Phenomenology

of a

Gauge Flavour Model

Emmanuel Stamou

estamou@ph.tum.de

In collaboration with:

A. J. Buras, M. V. Carlucci, and L. Merlo `arXiv:1112.4477v1`

A. J. Buras and L. Merlo `arXiv:1105.5146v2`

TU Munich

Les Rencontres De Physique
De La Vallee D´Aoste

29 February 2012

Introduction

If all Yukawas were zero the SM would have an extra $U(3) \times U(3) \times U(3)$ symmetry

Is this a "fundamental" symmetry of nature?

MFV

- **M**inimal **F**lavour **V**iolation (D'Ambrosio et al, '02)
- **global** flavour symmetry
- yukawas Y_u, Y_d are spurion fields
- $Y_u,\ Y_d$ break the flavour-symmetry
  $\longrightarrow$ massless Goldstone bosons?

MGF

- **M**aximally **G**auged **F**lavour
- **gauge** flavour symmetry
- $Y_u,\ Y_d$ are the corresponding "Higgs" fields
  (so-called flavons)
- example: $SU(3)_Q \times SU(3)_U \times SU(3)_D$ (Grinstein et al, '10)
  other (Feldmann, '11; Guadagnoli et al, '11; D'Agnolo et al , '12)

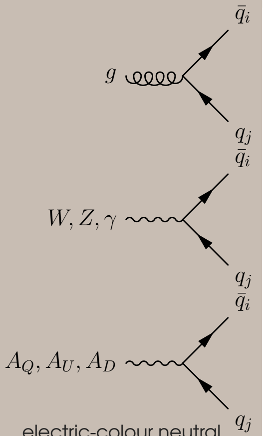
Part 1: gauging flavour symmetries

- ∘ anomaly cancellation with exotic fermions
- ∘ see-saw for quark masses
- ∘ FCNCs $\propto 1/Y^2$, automatic flavour protection
- ∘ a minimal quark $SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$ realisation

(Grinstein et al, '10)

Flavour Gauge Bosons and Flavons

$$\mathcal{L} = \underbrace{\mathcal{L}_{\text{kinetic}}} + \mathcal{L}_{\text{interaction}} + \underbrace{\mathcal{L}_{\text{scalar}}(H, Y_u, Y_d)}$$



electric-colour neutral

flavour-violating

gauge bosons

- flavour-violating scalar fields
- highly model-dependent
- account for EW and Flavour symmetry breaking
- find and minimise the right potential (Alonso et al, '11)
- not further considered here

3 new coupling constants g_Q, g_U, g_D

e.g. $SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R} \longrightarrow$ 24 flavour gauge bosons

Construction of a gauged flavour model

Recipe:

- Y_u, Y_d flavour-charged singlets under SM $\Big\}$ $\longrightarrow$ MFV
- anomaly-cancelation $\longrightarrow$ add exotic fermions (easy: vector-like under flavour)
- chiral under SM
- forbid $\bar{q}_L^{\mathrm{SM}}\ Y\ q_R^{\mathrm{SM}}$ $\longrightarrow$ See-saw

(Grinstein et al, '10)

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

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(Grinstein et al, '10)

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

Mass-eigenstates and See-saw

Break Flavour

- $Y_u,\ Y_d$ develop a VEV
- choose diagonal down-type basis

unitary
3×3
will-be V_{CKM}

$$\langle Y_d \rangle = \begin{pmatrix} * & 0 & 0 \\ 0 & * & 0 \\ 0 & 0 & * \end{pmatrix} \qquad \langle Y_u \rangle = \begin{pmatrix} * & 0 & 0 \\ 0 & * & 0 \\ 0 & 0 & * \end{pmatrix} \cdot V$$

Mass-matrices

(e.g. up-sector)

$$\begin{pmatrix} \overline{U}_L & \overline{\Psi}_{uL} \end{pmatrix} \begin{pmatrix} \boxed{\mathbf{0}} & M_1^D \\ M_2^D & \hat{M} \end{pmatrix} \begin{pmatrix} U_R \\ \Psi_{uR} \end{pmatrix}$$

rotate to mass-eigenstates $u,\ u'$

$$\begin{pmatrix} \overline{u}_L & \overline{u}'_L \end{pmatrix} \begin{pmatrix} \hat{m}_u & 0 \\ 0 & \hat{m}'_u \end{pmatrix} \begin{pmatrix} u_R \\ u'_R \end{pmatrix}$$

See-saw

$$\hat{m}_u \hat{m}'_u = M_1^D M_2^D$$

Mass-eigenstates and See-saw

Break Flavour

- $Y_u,\ Y_d$ develop a VEV
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unitary
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Mass-matrices

(e.g. up-sector)

$$\begin{pmatrix} \overline{U}_L & \overline{\Psi}_{uL} \end{pmatrix} \begin{pmatrix} \boxed{\mathbf{0}} & \lambda_u \frac{v}{\sqrt{2}} \times \mathbb{I} \\ M_u \times \mathbb{I} & \lambda'_u \langle Y_u \rangle \end{pmatrix} \begin{pmatrix} U_R \\ \Psi_{uR} \end{pmatrix}$$

2 new couplings $\lambda_u\ \lambda'_u$
1 new mass M_u

rotate to mass-eigenstates $u,\ u'$

$$\begin{pmatrix} \overline{u}_L & \overline{u}'_L \end{pmatrix} \begin{pmatrix} \hat{m}_u & 0 \\ 0 & \hat{m}'_u \end{pmatrix} \begin{pmatrix} u_R \\ u'_R \end{pmatrix}$$

See-saw

$$\hat{m}_u \hat{m}'_u = \lambda_u\ M_u\ v/\sqrt{2}$$

General features of MGF

See-saw:

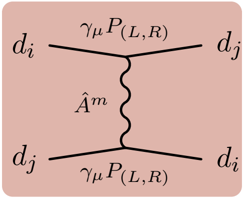
- $m_u m'_u = m_c m'_c = m_t m'_t$
- $m_d m'_d = m_s m'_s = m_b m'_b$

For case of large splitting $m \ll m'$ (true except for top-quark):

$$m \approx \frac{v}{\sqrt{2}} \frac{\lambda M}{\lambda' \langle \hat{Y} \rangle}$$

$$m' \approx \lambda' \langle \hat{Y} \rangle$$

Tree-level FCNCs automatically suppressed for light generations



$$\propto \frac{1}{\langle Y \rangle^2} \left(\bar{q}_i \, \gamma^\mu P_{(L,R)} \, q_j\right)^2$$

Flavour-violation governed by the unitary V matrix in $\langle Y \rangle$.
Connection to V_{CKM}?

General features of MGF

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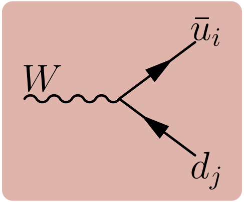
V_{CKM} determined from tree-level processes



$$\propto \gamma_\mu \, P_L \underbrace{\cos^i_{uL} \; V_{ij} \; \cos^j_{dL}}_{V^{ij}_{\mathrm{CKM}}}$$

V_{CKM} not unitary due to mixing with exotics.

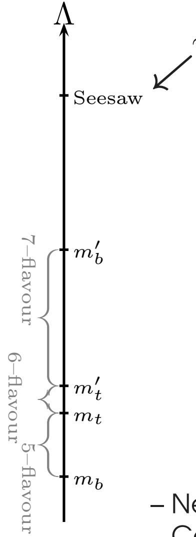
Part 2: flavour phenomenology

Are sizeable deviations in flavour observables possible?

- $\Delta F = 2$ $\quad(\epsilon_K,\ \Delta M_{B_d}, \Delta M_{B_s},\ S_{\psi K_s},\ S_{\psi\phi},\ A^b_{sl})$
- $\Delta F = 1$ $\quad(\mathrm{BR}(B^+ \to \tau^+\nu_\tau), \overline{B} \to X_s\gamma)$
- constrains and patterns from flavour data

(arXiv:1112.4477v1)

Spectrum



$\sim$ mass of lightest flavour gauge boson

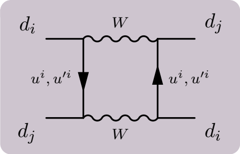
Iteratively fix

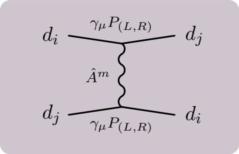
- seesaw-scale
- masses of exotic quarks
- masses of gauge bosons
- couplings of flavour gauge-bosons
- scan the parameter space

- m'_t and m'_b constrained by direct searches (not same as 4^{th}generation searches)
- modification of $Z \to b\, b$ strongest constraint (Grinstein et al, '10)
- still, light gauge boson masses allowed

– New sources of CP and flavour violation $\to$ Effects?
– Can the model account for tensions in flavour data?

$\Delta F = 2$ observables





- @ $\sim m_t$
- SM operator
- t' main contribution

(c' relevant only in Kaon sector)

- @ $\sim M_{\hat{A}}$
- new current-current operators generated
- e.g. $Q_1^{LR} = (\bar{s}\gamma_\mu P_L d)(\bar{d}\gamma^\mu P_R s)$

enhanced by QCD evolution

K	:	ε_K	measure of indirect $\cancel{CP}$
B_d	:	ΔM_{B_d}	mass difference
		$S_{\psi K_S}$	CP asymmetry in $B_d^0 \to J/\psi K_S$
B_s	:	ΔM_{B_s}	mass difference
		$S_{\psi\phi}$	CP asymmetry in $B_s^0 \to J/\psi \phi$

The V_{ub} issue

V_{ub} is determined by tree-level processes – 2 independent determinations

Inclusive

$$|V_{ub}^{incl}| = (4.27 \pm 0.38) \times 10^{-3}$$

$$\varepsilon_K^{\rm SM} \approx 2.2 \times 10^{-3} \approx \varepsilon_K^{\rm exp}$$

$$S_{\psi K_S}^{\rm SM} \approx 0.81$$

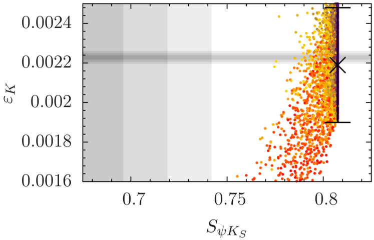
Exclusive

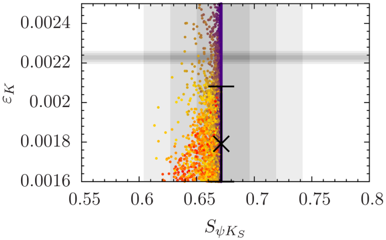
$$|V_{ub}^{excl}| = (3.38 \pm 0.36) \times 10^{-3}$$

$$\varepsilon_K^{\rm SM} \approx 1.8 \times 10^{-3}$$

$$S_{\psi K_S}^{\rm SM} \approx 0.67 \approx S_{\psi K_S}^{\rm exp}$$

MGF can accomodate the tension only for V_{ub}^{excl}.

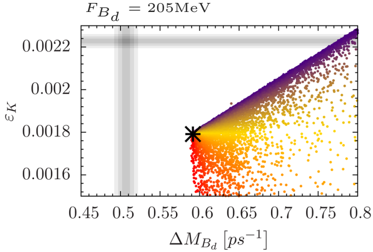


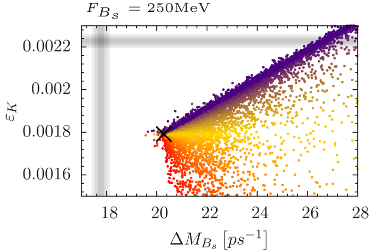


Clear pattern of different contributions

exotic quarks (purple) enhancement of ε_K and $\Delta M_{B_{d,s}}$

gauge bosons (red) suppression of ε_K no effect on $\Delta M_{B_{d,s}}$



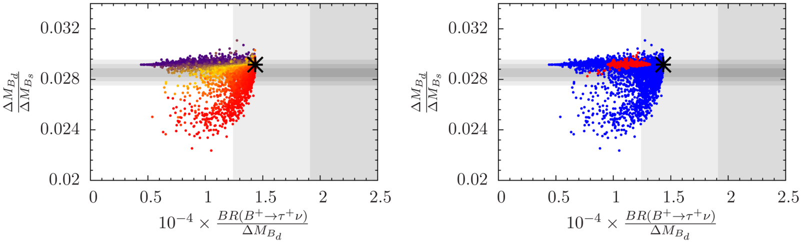


Large theory errors in both ϵ_K (charm dominant) and especially in $\Delta M_{B_{d,s}}$ from meson decay constants F_{B_s} and F_{B_d} (lattice input)!

To constraint MGF look at theorecally clean observables:

$$\frac{\Delta M_{B_d}}{\Delta M_{B_s}} \quad \text{and} \quad \frac{\mathrm{BR}(B^+ \to \tau^+\nu_\tau)}{\Delta M_{B_d}}$$

B-meson decay constants cancel.



exotics fermions gauge boson decomposition

red points reach experimental ε_K^{exp}

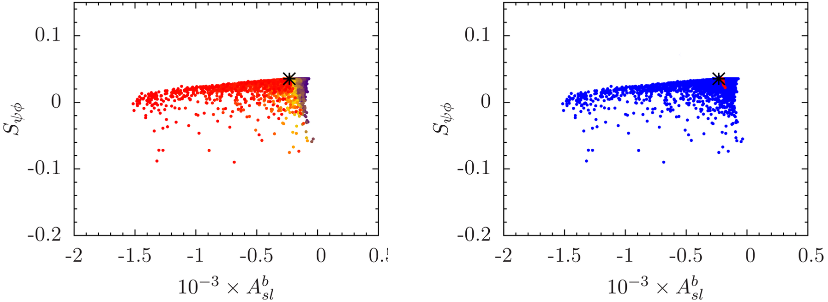
The price of ε_K is the "wrong" suppresion of $\mathrm{BR}(B^+ \to \tau^+\nu_\tau)/\Delta M_{B_d}$.

Can we still have large effects in $S_{\psi\phi}$ and A^b_{sl} after the constraints?

the b semileptonic CP-asymmetry

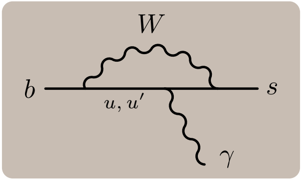
$$A_{sl}^{b,exp} = (-0.787 \pm 0.172 \pm 0.093) \times 10^{-2}$$ (D0, '11)

$\longrightarrow$ controversial measurement
$\longrightarrow$ hard to measure in LHC

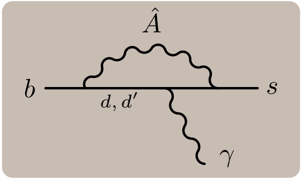


Result: ○ Large deviations possible but not allowed by constraints.
○ $S_{\psi\phi}$, A^b_{sl} SM-like

$\Delta F = 1 \qquad \overline{B} \to X_s\gamma$

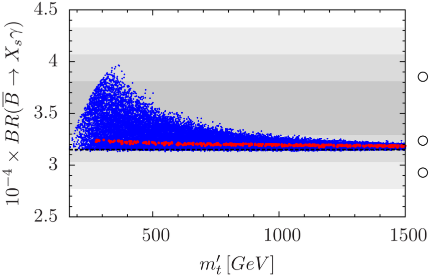


- $@ \sim m_t$
- SM-like



- $@ \sim M_{\hat{A}}$
- $M_{\hat{A}}$ can be $< 1\mathrm{TeV}$
- QCD generates 48 new operators

(arXiv:1105.5146v2)



- Neutral gauge boson contribution negligible
- Exotics can only enhance BR
- NO large effects are possible after the constraints

Concluding Remarks

Gauging non-abelian sector of the Quark Flavour Symmety

Theory

- flavour-violating gauge bosons
- exotic fermions for anomaly cancellation
- natural supression of FCNCs

Phenomenology

- few parameters $\longrightarrow$ clear flavour patterns
- ε_K, $S_{\psi K_s}$, $\Delta M_{B_d}/\Delta M_{B_s}$ and $\mathrm{BR}(B^+ \to \tau^+\nu_\tau)/\Delta M_{B_d}$ best flavour constraints
- correct $S_{\psi K_s}$ only if V_{ub} small
- constraints $\longrightarrow$ increases tension in $\mathrm{BR}(B^+ \to \tau^+\nu_\tau)/\Delta M_{B_d}$
- constraints $\longrightarrow$ no large effects in $S_{\psi\phi},\ A_b^{sl},\ \bar{B} \to X_s\gamma$

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Thank you.

Extra Slides

Lagrangian interactions

$$\mathcal{L} = \mathcal{L}_{\text{kinetic}} + \underbrace{\mathcal{L}_{\text{interaction}}} + \mathcal{L}_{\text{scalar}}(H, Y_u, Y_d)$$

Vector-like under flavour

$\boldsymbol{SU(3)_{Q_L}}$: $\lambda_u \underbrace{\overline{Q}_L}_{\bar{\mathbf{3}}} \tilde{H} \underbrace{\Psi_{uR}}_{\mathbf{3}} \qquad \lambda_d \underbrace{\overline{Q}_L}_{\bar{\mathbf{3}}} H \underbrace{\Psi_{dR}}_{\mathbf{3}}$

$\boldsymbol{SU(3)_{U_R}}$: $M_u \underbrace{\overline{\Psi}_{uL}}_{\bar{\mathbf{3}}} \underbrace{U_R}_{\mathbf{3}}$

$\boldsymbol{SU(3)_{D_R}}$: $M_d \underbrace{\overline{\Psi}_{dL}}_{\bar{\mathbf{3}}} \underbrace{D_R}_{\mathbf{3}}$

Allowed flavon interactions

"Yukawa"-type masses only for exotic fields: $\lambda'_u \overline{\Psi}_{uL} Y_u \Psi_{uR} \qquad \lambda'_d \overline{\Psi}_{dL} Y_u \Psi_{dR}$

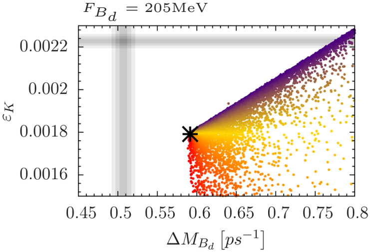
only 6 new parameters:

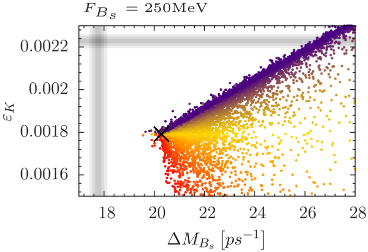
- 4 couplings $\lambda_u,\ \lambda'_u,\ \lambda_d,\ \lambda'_d$
- 2 masses $M_u,\ M_d$

Clear pattern of different contributions

exotic quarks (purple) — enhancement of ε_K and $\Delta M_{B_{d,s}}$

gauge bosons (red) — suppression of ε_K no effect on $\Delta M_{B_{d,s}}$





Large theory errors in both ϵ_K (charm dominant) and especially in $\Delta M_{B_{d,s}}$ from meson decay constants F_{B_s} and F_{B_d} (lattice input)!

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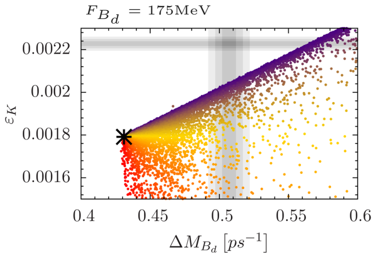

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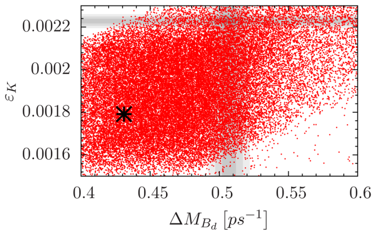

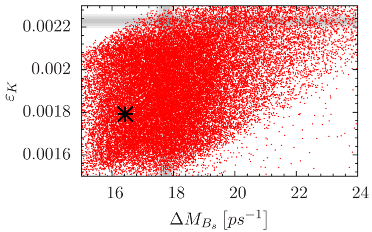

Good news: hope for future improvement for both.
Last week: $F_{B_d} = 189(4)\mathrm{MeV}$ $F_{B_s} = 225(4)\mathrm{GeV}$

(HPQCD Collaboration, '12)