Gauging Flavour Symmetries

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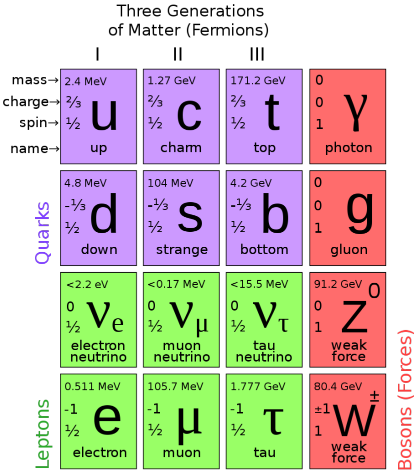
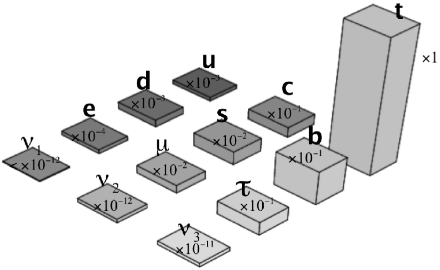
Matter content of the SM



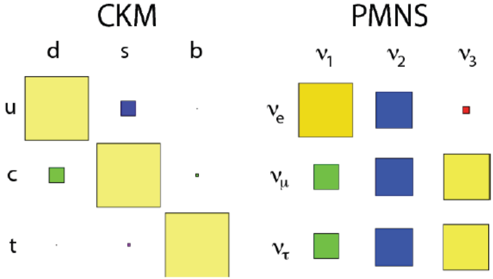
- Why do we have three families of quarks and leptons?

Masses



- Why do quarks and leptons have so different masses?
- Mass hierarchy

Mixings



- Why is quark mixing so small?
- Why is neutrino mixing so large?

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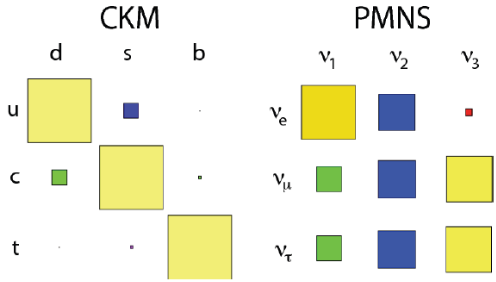

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The New Physics Flavour puzzle

- Flavour Changing Neutral Currents are highly suppressed in the SM (loop-, CKM- and GIM suppressed).
- In general, theories BSM do include flavour changing processes.
- However, so far all FCNC data is compatible with the SM.

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- Why there is no Flavour Violation BSM?

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Lagrangian of the Standard Model

$$\mathcal{L}_{SM} = \mathcal{L}_{gauge} + \mathcal{L}_{Higgs} \qquad (1)$$

$\mathcal{L}_{gauge}$

- Natural
- Experimentally tested with high accuracy
- Three identical replica of the basic fermion family
- Highly symmetric

$\mathcal{L}_{Higgs}$

- Ad hoc.
- Needed to describe data but not tested in its dynamical form
- Generates the yukawa terms $\Longrightarrow$ different masses for each fermion.

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Contenido

Flavour symmetry in the quark sector

- In the massless limit, the quark sector has the flavour or horizontal symmetry:

$$U(3)_{Q_L} \otimes U(3)_{u_R} \otimes U(3)_{d_R} \tag{2}$$

$$Q_L^\alpha = \left\{ \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \begin{pmatrix} t_L \\ b_L \end{pmatrix} \right\}, \quad U_R^\alpha = \{u_R, c_R, t_R\} \quad D_R^\alpha = \{d_R, s_R, b_R\},$$

- It can be decomposed in:

$$U_B(1) \otimes U_Y(1) \otimes U_R(1) \otimes G_f \tag{3}$$

- We will focus on:

$$G_f = SU(3)_{Q_L} \otimes SU(3)_{u_R} \otimes SU(3)_{d_R} \tag{4}$$

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Minimal Flavour Violation

- Hypothesis: there is an underlying flavour dynamics that at low energies only manifests through the Yukawa couplings.
- We can implement it considering G_f as a good symmetry

$$G_f = SU(3)_{Q_L} \otimes SU(3)_{u_R} \otimes SU(3)_{d_R} \tag{5}$$

- and promoting the Yukawa couplings to non-dynamical fields (spurions) that transform:

$$Y_u \sim (\bar{3}, 3, 1) \qquad Y_d \sim (\bar{3}, 1, 3) \tag{6}$$

- Simple idea but predictive.
- Does not explain the hierarchical structure of the Yukawa couplings $\implies$ not a theory of flavour.
- Difficult to implement the high energy dynamics: to recover the mass terms at low energies this flavour symmetry must be broken by the VEV of Y_u, Y_d:

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Gauging the flavour symmetry

- Promoting the global symmetry to a local (gauge) one we avoid the unwanted GB.
- By solving flavour $\Longrightarrow$ new interaction BSM.
- New gauge bosons: $8+8+8=24$

$$A_Q^a \qquad A_U^a \qquad A_D^a \qquad a=0,1,...,8 \tag{8}$$

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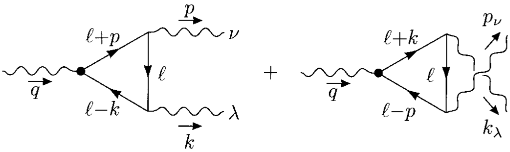

$$\propto Tr[t^a\{t^b,t^c\}] \quad (9)$$

- Problematic ones, hypercharge in the left vertex. We need:

$$\sum(Y_{RH}-Y_{LH})=0 \quad (10)$$

- We introduce new fermionic fields that willl cancell the anomalies: $\Psi_{u_L}, \Psi_{d_L}, \Psi_{u_R}, \Psi_{d_R}$(colourful, but singlets of $SU(2)_L$)

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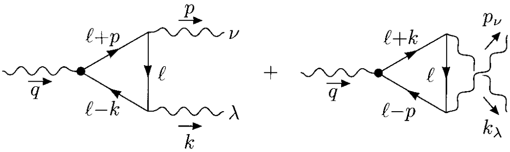

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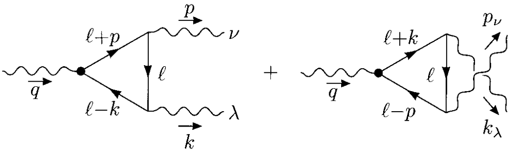

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Transformation properties

	Q_L	U_R	D_R	H	Ψ_{u_R}	Ψ_{d_R}	Ψ_{u_L}	Ψ_{d_L}	Y_u	Y_d
$SU(3)_c$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	$+^1/_6$	$+^2/_3$	$-^1/_3$	$+^1/_2$	$+^2/_3$	$-^1/_3$	$+^2/_3$	$-^1/_3$	0	0
$SU(3)_{Q_L}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\overline{\mathbf{3}}$	$\overline{\mathbf{3}}$
$SU(3)_{U_R}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$
$SU(3)_{D_R}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{3}$

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Breaking of the Flavour Symmetry

- Analogous to Higgs mechanism
- We do not encounter GB, but give mass to the new gauge bosons A_Q, A_U, A_D
- Higgs role $\Longleftrightarrow$Yukawa fields (flavons) Y_u, Y_d promoted to dynamical fields
- The most general renormalizable Lagrangian:
- The scalar potential $V(Y_u, Y_d, H)$ will give rise to the electroweak and flavour symmetry breaking.

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\begin{aligned}
\mathcal{L} =& \mathcal{L}_{kin} - V(Y_u, Y_d, H) + \\
& (\lambda_u \overline{Q}_L \tilde{H} \Psi_{uR} + \lambda'_u \overline{\Psi}_u Y_u \Psi_{uR} + M_u \overline{\Psi}_u U_R + \\
& \lambda_d \overline{Q}_L H \Psi_{dR} + \lambda'_d \overline{\Psi}_d Y_d \Psi_{dR} + M_d \overline{\Psi}_d D_R + h.c.) ,
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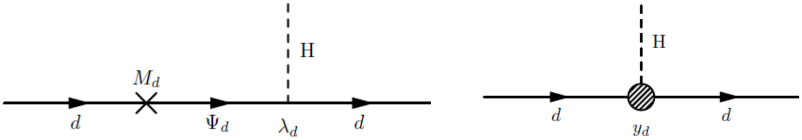
Masses of the SM quarks

- See-saw mechanism



- When we integrate out the exotic fermions we generate an effective mass for the SM quarks:

$$y_u = V^\dagger \frac{\lambda_u M_u}{\lambda'_u \hat{Y}_u} \qquad y_d = \frac{\lambda_d M_d}{\lambda'_d \hat{Y}_d} \tag{11}$$

$\Longrightarrow$ Inverted hierarchy $\Longrightarrow$ electroweak precision bounds are easlily avoided.

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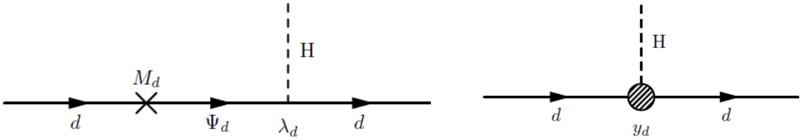

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Masses of the gauge bosons

- Generated by the breaking of the flavour symmetry.

$$D_\mu \langle Y_u \rangle = \partial_\mu - i g_Q A^a_{Q\,\mu} \langle Y_u \rangle \frac{\lambda^a}{2} + i g_U A^a_{U\,\mu} \frac{\lambda^a}{2} \langle Y_u \rangle \tag{12}$$

$$D_\mu \langle Y_d \rangle = \partial_\mu - i g_Q A^a_Q \langle Y_d \rangle \frac{\lambda^a}{2} + i g_D A^a_D \frac{\lambda^a}{2} \langle Y_d \rangle \tag{13}$$

- The mass arises from the quadratic terms of the kinetic term of the flavon field:

$$Tr\left[(D_\mu \langle Y_u \rangle)^\dagger (D^\mu \langle Y_u \rangle) \right] + Tr\left[(D_\mu \langle Y_d \rangle)^\dagger (D^\mu \langle Y_d \rangle) \right] \tag{14}$$

$$\mathscr{L}_{mass} = Tr \left| g_U A_U \langle Y_u \rangle - g_Q \langle Y_u \rangle A_Q \right|^2 + Tr \left| g_D A_D \langle Y_d \rangle - g_Q \langle Y_d \rangle A_Q \right|^2 \tag{15}$$

$$= \frac{1}{2} V_{Aa} \left(M_V^2 \right)^{Aa,Bb} V_{Bb} \tag{16}$$

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$$= \frac{1}{2} V_{Aa} \left(M_V^2 \right)^{Aa,Bb} V_{Bb} \tag{16}$$

Example

- We choose the following values for the free parameters of the model:

M_u (GeV)	M_d (GeV)	λ_u	λ'_u	λ_d	λ'_d	g_Q	g_U	g_D
400	100	1	0.5	0.25	0.3	0.4	0.3	0.5

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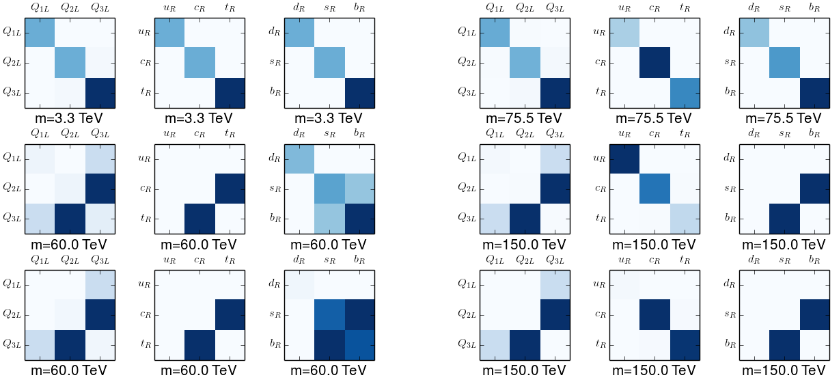
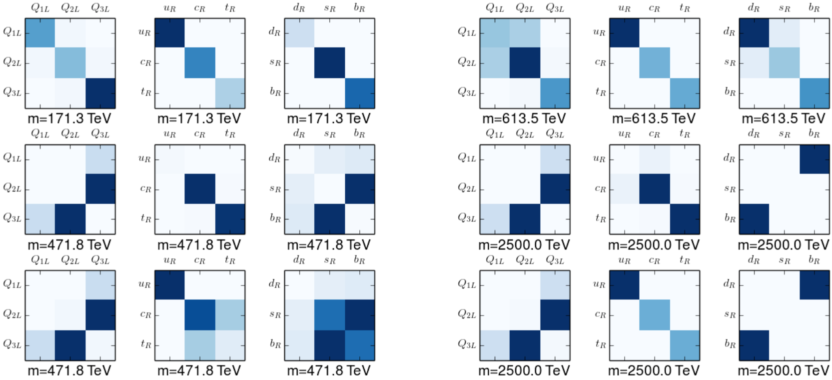
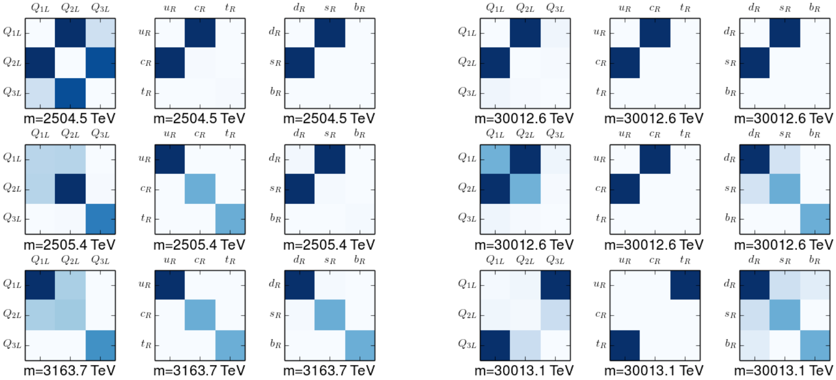
Quark Mixings by the flavour gauge bosons I



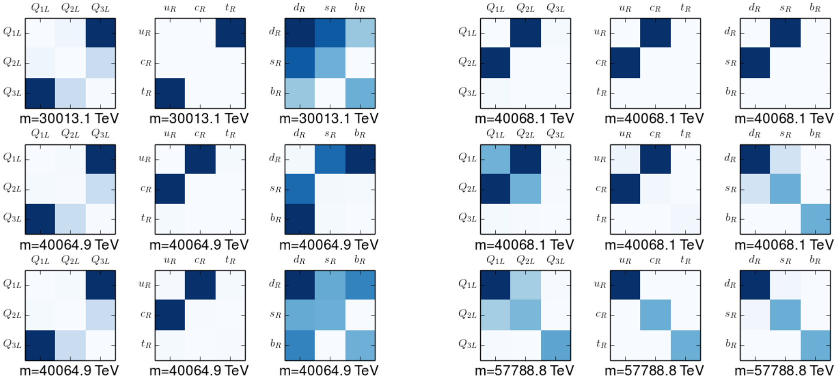
Quark Mixings by the flavour gauge bosons II



Quark Mixings by the flavour gauge bosons III



Quark Mixings by the flavour gauge bosons IV



Summary

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  - 24 new gauge bosons
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What is next?

- Moving to the lepton sector
- Different possible symmetry groups due to neutrinos:
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