatrix}\ \mathscr{M}_d\ \begin{pmatrix}\boldsymbol{n_R}\end{pmatrix} - \begin{pmatrix}\bar{\boldsymbol{P}}_{\boldsymbol{L}} & \bar{\boldsymbol{p}}_{\boldsymbol{L}}\end{pmatrix}\ \mathscr{M}_u\ \begin{pmatrix}\boldsymbol{p_R}\end{pmatrix}$$

Mass matrices

$$\mathscr{M}_d = \begin{pmatrix} \boxed{\begin{matrix} v\boldsymbol{Y_d}/\sqrt{2} & \uparrow \\ & \#(\boldsymbol{N_L}) \\ & \downarrow \\ \leftarrow \quad \#(\boldsymbol{n_R}) \quad \rightarrow & \end{matrix}} \\ \\ \boxed{\begin{matrix} & \uparrow \\ \boldsymbol{\mu_d} & \#(\boldsymbol{n_L}) \\ & \downarrow \\ \leftarrow \quad \#(\boldsymbol{n_R}) \quad \rightarrow & \end{matrix}} \end{pmatrix}, \quad \mathscr{M}_u = \begin{pmatrix} \boxed{\begin{matrix} v\boldsymbol{Y_u}/\sqrt{2} & \uparrow \\ & \#(\boldsymbol{P_L}) \\ & \downarrow \\ \leftarrow \quad \#(\boldsymbol{p_R}) \quad \rightarrow & \end{matrix}} \\ \\ \boxed{\begin{matrix} & \uparrow \\ \boldsymbol{\mu_u} & \#(\boldsymbol{p_L}) \\ & \downarrow \\ \leftarrow \quad \#(\boldsymbol{p_R}) \quad \rightarrow & \end{matrix}} \end{pmatrix}$$

Unitary transformation to the mass basis

Down quarks

$$\begin{pmatrix} \boldsymbol{N_L} \\ \boldsymbol{n_L} \end{pmatrix} = \left(\begin{array}{c} \boxed{\begin{array}{cc} A_{dL} & \begin{array}{c}\uparrow \\ \#(\boldsymbol{N_L}) \\ \downarrow\end{array} \\ \leftarrow \quad \#(\boldsymbol{d_L}) \quad \rightarrow & \end{array}} \\ \\ \boxed{\begin{array}{cc} B_{dL} & \begin{array}{c}\uparrow \\ \#(\boldsymbol{n_L}) \\ \downarrow\end{array} \\ \leftarrow \quad \#(\boldsymbol{d_L}) \quad \rightarrow & \end{array}} \end{array}\right) \boldsymbol{d_L} \equiv \mathcal{U}_{dL}\, \boldsymbol{d_L}, \quad \begin{array}{c} \boldsymbol{n_R} \equiv A_{dR}\, \boldsymbol{d_R} \\ \\ \boldsymbol{n_R} \equiv \mathcal{U}_{dR}\, \boldsymbol{d_R} \end{array}$$

where $n_d = \#(\boldsymbol{d_L}) = \#(\boldsymbol{N_L}) + \#(\boldsymbol{n_L}) = \#(\boldsymbol{n_R}) = \#(\boldsymbol{d_R})$.

Unitary transformation to the mass basis

Up quarks

$$\begin{pmatrix}\boldsymbol{P_L}\\ \boldsymbol{p_L}\end{pmatrix} = \begin{pmatrix} \boxed{\begin{array}{ccc} & & \uparrow \\ & A_{uL} & \#(\boldsymbol{P_L}) \\ & & \downarrow \\ \leftarrow & \#(\boldsymbol{u_L}) & \rightarrow \end{array}} \\ \\ \boxed{\begin{array}{ccc} & & \uparrow \\ & B_{uL} & \#(\boldsymbol{p_L}) \\ & & \downarrow \\ \leftarrow & \#(\boldsymbol{u_L}) & \rightarrow \end{array}} \end{pmatrix} \boldsymbol{u_L} \equiv \mathcal{U}_{uL}\,\boldsymbol{u_L}, \quad \begin{array}{l} \boldsymbol{p_R} \equiv A_{uR}\,\boldsymbol{u_R} \\ \\ \boldsymbol{p_R} \equiv \mathcal{U}_{uR}\,\boldsymbol{u_R} \end{array}$$

and $n_u = \#(\boldsymbol{u_L}) = \#(\boldsymbol{P_L}) + \#(\boldsymbol{p_L}) = \#(\boldsymbol{p_R}) = \#(\boldsymbol{u_R})$.

Unitarity of the “weak to mass” basis transformations

$$\mathcal{U}_{dL}\,\mathcal{U}_{dL}^{\dagger}=\begin{pmatrix}A_{dL}\,A_{dL}^{\dagger} & A_{dL}\,B_{dL}^{\dagger}\\ B_{dL}\,A_{dL}^{\dagger} & B_{dL}\,B_{dL}^{\dagger}\end{pmatrix}=\begin{pmatrix}\mathbf{1}_{\#(\boldsymbol{N_L})\times\#(\boldsymbol{N_L})} & \mathbf{0}_{\#(\boldsymbol{n_L})\times\#(\boldsymbol{N_L})}\\ \mathbf{0}_{\#(\boldsymbol{N_L})\times\#(\boldsymbol{n_L})} & \mathbf{1}_{\#(\boldsymbol{n_L})\times\#(\boldsymbol{n_L})}\end{pmatrix}$$

$$\mathcal{U}_{dL}^{\dagger}\,\mathcal{U}_{dL}=\left(A_{dL}^{\dagger}\,A_{dL}+B_{dL}^{\dagger}\,B_{dL}\right)=\mathbf{1}_{n_d\times n_d}$$

$$\mathcal{U}_{dR}\,\mathcal{U}_{dR}^{\dagger}=A_{dR}\,A_{dR}^{\dagger}=\mathbf{1}_{\#(\boldsymbol{n_R})\times\#(\boldsymbol{n_R})}=\mathbf{1}_{n_d\times n_d}$$

$$\mathcal{U}_{uL}\,\mathcal{U}_{uL}^{\dagger}=\begin{pmatrix}A_{uL}\,A_{uL}^{\dagger} & A_{uL}\,B_{uL}^{\dagger}\\ B_{uL}\,A_{uL}^{\dagger} & B_{uL}\,B_{uL}^{\dagger}\end{pmatrix}=\begin{pmatrix}\mathbf{1}_{\#(\boldsymbol{P_L})\times\#(\boldsymbol{P_L})} & \mathbf{0}_{\#(\boldsymbol{p_L})\times\#(\boldsymbol{P_L})}\\ \mathbf{0}_{\#(\boldsymbol{P_L})\times\#(\boldsymbol{p_L})} & \mathbf{1}_{\#(\boldsymbol{p_L})\times\#(\boldsymbol{p_L})}\end{pmatrix}$$

$$\mathcal{U}_{uL}^{\dagger}\,\mathcal{U}_{uL}=\left(A_{uL}^{\dagger}\,A_{uL}+B_{uL}^{\dagger}\,B_{uL}\right)=\mathbf{1}_{n_u\times n_u}$$

$$\mathcal{U}_{uR}\,\mathcal{U}_{uR}^{\dagger}=A_{uR}\,A_{uR}^{\dagger}=\mathbf{1}_{\#(\boldsymbol{p_R})\times\#(\boldsymbol{p_R})}=\mathbf{1}_{n_u\times n_u}$$

Diagonalisation

$$-\begin{pmatrix}\bar{\boldsymbol{N}}_{\boldsymbol{L}} & \bar{\boldsymbol{n}}_{\boldsymbol{L}}\end{pmatrix}\ \mathscr{M}_d\ \begin{pmatrix}\boldsymbol{n}_{\boldsymbol{R}}\end{pmatrix} = -\bar{\boldsymbol{d}}_{\boldsymbol{L}}\,\mathcal{U}_{dL}^{\dagger}\,\mathscr{M}_d\,\mathcal{U}_{dR}\,\boldsymbol{d}_{\boldsymbol{R}} = -\bar{\boldsymbol{d}}_{\boldsymbol{L}}\,\mathrm{diag}(m_{d_j})\,\boldsymbol{d}_{\boldsymbol{R}}$$

$$\begin{pmatrix}A_{dL}^{\dagger} & B_{dL}^{\dagger}\end{pmatrix}\begin{pmatrix}\frac{v}{\sqrt{2}}\boldsymbol{Y}_{\boldsymbol{d}} \\ \boldsymbol{\mu}_{\boldsymbol{d}}\end{pmatrix}\begin{pmatrix}A_{dR}\end{pmatrix} = \mathrm{diag}(m_{d_j}) \equiv \mathscr{D}_d$$

$$-\begin{pmatrix}\bar{\boldsymbol{P}}_{\boldsymbol{L}} & \bar{\boldsymbol{p}}_{\boldsymbol{L}}\end{pmatrix}\ \mathscr{M}_u\ \begin{pmatrix}\boldsymbol{p}_{\boldsymbol{R}}\end{pmatrix} = -\bar{\boldsymbol{u}}_{\boldsymbol{L}}\,\mathcal{U}_{uL}^{\dagger}\,\mathscr{M}_u\,\mathcal{U}_{uR}\,\boldsymbol{u}_{\boldsymbol{R}} = -\bar{\boldsymbol{u}}_{\boldsymbol{L}}\,\mathrm{diag}(m_{u_j})\,\boldsymbol{u}_{\boldsymbol{R}}$$

$$\begin{pmatrix}A_{uL}^{\dagger} & B_{uL}^{\dagger}\end{pmatrix}\begin{pmatrix}\frac{v}{\sqrt{2}}\boldsymbol{Y}_{\boldsymbol{u}} \\ \boldsymbol{\mu}_{\boldsymbol{u}}\end{pmatrix}\begin{pmatrix}A_{uR}\end{pmatrix} = \mathrm{diag}(m_{u_j}) \equiv \mathscr{D}_u$$

Gauge interactions, charged

$$\mathscr{L}_{\mathrm{W}} = -\frac{g}{\sqrt{2}} W^+_\mu J^\mu_{\mathrm{W}} + \text{H.C.}, \quad J^\mu_{\mathrm{W}} = \bar{\boldsymbol{P}}_{\boldsymbol{L}} \gamma^\mu \boldsymbol{N}_{\boldsymbol{L}}, \quad \sqrt{2} W^+ = W_1 - i W_2,$$

$$J^\mu_{\mathrm{W}} = \bar{\boldsymbol{P}}_{\boldsymbol{L}} \gamma^\mu \boldsymbol{N}_{\boldsymbol{L}} = \bar{\boldsymbol{u}}_{\boldsymbol{L}} A^\dagger_{uL} \gamma^\mu A_{dL} \boldsymbol{d}_{\boldsymbol{L}} = \bar{\boldsymbol{u}}_{\boldsymbol{L}} \gamma^\mu V_L \boldsymbol{d}_{\boldsymbol{L}}$$

- CKM matrix V_L, mismatch of rotations

$$V_L \equiv A^\dagger_{uL} A_{dL}, \quad \text{dimensions } [n_u \times \#(\mathbf{2}_{\boldsymbol{L}})] \cdot [\#(\mathbf{2}_{\boldsymbol{L}}) \times n_d] = [n_u \times n_d]$$

- CKM unitarity deviations

$$U_L \equiv V_L V_L^\dagger = A^\dagger_{uL} A_{uL} = \mathbf{1} - B^\dagger_{uL} B_{uL} \quad \text{dimensions } [n_u \times n_u]$$

$$D_L \equiv V_L^\dagger V_L = A^\dagger_{dL} A_{dL} = \mathbf{1} - B^\dagger_{dL} B_{dL} \quad \text{dimensions } [n_d \times n_d]$$

$$U_L V_L = V_L, \quad V_L D_L = V_L,$$

Gauge interactions, neutral

$$\mathscr{L}_{\rm NC} = -g \begin{pmatrix} \bar{\boldsymbol{P}}_{\boldsymbol{L}} & \bar{\boldsymbol{N}}_{\boldsymbol{L}} \end{pmatrix} \gamma_\mu \begin{pmatrix} \frac{\mathbf{1}}{\mathbf{2}} & \mathbf{0} \\ \mathbf{0} & -\frac{\mathbf{1}}{\mathbf{2}} \end{pmatrix} \begin{pmatrix} \boldsymbol{P}_{\boldsymbol{L}} \\ \boldsymbol{N}_{\boldsymbol{L}} \end{pmatrix} W_3^\mu$$
$$- g' y_{\mathbf{2_L}} \bar{\boldsymbol{P}}_{\boldsymbol{L}} \gamma_\mu \boldsymbol{P}_{\boldsymbol{L}} B^\mu - g' y_{\mathbf{2_L}} \bar{\boldsymbol{N}}_{\boldsymbol{L}} \gamma_\mu \boldsymbol{N}_{\boldsymbol{L}} B^\mu$$
$$- g' y_{\mathbf{1_u}} \bar{\boldsymbol{p}}_{\boldsymbol{L}} \gamma_\mu \boldsymbol{p}_{\boldsymbol{L}} B^\mu - g' y_{\mathbf{1_u}} \bar{\boldsymbol{p}}_{\boldsymbol{R}} \gamma_\mu \boldsymbol{p}_{\boldsymbol{R}} B^\mu$$
$$- g' y_{\mathbf{1_d}} \bar{\boldsymbol{n}}_{\boldsymbol{L}} \gamma_\mu \boldsymbol{n}_{\boldsymbol{L}} B^\mu - g' y_{\mathbf{1_d}} \bar{\boldsymbol{n}}_{\boldsymbol{R}} \gamma_\mu \boldsymbol{n}_{\boldsymbol{R}} B^\mu$$

...

$$\mathscr{L}_{\rm NC} = -\frac{g}{c_w} Z_\mu J^\mu_{\rm Z} - e A_\mu J^\mu_{\rm EM}$$

with

$$J^\mu_{\rm Z} = \frac{1}{2} \left[\bar{\boldsymbol{u}}_{\boldsymbol{L}} \gamma^\mu U_L \boldsymbol{u}_{\boldsymbol{L}} - \bar{\boldsymbol{d}}_{\boldsymbol{L}} \gamma^\mu D_L \boldsymbol{d}_{\boldsymbol{L}} \right] - s_w^2 J^\mu_{\rm EM}$$

$$J^\mu_{\rm EM} = \frac{2}{3} \bar{\boldsymbol{u}}_{\boldsymbol{L}} \gamma^\mu \boldsymbol{u}_{\boldsymbol{L}} + \frac{2}{3} \bar{\boldsymbol{u}}_{\boldsymbol{R}} \gamma^\mu \boldsymbol{u}_{\boldsymbol{R}} - \frac{1}{3} \bar{\boldsymbol{d}}_{\boldsymbol{L}} \gamma^\mu \boldsymbol{d}_{\boldsymbol{L}} - \frac{1}{3} \bar{\boldsymbol{d}}_{\boldsymbol{R}} \gamma^\mu \boldsymbol{d}_{\boldsymbol{R}}$$

Higgs couplings to fermions

Down sector

$$\mathscr{L}_{h\bar{d}d} = -\frac{h}{\sqrt{2}} \begin{pmatrix} \bar{\boldsymbol{N}}_{\boldsymbol{L}} & \bar{\boldsymbol{n}}_{\boldsymbol{L}} \end{pmatrix} \begin{pmatrix} \boldsymbol{Y_d} \\ \boldsymbol{0} \end{pmatrix} \begin{pmatrix} \boldsymbol{n_R} \\ \boldsymbol{N_R} \end{pmatrix} = \\ -\frac{h}{\sqrt{2}} \bar{\boldsymbol{d}}_{\boldsymbol{L}} \begin{pmatrix} A_{dL}^{\dagger} & B_{dL}^{\dagger} \end{pmatrix} \begin{pmatrix} \boldsymbol{Y_d} \\ \boldsymbol{0} \end{pmatrix} \begin{pmatrix} A_{dR} \end{pmatrix} \boldsymbol{d_R}$$

In the mass matrix

$$A_{dL}^{\dagger} \frac{v}{\sqrt{2}} \boldsymbol{Y_d} A_{dR} + B_{dL}^{\dagger} \boldsymbol{\mu_d} A_{dR} = \mathscr{D}_d$$

Left multiplication with D_L, using $D_L A_{dL}^{\dagger} = A_{dL}^{\dagger}$ and $D_L B_{dL}^{\dagger} = \boldsymbol{0}$,

$$A_{dL}^{\dagger} \frac{1}{\sqrt{2}} \boldsymbol{Y_d} A_{dR} = \frac{1}{v} D_L \mathscr{D}_d$$

Higgs couplings to fermions

Up sector

As in the down sector, U_L instead of D_L, etc.

Higgs couplings to fermions

$$\mathscr{L}_{h\bar{d}d} = -\frac{h}{v}\,\boldsymbol{\bar{d}_L}\,D_L\,\mathscr{D}_d\,\boldsymbol{d_R} + \text{H.C.}$$

$$\mathscr{L}_{h\bar{u}u} = -\frac{h}{v}\,\boldsymbol{\bar{u}_L}\,U_L\,\mathscr{D}_u\,\boldsymbol{u_R} + \text{H.C.}$$

Unitary embedding of CKM

$$\widehat{V_L} = \begin{pmatrix} V_L = A_{uL}^{\dagger} A_{dL} & B_{uL}^{\dagger} \\ B_{dL} & 0 \end{pmatrix} =$$

$$\begin{pmatrix} \boxed{\begin{matrix} & V_L & & \uparrow \\ & & & n_u \\ & & & \downarrow \\ \leftarrow & n_d & \rightarrow & \end{matrix}} & \boxed{\begin{matrix} & B_{uL}^{\dagger} & & \uparrow \\ & & & n_u \\ & & & \downarrow \\ \leftarrow & \#(\boldsymbol{p_L}) & \rightarrow & \end{matrix}} \\ \boxed{\begin{matrix} & B_{dL} & & \uparrow \\ & & & \#(\boldsymbol{n_L}) \\ & & & \downarrow \\ \leftarrow & n_d & \rightarrow & \end{matrix}} & \boxed{\begin{matrix} & 0 & & \uparrow \\ & & & \#(\boldsymbol{n_L}) \\ & & & \downarrow \\ \leftarrow & \#(\boldsymbol{p_L}) & \rightarrow & \end{matrix}} \end{pmatrix}$$

Dimension

$$\#(\boldsymbol{n_L}) + n_u = \#(\boldsymbol{p_L}) + n_d = \#(\boldsymbol{Q_L}) + \#(\boldsymbol{p_L}) + \#(\boldsymbol{n_L}) \equiv (\#L)$$

Unitary embedding of CKM

$$\widehat{V_L}\widehat{V_L}^\dagger = \begin{pmatrix} V_L V_L^\dagger + B_{uL}^\dagger B_{uL} & V_L B_{dL}^\dagger \\ B_{dL} V_L^\dagger & B_{dL} B_{dL}^\dagger \end{pmatrix} = \begin{pmatrix} U_L + B_{uL}^\dagger B_{uL} & A_{uL}^\dagger A_{dL} B_{dL}^\dagger \\ B_{dL} A_{dL}^\dagger A_{uL} & B_{dL} B_{dL}^\dagger \end{pmatrix} = \begin{pmatrix} \mathbf{1}_{n_u\times n_u} & \mathbf{0} \\ \mathbf{0} & \mathbf{1}_{\#(\boldsymbol{n_L})\times\#(\boldsymbol{n_L})} \end{pmatrix} = \mathbf{1}_{(\#L)\times(\#L)}$$

$$\widehat{V_L}^\dagger\widehat{V_L} = \begin{pmatrix} V_L^\dagger V_L + B_{dL}^\dagger B_{dL} & V_L^\dagger B_{uL}^\dagger \\ B_{uL} V_L & B_{uL} B_{uL}^\dagger \end{pmatrix} = \begin{pmatrix} D_L + B_{dL}^\dagger B_{dL} & A_{dL}^\dagger A_{uL} B_{uL}^\dagger \\ B_{uL} A_{uL}^\dagger A_{dL} & B_{uL} B_{uL}^\dagger \end{pmatrix} = \begin{pmatrix} \mathbf{1}_{n_d\times n_d} & \mathbf{0} \\ \mathbf{0} & \mathbf{1}_{\#(\boldsymbol{p_L})\times\#(\boldsymbol{p_L})} \end{pmatrix} = \mathbf{1}_{(\#L)\times(\#L)}$$

Short summary

- CKM is not 3×3 unitary (embedded in a larger unitary matrix)
- Modified tree level W Flavour Changing couplings
- Tree level Z Flavour Changing couplings
- Modified tree level Z Flavour Conserving couplings
- Tree level h Flavour Changing couplings
- New particles

Example with just a 1 Up Vector-like singlet

- CKM has dimensions 4×3, orthonormal *columns*
- CKM embedded in 4×4 unitary matrix

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

- No tree-level FCNC in the *down* sector
- Tree-level FCNC in the *up* sector, e.g. tcZ coupling

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

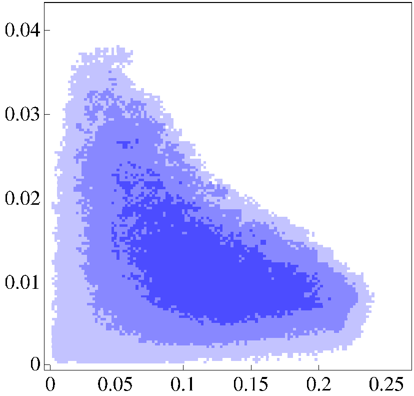
- Modified Z couplings, e.g. ttZ

$$\frac{g}{c_W}\bar{t}_L\gamma^\mu(1-|U_{t4}|^2)t_L\ Z_\mu$$

Observables – Summary & values

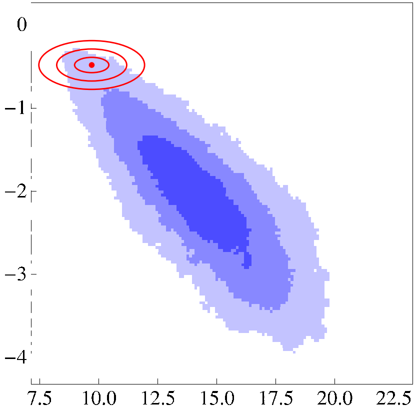
Observable	Exp. Value	Observable	Exp. Value
$\|V_{ud}\|$	0.97425 ± 0.00022	$\|V_{us}\|$	0.2252 ± 0.0009
$\|V_{cd}\|$	0.230 ± 0.011	$\|V_{cs}\|$	1.023 ± 0.036
$\|V_{ub}\|$	0.00375 ± 0.00040	$\|V_{cb}\|$	0.041 ± 0.001
$A_{J/\psi K_S} = \sin 2\bar{\beta}$	0.68 ± 0.02	$\Delta M_{B_d} (\times \text{ ps})$	0.508 ± 0.004
$A_{J/\Psi\Phi} = \sin 2\bar{\beta}_s$	0.01 ± 0.07	$\Delta M_{B_s} (\times \text{ ps})$	17.725 ± 0.049
γ	$(68 \pm 8)^\circ \bmod 180^\circ$	$\sin(2\bar{\alpha})$	0.00 ± 0.15
$\sin(2\bar{\beta} + \gamma)$	1.00 ± 0.16	$\cos(2\bar{\beta})$	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

Botella, Branco & N 1207.4440 (JHEP)

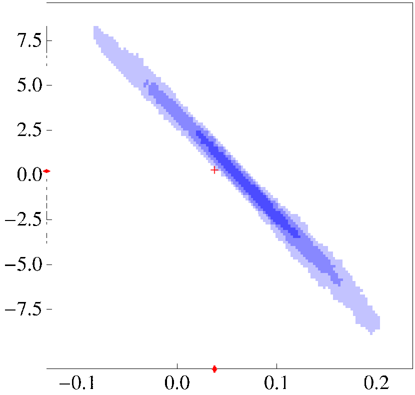


$|V_{Td}|$ vs.$|V_{Tb}|$

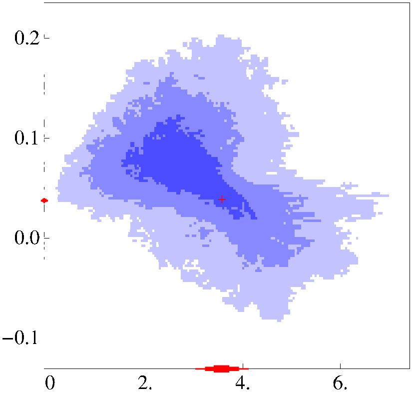
68%, 95% and 99% CL regions (darker to lighter)



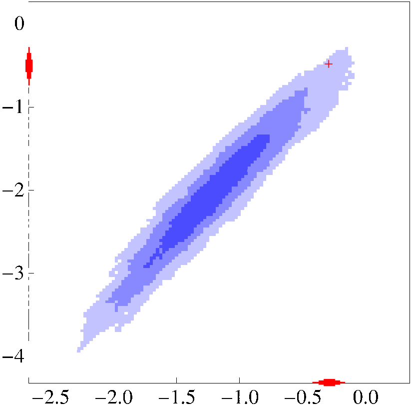
$A_{SL}^{d} \times 10^{3}$ vs. $\mathrm{Br}(B^{+} \to \tau^{+}\nu_{\tau}) \times 10^{5}$



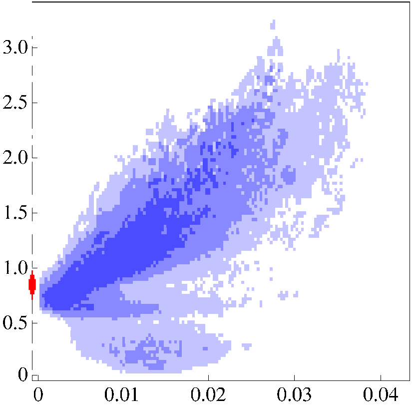
$$A^s_{SL} \times 10^4 \text{ vs. } A_{J/\Psi\Phi}$$



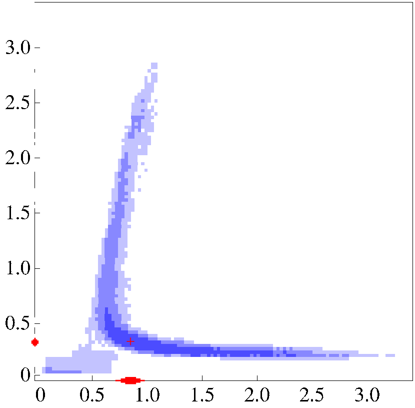
$A_{J/\Psi\Phi}$ vs. $\text{Br}(B_s \to \mu^+\mu^-) \times 10^9$



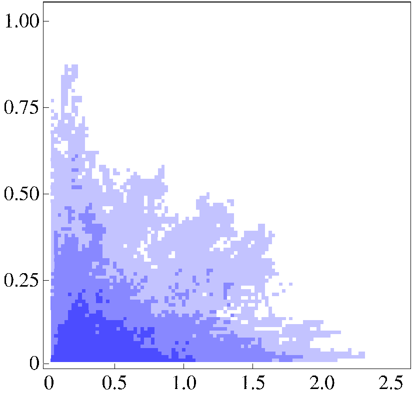
$$A^d_{SL} \times 10^3 \text{ vs. } A^b_{SL} \times 10^3$$



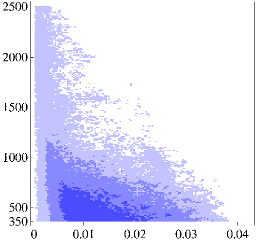
$$\mathrm{Br}(K^+ \to \pi^+\nu\bar{\nu}) \times 10^{10} \text{ vs. } |V_{Ts}|$$



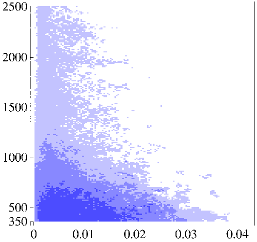
$$\mathrm{Br}(K_L \to \pi^0 \nu \bar{\nu}) \times 10^{10} \text{ vs. } \mathrm{Br}(K^+ \to \pi^+ \nu \bar{\nu}) \times 10^{10}$$



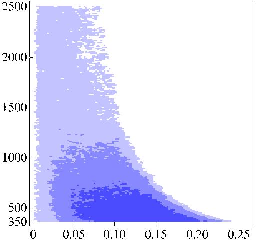
$$\mathrm{Br}(t \to cZ) \times 10^5 \text{ vs. } \mathrm{Br}(t \to uZ) \times 10^5$$



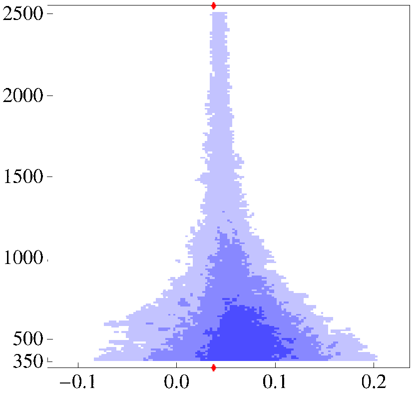
m_T vs. $|V_{Td}|$



m_T vs. $|V_{Ts}|$



m_T vs. $|V_{Tb}|$



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

Model with 3 Up + 3 Down VLQ singlets

- The scope of this scenario is completely different (generate CKM and masses)
- "Safe" example from the flavour point of view
- CKM is 6×6
- Additional aspect: decays

Botella, Branco, N, Rebelo & Silva-Marcos, 1610.03018, *to appear* EPJC

Interlude – Fermion decays

$F_1 \to F_2 h$, $F_1 \to F_2 V$

Coupling $h\bar{F}_2\,(a+ib\gamma_5)\,F_1$

$$\Gamma(F_1 \to F_2 h) = \frac{m_{F_1}}{16\pi}\sqrt{(1-(\sqrt{x}+\sqrt{y})^2)(1-(\sqrt{x}-\sqrt{y})^2)} \times \left\{(|a|^2+|b|^2)(1+y-x)+2(|a|^2-|b|^2)\sqrt{y}\right\},$$

$$y=\frac{m_{F_2}^2}{m_{F_1}^2},\ x=\frac{m_h^2}{m_{F_1}^2}$$

Coupling $V_\mu\bar{F}_2\,\gamma^\mu(a+b\gamma_5)\,F_1$

$$\Gamma(F_1 \to F_2 V) = \frac{m_{F_1}}{16\pi}\sqrt{(1-(\sqrt{x}+\sqrt{y})^2)(1-(\sqrt{x}-\sqrt{y})^2)} \times \left\{(|a|^2+|b|^2)(1+y-2x+[1-y]^2/x)-6(|a|^2-|b|^2)\sqrt{y}\right\},$$

$$y=\frac{m_{F_2}^2}{m_{F_1}^2},\ x=\frac{m_V^2}{m_{F_1}^2}$$

Interlude – Fermion decays

No right-handed doublets

$$\Gamma(D_j \to D_i Z) = \frac{M_{D_j}^3}{32\pi v^2} |(V_L^\dagger V_L)_{ij}|^2 \, f_V(x_{Zj}, y_{ij})$$

$$\Gamma(D_j \to D_i h) = \frac{M_{D_j}^3}{32\pi v^2} |(V_L^\dagger V_L)_{ij}|^2 \, f_S(x_{hj}, y_{ij})$$

$$\Gamma(D_j \to U_i W) = \frac{M_{D_j}^3}{16\pi v^2} |(V_L)_{ij}|^2 \, f_V(x_{Wj}, y_{ij})$$

$$x_{Vj} = \frac{M_V^2}{M_{F_j}^2},\ x_{hj} = \frac{M_h^2}{M_{F_j}^2},\ y_{ij} = \frac{M_{F_i}^2}{M_{F_j}^2}$$

$$f_V(x,y) = \sqrt{(1-(\sqrt{y}+\sqrt{x})^2)(1-(\sqrt{y}-\sqrt{x})^2)}\,((1-y)^2+x(1+y)-2x^2)$$

$$f_S(x,y) = \sqrt{(1-(\sqrt{y}+\sqrt{x})^2)(1-(\sqrt{y}-\sqrt{x})^2)}(1+y-x)$$

Interlude – Fermion decays

No right-handed doublets

Similarly

$$\Gamma(U_j \to U_i Z) = \frac{M_{U_j}^3}{32\pi v^2} |(V_L V_L^\dagger)_{ij}|^2 \, f_V(x_{Zj}, y_{ij})$$

$$\Gamma(U_j \to D_i W) = \frac{M_{U_j}^3}{16\pi v^2} |(V_L)_{ji}|^2 \, f_V(x_{Wj}, y_{ij})$$

$$\Gamma(U_j \to U_i h) = \frac{M_{U_j}^3}{32\pi v^2} |(V_L V_L^\dagger)_{ij}|^2 \, f_S(x_{hj}, y_{ij})$$

$$f_V(0,0) = f_S(0,0) = 1$$

For decays *heavy* generation j to *light* generation i,

$$\Gamma(j \to iW) : \Gamma(j \to iZ) : \Gamma(j \to ih) \simeq 2 : 1 : 1$$

per generation

3 Up + 3 Down singlets

Back to the example ...
Yukawa and mass matrices ...

Masses (GeV)

$$\begin{pmatrix} m_{D_1} \\ m_{D_2} \\ m_{D_3} \end{pmatrix} = \begin{pmatrix} 775 \\ 1621 \\ 1957 \end{pmatrix}, \quad \begin{pmatrix} m_{U_1} \\ m_{U_2} \\ m_{U_3} \end{pmatrix} = \begin{pmatrix} 1313 \\ 1507 \\ 2261 \end{pmatrix}$$

Mixings

$$|V| =$$

$$\begin{pmatrix}
0.97446 & 0.22459 & 0.003631 & 2.2\cdot 10^{-6} & 9.8\cdot 10^{-6} & 2.9\cdot 10^{-5} \\
0.22446 & 0.97361 & 0.041118 & 2.8\cdot 10^{-5} & 2.3\cdot 10^{-4} & 3.7\cdot 10^{-5} \\
0.00850 & 0.039901 & 0.987685 & 1.4\cdot 10^{-5} & 4.9\cdot 10^{-4} & 3.7\cdot 10^{-4} \\
1.3\cdot 10^{-3} & 6.1\cdot 10^{-3} & 0.150913 & 2.1\cdot 10^{-6} & 7.5\cdot 10^{-5} & 5.7\cdot 10^{-5} \\
5.4\cdot 10^{-4} & 2.4\cdot 10^{-3} & 1.0\cdot 10^{-4} & 6.7\cdot 10^{-8} & 5.5\cdot 10^{-7} & 9.0\cdot 10^{-8} \\
8.5\cdot 10^{-6} & 3.3\cdot 10^{-5} & 1.4\cdot 10^{-6} & 9.2\cdot 10^{-10} & 7.6\cdot 10^{-9} & 1.2\cdot 10^{-9}
\end{pmatrix}$$

Mixings – Unitarity deviations, Up

$$|V_L V_L^\dagger| =$$

$$\begin{pmatrix} 1 & 1.1\cdot 10^{-8} & 2.9\cdot 10^{-17} & 4.5\cdot 10^{-18} & 4.7\cdot 10^{-6} & 4.0\cdot 10^{-6} \\ 1.1\cdot 10^{-8} & 1 & 2.2\cdot 10^{-17} & 5.7\cdot 10^{-17} & 2.4\cdot 10^{-3} & 3.4\cdot 10^{-5} \\ 2.9\cdot 10^{-17} & 2.2\cdot 10^{-17} & 0.977 & 0.149 & 1.7\cdot 10^{-16} & 2.2\cdot 10^{-18} \\ 4.5\cdot 10^{-18} & 5.7\cdot 10^{-17} & 0.149 & 2.28\cdot 10^{-2} & 2.6\cdot 10^{-17} & 3.3\cdot 10^{-19} \\ 4.7\cdot 10^{-6} & 2.4\cdot 10^{-3} & 1.7\cdot 10^{-16} & 2.6\cdot 10^{-17} & 5.8\cdot 10^{-6} & 8.1\cdot 10^{-8} \\ 4.0\cdot 10^{-6} & 3.4\cdot 10^{-5} & 2.2\cdot 10^{-18} & 3.3\cdot 10^{-19} & 8.1\cdot 10^{-8} & 1.1\cdot 10^{-9} \end{pmatrix}$$

Mixings – Unitarity deviations, Down

$$|V_L^\dagger V_L| =$$

$$\begin{pmatrix} 1 & 1.4\cdot 10^{-8} & 3.0\cdot 10^{-8} & 6.0\cdot 10^{-16} & 6.3\cdot 10^{-5} & 2.3\cdot 10^{-5} \\ 1.4\cdot 10^{-8} & 1 & 1.4\cdot 10^{-7} & 2.8\cdot 10^{-5} & 2.4\cdot 10^{-4} & 5.6\cdot 10^{-5} \\ 3.0\cdot 10^{-8} & 1.4\cdot 10^{-7} & 1 & 1.3\cdot 10^{-5} & 4.9\cdot 10^{-4} & 3.7\cdot 10^{-4} \\ 6.0\cdot 10^{-6} & 2.8\cdot 10^{-5} & 1.3\cdot 10^{-5} & 9.6\cdot 10^{-10} & 1.3\cdot 10^{-8} & 6.3\cdot 10^{-9} \\ 6.3\cdot 10^{-5} & 2.4\cdot 10^{-4} & 4.9\cdot 10^{-4} & 1.3\cdot 10^{-8} & 3.0\cdot 10^{-7} & 1.9\cdot 10^{-7} \\ 2.3\cdot 10^{-5} & 5.6\cdot 10^{-5} & 3.7\cdot 10^{-4} & 6.3\cdot 10^{-9} & 1.9\cdot 10^{-7} & 1.4\cdot 10^{-7} \end{pmatrix}$$

Decays

	Width (MeV)	Branching ratio to channel (%):								
		Zd	Zs	Zb	hd	hs	hb	Wu	Wc	Wt
D_1	$3 \cdot 10^{-4}$	0.9	20.3	4.4	0.9	19.3	4.2	0.2	40.7	8.8
D_2	0.81	0.3	4.9	20.4	0.3	4.9	20.2	0	8.9	40.0
D_3	0.69	0	0.5	24.9	0	0.5	24.7	0.3	0.5	48.1

	Width (GeV)	Branching ratio to channel (%):								
		Zu	Zc	Zt	hu	hc	ht	Wd	Ws	Wb
U_1	32.9	0	0	23.9	0	0	24.7	0	0	51.4
U_2	10^{-2}	0	25.1	0	0	24.7	0	2.5	47.6	0
U_3	$9 \cdot 10^{-6}$	0.3	24.7	0	0.3	24.5	0	3.2	46.8	0

Conclusions

- Rich class of Standard Model extensions
- Can produce patterns of deviations from SM in different observables (correlations)
- Could be directly produced

There's nothing remarkable about it. All one has to do is hit the right keys at the right time and the instrument plays itself.

Johann Sebastian Bach

Thank you

Backup

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

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

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–$\bar{D}^0$.