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MAXIMALLY GAUGED FLAVOUR SYMMETRIES



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• Introduction: Flavour Models

• Building a model with Gauged Flavour Symmetries

• Characteristics and phenomenology of the model

• Conclusions and Outlook

FLAVOUR SYMMETRY...



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

... AND ITS BREAKING

INTRODUCTION



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

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

INTRODUCTION FLAVOUR MODELS



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Why three generations?

Why such a large hierarchy?

MOTIVATIONS FOR FLAVOUR MODELS - 1

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

Building a Model with Gauged Flavour Symmetries 8/18 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 $SU(2)_{L} x U(1)_{Y}$ Breaks gauge $SU(2)_{L} x U(1)_{Y}$

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

Invariant under gauge $SU(2)_L x U(1)_Y$

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

Building a Model with Gauged Flavour Symmetries PROMOTING FLAVOUR SYMMETRY



- 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

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

$$- \left(D_{\mu} Y_{U} \right)^{2} - \left(D_{\mu} Y_{D} \right)^{2} - V(H, Y_{U}, Y_{D}) + f \left(Q_{L}, U_{R}, D_{R}; H, Y_{U}, Y_{D} \right)$$

$$\propto \bar{Q}_{L} \left\langle Y_{U} \right\rangle U_{R} H^{c} \qquad \propto \bar{Q}_{L} \left\langle Y_{D} \right\rangle D_{R} H$$
Invariant

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GF

Building a Model with Gauged Flavour Symmetries GAUGING FLAVOUR SYMMETRY

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Spontaneous breaking of global flavour symmetry

Goldstone bosons which mediate Flavour Changing Neutral Currents

We must assume that G_F is a gauge symmetry.

$$\begin{array}{ccccccc} SU(3)_{Q_L} & \times & SU(3)_{U_R} & \times & SU(3)_{D_R} \\ \downarrow & & \downarrow & & \downarrow \\ (A^a_Q)_{\mu} & & (A^a_U)_{\mu} & & (A^a_D)_{\mu} \end{array}$$

$$\partial_{\mu} \longrightarrow \partial_{\mu} - ig_Q N_Q \sum_{a=1}^8 (A^a_Q)_{\mu} \frac{\lambda^a}{2} - ig_U N_U \sum_{a=1}^8 (A^a_U)_{\mu} \frac{\lambda^a}{2} - ig_D N_D \sum_{a=1}^8 (A^a_D)_{\mu} \frac{\lambda^a}{2}$$

BUILDING A MODEL WITH GAUGED FLAVOUR SYMMETRIES PROBLEM I: TREE-LEVEL FCNCS

Fermion mass terms:

$$\left\langle H \right\rangle \left\langle Y_D \right\rangle ar{Q}_L D_R$$

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

 \propto

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

1

 $\langle Y_F \rangle \propto \, {
m SM} \, {
m Yukawas}$



BUILDING A MODEL WITH GAUGED FLAVOUR SYMMETRIES PROBLEM II: ANOMALIES



Anomaly:

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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:

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

The theory we have built until now is anomalous.



Grinstein, Redi, Villadoro - JHEP 1011

CHARACTERISTICS AND PHENOMENOLOGY OF THE MODEL

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	3	3	1	1
Y_D	1	1/2	3	1	3	1
Gauge Bosons	A,W^{\pm},Z		A^a_Q	A^a_U	A_D^a	g^a

CHARACTERISTICS AND PHENOMENOLOGY OF THE MODEL

FERMION SPECTRUM AND BOSON SPECTRUM



Grinstein, Redi, Villadoro - JHEP 1011

• V_{CKM} is not unitary:

 $\bar{u}_{L}(c_{u_{L}}Vc_{d_{L}})\gamma^{\mu}d_{L} + \bar{u}_{L}(c_{u_{L}}Vs_{d_{L}})\gamma^{\mu}d'_{L} + \bar{u}'_{L}(s_{u_{L}}Vc_{d_{L}})\gamma^{\mu}d_{L} + \bar{u}'_{L}(s_{u_{L}}Vs_{d_{L}})\gamma^{\mu}d'_{L}$

• 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:

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

Grinstein, Redi, Villadoro - JHEP 1011

and corrections to W quark vertices according to the revinitant rules in repertences e following contributions to the Wilson coefficients relevant for the $K^{\text{beir}} W^{\text{idson coefficients are are suppressed by } m_s/m_b$ with respect to the un matching scale μ_t in the ballpark of the top quark mass P HENOMPeticients However, the mixing of neutral current-current operators int Similarly to the Hamiltonian for the $\Delta F = 2$ transitions, the Wilson co $\Delta_{\text{Box}}^{(K)}C_1^{VLL}(\mu_t) = \Delta_1(\mu_t, K) + \Delta_2(\mu_t, K) + M(\mu_t, K) + M(\mu$ - The SM-like contribution from diagrams with W bosons with modif. explain this choice in the context of our discussion of QCD corrections below. both SM and exotic quarks of charge +2/3, denoted below by u and We have deep to be contribution; of the interpretent of the pole optimate G'_{s} and G'_{s} and d_{β} are an expected and d_{β} and d_{β} and d_{β} are an expected and d_{β} and d_{β} are a set of the expected and d_{β} and d_{β} are a set of the expected an expe W S u_i, u'_i Simstantyatevthe Harnian faister Alera transitions othe Wilson softig the institute the Hapiltonian can be separated into the part on to the mass eigenstates of the heavy gauge bosons redefines - The TSM Sive inentribution in diagrams by the boson it is in the boson it is the boson in the boson is exchanges with virtual terms of the boson is exchanged by the d Wboth SM SM dark pticon ackards charger 2/32/32 dender de la bir charge and the provident of the bir of a poind, respectively: The box-diagrams contributing to $K^{0}_{R} = K^{0}_{R}$ mixing Similarly for $B^{0}_{q} = B^{0}_{q}$ mixing, $U_{u}uU$ D^{0}_{R} $Sin(G_{R}^{0}r_{i})$, B^{0}_{R} D^{0}_{i} , B^{0}_{i} , $B^{0}_$ where the indices $d_{\lambda}s$ stand for the external quarks d_{λ} and s $L_{In}^{u,u} = equivalent expressions$ where the indices a, s stand for the external quarket of the previous offers by substituting d, s, with gfor the B_d (B_s) system are easily derived by the previous offers by substituting d, s, with gwith the actual values for \bar{f} , f- The previous offers of the complings quarket for the flavour basis as quarket for args of the complete system and the flavour basis as of $b \in S^{*}$, has been recently pointed $\hat{C}_{L,R}^{ij}(\hat{A}^m)$ are boson contributions can strongly affect the branching ratio of \overline{B}_{SuLi} $A^a_Q \xrightarrow{A^a_Q}_{h} \xrightarrow{g_Q}_{h} \xrightarrow$ New CP-violating phases where $\mathcal{W}(A^m, A_f^a)$ are known numerical coefficients defining the transformation to $\mathrm{move}_L = +c_{uLi}$ from the flavour basis to the mass basis (see App. A.2). The $C_{I,R}^{i,j}$ couplings involved in $C_R = +c_{uRi}$ our analysis are with the actual values for f f and $C_{i,R}^{i,j}$ performed at the EW C_{L} and u' contributions are hereined at the environment of f and $C_{i,R}^{i,j}$ and $C_{i,R}^{i,j}$ and u' contributions are hereined at the environment of f f and $C_{i,R}^{i,j}$ and u' contributions are hereined at the environment of f f and $C_{i,R}^{i,j}$ and u' contributions are hereined at the environment of f f and $C_{i,R}^{i,j}$ and u' contributions are hereined at the environment of f f and $C_{i,R}^{i,j}$ and u' and u' contributions are hereined at the environment of f f and $C_{i,R}^{i,j}$ and u' and u' contributions are hereined at the environment of f f and $G_{i,R}^{i,j}$ and $G_{i,R}^{i,j}$ and u' contributions are hereined at the environment of f f and $G_{i,R}^{i,j}$ and Therfirstfiesnerab osphates to be say and the in sure the one of the stand of the set of the set of the wilson coefficients of the of the theane partiaulitrhas have been the the decomposition of the theory of theory of theory of the theory of the theory of theory of theory of theory of theory of the $A_Q^a \bar{u}_i' u_j'$:with $C_R = +c_{uRi} (V \lambda^a V^{\dagger})_{ij} c_{uRj}$ Properties

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