Gauged Flavour Symmetries

and their

Flavour Phenomenology

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A. J. Buras, L. Merlo, & E. Stamou arXiv:1105.5146v2

PLANCK 2012

FROM THE PLANCK SCALE
TO THE ELECTROWEAK SCALE

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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)

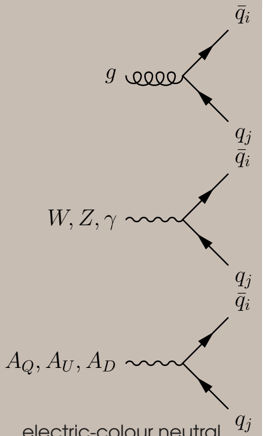
Part 1: gauging flavour symmetries

- ∘ anomaly cancellation with exotic fermions
- ∘ see-saw for quark masses $m \propto 1/Y$
- ∘ FCNCs $\propto 1/Y^2$, flavour protection for light generations
- ∘ 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 TeV gauged flavour model

Recipe:

- Y_u, Y_d flavour-charged singlets under SM } ⟶ MFV
- anomaly cancellation ⟶ add exotic fermions (easy: vector-like under flavour)
- chiral under SM
- forbid $\bar{q}_L^{\rm SM}\, Y\, q_R^{\rm SM}$ ⟶ 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	$\bar{3}$	$\bar{3}$
$SU(3)_{U_R}$	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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$SU(3)_{D_R}$	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

Mass eigenstates and see-saw

Break Flavour

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

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

unitary 3×3 will-be V_{CKM}

only source of FV

Mass matrices

(e.g. up-sector)

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

$\mathbf{0}$ comes from charge assignments

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

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- choose diagonal down-type basis

unitary
3×3
will-be V_{CKM}

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only source of FV

Mass matrices

(e.g. up-sector)

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

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

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

Inverse quark see-saw

See-saw:

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

Inverse Hierarchy

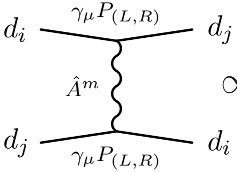
For case of large splitting $m \ll m'$ (true except for top-quark):

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

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

data: $\langle \hat{Y}_{11} \rangle \gg \langle \hat{Y}_{22} \rangle \gg \langle \hat{Y}_{33} \rangle$

Tree-level FCNCs automatically suppressed for light generations

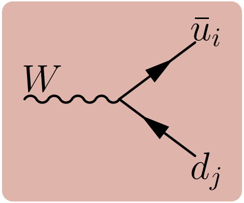


$$\propto \frac{1}{\langle Y \rangle^2} \left(\bar{q}_i \, \gamma^\mu P_{(L,R)} \, q_j \right)^2$$

Lowest NP scale fixed by $\langle Y_{33} \rangle$
$\longrightarrow$ **can be TeV scale!** $\longleftarrow$

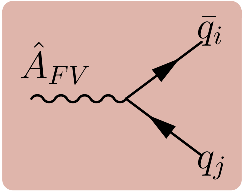
Non-MFV aspects

V_{CKM} determined from tree-level processes



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

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



$$\propto \gamma_\mu \, P_{L,R} \, \mathcal{G}^{ij}_d$$

complex couplings
$\longrightarrow$ "new" phases
$\Delta F = 2$ obs. sensitive probes

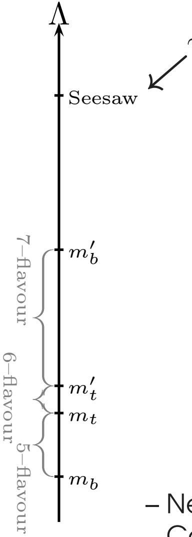
Part 2: flavour phenomenology

Are sizeable deviations in flavour observables possible?

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

(arXiv:1112.4477v2)

Spectrum



$\sim$ mass of lightest flavour gauge boson

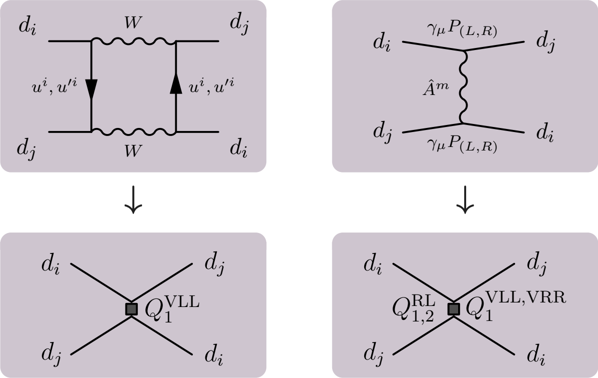
Iteratively fix

- 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?

Effective operators $\Delta F = 2$



SM-like

- loop-induced at μ_{EW}
- in B-system only t' relevant
- in K-system c-modification relevant

NP

- tree-level induced at $\mu_{\hat{M}}$
- only 2 lightest gauge bosons relevant
- $Q_{1,2}^{RL}$ QCD enhanced

$\Delta F = 2$ observables

Kaon-sector

$\boldsymbol{\epsilon_K}$ measure of indirect $\not{C}\not{P}$

$|\epsilon_K|^{\rm SM} = 1.81(28) \times 10^{-3}$

$|\epsilon_K|^{\rm exp} = 2.228(11) \times 10^{-3}$

$$\epsilon_K = \frac{\kappa_\varepsilon e^{i\varphi_\varepsilon}}{\sqrt{2}(\Delta M_K)_{\rm exp}} {\rm Im} M_{12}^K$$

(Brod, Gorbahn, '12)

(PDG, '10)

B_d-system

$\boldsymbol{\Delta M_{B_d}}$ mass difference

$\boldsymbol{S_{\psi K_S}}$ CP-asymmetry in $B_d^0 \to J/\psi K_S$

$$S_{\psi K_s} = \sin(2\beta + 2\phi_{Bd})$$

$$\beta \simeq 22^\circ \quad \phi_{Bd} = ?$$

B_s-system

$\boldsymbol{\Delta M_{B_s}}$ mass difference

$\boldsymbol{S_{\psi\phi}}$ CP-asymmetry in $B_s^0 \to J/\psi\phi$

$$S_{\psi\phi} = \sin(2|\beta_s| + 2\phi_{Bs})$$

$$\beta_s \simeq -1^\circ \quad \phi_{Bs} = ?$$

(new LHCb value points to SM)

$\boldsymbol{A_{sl}^b}$ the b-semileptonic like-sign dimuon charge assymmetry

$A_{sl}^{b,\rm exp} = (-0.787 \pm 0.172 \pm 0.093) \times 10^{-2}$ (**D0**,11) $\quad A_{sl}^b = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$

The V_{ub} issue

Inclusive

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

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

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

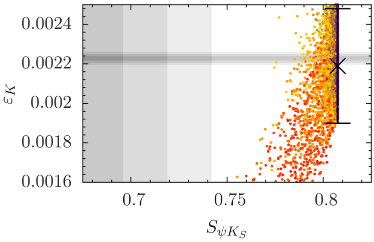
Exclusive

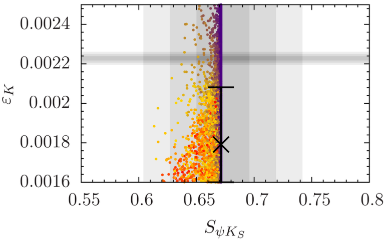
$$|V_{ub}^{excl}| = (3.38 \pm 0.36) \times 10^{-3}$$

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

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

MGF can accomodate the data only for V_{ub}^{excl}. (tree-contr. too small)

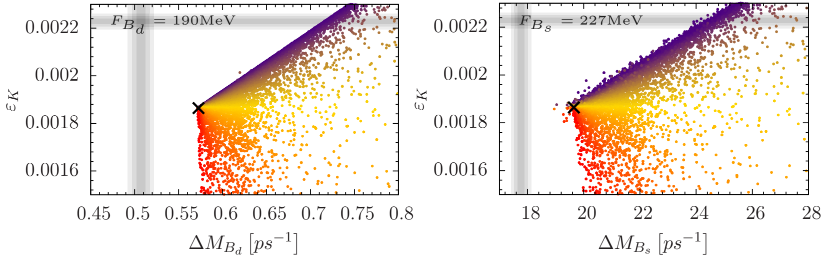




Clear pattern of different contributions

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 (theo. charm dominated) and in $\Delta M_{B_{d,s}}$ from meson decay constants F_{B_s} and F_{B_d} (lattice input)!

Clear pattern of different contributions

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

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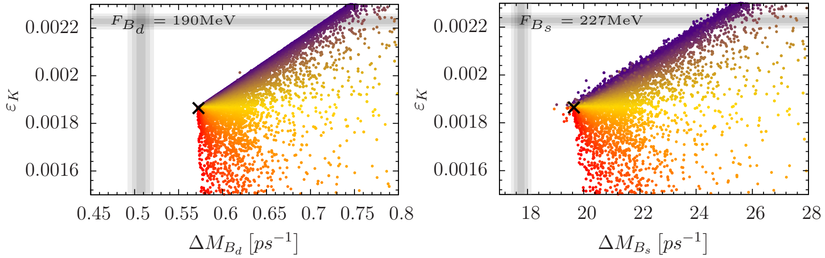


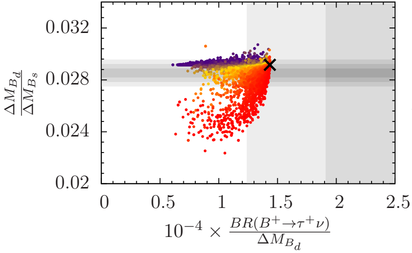
Good news: hope for future improvement in both ϵ_K and ΔM_B!

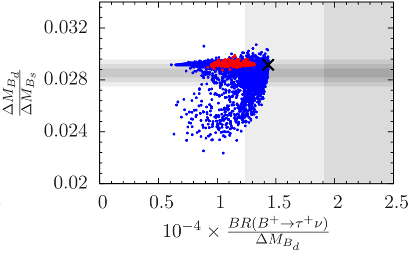
- ϵ_K : matching of MOM- and $\overline{\text{MS}}$-scheme
- F_B : lattice improving rapidly

To constraint MGF look at theoretically 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

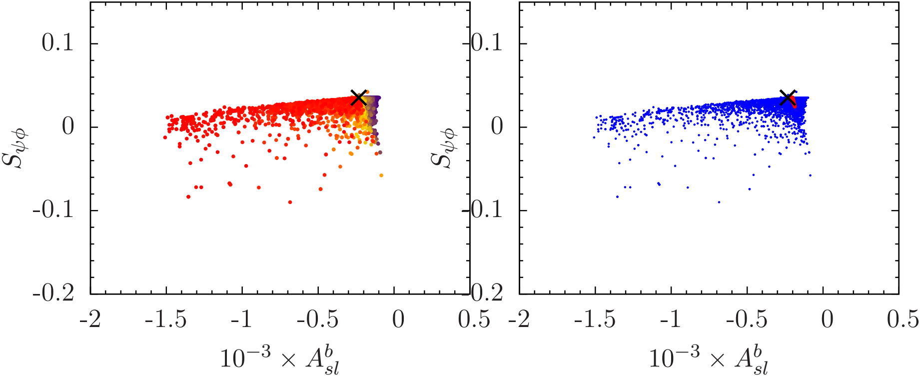
red points reach
experimental ε_K^{exp}

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

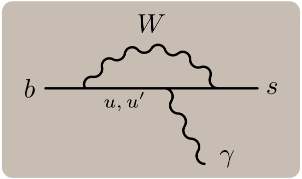
Can we still have large effects in $S_{\psi\phi}$ and A^b_{sl} after the constraints?

the b semileptonic CP-asymmetry

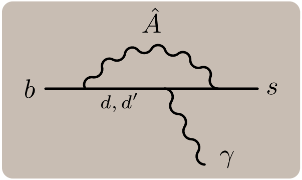
$A^{b,exp}_{sl}$ $\longrightarrow$ controversial measurement
$\longrightarrow$ hard to measure at LHC



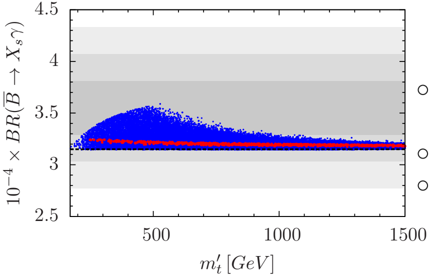
Result: ∘ no large deviations allowed by constraints.
∘ $S_{\psi\phi}$, A^b_{sl} SM-like



- @ $\sim m_t$
- SM-like



- @ $\sim M_{\hat{A}}$
- $M_{\hat{A}}$ can be $< 1\text{TeV}$
- mixing of 48 new operators



- Neutral gauge boson contribution negligible
- Exotics can only enhance BR
- No large effects are possible

Part 4 : conclusions and outlook

Conclusions and Outlook

Gauging non-abelian sector of the Quark Flavour Symmetry

Theory

- compatible with NP at the TeV scale
- a step towards the explanation of quark masses
- implications beyond flavour?
  - $\longrightarrow$connection to GUTs (Feldmann, '11)
  - $\longrightarrow$LR symmetry (Guadagnoli et al, '11)

Phenomenology

- few parameters $\longrightarrow$ clear flavour patterns
- ϵ_K, $S_{\psi K_s}$, $\Delta M_{B_d}/\Delta M_{B_s}$, $\mathrm{BR}(B^+ \to \tau^+ \nu_\tau)/\Delta M_{B_d}$ and V_{tb} best flavour constraints
- correct $S_{\psi K_s}$ if V_{ub} small
- constraints $\longrightarrow$ increased 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.

Backup

Flavour violation in the SM

$$\begin{aligned}\mathcal{L}_{\rm SM} = \quad & \mathcal{L}_{\rm kinetic} \\ & -\left(\boldsymbol{y_d^{ij}}\, \overline{Q}_{Li}\, H\, d_{Rj} + \boldsymbol{y_u^{ij}}\, \overline{Q}_{Li}\, \tilde{H}\, u_{Rj} + h.c.\right) \\ & -\left(y_e^{ij}\, \overline{E}_{Li}\, H\, e_{Rj} + h.c.\right) \\ & - V(H)\end{aligned}$$

- $\boldsymbol{y_d^{ij}}$ and $\boldsymbol{y_u^{ij}}$ free complex parameters (not all physical)
- may be expressed in terms of masses and mixings of the low energy d.o.f. (up and down quarks)
- $\boldsymbol{y_d^{ij}}, \boldsymbol{y_u^{ij}} \longrightarrow$ 6 masses, 3 mixing angles, and 1 phase.

the SM "lesson"

masses and flavour violation governed both by the same parameters:

$\boldsymbol{y}_u$ and $\boldsymbol{y}_d$

(in the SM masses and mixings are different sides of the same coin)

Masses and Mixings from Data

$$\begin{pmatrix} u & c & t \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

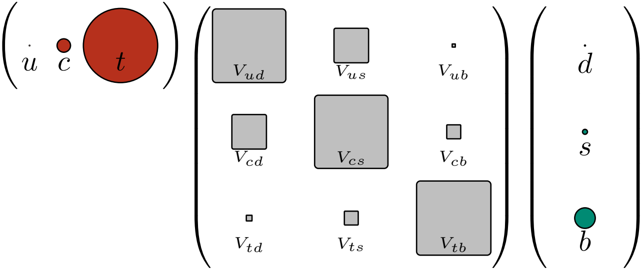
- SM accounts for data if $V_{\rm CKM}$ unitary
- SM does not know the origin of the masses and mixings

  (they are just y_u and y_d)
- understanding the masses and mixings is the distant goal of flavour-physics

y_u & y_d $\Longleftrightarrow$ masses & mixings
is a SM peculiarity

not respected by generic extensions of the SM

Masses and Mixings from Data



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is a SM peculiarity

not respected by generic extensions of the SM

The concept of Minimal Flavour Violation

Minimal Flavour Violation
y_u and y_d are the only sources of flavour violation

(Chivukula, Georgi, '87 ; Hall, Randall '90 ; Buras et al, 01 ; D'Ambrosio et al, 02)

SM: $y_u \to 0$ & $y_d \to 0$ $\Longrightarrow$ no FV, massless quarks
$\Longrightarrow$ extra global symmetry $U(3)_{Q_L} \times U(3)_{U_R} \times U(3)_{D_R}$

Formalising MFV:

all FV comes from the breaking of $U(3)_{Q_L} \times U(3)_{U_R} \times U(3)_{D_R}$

The implications of Minimal Flavour Violation

global symmetry
$U(3)_{Q_L} \times U(3)_{U_R} \times U(3)_{D_R}$

$$\mathcal{L} = -\left(\boldsymbol{Y_d^{ij}}\ \overline{Q}_{Li}\ H\ d_{Rj} + \boldsymbol{Y_u^{ij}}\ \overline{Q}_{Li}\ \tilde{H}\ u_{Rj} + h.c. \right) + \mathcal{L}_{\text{SMrest}} + \mathcal{L}_{\text{UV}}$$

- Y_u, Y_d spurion fields transforming under the flavour symmetry
- simplest realisation

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

- FV in $\mathcal{L}_{UV}$ is build out out of flavour-invariant non-renormalisable operators with Y_u and Y_d.

(D'Ambrosio et al, '02)

- automatically safe from large FCNC's

The implications of Minimal Flavour Violation

global symmetry
$U(3)_{Q_L} \times U(3)_{U_R} \times U(3)_{D_R}$

$$\mathcal{L} = -\left(\boldsymbol{Y_d^{ij}}\, \overline{Q}_{Li}\, H\, d_{Rj} + \boldsymbol{Y_u^{ij}}\, \overline{Q}_{Li}\, \tilde{H}\, u_{Rj} + h.c. \right) + \mathcal{L}_{\text{SMrest}} + \mathcal{L}_{\text{UV}}$$

$\longrightarrow$ setup for building models safe from Flavour

$\longrightarrow$ explanation masses and mixings

$\Updownarrow$

understanding the breaking of the flavour symmetry

Minimisation of scalar potential?(Alonso et al, '11)

Problem
Where are the Goldstone modes of the spontaneously broken flavour symmetry?

The implications of Minimal Flavour Violation

global symmetry
$U(3)_{Q_L} \times U(3)_{U_R} \times U(3)_{D_R}$

$$\mathcal{L} = -\left(\boldsymbol{Y_d^{ij}}\, \overline{Q}_{Li}\, H\, d_{Rj} + \boldsymbol{Y_u^{ij}}\, \overline{Q}_{Li}\, \tilde{H}\, u_{Rj} + h.c. \right) + \mathcal{L}_{\text{SMrest}} + \mathcal{L}_{\text{UV}}$$

$\longrightarrow$ setup for building models safe from Flavour

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$\Updownarrow$

understanding the breaking of the flavour symmetry

Minimisation of scalar potential?(Alonso et al, '11)

A way out
gauge the flavour symmetry

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

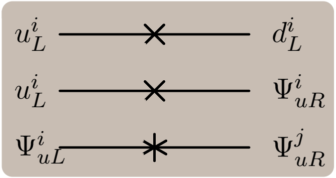
$$\lambda'_u \overline{\Psi}_{uL} Y_u \Psi_{uR} \qquad \lambda'_d \overline{\Psi}_{dL} Y_d \Psi_{dR}$$

only 6 new parameters:

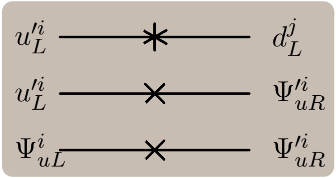
- ∘ 4 couplings $\lambda_u, \ \lambda'_u, \ \lambda_d, \ \lambda'_d$
- ∘ 2 masses $M_u, \ M_d$

Is MGF MFV?

- V_{CKM} determined from tree-level processes of mass eigenstates
- rotate all FV to u_{Li}, $Y_u = \hat{Y}_u \cdot V$, mass-insertion notation:



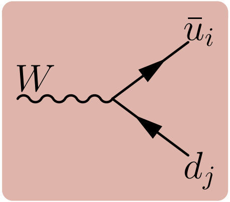
$\Longrightarrow$



(just like in SM)

- q's still mix with Ψ's, integrate out heavy Ψ's

$$|u\rangle^{\text{mass}} = \cos\theta_u\,|u\rangle + \sin\theta_u\,|\Psi_u\rangle \qquad |d\rangle^{\text{mass}} = \cos\theta_d\,|d\rangle + \sin\theta_d\,|\Psi_d\rangle$$



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

V_{CKM} **not** unitary beyond MFV

Flavour Gauge Bosons

- mass matrix from kinetic terms of flavons Y_u and Y_d

(like W,Z-masses in SM)

- $SU(3)_Q \times SU(3)_U \times SU(3)_D$ realisation

$$\chi = \left(A_Q^1, \ldots, A_Q^8, A_U^1, \ldots, A_U^8, A_D^1, \ldots, A_D^8\right)^T$$

Mass Lagrangian:

$$\mathcal{L}_{\text{mass}} = \frac{1}{2}\,\chi^T\,\mathcal{M}_A^2\,\chi$$

$$\mathcal{M}_A^2 = \begin{pmatrix} M_{QQ}^2 & M_{QU}^2 & M_{QD}^2 \\ M_{UQ}^2 & M_{UU}^2 & 0 \\ M_{DQ}^2 & 0 & M_{DD}^2 \end{pmatrix}$$

e.g. $\left(M_{QU}^2\right)_{ab} = -\frac{1}{2}\,g_Q\,g_U\,Tr\left[\lambda_{SU(3)}^a\,\langle Y_u\rangle^\dagger\,\lambda_{SU(3)}^b\,\langle Y_u\rangle\right]$

Diagonalisation $\Longrightarrow$ tree-level flavour-violating couplings $\mathcal{G}_{LR}^{ud,i}$

Naïve Gauging

- gauging without introducing new fermions
- anomaly cancellation → only vector subgroup ($SU(3)_{qV}$) "gaugeable"

$$\mathcal{L} = -\left(\boldsymbol{Y}_{\boldsymbol{d}}^{\boldsymbol{ij}}\, \overline{Q}_{Li}\, H\, d_{Rj} + \boldsymbol{Y}_{\boldsymbol{u}}^{\boldsymbol{ij}}\, \overline{Q}_{Li}\, \tilde{H}\, u_{Rj} + h.c. \right) + \mathcal{L}_{\text{SMrest}} + \mathcal{L}_{\text{UV}}$$

data: $\langle Y_{11} \rangle \ll \langle Y_{22} \rangle \ll \langle Y_{33} \rangle$

- NP scale Λ_Y fixed by the smallness of FCNC's.

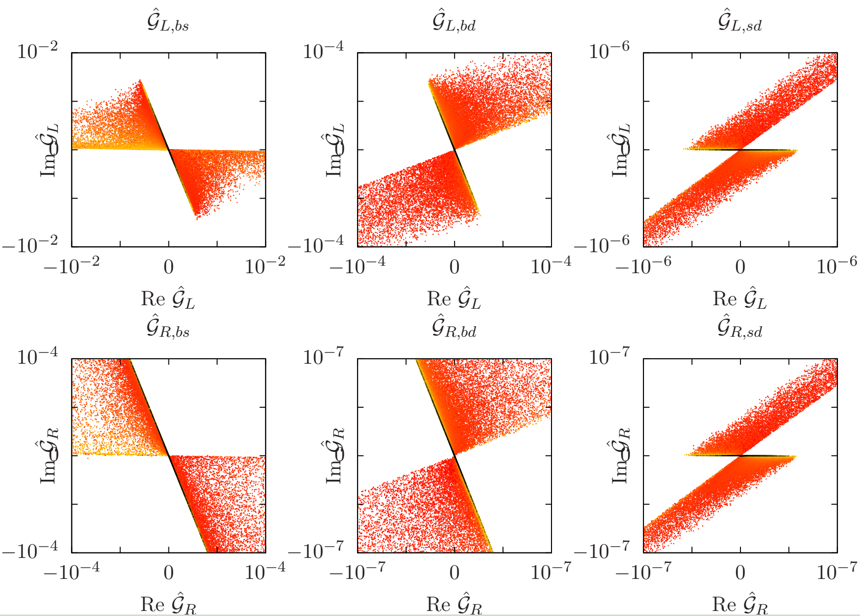
$$\mathcal{L}_{\Delta F=2} = -\frac{g^2}{\Lambda_Y^2} \left(\bar{q}_i \gamma_\mu P_{L,R} q_j\right) \left(\bar{q}_j \gamma^\mu P_{L,R} q_i\right)$$

- Lowest NP scale fixed by FCNC's of **light** generations!

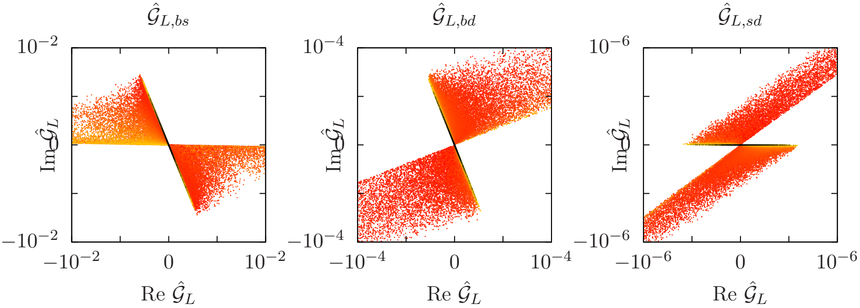
$\Longrightarrow \Lambda_Y \geq 1000$ TeV (Bona et al)

- Can we evade this? **Yes.** (Grinstein, Redi, Villadoro '10)

FV of the lightest Gauge Boson



FV of the lightest Gauge Boson

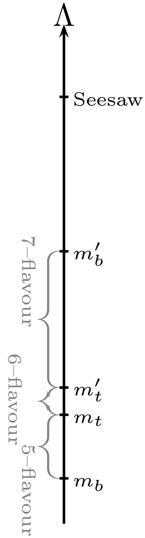


- origin of couplings and masses of lightest boson: $\langle \mathbf{Y_{33}} \rangle$
- large hierarchies in couplings
- couplings are complex: **“new phases”**

  (not really new – V has still the only phase in the theory)

Low energy $\Delta F = 2$ observables are very sensitive to such “new phases”!

The problem of scales



Input

- SM masses and V_{CKM}^{exp}
- $\lambda_u\,,\lambda'_u\,,M_u$ and $\lambda_d\,,\lambda'_d\,,M_d$
- $g_Q\,,g_U\,,g_D$

Output

- $m'^i_{u,d}$ and $\hat{M}^1,\ldots,\hat{M}^{24}$
- $\sin_u^{LR,i}\,,\sin_d^{LR,i}$
- $\mathcal{G}_{u,ij}^{LR}\,,\mathcal{G}_{d,ij}^{LR}$

All output is defined at the seesaw scale Λ_{seesaw}, the mass of the lightest gauge boson

$$m(\Lambda_{\text{seesaw}})m'(\Lambda_{\text{seesaw}}) = \lambda M v/\sqrt{2}$$

intermediate thresholds (QCD evolution important)

$\longrightarrow$ Spectrum fixed iteratively

$\longrightarrow$ Evolve masses down to M_{EW}

many different spectra

Direct constraints

light vector fermions

- LHC searches $m_t' > 475$ GeV and $m_b' > 268$ GeV (CMS)
- searches assume 100% $q' \to qZ$
- not fully applicable here (mixing and higgs channel)

down-sector

- strongest constraint $\boldsymbol{Z}$**-width** from modified Zbb coupling

up-sector

- EW precision observables, $\boldsymbol{T}$**-parameter** after breaking custodial symmetry
- SM modification included only at LO – careful.

non-unitary CKM

- no constraints from light-quarks (1^{st} row of V_{CKM}!)
- direct tWb coupling constrained by $|V_{tb}|$
  $\longrightarrow c_{tL} > 0.77$ not very constraining

Direct constraints

light vector fermions

- LHC searches $m_t' > 475$ GeV and $m_b' > 268$ GeV (CMS)
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down-sector

- stronges… …oupling

up-se…

What is flavour telling us?

- EW precision observables, T**-parameter** after breaking custodial symmetry
- SM modification included only at LO – careful.

non-unitary CKM

- no constraints from light-quarks (1^{st} row of V_{CKM}!)
- direct tWb coupling constrained by $|V_{tb}|$ $\longrightarrow c_{tL} > 0.77$ not very constraining