Flavour
as a Spontaneously Broken
Gauge Symmetry

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Introduction
  * Interest in flavour
  * Present picture of flavour physics

Building the model
  * Flavour symmetry and its breaking
  * Model structure

Phenomenological analysis
  * Impact on the transitions
  * Parameter space
  * Results in the flavour sector

Conclusions and outlook
2012: A Historical Year for Particle Physics

Genève, Jul 4th
ATLAS+CMS

Kyoto, Nov 12th
LHCb
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Same message:

triumph of the Standard Model

... but we know there should be something beyond!
**Introduction**

**Twofold Interest in Flavour**

- **Powerful experimental tests**
  - Role of loop processes
    Probes of energies higher than the ones directly accessible
  - Precision physics
    Intensity frontier in experiments together with more and more accurate predictions

- **Unknown origin**
  - Ad hoc
    13 parameters, 5 orders of magnitude
  - 3 sequential generations
    Proliferation often suggests an underlying structure
  - CP violation
    Not enough for matter-antimatter asymmetry
  - Flavour problem
    How can it perform so well? Has New Physics a non-trivial flavour structure?
Introduction

Vanishing Hopes and Old Tensions

LHCb @ Moriond 2012

CKMfitter @ ICHEP 2012

LHCb @ HCP 2012
**Introduction**

**Vanishing Hopes and Old Tensions**

- LHCb @ Moriond 2012
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- LHCb @ HCP 2012

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- \( B(B_s \rightarrow \mu^+ \mu^-) \times 10^{9} \)
- \( B(B_d \rightarrow \mu^+ \mu^-) \times 10^{9} \)

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Unitarity Triangle

- \(|V_{ub}|\)
- \(\sin 2\beta\)

- \(S_{\psi K_S} \propto \sin 2\beta\)
- \(\epsilon_K = f(\sin 2\beta, |V_{ub}|)\)

- from exclusive decays
- from inclusive decays
**Building the Model**

**Flavour Symmetry and its Breaking**

\[ G_F = (U(3))^3 \]

- 3 ew multiplets: \( Q_L, U_R, D_R \)
- 3 generations
Flavour Symmetry and its Breaking

\[ G_F = (U(3))^3 \]

3 ew multiplets: Q_L, U_R, D_R

3 generations

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

\[ G_F \rightarrow U(1)_B \times U(1)_Y \]
Building the Model

An Analogy with Something We (should) Know Well

\[ \mathcal{L} = \sum_{\text{fermions}} \bar{\Psi} i \partial \Psi - \sum_{\text{gauge bosons}} \text{Tr} \left[ A_{\mu \nu} A^{\mu \nu} \right] - \sum_{\text{fermions}} m_{\Psi} \bar{\Psi} \Psi - \sum_{\text{gauge bosons}} m_{A}^{2} A_{\mu} A^{\mu} \]

invariant under gauge $\text{SU}(2)_{L} \times \text{U}(1)_{Y}$

breaks gauge $\text{SU}(2)_{L} \times \text{U}(1)_{Y}$
Building the Model

An Analogy with Something We (should) Know Well

\[ \mathcal{L} = \sum_{\text{fermions}} \bar{\Psi} i \gamma^\mu \gamma^5 \Psi - \sum_{\text{gauge bosons}} \text{Tr} \left[ A_{\mu\nu} A^{\mu\nu} \right] - \sum_{\text{fermions}} m_\Psi \bar{\Psi} \Psi - \sum_{\text{gauge bosons}} m_A^2 A_\mu A^\mu \]

- invariant under gauge SU(2)_L x U(1)_Y
- breaks gauge SU(2)_L x U(1)_Y

1. Assume that SU(2)_L x U(1)_Y is an exact symmetry of Nature
2. Introduce a new scalar field H that gets a vev which breaks SU(2)_L x U(1)_Y
Building the Model

An Analogy with Something We (Should) Know Well

\[
\mathcal{L} = \sum_{\text{fermions}} \bar{\Psi} i D \Psi - \sum_{\text{gauge bosons}} \text{Tr} \left[ A_{\mu \nu} A^{\mu \nu} \right] - \sum_{\text{fermions}} m_\Psi \bar{\Psi} \Psi - \sum_{\text{gauge bosons}} m_A^2 A_{\mu} A^\mu
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\]

- invariant under gauge SU(2)_L x U(1)_Y

\[
\propto \langle H \rangle^2 A_{\mu} A^\mu \quad \propto \langle H \rangle \bar{\Psi} \Psi
\]
$\mathcal{L} = \sum_{\text{fermions}} \bar{\Psi} i \gamma^\mu \Psi - \sum_{\text{gauge bosons}} \text{Tr} [A_{\mu \nu} A^{\mu \nu}] - (D_\mu H)^2 + V(H)$

- invariant under global $G_F$

- breaks global $G_F$

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

Promoting Flavour Symmetry

\[ \mathcal{L} = \sum_{\text{fermions}} \bar{\Psi}_i \gamma_\mu \Psi_i - \sum_{\text{gauge bosons}} \text{Tr} \left[ A_{\mu \nu} A^{\mu \nu} \right] - (D_\mu H)^2 + V(H) \]

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 $G_F$

1. Assume that $G_F$ is an exact symmetry of Nature
2. Introduce two new scalar fields $Y_U, Y_D$ that get vevs which break $G_F$
Building the Model

Promoting Flavour Symmetry

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

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 \( G_F \)

1. Assume that \( G_F \) is an exact symmetry of Nature

2. Introduce two new scalar fields \( Y_U, Y_D \) that get vevs which break \( G_F \)
Avoiding Goldstone bosons

$G_F$ should be a gauge symmetry

Flavour gauge symmetry

gauge bosons mediating FCNCs

Anomaly cancellation

new heavy fermions
Avoiding Goldstone bosons

\( G_F \) should be a gauge symmetry

Flavour gauge symmetry

gauge bosons mediating FCNCs

Anomaly cancellation

new heavy fermions

Minimal non-anomalous fermion content

See-saw-like mechanism suppressing tree-level FCNCs

Grinstein, Redi, Villadoro, JHEP 2011
Building the Model

Model Structure

- **Gauge group**: $SU(3)_c \times SU(2)_L \times U(1)_Y \times (SU(3)_f)^3$

- **8x3 new flavour gauge bosons**: $A_Q^a, A_U^a, A_D^a$
  Neutral and flavour-charged
  Mix in 24 mass eigenstates

- **6 new quarks**
  From the diagonalization of the new vector-like fermions

- **the SM Higgs boson**

- **2 flavons**
  The Yukawa couplings become scalar fields
  6+4 physical states
  Problematic potential
**Vertices**

- Mixing with exotic quarks
- Mixing of flavour bosons
- $V_{CKM}$ is not unitary
- Modified flavour-dependent $Z$ and $h$ interactions
- New sources of CP violation

**$\Delta F = 2$ down-type FCNCs**

\[
\langle K^0 | \mathcal{H}_{\text{eff}}^{\Delta S=2} | K^0 \rangle = \frac{G_F m_W^2 F_K^2}{24 \pi^2} \times \\
\left\{ \hat{B}_K \eta_1 (\lambda_2^K)^2 S_c^K(K) + \hat{B}_K \eta_2 (\lambda_3^K)^2 S_c^K(K) + \right. \\
\left. + 2\hat{B}_K \eta_3 \lambda_2^K \lambda_3^K S_c^K(K) + \right. \\
\left. + \sum_{a=1}^{24} \left[ P_{1VLL}^{VLL}(\mu_{\hat{A}_m}, K) \left( \Delta_{\text{tree}}^{(K)} C_{1VLL}(\mu_{\hat{A}_m}) + \Delta_{\text{tree}}^{(K)} C_{1VRR}(\mu_{\hat{A}_m}) \right) \\
+ P_{1LR}^{LR}(\mu_{\hat{A}_m}, K) \Delta_{\text{tree}}^{(K)} C_{1LR}(\mu_{\hat{A}_m}) \right] \right\}
\]
Phenomenological Analysis

Parameter Space

9 parameters

- Gauge couplings: $g_Q$, $g_U$, $g_D$
- Scalars-quarks couplings: $\lambda_u$, $\lambda_d$, $\lambda'_u$, $\lambda'_d$
- Allowed mass terms: $M_u$, $M_d$

Lower bounds on $b'$

Non-universality of Z coupling

Lower bounds on $t'$

CKM matrix $|V_{tb}|$

EW precision tests

Unphysical

Grinstein, Redi, Villadoro, JHEP 2011
**Phenomenological Analysis**

**Results 1 - $\Delta F=2$ Key Observables**

- $S_{\psi K_s}$ only slightly suppressed
- $\varepsilon_K$ either enhanced or suppressed
- Solution of the $\varepsilon_K-S_{\psi K_s}$ tension with exclusive $|V_{ub}|$

- $\Delta M_{d,s}$ enhanced when $\varepsilon_K$ enhanced
- Worsening of the $\varepsilon_K-\Delta M_{d,s}$ tension

Buras, MVC, Merlo, Stamou - JHEP 2012
**Results II - More Observables**

- **Favorite points**
  - Small effects on $S_{\psi \phi}$, $A_{s1}^b$, $B^+ \rightarrow \tau^+ \nu$
  - Within or not the reach of LHC
Conclusions and Outlook
All data from the first run of LHC seems to confirm the SM. This motivates updated and accurate phenomenological analyses of models beyond, and flavour is an interesting and powerful sector to investigate.
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The model contains new sources of flavour and CP violation. We have constrained the parameter space and studied the impact on the flavour observables.
Conclusions and Outlook

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- The origin of flavour is still a mystery. It could be a **gauge symmetry** of Nature, **spontaneously broken**. We have shown how to build a consistent model based on this fascinating idea.

- The model contains new sources of **flavour and CP violation**. We have constrained the parameter space and studied the impact on the flavour observables.

- Our predictions could be testable in the very next years. We will be able either to relax some flavour tensions or rule out the models.
THANKS!
Backup
INTRODUCTION

PROTAGONISTS OF FLAVOUR PHENOMENOLOGY

Flavour-Changing Neutral Currents & CP Violation

<table>
<thead>
<tr>
<th>$K^0$</th>
<th>$\Delta M_K$</th>
<th>$\epsilon_K \sim (K_L \rightarrow \pi \pi \pi)/(K_S \rightarrow \pi \pi \pi)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0$</td>
<td>$\Delta M_d$</td>
<td>$S_{\psi K_S} \sim B^0 \rightarrow J/\psi K_S \sim \beta$</td>
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</tr>
</tbody>
</table>

Mixing of neutral mesons

Rare decays

- $B_{d,s} \rightarrow \mu^+\mu^-$
- $B \rightarrow X_S \gamma$
- $B^0 \rightarrow X_S \nu \nu$
- $K \rightarrow \pi \nu \nu$
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:

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

The theory we have built until now is anomalous.
Building a Model with Gauged Flavour Symmetries

Problem: Tree-Level FCNCs

Fermion mass terms:
\[ \langle H \rangle \langle Y_D \rangle \tilde{Q}_L D_R \rightarrow \langle Y_F \rangle \propto \text{SM Yukawas} \]

Boson mass terms:
\[ \langle H \rangle^2 \langle Y_D \rangle^2 (A_D)_\mu (A_D)^\mu \rightarrow m_{A_F} \propto \text{SM Yukawas} \]

\[ \propto \frac{1}{y_d^2 y_s^2} \]
**Solution: New Fermions**

\[
\Psi_u = \begin{pmatrix} \Psi_{uL} \\ \Psi_{uR} \end{pmatrix} \quad \Psi_d = \begin{pmatrix} \Psi_{dL} \\ \Psi_{dR} \end{pmatrix}
\]

**SM fermion mass terms:**
\[
\frac{\langle H \rangle}{\langle Y_D \rangle} \bar{Q}_L D_R \quad \Rightarrow \quad \langle Y_F \rangle \propto \frac{1}{\text{SM Yukawas}}
\]

**Boson mass terms:**
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\]

\[\propto y_d^2 y_s^2\]

Grinstein, Redi, Villadoro - JHEP 1011