YOUNG SCIENTIST WORKSHOP 2011

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MAXIMALLY GAUGED FLAVOUR SYMMETRIES

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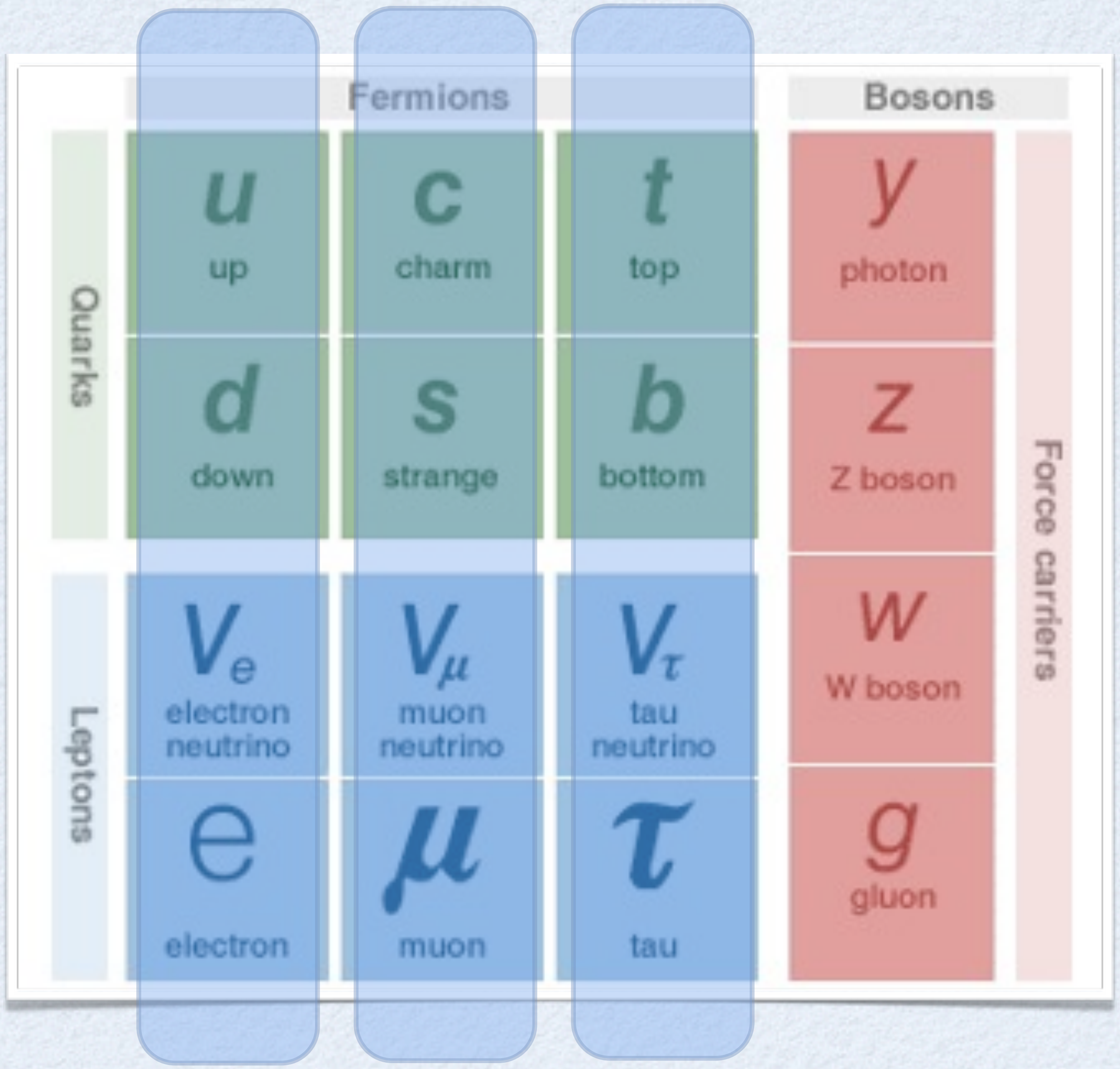
MAX-PLANCK-GESELLSCHAFT

Outline

- Introduction: Flavour Models
- Building a model with Gauged Flavour Symmetries
- Characteristics and phenomenology of the model
- Conclusions and Outlook

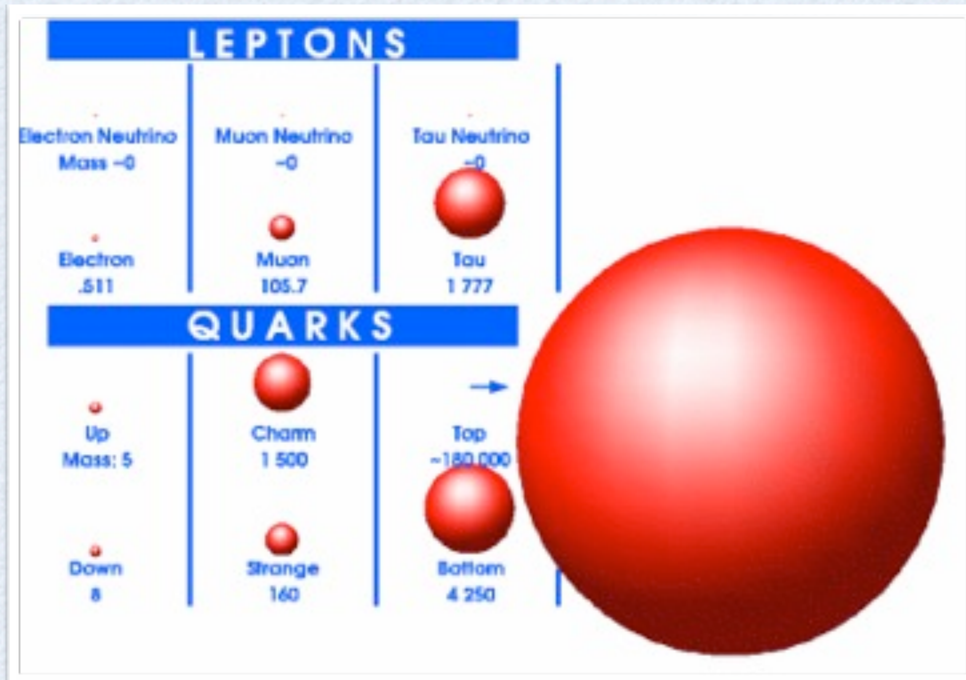
Introduction

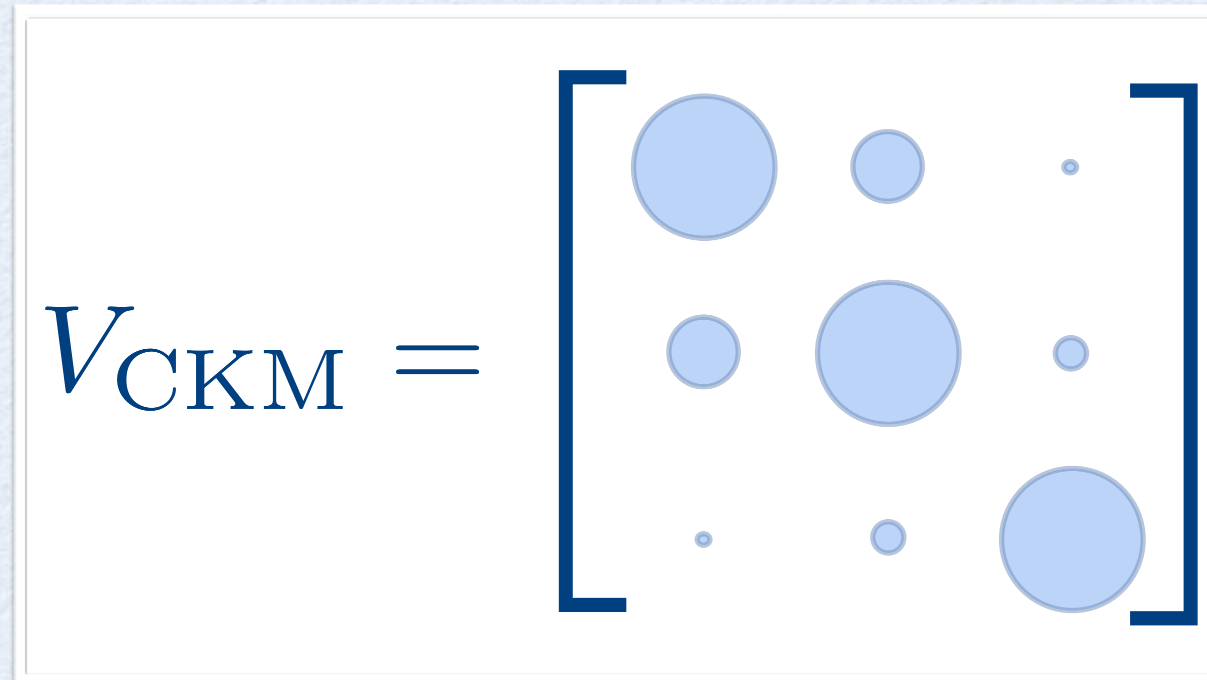
Flavour Symmetry...



$$\mathcal{G}_F = U(3)_{Q_L} \times U(3)_{U_R} \times U(3)_{D_R}$$

… AND ITS BREAKING





$$\mathcal{L}_Y = -\bar{Q}_L Y_d D_R H - \bar{Q}_L Y_u U_R H^c$$

$$\mathcal{G}_F \to U(1)_B \times U(1)_Y$$

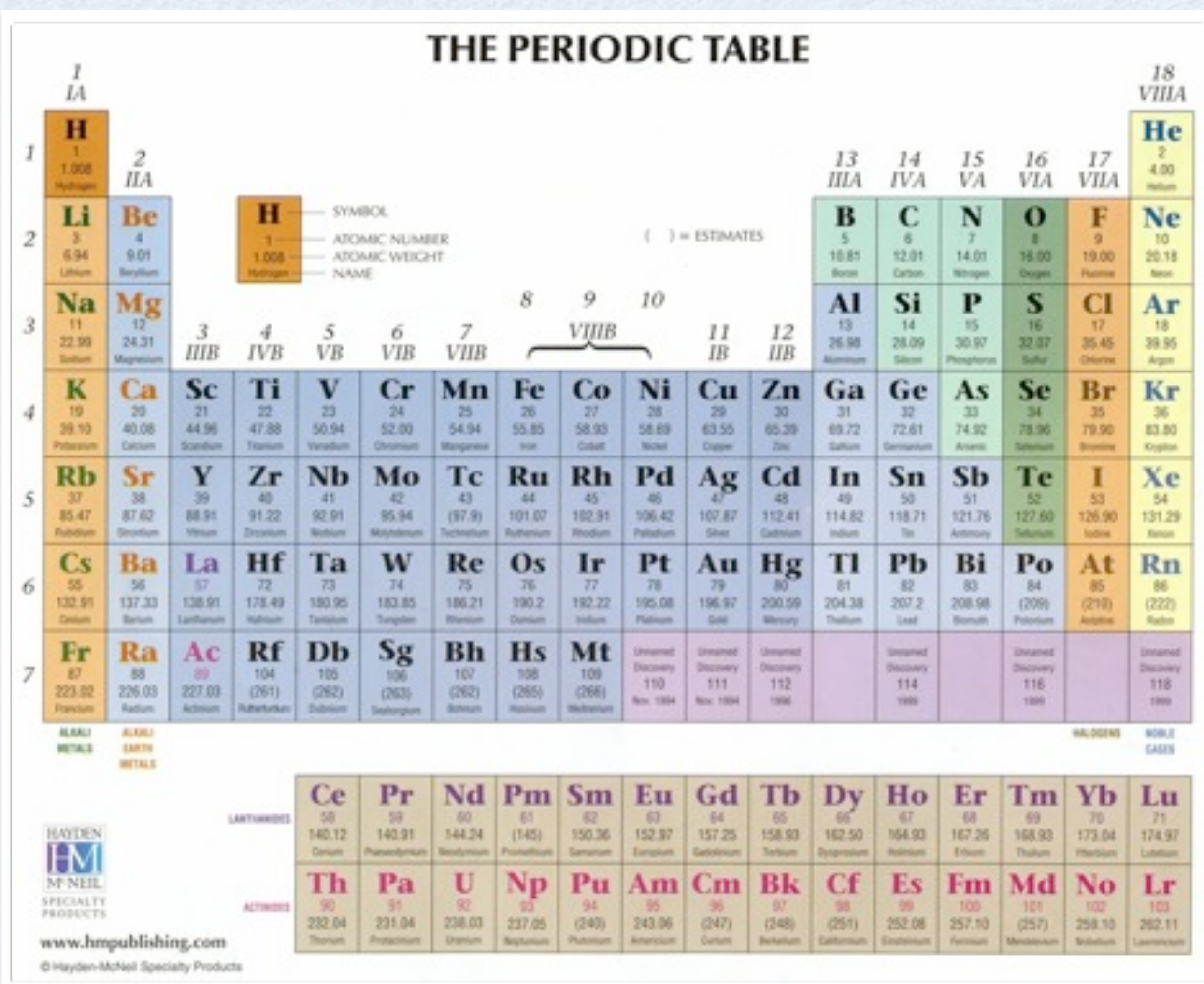
Flavour Models

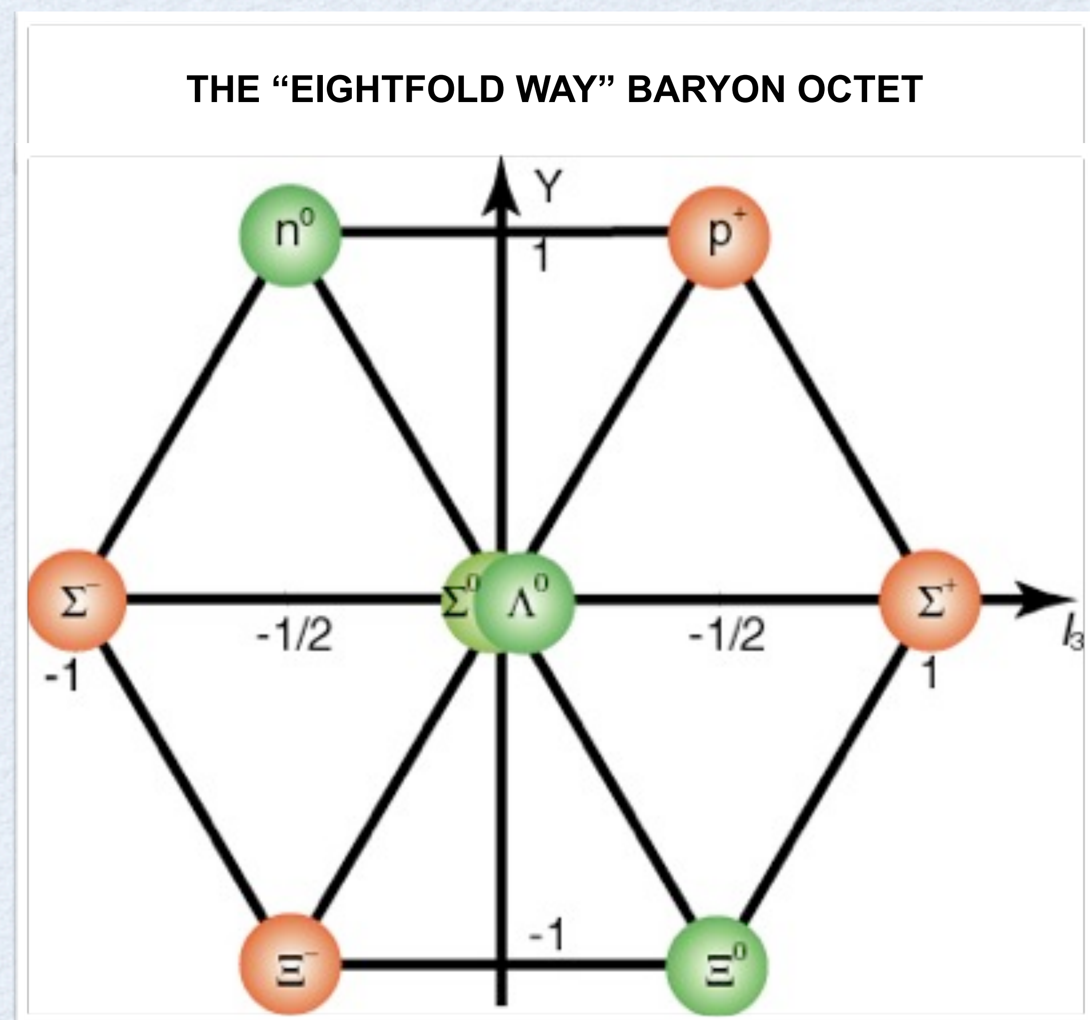
Why three generations?

Why such a large hierarchy?

MOTIVATIONS FOR FLAVOUR MODELS – I

Regularities often hide an undelying structure.





MOTIVATIONS FOR FLAVOUR MODELS - II

The Standard Model needs an **UV completion.**

Theory

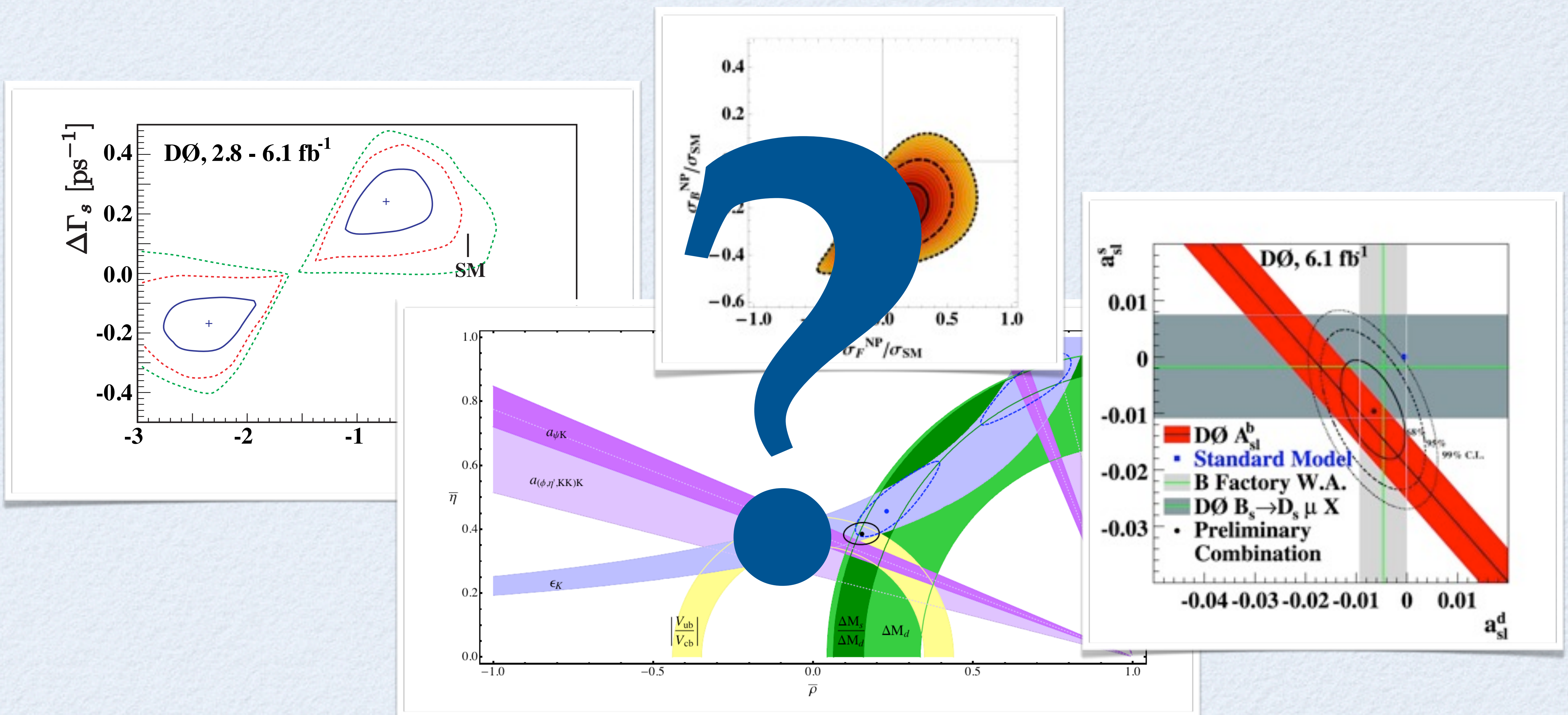
- Quadratic divergence of the Higgs mass
- Landau pole / vacuum instability: possible internal inconsistency
- Structure of the Yukawa coupling

Experiments

- Where is the Higgs boson?
- Not enough CP violation
- Dark matter
- Gravity

MOTIVATIONS FOR FLAVOUR MODELS – III

Interesting phenomenology to compare
with the hints of New Physics from experiments.



"... too early to despair, enough for depressing..." (G. Altarelli, a few days ago)

Building a Model with Gauged Flavour Symmetries

An Analogy with Something We (should) Know Well

$$\mathscr{L} = \sum_{\text{fermions}} \bar{\Psi} i \not{D} \Psi - \sum_{\text{gauge bosons}} \text{Tr}\left[A_{\mu\nu}A^{\mu\nu}\right] - \sum_{\text{fermions}} m_\Psi \bar{\Psi}\Psi - \sum_{\text{gauge bosons}} m_A^2 A_\mu A^\mu$$

Invariant under gauge $SU(2)_L xU(1)_Y$ — Breaks gauge $SU(2)_L xU(1)_Y$

- Assume that $SU(2)_L xU(1)_Y$ is an exact symmetry of Nature
- Introduce a new scalar field H that gets a vev which breaks $SU(2)_L xU(1)_Y$

Invariant under gauge $SU(2)_L xU(1)_Y$

$$\mathscr{L} = \sum_{\text{fermions}} \bar{\Psi} i \not{D} \Psi - \sum_{\text{gauge bosons}} \text{Tr}\left[A_{\mu\nu}A^{\mu\nu}\right] - (D_\mu H)^2 + V(H) - \sum_{\text{fermions}} \bar{\Psi}_L \, y \, \Psi_R \, H$$

$$-(D_\mu H)^2 + V(H) \rightarrow \propto \langle H \rangle^2 A_\mu A^\mu \qquad\qquad \sum_{\text{fermions}} \bar{\Psi}_L \, y \, \Psi_R \, H \rightarrow \propto \langle H \rangle \, \bar{\Psi}\Psi$$

Promoting Flavour Symmetry

$$\mathscr{L} = \sum_{\text{fermions}} \bar{\Psi} i \not{D} \Psi - \sum_{\text{gauge bosons}} \text{Tr}\,[A_{\mu\nu}A^{\mu\nu}] - (D_\mu H)^2 + V(H)$$

Invariant under global G_F

$$- \sum_{\text{3 generations}} \bar{Q}_L\, y_U\, U_R\, H^c - \sum_{\text{3 generations}} \bar{Q}_L\, y_D\, D_R\, H$$

Breaks global G_F

- Assume that G_F is an exact symmetry of Nature
- Introduce two new scalar fields Y_U, Y_D that get vevs which break G_F

$$\mathscr{L} = \sum_{\text{fermions}} \bar{\Psi} i \not{D} \Psi - \sum_{\text{gauge bosons}} \text{Tr}\,[A_{\mu\nu}A^{\mu\nu}] - (D_\mu H)^2$$

$$- (D_\mu Y_U)^2 - (D_\mu Y_D)^2 - V(H, Y_U, Y_D) + f(Q_L, U_R, D_R; H, Y_U, Y_D)$$

Invariant under global G_F

$$\propto \bar{Q}_L\, \langle Y_U \rangle\, U_R\, H^c \qquad \propto \bar{Q}_L\, \langle Y_D \rangle\, D_R\, H$$

Gauging Flavour Symmetry

Spontaneous breaking of global flavour symmetry

↓

Goldstone bosons which mediate Flavour Changing Neutral Currents

↓

We must assume that G_F is a gauge symmetry.

$$SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$$

↓ ↓ ↓

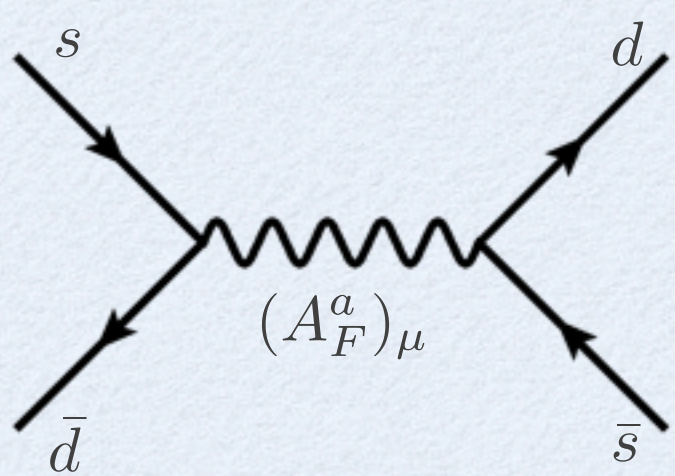
$$(A^a_Q)_\mu \qquad (A^a_U)_\mu \qquad (A^a_D)_\mu$$

$$\partial_\mu \longrightarrow \partial_\mu - i g_Q N_Q \sum_{a=1}^{8} (A^a_Q)_\mu \frac{\lambda^a}{2} - i g_U N_U \sum_{a=1}^{8} (A^a_U)_\mu \frac{\lambda^a}{2} - i g_D N_D \sum_{a=1}^{8} (A^a_D)_\mu \frac{\lambda^a}{2}$$

PROBLEM I: TREE-LEVEL FCNCS

Fermion mass terms: $\langle H\rangle \langle Y_D\rangle \bar{Q}_L D_R \longrightarrow \langle Y_F\rangle \propto$ SM Yukawas

Boson mass terms: $\langle H\rangle^2 \langle Y_D\rangle^2 (A_D)_\mu (A_D)^\mu \longrightarrow m_{A_F} \propto$ SM Yukawas



$$\propto \frac{1}{y_d^2\, y_s^2}$$

PROBLEM II: ANOMALIES

Anomaly:
a symmetry of the classical action is destroyed by loop corrections.

A **gauge anomaly** leads to the inconsistency of the theory!

Using group theory we can say if a theory is anomaly free:

$$\mathcal{A}^{abc} = \mathrm{Tr}\left[t^a \left\{t^b, t^c\right\}\right]$$

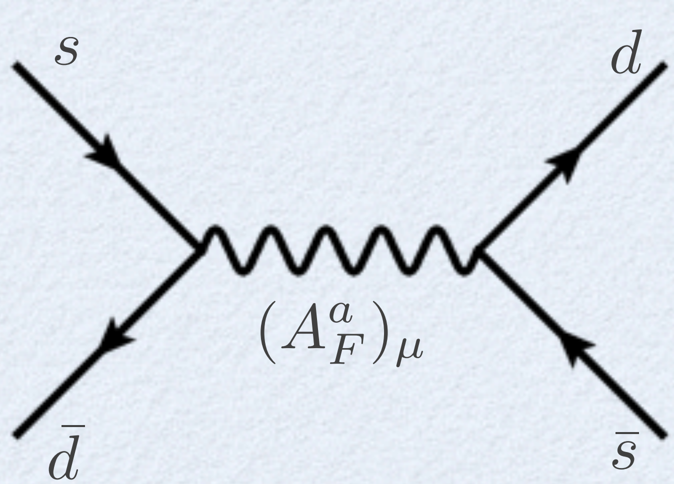
The theory we have built until now is anomalous.

Solution: New Fermions

$$\Psi_u = \begin{pmatrix} \Psi_{uL} \\ \Psi_{uR} \end{pmatrix} \qquad \Psi_d = \begin{pmatrix} \Psi_{dL} \\ \Psi_{dR} \end{pmatrix}$$

SM fermion mass terms: $\frac{\langle H \rangle}{\langle Y_D \rangle} \bar{Q}_L D_R \longrightarrow \langle Y_F \rangle \propto \frac{1}{\text{SM Yukawas}}$ **Inverted hierarchy**

Boson mass terms: $\langle H \rangle^2 \langle Y_D \rangle^2 (A_D)_\mu (A_D)^\mu \longrightarrow m_{A_F} \propto \frac{1}{\text{SM Yukawas}}$



$\propto \quad y_d^2 \, y_s^2$

Grinstein, Redi, Villadoro - JHEP 1011

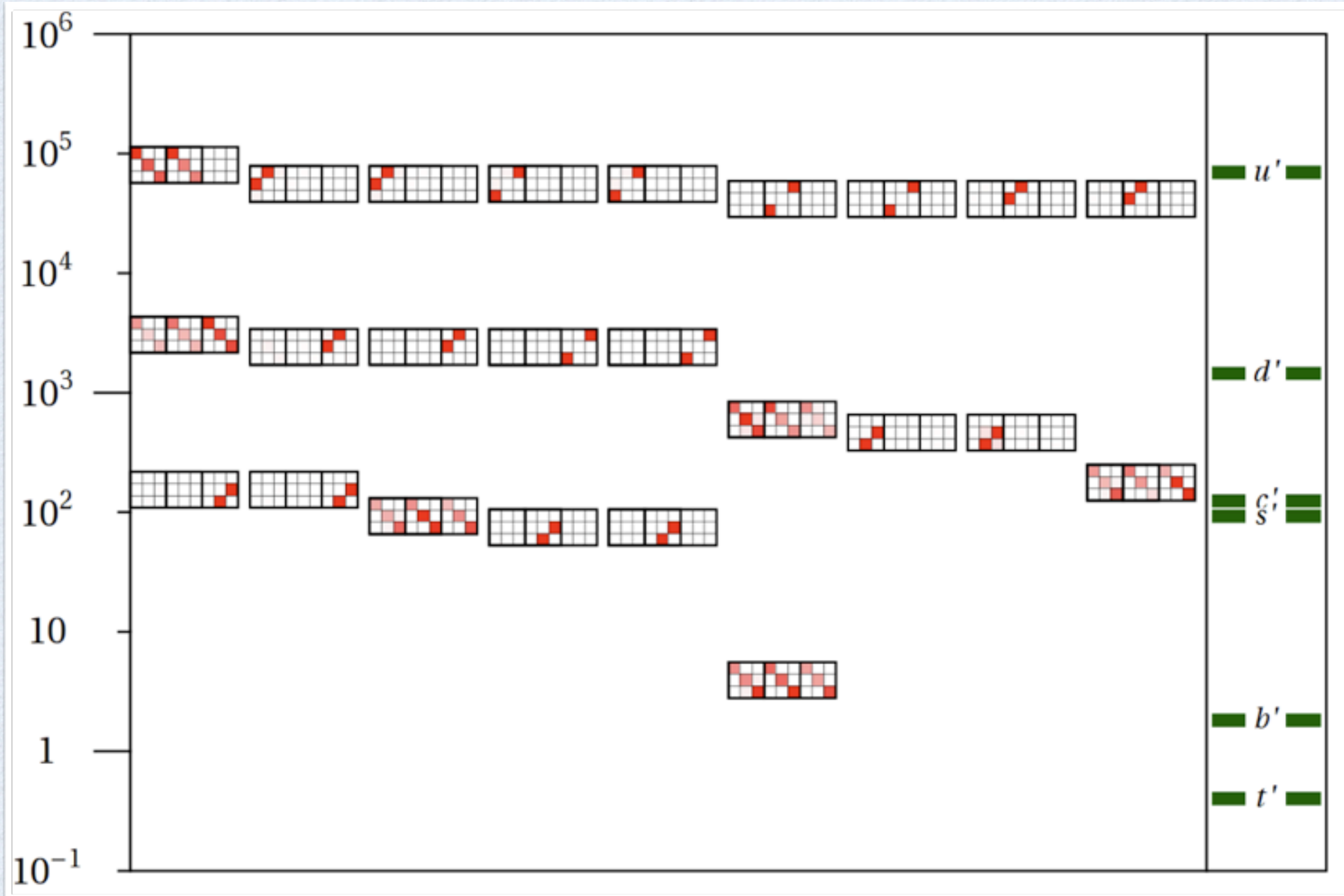
Characteristics and Phenomenology of the Model

PARTICLE CONTENT

	EW Group		Flavour Group			Color
	$SU(2)_L$	$U(1)_Y$	$SU(3)_Q$	$SU(3)_U$	$SU(3)_D$	$SU(3)_c$
Q_L	2	1/6	3	1	1	3
U_R	1	2/3	1	3	1	3
D_R	1	-1/3	1	1	3	3
Ψ_{uL}	1	2/3	1	3	1	3
Ψ_{dL}	1	-1/3	1	1	3	3
Ψ_{uR}	1	2/3	3	1	1	3
Ψ_{dR}	1	-1/3	3	1	1	3
H	2	0	1	1	1	1
Y_U	1	0	$\bar{3}$	3	1	1
Y_D	1	1/2	$\bar{3}$	1	3	1
Gauge Bosons	$A, W^{\pm}, Z$		A_Q^a	A_U^a	A_D^a	g^a

Grinstein, Redi, Villadoro - JHEP 1011

FERMION SPECTRUM AND BOSON SPECTRUM



Grinstein, Redi, Villadoro - JHEP 1011

MAIN DIFFERENCES IN THE SM SECTOR

- V_{CKM} is not unitary:

$$\bar{u}_L(c_{u_L} V c_{d_L})\gamma^\mu d_L + \bar{u}_L(c_{u_L} V s_{d_L})\gamma^\mu d'_L + \bar{u}'_L(s_{u_L} V c_{d_L})\gamma^\mu d_L + \bar{u}'_L(s_{u_L} V s_{d_L})\gamma^\mu d'_L$$

- The coupling of left handed quarks to the Z is modified:

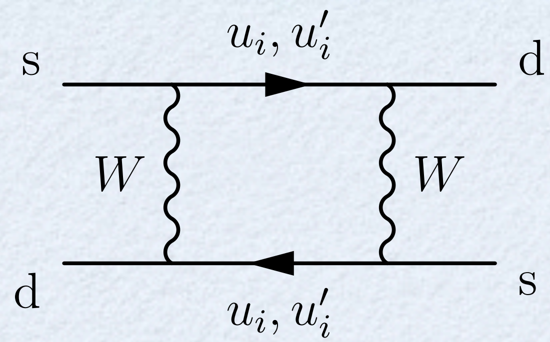
$$\bar{u}_L(T_3^u c_{u_L}^2 - s_w^2 Q_u)\gamma^\mu u_L + \bar{u}_L(T_3^u c_{u_L} s_{u_L})\gamma^\mu u'_L + \bar{u}'_L(T_3^u s_{u_L} c_{u_L})\gamma^\mu u_L + \bar{u}'_L(T_3^u s_{u_L}^2 - s_w^2 Q_u)\gamma^\mu u'_L$$

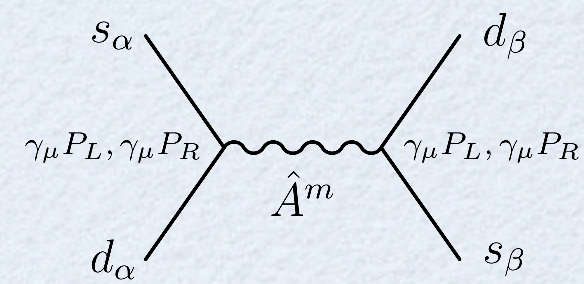
- The couplings of quarks to the Higgs is modified:

$$\frac{1}{\sqrt{2}}\lambda_u h[-\bar{t}_L c_{u_L} s_{u_R} t_R + \bar{t}_L c_{u_L} c_{u_R} t'_R - \bar{t}'_L s_{u_L} s_{u_R} t_R + \bar{t}'_L s_{u_L} c_{u_R} t'_R] + (u \to d) + \text{h.c.}$$

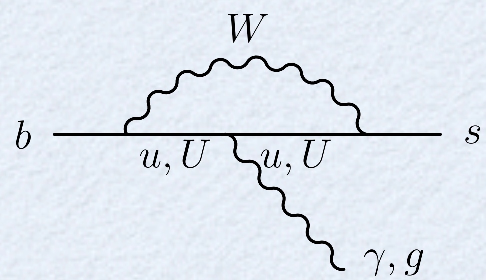
Phenomenological Tests

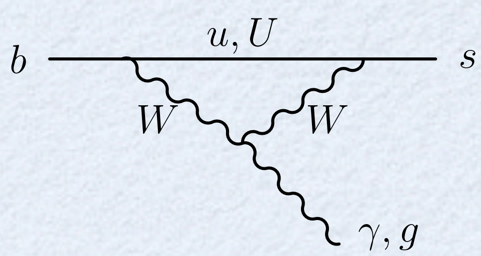
- FCNCs: $\Delta F = 2$

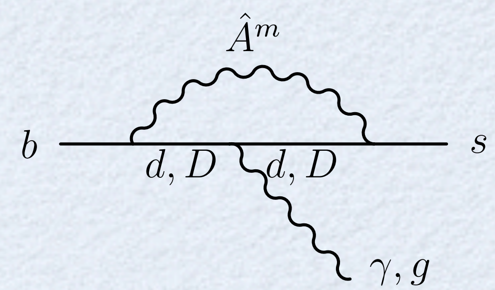




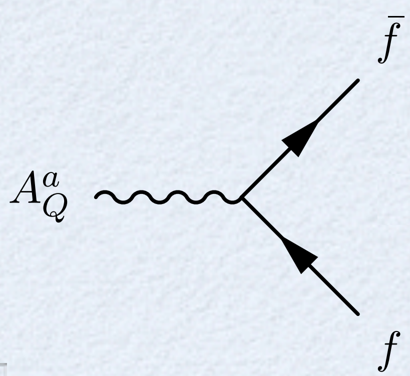
- FCNCs: $b \to s\gamma$







- New CP-violating phases



- Z penguins

Buras, MVC, Merlo, Stamou - in preparation

Conclusions

Conclusions

- The origin of flavour is still a mystery.
- Waiting for hints from experiments, people is working with creativity to **build flavour models**.
- For example, flavour could be and **exact gauge symmetry** of Nature that is **spontaneously broken** by vacuum.
- We are testing the consequencies of this fascinating idea.

Thanks