Summer School “Physics of Heavy Quarks and Hadrons”, July 15–28, JINR Dubna

Rare Decays beyond the Standard Model

Photo: © Adam Romig

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Plan of Part I (today)

1. Introduction: flavour and new physics
   - Flavour puzzle & flavour problem
   - Minimal Flavour Violation
2. Effective Hamiltonian for rare decays
3. Rare decays in MFV
   - Dipole operators
   - Semi-leptonic operators
   - Scalar operators

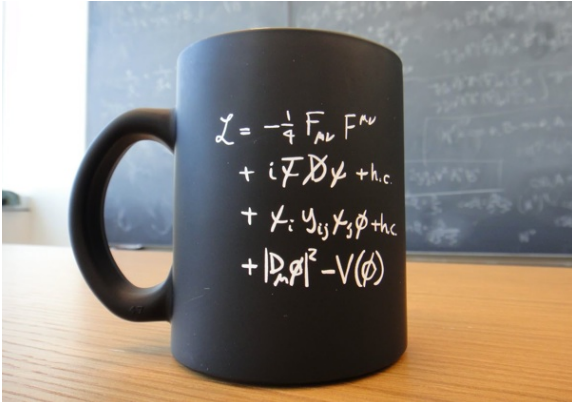
Plan of Part II (tomorrow)

4. The special role of the third generation: $U(2)^3$ flavour symmetry
   - $U(2)^3$ as an EFT
   - Rare decays in $U(2)^3$
   - Natural SUSY
5. Froggatt-Nielsen and $U(1)^9$ flavour symmetry
   - Froggatt-Nielsen mechanism
   - $U(1)^9$ flavour symmetry
   - Rare decays in $U(1)^9$
6. Rare decays in Composite Higgs Models
   - Partial compositeness
   - Rare decays

Part I

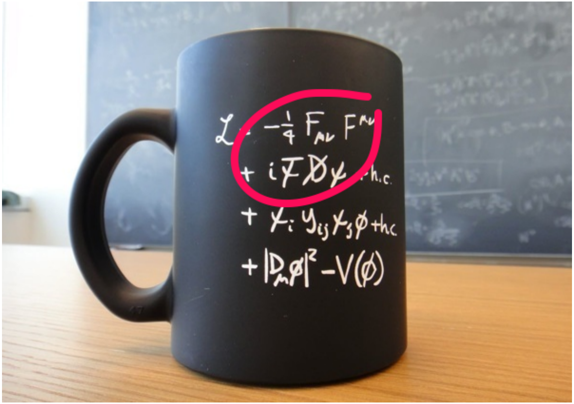
Minimal Flavour Violation & Rare Decays

The SM Lagrangian



[Photo: Ph. Tanedo, see http://bit.ly/jw6PUh]

The SM Lagrangian

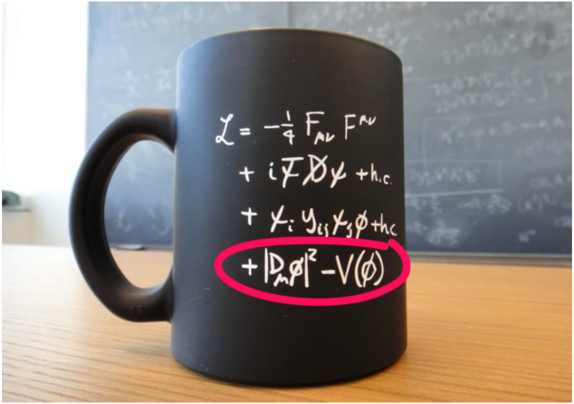


[Photo: Ph. Tanedo, see `http://bit.ly/jw6PUh`]

- ✓ Natural
- ✓ well tested
- ✓ only 3 parameters

(g_1, g_2, g_3)

The SM Lagrangian



[Photo: Ph. Tanedo, see `http://bit.ly/jw6PUh`]

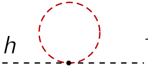
✓ finally tested!

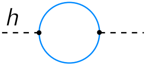
✓ 2 parameters (v, m_h)

X highly unnatural!

The gauge hierarchy problem

The Higgs mass receives contributions from all the heavy particles it couples to

$(m_h^2)_{\text{fund}} +$ 

$+$ 

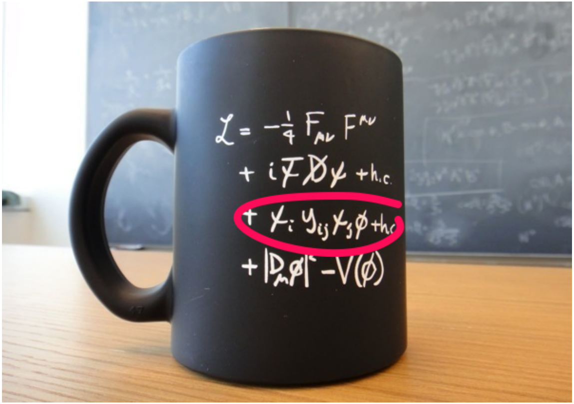
$= (m_h^2)_{\text{phys}}$

A new heavy state requires extreme fine-tuning. Two main solutions:

1. Supersymmetry
2. Composite Higgs

New physics at the TeV scale!

The SM Lagrangian



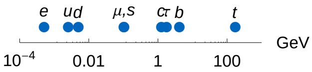
[Photo: Ph. Tanedo, see `http://bit.ly/jw6PUh`]

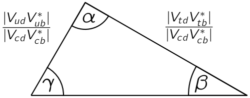
✓ well tested
✓ technically natural

✗ many parameters, origin poorly understood

Flavour puzzle

$$-\mathcal{L}_{\text{Yukawa}} = \bar{q}_L Y_u \tilde{H} u_R + \bar{q}_L Y_d H d_R + \bar{\ell}_L Y_\ell H e_R$$





$9 \quad + 3 \quad + 1 \quad = 13$

What is the origin of the peculiar structure of fermion masses and mixings?

Flavour and new physics

A solution to the gauge hierarchy problem requires new physics not too far above the weak scale.

In our low-energy EFT, we see the SM + a tower of higher-dimensional operators:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^{D-4}} \mathcal{O}_i^{(D)}$$

- At $D = 5$: neutrino mass term $(\bar{L}_L \epsilon H)(H^T \epsilon L_L)$
  - Needed anyway to explain neutrino oscillations
- At $D = 6$: e.g. FCNC operators such as $(\bar{Q}_L^i \gamma^\mu Q_L^j)^2$
  - Strongly constrained experimentally

Bounds on the scale of new physics

[Isidori et al. 1002.0900]

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^{D-4}} \mathcal{O}_i^{(D)}$$

Operator	Bounds on Λ in TeV ($c_{ij} = 1$) Re	Im	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	Δm_D; $\lvert q/p \rvert$, ϕ_D
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	Δm_D; $\lvert q/p \rvert$, ϕ_D
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		Δm_{B_s}

Flavour problem vs. flavour puzzle

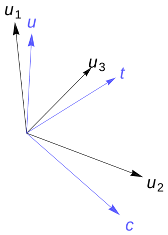
- TeV-scale NP – as suggested by the hierarchy problem – is incompatible with *generic* flavour-violation. This is the **flavour problem** of NP.
- But the size of the c_i depends on the *flavour structure* of the NP theory. What determines this structure could be related to the solution to the **flavour puzzle**!
- The NP sector has to be approximately invariant under some global **flavour symmetry**.

Flavour symmetry in the SM

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

- $\mathcal{L}_{\text{gauge}}$ and $\mathcal{L}_{\text{Higgs}}$ are flavour invariant

$$U(3)_{q_L} \otimes U(3)_{u_R} \otimes U(3)_{d_R} \otimes U(3)_{\ell_L} \otimes U(3)_{e_R}$$



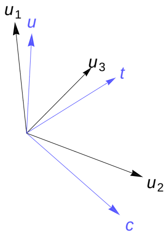
Flavour symmetry in the SM

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

- $\mathcal{L}_{\text{gauge}}$ and $\mathcal{L}_{\text{Higgs}}$ are flavour invariant

$$U(3)_{q_L} \otimes U(3)_{u_R} \otimes U(3)_{d_R} \otimes U(3)_{\ell_L} \otimes U(3)_{e_R} \to U(1)_B \times U(1)_L^3$$

- Only $\mathcal{L}_{\text{Yukawa}}$ distinguishes flavour (=breaks the flavour symmetry)



Minimal Flavour Violation

Goal: construct a physical criterion under which flavour violation in a NP theory is **minimized**.

Note: NP **cannot** be invariant under $U(3)^3$ since already the SM Yukawas break it.

The MFV assumption

The SM Yukawas are the only sources of breaking of $U(3)^3$ **even beyond the SM**

MFV as an effective field theory [D'Ambrosio et al. hep-ph/0207036]

- Starting point: **maximal flavour symmetry**

$$U(3)_{q_L} \otimes U(3)_{u_R} \otimes U(3)_{d_R}$$

- **Minimal breaking terms**: Yukawas as spurions

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

- All operators have to be made formally invariant under the flavour symmetry, e.g.

$$v \left\{ \bar{d}_R \, Y_d Y_u Y_u^\dagger \, \sigma^{\mu\nu} \, s_L \right\}_{32} F_{\mu\nu} \approx m_b \, V_{tb}^* V_{ts} \, \bar{b}_R \, \sigma^{\mu\nu} \, s_L \, F_{\mu\nu}$$

Consequences of MFV

All FCNC amplitudes are governed by the **same** CKM factors as in the SM

- NP effects in $b \to s$, $b \to d$ and $s \to d$ transitions are perfectly **correlated**

$$A(b \to s) : A(b \to d) : A(s \to d) = (V_{tb} V_{ts}^*)^{1,2} : (V_{tb} V_{td}^*)^{1,2} : (V_{ts} V_{td}^*)^{1,2}$$

- Ratios such as

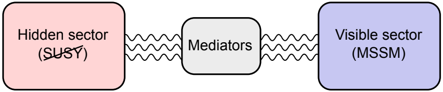
$$\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_d \to \mu^+\mu^-)} = \frac{\tau_{B_s} f_{B_s}^2 m_{B_s} |V_{ts}|^2}{\tau_{B_d} f_{B_d}^2 m_{B_d} |V_{td}|^2}$$

are **not modified** and consitute a test of the MFV paradigm

- CP violating phase aligned with the SM $\Rightarrow$ CP asymmetries mostly **SM-like**

Examples of MFV models

- **Gauge mediated SUSY breaking**
  Soft terms mediated by flavour-blind gauge interactions, RG induced flavour effects are governed by the Yukawa couplings

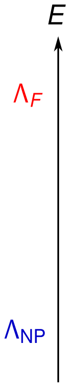


- **Constrained MSSM**
  Flavour-blind soft terms at GUT scale assumed ad hoc. Again, RG induced effects compatible with the MFV assumption.

$$m_{\tilde{q}}^2 = m_0 \times \mathbb{1} \qquad A_{u,d} = A_0 \times Y_{u,d}$$

NB: MFV assumption is RG invariant and can be imposed on many NP models, SUSY or non-SUSY.

MFV, flavour puzzle & flavour problem



- Imposing MFV is a brute-force “solution” to the **flavour problem**.
- The **flavour puzzle** about the origin of the Yukawa hierarchies is not addressed – its solution may lie at unaccessible energy scales.
- Models addressing the **flavour puzzle** typically contain sources of flavour violation beyond MFV! More on that tomorrow.

Rare B and K decays

	$b \to s$	$b \to d$	$s \to d$
γ	$B \to X_s\gamma$	$B \to X_d\gamma$	
	$B \to K^*\gamma$	$B \to \rho\gamma$	
$\ell^+\ell^-$	$B \to K\ell^+\ell^-$	$B \to \pi\ell^+\ell^-$	$K_L \to \pi\ell^+\ell^-$
	$B \to K^*\ell^+\ell^-$	$B \to \rho\ell^+\ell^-$	
	$B \to X_s\ell^+\ell^-$	$B \to X_d\ell^+\ell^-$	
	$B_s \to \mu^+\mu^-$	$B \to \mu^+\mu^-$	$K_L \to \mu^+\mu^-$
$\nu\bar{\nu}$	$B \to X_s\nu\bar{\nu}$	$B \to X_d\nu\bar{\nu}$	$K^+ \to \pi^+\nu\bar{\nu}$
	$B \to K\nu\bar{\nu}$		$K_L \to \pi^0\nu\bar{\nu}$
	$B \to K^*\nu\bar{\nu}$		

Rare B and K decays

	$b \to s$ ($\propto \lambda^2$)	$b \to d$ ($\propto \lambda^3$)	$s \to d$ ($\propto \lambda^5$)
γ	$B \to X_s \gamma$	$B \to X_d \gamma$	
	$B \to K^* \gamma$	$B \to \rho \gamma$	
$\ell^+\ell^-$	$B \to K \ell^+\ell^-$	$B \to \pi \ell^+\ell^-$	$K_L \to \pi \ell^+\ell^-$
	$B \to K^* \ell^+\ell^-$	$B \to \rho \ell^+\ell^-$	
	$B \to X_s \ell^+\ell^-$	$B \to X_d \ell^+\ell^-$	
	$B_s \to \mu^+\mu^-$	$B \to \mu^+\mu^-$	$K_L \to \mu^+\mu^-$
$\nu\bar{\nu}$	$B \to X_s \nu\bar{\nu}$	$B \to X_d \nu\bar{\nu}$	$K^+ \to \pi^+ \nu\bar{\nu}$
	$B \to K \nu\bar{\nu}$		$K_L \to \pi^0 \nu\bar{\nu}$
	$B \to K^* \nu\bar{\nu}$		

In MFV, strongest constraints on NP typically come from $b \to s$ transitions

$\Delta F = 1$ operators in the SM and in MFV

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\frac{e^2}{16\pi^2} V_{tb}V_{ts}^* \sum_i C_i O_i + \text{h.c.}$$

Current-current operators

$$O_1 = (\bar{s}\gamma^\mu T^a P_L c) \otimes (\bar{c}\gamma_\mu T^a P_L b) \qquad O_2 = (\bar{s}\gamma^\mu P_L c) \otimes (\bar{c}\gamma_\mu P_L b)$$

QCD penguin operators

$$O_3 = (\bar{s}\gamma^\mu P_L b) \otimes \sum_q (\bar{q}\gamma_\mu q) \qquad O_4 = (\bar{s}\gamma^\mu T^a P_L b) \otimes \sum_q (\bar{q}\gamma_\mu T^a q)$$

$$O_5 = (\bar{s}\gamma^\mu \gamma^\nu \gamma^\rho P_L b) \otimes \sum_q (\bar{q}\gamma_\mu \gamma_\nu \gamma_\rho q) \qquad O_6 = (\bar{s}\gamma^\mu \gamma^\nu \gamma^\rho T^a P_L b) \otimes \sum_q (\bar{q}\gamma_\mu \gamma_\nu \gamma_\rho T^a q)$$

C_{1-6} dominated by QCD contributions and hardly sensitive to NP!

$\Delta F = 1$ operators in the SM and in MFV

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\frac{e^2}{16\pi^2} V_{tb}V_{ts}^* \sum_i C_i O_i + \text{h.c.}$$

Dipole operators

$$O_7 = \frac{m_b}{e}(\bar{s}_L \sigma_{\mu\nu} b_R) F^{\mu\nu} \qquad O_8 = \frac{g_s m_b}{e^2}(\bar{s}_L \sigma_{\mu\nu} T^a b_R) G^{\mu\nu\,a}$$

Semileptonic operators

$$O_9 = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell) \qquad O_{10} = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$O_\nu = (\bar{s}_L \gamma_\mu b_L)(\bar{\nu}_L \gamma^\mu \nu_L)$$

$C_{7-10,\nu}$ are generated in the SM and **sensitive** to many **NP** models

$\Delta F = 1$ operators in the SM and in MFV

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\frac{e^2}{16\pi^2}V_{tb}V_{ts}^*\sum_i C_i O_i + \text{h.c.}$$

Scalar operators

$$O_S = \frac{m_b}{m_{B_s}}(\bar{s}_L b_R)(\bar{\ell}\ell) \qquad O_P = \frac{m_b}{m_{B_s}}(\bar{s}_L b_R)(\bar{\ell}\gamma_5\ell)$$

$C_{S,P}$ **vanish** in the SM but can be sizable in models with extended Higgs sector

$\Delta F = 1$ operators in the SM and in MFV

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\frac{e^2}{16\pi^2} V_{tb}V_{ts}^* \sum_i C_i O_i + \text{h.c.}$$

Scalar operators

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$C_{S,P}$ **vanish** in the SM but can be sizable in models with extended Higgs sector

NB: in MFV, all Wilson coefficients C_i are **real**, dimensionless numbers

Rare B and K decays

	$b \to s$	
γ	$B \to X_s\gamma$ $B \to K^*\gamma$	$O_{7,8}$
$\ell^+\ell^-$	$B \to K\ell^+\ell^-$ $B \to K^*\ell^+\ell^-$ $B \to X_s\ell^+\ell^-$	$O_{7,8}$, O_9, O_{10}
	$B_s \to \mu^+\mu^-$	O_{10}, $O_{S,P}$
$\nu\bar{\nu}$	$B \to X_s\nu\bar{\nu}$ $B \to K\nu\bar{\nu}$ $B \to K^*\nu\bar{\nu}$	O_ν

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Dipole operators

$$O_7 = \frac{m_b}{e}(\bar{s}_L \sigma_{\mu\nu} b_R) F^{\mu\nu} \qquad O_8 = \frac{g_s m_b}{e^2}(\bar{s}_L \sigma_{\mu\nu} T^a b_R) G^{\mu\nu\, a}$$

O_8 only enters the $b \to s\gamma$ and $b \to s\ell^+\ell^-$ amplitudes only via mixing with O_7:

$$C_7^{\text{eff}}(m_b) = \eta^{\frac{16}{23}} C_7(m_W) + \frac{8}{3}\left(\eta^{\frac{14}{23}} - \eta^{\frac{16}{23}}\right) C_8(m_W) + \sum_i h_i \eta^{a_i} C_2(m_W)$$
$$\approx 0.70\, C_7(m_W) + 0.09\, C_8(m_W) - 0.16\, C_2(m_W)$$

Consider NP effects only in C_7 in the following

$$C_7^{\text{eff}} = C_7^{\text{SM,eff}} + C_7^{\text{NP}}$$

Magnitude of C_7

In MFV models, the strongest constraint on C_7 comes from the measurement of $B \to X_s\gamma$

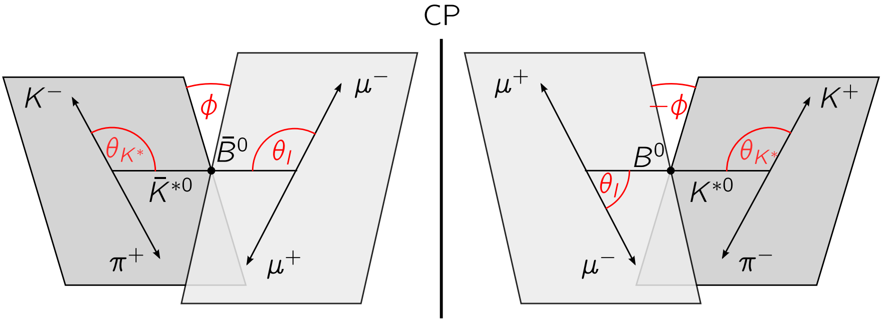
$$\text{BR}(B \to X_s\gamma)_{\text{exp}} = (3.43 \pm 0.22) \times 10^{-4}$$

$$\text{BR}(B \to X_s\gamma)_{\text{NP}} \simeq (3.14 \pm 0.22) \times 10^{-4} \times |1 + \Delta_7|^2$$

$$\Delta_7 = \frac{C_7^{\text{NP}}(m_b)}{C_7^{\text{SM,eff}}(m_b)}$$

$$\Rightarrow \Delta_7 \supset [-0.05, 0.14] \quad \vee \quad [-2.14, -1.95] \quad (\text{at } 2\sigma)$$

$B \to K^* \mu^+ \mu^-$



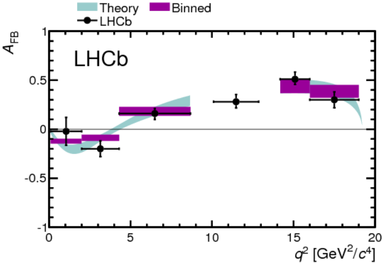
- 4-body decay: angular distribution with many observables sensitive to NP
- "self-tagging": sensitive to CP violation

Forward-backward asymmetry

$$A_{\rm FB}(B \to K^* \mu^+ \mu^-) = \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_l \frac{d^2(\Gamma - \bar\Gamma)}{dq^2\, d\cos\theta_l} \Big/ \frac{d(\Gamma + \bar\Gamma)}{dq^2}$$

$$\propto \text{Re}\left[\left(C_9^{\rm eff} + \frac{2 m_b m_B}{q^2} C_7^{\rm eff}\right) C_{10}\right]$$

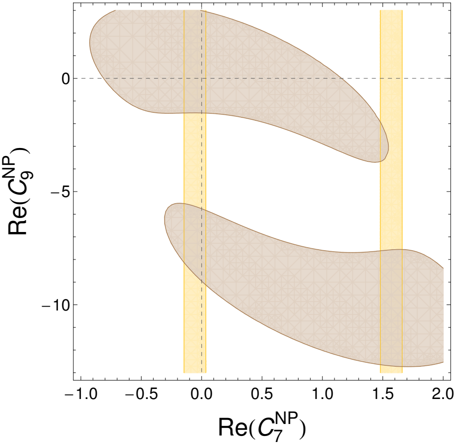
Sensitive to the sign of C_7!



LHCb 2013

[Aaij et al. 1304.6325]

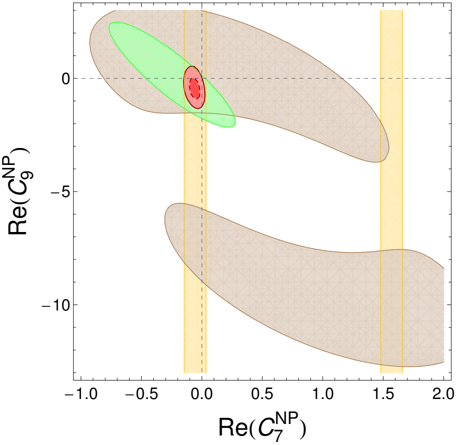
Bounds on C_7



Constraints from $B \to X_s\gamma$, $B \to X_s\mu\mu$

[Altmannshofer and Straub 1206.0273]

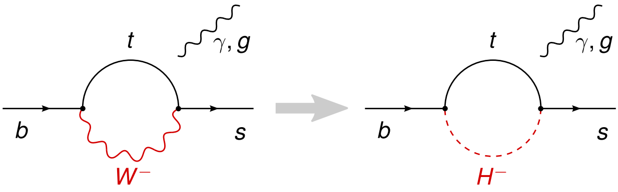
Bounds on C_7



Constraints from $B \to X_s\gamma$, $B \to X_s\mu\mu$, $B \to K^*\mu\mu$

[Altmannshofer and Straub 1206.0273]

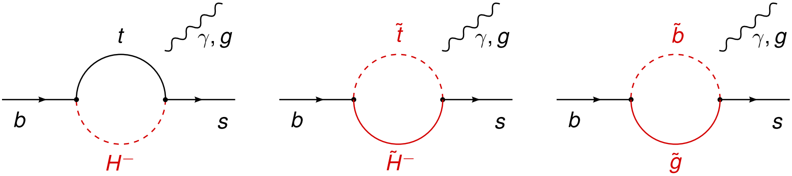
$B \to X_s\gamma$ in the two Higgs doublet model



$$\Rightarrow M_{H^\pm} \gtrsim 300 \text{ GeV}$$

[Misiak et al. hep-ph/0609232]

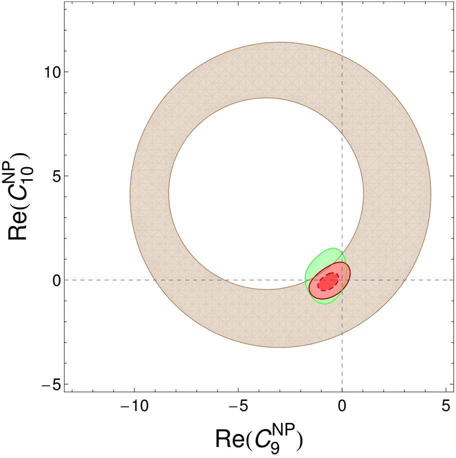
$B \to X_s\gamma$ in the MFV MSSM



$$\propto f\left(\frac{m_t^2}{M_{H^\pm}^2}\right) \qquad \sim \frac{m_t^2}{m_{\tilde t}^2}\frac{A_t\mu}{m_{\tilde t}^2}\tan\beta \qquad \sim \frac{m_t^2}{m_{\tilde b}^2}\frac{M_3\mu}{m_{\tilde b}^2}\tan\beta\left(\frac{m_{\tilde t}^2 - m_{\tilde c}^2}{m_{\tilde t}^2}\right)$$

$\Rightarrow$ cancellation between various contributions makes bound more model-dependent

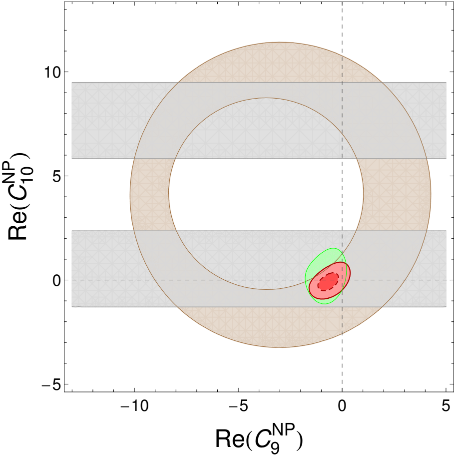
Bounds on C_9 and C_{10}



Constraints from $B \to X_s \mu\mu$, $B \to K^* \mu\mu$

[Altmannshofer and Straub 1206.0273]

Bounds on C_9 and C_{10}

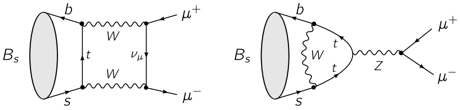


Constraints from $B \to X_s\mu\mu$, $B \to K^*\mu\mu$ and $B_s \to \mu\mu$

[Altmannshofer and Straub 1206.0273]

$B_s \to \mu^+\mu^-$

Strongly helicity suppressed in the SM: one of the rarest B decays



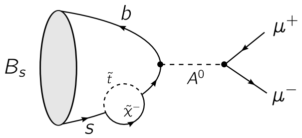
$$\mathrm{BR}_{\mathrm{SM}} = (3.5 \pm 0.3) \times 10^{-9} \qquad \mathrm{BR}_{\mathrm{exp}}(3.2^{+1.5}_{-1.2}) \times 10^{-9}$$

$$\mathrm{BR}(B_s \to \mu^+\mu^-) \propto \left[|S|^2 \left(1 - \frac{4m_\mu^2}{m_{B_s}^2} \right) + |P|^2 \right]$$

$$S = \frac{m_{B_s}}{2} C_S \qquad P = \frac{m_{B_s}}{2} C_P + m_\mu C_{10}$$

$B_s \to \mu\mu$ in the MSSM with MFV

Contributions to $C_{S,P}$ are generated by H^0 and A^0 exchange. In the decoupling limit ($M_{H^0,A^0} \gg m_h$) one has $C_S \simeq -C_P$

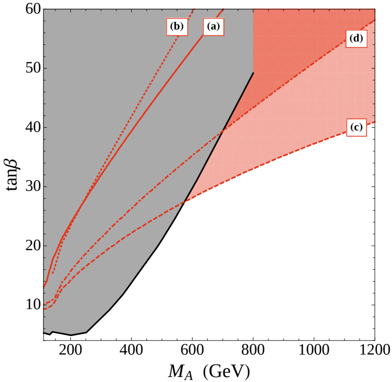


Dominant contribution: chargino-stop loop

$$C_S \simeq -C_P \propto \frac{\mu A_t}{m_{\tilde{t}}^2} \frac{m_{B_s} m_\mu}{m_A^2} \tan^3 \beta$$

Potentially huge enhancement for large $\tan \beta$

$B_s \to \mu\mu$ constrains $\tan\beta / M_A$



MFV; (a,b) $\mu A_t > 0$; (c,d) $\mu A_t < 0$

gray: $A, H \to \tau^+\tau^-$

[Altmannshofer et al. 1211.1976]

- Large $\tan\beta$ + light Higgs spectrum disfavoured
- Direct Higgs searches more constraining for $\tan\beta \lesssim 25$
- Milder bounds for $\mu A_t > 0$ (destructive interference with SM)

NB: in CMSSM, $A_t \approx 0.8 A_0 - 2.2 m_{1/2}$

Summary of Part I

- NP models have to be approximately invariant under some **flavour symmetry**
- The **MFV assumption** combines the maximal flavour symmetry with the minimal breaking terms
- Even with MFV, sizable effects in **rare decays** possible
- LHCb results **strongly constrain** the room for MFV-NP in rare decays

Summary of Part I

- NP models have to be approximately invariant under some **flavour symmetry**
- The **MFV assumption** combines the maximal flavour symmetry with the minimal breaking terms
- Even with MFV, sizable effects in **rare decays** possible
- LHCb results **strongly constrain** the room for MFV-NP in rare decays

But there are good reasons to go beyond MFV!

Summer School “Physics of Heavy Quarks and Hadrons”, July 15–28, JINR Dubna

Rare Decays beyond the Standard Model

Photo: © Adam Romig

David M. Straub | Johannes Gutenberg University Mainz

JG|U

Part II

Beyond MFV

Recap

- TeV scale new physics (suggested by the hierarchy problem) has to be approximately invariant under some global **flavour symmetry.**
- Minimal Flavour Violation assumes the **maximal** flavour symmetry $U(3)^3$ **minimally** broken by the SM Yukawas
- MFV leads to a protection of FCNCs, but it is **too pessimistic**: it does not even address the **flavour puzzle**

Today: Steps towards a solution of the **flavour puzzle**, while keeping the necessary protection of FCNCs

Plan of Part II

4. The special role of the third generation: $U(2)^3$ flavour symmetry
   - $U(2)^3$ as an EFT
   - Rare decays in $U(2)^3$
   - Natural SUSY
5. Froggatt-Nielsen and $U(1)^9$ flavour symmetry
   - Froggatt-Nielsen mechanism
   - $U(1)^9$ flavour symmetry
   - Rare decays in $U(1)^9$
6. Rare decays in Composite Higgs Models
   - Partial compositeness
   - Rare decays

MFV and $U(2)^3$

MFV is based on the **maximal** flavour symmetry

$$U(3)^2 = U(3)_Q \times U(3)_U \times U(3)_D$$

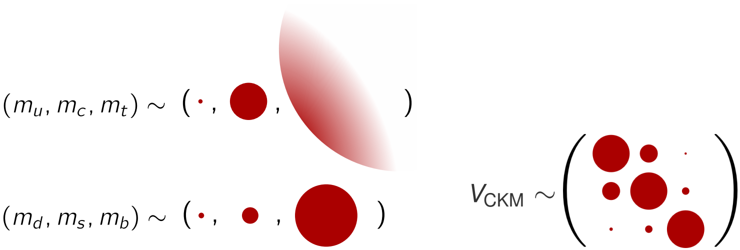
and the **minimal** breaking terms (Y_u, Y_d).

Now: consider the flavour symmetry

$$U(2)^3 = U(2)_Q \times U(2)_U \times U(2)_D$$

with the first two generations transforming as doublet, the 3rd as singlet

$U(2)^3$ and the flavour puzzle



$$U(2)^3 \Rightarrow m^{1,2}_{u,d} = 0, \; V_{i3,3i} = 0$$

The SM is approximately invariant under $U(2)^3$ $\Rightarrow$ breaking can be weak

$U(2)^3$ as EFT

[Barbieri et al. 1105.2296, Barbieri et al. 1203.4218]

As in MFV, we have to specify a symmetry (now **non-maximal**!)

$$U(2)^3 = U(2)_Q \times U(2)_U \times U(2)_D$$

$$Y_u = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \qquad Y_d = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

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[Barbieri et al. 1105.2296, Barbieri et al. 1203.4218]

As in MFV, we have to specify a symmetry (now **non-maximal**!)

$$U(2)^3 = U(2)_Q \times U(2)_U \times U(2)_D$$

and the breaking terms (still **minimal**!)

$$\Delta Y_u = (2, \bar{2}, 1) \qquad \Delta Y_d = (2, 1, \bar{2})$$

$$Y_u = \begin{pmatrix} \Delta Y_u & 0 \\ 0 & 1 \end{pmatrix} \qquad Y_d = \begin{pmatrix} \Delta Y_d & 0 \\ 0 & 1 \end{pmatrix}$$

$U(2)^3$ as EFT

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$$\Delta Y_u = (2, \bar{2}, 1) \qquad \Delta Y_d = (2, 1, \bar{2}) \qquad V = (2, 1, 1)$$

$$Y_u = \begin{pmatrix} \Delta Y_u & V \\ 0 & 1 \end{pmatrix} \qquad Y_d = \begin{pmatrix} \Delta Y_d & V \\ 0 & 1 \end{pmatrix}$$

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$$Y_u = \begin{pmatrix} \Delta Y_u & V \\ 0 & 1 \end{pmatrix} \qquad Y_d = \begin{pmatrix} \Delta Y_d & V \\ 0 & 1 \end{pmatrix}$$

Spurions are small and determined by masses, CKM

$$\Delta Y_u \supset y_u, y_c, \theta_u \qquad \Delta Y_u \supset y_d, y_s, \theta_d \qquad |V| \sim O(V_{cb})$$

Spurion analysis

Operators have to be made formally invariant under the flavour symmetry by spurion insertions.

Consider the quark bilinear $\bar{q}\gamma_\mu q$. In MFV,

$$\bar{q}\gamma_\mu \left(a\,\mathbb{1} + b\, Y_u Y_u^\dagger + c\, Y_d Y_d^\dagger + O(Y_{u,d}^4) \right) q$$

In $U(2)^3$ one has instead

$$a\, \bar{q}_{3L}\gamma_\mu q_{3L} + b\, \bar{\boldsymbol{q}}_{\boldsymbol{L}}\gamma_\mu \boldsymbol{q}_{\boldsymbol{L}} + c\, \bar{q}_{3L}\gamma_\mu (\boldsymbol{V}^\dagger \boldsymbol{q}_{\boldsymbol{L}}) + c^*\, (\bar{\boldsymbol{q}}_{\boldsymbol{L}} \boldsymbol{V})\gamma_\mu q_{3L} \\ + d\, (\bar{\boldsymbol{q}}_{\boldsymbol{L}} \boldsymbol{V})\gamma_\mu (\boldsymbol{V}^\dagger \boldsymbol{q}_{\boldsymbol{L}}) + O(\Delta Y_{u,d})$$

where $q_L = (\boldsymbol{q}_{\boldsymbol{L}}\ q_{3L})^T$

Comparison of MFV and $U(2)^3$ in $\Delta F = 1$

	$U(3)^3$	$U(2)^3$
$A(b \to s)$	$\lambda_{32}\, C$	$\lambda_{32}\, C_B\, e^{i\phi_B}$
$A(b \to d)$	$\lambda_{31}\, C$	$\lambda_{31}\, C_B\, e^{i\phi_B}$
$A(s \to d)$	$\lambda_{21}\, C$	$\lambda_{21}\, C_K$

where $C, C_K, C_B \in \mathbb{R},\ \lambda_{ij} = V_{ti} V_{tj}^*$

- Correlation between B and K decays **broken**
- New **CPV phase** in B decays

Recap: $\Delta F = 1$ operators

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\frac{e^2}{16\pi^2} V_{tb}V_{ts}^* \sum_i C_i O_i + \text{h.c.}$$

Dipole operators

$$O_7 = \frac{m_b}{e}(\bar{s}_L \sigma_{\mu\nu} b_R)F^{\mu\nu} \qquad O_8 = \frac{g_s m_b}{e^2}(\bar{s}_L \sigma_{\mu\nu} T^a P_R b_R)G^{\mu\nu\,a}$$

Semileptonic operators

$$O_9 = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell) \qquad O_{10} = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$O_\nu = (\bar{s}_L \gamma_\mu b_L)(\bar{\nu}_L \gamma^\mu \nu_L)$$

In $U(2)^3$, no new operators beyond MFV are generated, but Wilson coefficients are now **complex numbers**!

CP phases in $b \to s$ transitions

Branching ratios are not very sensitive to CP phases since imaginary parts of Wilson coefficients don't interfere with SM:

$$|C|^2 = |C^{\rm SM} + C^{\rm NP}|^2 = (C^{\rm SM})^2 + 2\,C^{\rm SM}\,\mathrm{Re}(C^{\rm NP}) + |C^{\rm NP}|^2$$

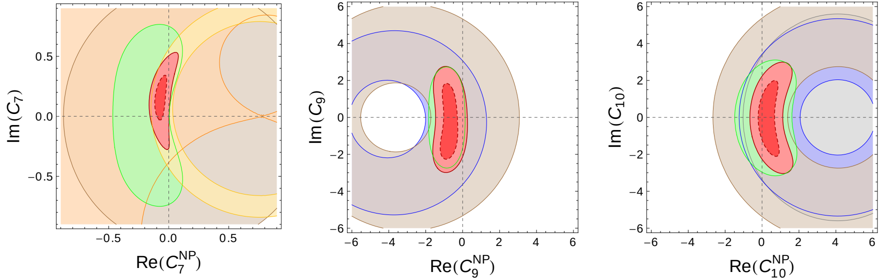
Need to measure **CP asymmetries.** Example: direct CP asymmetry in $b \to s\gamma$

$$A_{\rm CP} = \frac{\Gamma(\bar b \to \bar s\gamma) - \Gamma(b \to s\gamma)}{\Gamma(\bar b \to \bar s\gamma) + \Gamma(b \to s\gamma)}$$

Unfortunately, spoiled by poorly known long-distance contributions

[Benzke et al. 1012.3167]

Constraints on complex Wilson coefficients

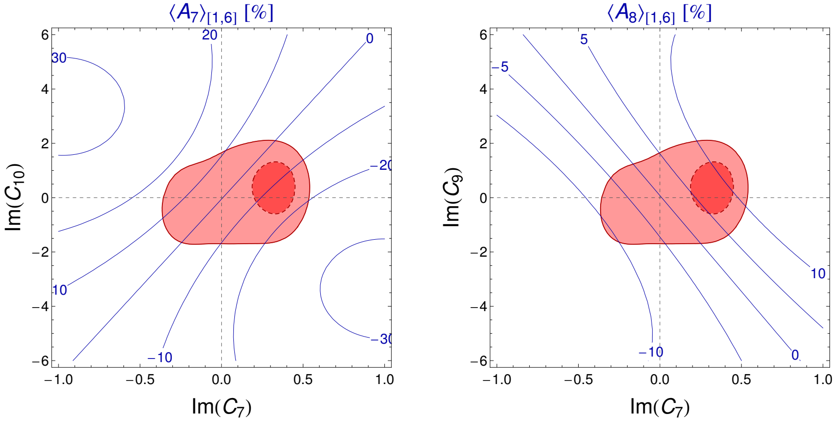


Constraints from $B \to X_s\gamma$, $B \to (K, K^*, X_s)\mu\mu$ and $B_s \to \mu\mu$

[Altmannshofer and Straub 1206.0273]

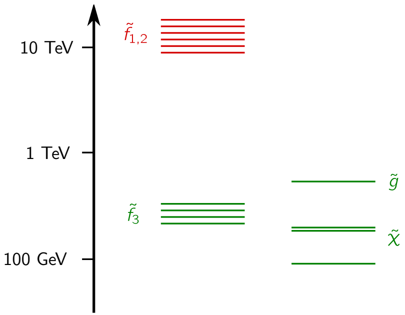
Angular CP asymmetries [Bobeth et al. 0805.2525]

In the future, improved bounds (our signs for NP!) can be obtained at LHCb by measuring T-odd **angular CP asymmetries** in $B \to K^* \mu^+ \mu^-$



Natural SUSY and $U(2)^3$

[Barbieri et al. 1105.2296, Barbieri et al. 1108.5125]



- **LHC bounds** strongest for the first two generations
- third generation ($\tilde{t}_{L,R}$, $\tilde{b}_L$) has to be light to solve **hierarchy problem**
- $U(3)^3$ explicitly **broken** in the spectrum! Natural to assume $U(2)^3$

Natural SUSY and $U(2)^3$

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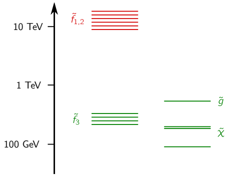

- Additional motivation for split families: electric dipole moments mediated by 1st generation sfermions lead to the **SUSY CP problem.** Solved if 1st generation sfermions are heavy
- Rare decays in SUSY $U(2)^3$ effects in C_9 and C_{10} are always negligible, so **only C_7** modified

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Froggatt-Nielsen mechanism

[Froggat and Nielsen (1979)]

Introduce

- $U(1)$ symmetry under which quarks have charge q_i and H is neutral
- scalar "flavon" ϕ with charge -1 and VEV $\langle\phi\rangle$
- pair of heavy fermions $\chi, \bar{\chi}$ with mass M

Froggatt-Nielsen mechanism

[Froggat and Nielsen (1979)]

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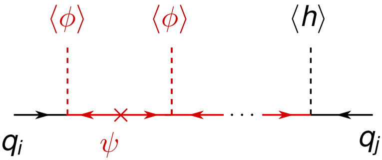

After integrating out heavy fields, Yukawas of the form $\left(\frac{\langle\phi\rangle}{M}\right)^{q_i+q_j} \bar{q}_i q_j H$ generated

Quark masses an CKM from FN

E.g. $q_{1,2,3} = \{2, 1, 0\}$, $\langle\phi\rangle/M \equiv \epsilon$

$$\Rightarrow Y_{u,d} \sim \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon^1 \\ \epsilon^2 & \epsilon^1 & 1 \end{pmatrix}$$

$$\Rightarrow m_{u,d} \ll m_{c,s} \ll m_{t,b} \qquad V \sim \begin{pmatrix} 1 & \epsilon & \epsilon^2 \\ \epsilon & 1 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix}$$

Hierarchical Yukawas are naturally generated

FN & flavour symmetry

Now, let's **forget** about flavons and fundamental $U(1)$s.

We want to study rare decays in models giving hierarchical Yukawas of the form

$$\Rightarrow Y_{u,d} \sim \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon^1 \\ \epsilon^2 & \epsilon^1 & 1 \end{pmatrix}$$

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In the flavour symmetry language, these models have a small parameter associated to every field of every generation $\Rightarrow$ an approximate $U(1)^9$ **flavour symmetry**

$U(1)^9$ flavour symmetry

Starting point: **symmetry**

$$U(1)^9 = \prod_{i=1}^{3} U(1)_{q_L^i} \times U(1)_{u_R^i} \times U(1)_{d_R^i}$$

Breaking terms

$$\epsilon_1^q \ll \epsilon_2^q \ll \epsilon_3^q \qquad \epsilon_1^u \ll \epsilon_2^u \ll \epsilon_3^u \qquad \epsilon_1^d \ll \epsilon_2^d \ll \epsilon_3^d$$

Masses and CKM elements

$$m_{u_i} \sim Y_* \epsilon_i^q \epsilon_i^u \qquad m_{d_i} \sim Y_* \epsilon_i^q \epsilon_i^d \qquad V_{ij} \sim \frac{\epsilon_i^q}{\epsilon_j^q}$$

$U(1)^9$ spurion analysis

- **LL** (relevant for $C_{9,10,\nu}$), $i > j$

$$q_{L\,i}\,\epsilon_i^q \epsilon_j^q\,\gamma^\mu q_{L\,j} \sim (\epsilon_3^q)^2\; V_{ti}^* V_{tj}\; q_{L\,i}\gamma^\mu q_{L\,j}$$

  - Almost like MFV (but complex and $O(1)$ factors different for different *ij*)

- **RL** (relevant for $C_{7,8}$), $i > j$

$$v d_{R\,i}\,\epsilon_i^d \epsilon_j^q\,\sigma^{\mu\nu} q_{L\,j} \sim \frac{1}{Y_*}\,\frac{m_{d_i}\,V_{tj}^*}{V_{ti}}\; d_{R\,i}\sigma^{\mu\nu} q_{L\,j}$$

  - MFV-like (but complex) for $i = 3$ since $V_{tb} \approx 1$
  - enhanced for $i = 2$ (K decays)

$U(1)^9$ spurion analysis: right-handed currents

In addition, one gets flavour structures with opposite chirality that are not present in the SM or MFV!

- **RR**, $i > j$

$$q_{L\,i}\,\epsilon_i^q \epsilon_j^q\,\gamma^\mu q_{L\,j} \sim \frac{1}{(\epsilon_3^q)^2}\,Y_*^2\,\frac{y_{d_i} y_{d_j}}{V_{ti}^* V_{tj}}\,q_{L\,i}\gamma^\mu q_{L\,j}$$

- **LR**, $i > j$

$$v q_{L\,i}\,\epsilon_i^d \epsilon_j^q\,\sigma^{\mu\nu} d_{R\,j} \sim \frac{1}{Y_*}\,\frac{m_{d_j}\,V_{ti}^*}{V_{tj}}\,q_{L\,i}\sigma^{\mu\nu} d_{R\,j}$$

$\Delta F = 1$ operators beyond MFV

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\frac{e^2}{16\pi^2} V_{tb} V_{ts}^* \sum_i C_i O_i + \text{h.c.}$$

$$O_7 = \frac{m_b}{e}(\bar{s}_L \sigma_{\mu\nu} b_R) F^{\mu\nu} \quad \to \quad O_7' = \frac{m_b}{e}(\bar{s}_R \sigma_{\mu\nu} b_L) F^{\mu\nu}$$

$$O_8 = \frac{g_s m_b}{e^2}(\bar{s}_L \sigma_{\mu\nu} T^a b_R) G^{\mu\nu\,a} \quad \to \quad O_8' = \frac{g_s m_b}{e^2}(\bar{s}_R \sigma_{\mu\nu} T^a b_L) G^{\mu\nu\,a}$$

$$O_9 = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell) \quad \to \quad O_9' = (\bar{s}_R \gamma_\mu b_R)(\bar{\ell}\gamma^\mu \ell)$$

$$O_{10} = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \quad \to \quad O_{10}' = (\bar{s}_R \gamma_\mu b_R)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$O_L^\nu = (\bar{s}_L \gamma_\mu b_L)(\bar{\nu}_L \gamma^\mu \nu_L) \quad \to \quad O_R^\nu = (\bar{s}_R \gamma_\mu b_R)(\bar{\nu}_L \gamma^\mu \nu_L)$$

C_7' & mixing-induced CP asymmetry in $B \to K^*\gamma$

$$\frac{\Gamma(\bar{B}^0(t) \to \bar{K}^{*0}\gamma) - \Gamma(B^0(t) \to K^{*0}\gamma)}{\Gamma(\bar{B}^0(t) \to \bar{K}^{*0}\gamma) + \Gamma(B^0(t) \to K^{*0}\gamma)} = S_{K^*\gamma} \sin(\Delta M_d) - C_{K^*\gamma} \cos(\Delta M_d)$$

$$S_{K^*\gamma} \propto \mathrm{Im}(C_7\, C_7')$$

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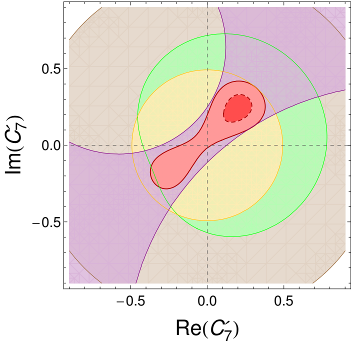
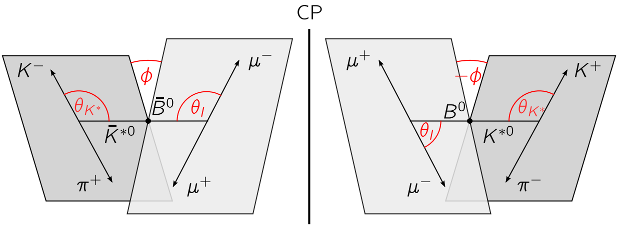


Constraints on C_7' from $B \to X_s\gamma$, $S_{K^*\gamma}$, $B \to (K^*, X_s)\mu\mu$

$B \to K^* \mu^+ \mu^-$



Two angular observables in $B \to K^* \mu^+ \mu^-$ sensitive to CP-conserving or CP-violating **right-handed currents**: S_3 and A_9

$$\frac{d(\Gamma + \bar{\Gamma})}{d\phi\, dq^2} \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2} = \frac{1}{2\pi} \left[1 + S_3(q^2)\cos(2\phi) + A_9(q^2)\sin(2\phi)\right] ,$$

S_3 and A_9

$$\langle S_3 \rangle_{[1,6]\,\text{GeV}^2} \sim [-12\,\text{Im}(C_7) - 4\,\text{Re}(C_{10})]\,\%$$

$$\langle A_9 \rangle_{[1,6]\,\text{GeV}^2} \sim [+12\,\text{Im}(C_7) + 4\,\text{Im}(C_{10})]\,\%$$

$$\langle A_9 \rangle_{[14.18,16]\,\text{GeV}^2} \sim [-12\,\text{Im}(C_7) - 7\,\text{Re}(C_9) + 8\,\text{Re}(C_{10})]\,\%$$

S_3 and A_9

$$\langle S_3 \rangle_{[1,6]\,\mathrm{GeV}^2} \sim [-12\,\mathrm{Im}(C_7) - 4\,\mathrm{Re}(C_{10})]\,\%$$
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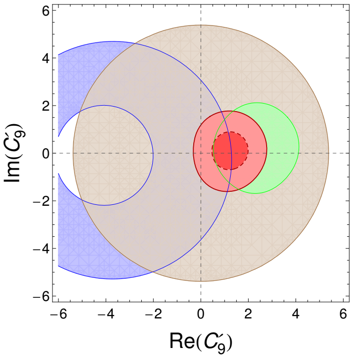
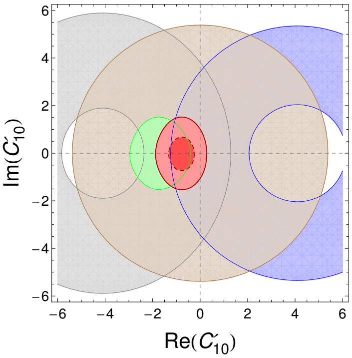
LHCb 2013 [Aaij et al. 1304.6325]

$$\langle S_3 \rangle_{[1,6]\,\mathrm{GeV}^2} = (3 \pm 7)\%$$
$$\langle A_9 \rangle_{[1,6]\,\mathrm{GeV}^2} = (3 \pm 8)\%$$
$$\langle A_9 \rangle_{[14.18,16]\,\mathrm{GeV}^2} = (-5 \pm 10)\%$$

Further improvement to be expected!

Contraints on C_9' and C_{10}'





Constraints from $B \to (K, K^*, X_s)\mu\mu$ and $B_s \to \mu\mu$

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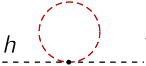
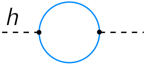
- Rare decays

Recall: gauge hierarchy problem

The Higgs mass receives contributions from all the heavy particles it couples to

$(m_h^2)_{\rm fund}$ +  +  = $(m_h^2)_{\rm phys}$

A new heavy state requires extreme fine-tuning. Two main solutions:

1. Supersymmetry
2. Composite Higgs

Composite Higgs & partial compositeness

Solving the hierarchy problem without SUSY: the **Higgs is composite**

- bound state of a new strong interaction which breaks EW symmetry

How to accomodate **fermion masses**?

Composite Higgs & partial compositeness

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- Composite fermions excluded by LEP ↯

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Solving the hierarchy problem without SUSY: the **Higgs is composite**

- bound state of a new strong interaction which breaks EW symmetry

How to accomodate **fermion masses**?

- Composite fermions excluded by LEP ↯
- TC-like bilinear coupling $\lambda\psi_L\psi_R\mathcal{O}$ disfavoured by FCNC ↯

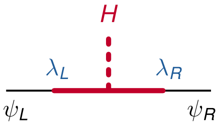
Composite Higgs & partial compositeness

Solving the hierarchy problem without SUSY: the **Higgs is composite**

- bound state of a new strong interaction which breaks EW symmetry

How to accomodate **fermion masses**?

- Composite fermions excluded by LEP ↯
- TC-like bilinear coupling $\lambda \psi_L \psi_R \mathcal{O}$ disfavoured by FCNC ↯
- **Linear coupling** $\lambda_L \bar{\psi}_L \mathcal{O}_R + \lambda_R \bar{\psi}_R \mathcal{O}_L$ ✓

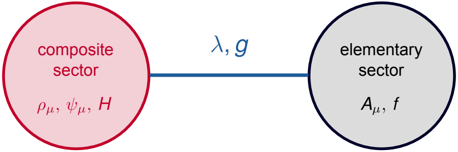


Partial compositeness

Two-site picture

[Contino et al. hep-ph/0612180]

A simple 4D theory realizing the partial compositeness paradigm



$$\mathcal{L}_s = -\bar{Q}_L\, m_Q\, Q_R - \bar{U}_L\, m_U\, U_R - \bar{D}_L\, m_D\, D_R + \bar{Q}_L \mathcal{H}\, Y_U\, U_R + \bar{Q}_L \mathcal{H}\, Y_D\, D_R + \text{h.c}$$

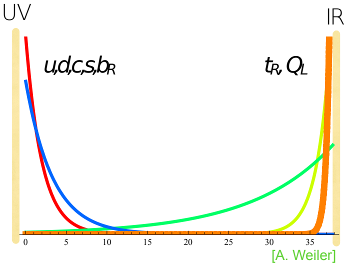
$$\mathcal{L}_{\text{mix}} = \lambda_L\, \bar{q}_L Q_R + \lambda_{Ru}\, \bar{U}_L u_R + \lambda_{Rd}\, \bar{D}_L d_R$$

$$q^{\text{phys}} = c_L\, q + s_L\, Q \qquad \frac{s_L}{c_L} = \frac{\lambda_L}{m_Q} \qquad m_{q^{\text{phys}}} = \frac{v}{\sqrt{2}} Y\, s_L\, s_R \qquad \text{etc.}$$

Comment: partial compositeness vs. extra dimensions

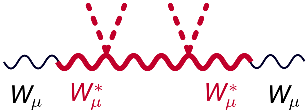
4D CHM with partial compositeness can arise as duals of 5D models.

- Composite resonances $\sim$ KK states
- degree of compositeness $\sim$ wavefunction overlap



T parameter requires custodial symmetry

Dangerous tree-level contributions to the ***T* parameter**



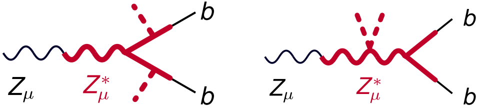
- The strong sector has to respect custodial symmetry

$$SU(2)_L \times SU(2)_R \times U(1)_X \qquad\qquad Y = T_{3R} + X$$

The vector resonances transform as adjoints under this group

$Z \to b\bar{b}$

Dangerous tree-level contributions to the $Z \to b_L \bar{b}_L$ coupling



- Quark mixing has to respect a discrete P_{LR} symmetry (restricts the choice of fermion representations)

[Agashe et al. hep-ph/0605341]

Choices for composite fermion representations

Fermion $SU(2)_L \times SU(2)_R$ representations allowed by the requirement of custodial symmetry & P_{LR}

Q_u	Q_d	U	D	
$(2, \mathbf{2})$		$(1, \mathbf{3})$		triplet model
$(2, \mathbf{2})$	$(2, \mathbf{2})$	$(1, \mathbf{1})$	$(1, \mathbf{1})$	bidoublet model

$$\lambda_{Lu}\, \bar{q}\, Q_u + \lambda_{Ld}\, \bar{q}\, Q_d + \lambda_{Ru}\, \bar{u}\, U + \lambda_{Rd}\, \bar{d}\, D$$

What about the flavour structure?

$$\mathcal{L}_s = -\bar{Q}^i m_Q^i Q^i - \bar{U}^i m_R^i U^i - \bar{D}^i m_R^i D^i$$
$$+ \left(Y_U^{ij} \bar{Q}_L^i \mathcal{H} U_R^j + Y_D^{ij} \bar{Q}_L^i \mathcal{H} D_R^j + \text{h.c} \right)$$
$$\mathcal{L}_{\text{mix}} = m_Q^j \lambda_L^{ij} \bar{q}_L^i Q_R^j + m_R^i \lambda_{Ru}^{ij} \bar{U}_L^i u_R^j + m_R^i \lambda_{Rd}^{ij} \bar{D}_L^i d_R^j$$

Case 1: **Anarchy**

- Y^{ij} are structureless/anarchic
- λ^{ij} are hierarchical

$\Rightarrow$ a realization of $U(1)^9$!

What about the flavour structure?

$$\mathcal{L}_s = -\bar{Q}^i m_Q^i Q^i - \bar{U}^i m_R^i U^i - \bar{D}^i m_R^i D^i + \left(Y_U^{ij} \bar{Q}_L^i \mathcal{H} U_R^j + Y_D^{ij} \bar{Q}_L^i \mathcal{H} D_R^j + \text{h.c} \right)$$

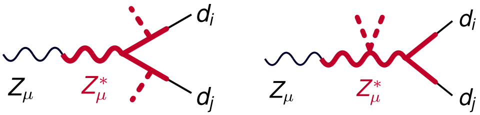
$$\mathcal{L}_{\text{mix}} = m_Q^j \lambda_L^{ij} \bar{q}_L^i Q_R^j + m_R^i \lambda_{Ru}^{ij} \bar{U}_L^i u_R^j + m_R^i \lambda_{Rd}^{ij} \bar{D}_L^i d_R^j$$

Case 2: $\boldsymbol{U(2)^3}$

- Y^{ij} are $U(2)^3$ symmetric: $\propto \text{diag}(\epsilon, \epsilon, 1)$
- λ_L^{ij} are $U(2)^3$ symmetric: $\propto \text{diag}(\epsilon, \epsilon, 1)$
- λ_R^{ij} are hierarchical

Flavour-changing Z couplings

Partial compositeness induces tree-level FC Z couplings



$$\delta g^{ij}_{L,R} = \underbrace{\frac{v^2}{f^2}}_{\equiv \xi} \left[a \underbrace{\left(\frac{Y f}{m_\psi}\right)^2}_{O(1)} + b \underbrace{\left(\frac{g_\rho f}{m_\rho}\right)^2}_{O(1)} \right] s^i_{L,R}\, s^j_{L,R}$$

P_{LR} symmetry protecting $Z \to b\bar{b}$ also acts on FC couplings!

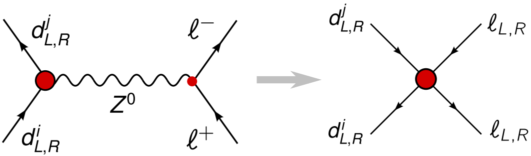
[Agashe et al. hep-ph/0605341, Blanke et al. 0812.3803]

Pattern of flavour-changing Z couplings

- triplet model: P_{LR} forbids g_L^{ij}
- bidoublet model: P_C forbids g_R^{ij}
- $U(2)^3$ forbids g_R^{ij}

		K		$B_{d,s}$		D	
		L	R	L	R	L	R
Ⓐ	triplet		$\mathbb{C}$		$\mathbb{C}$	$\mathbb{C}$	
	bidoublet	$\mathbb{C}$		$\mathbb{C}$		$\mathbb{C}$	
$U(2)^3_{\text{LC}}$	triplet					$\mathbb{R}$	
	bidoublet	$\mathbb{R}$		$\mathbb{C}$		$\mathbb{R}$	

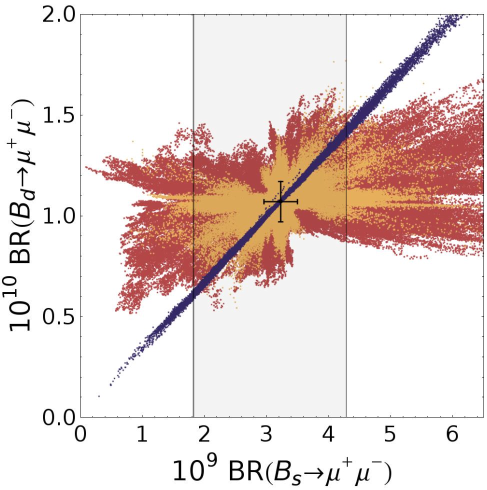
Flavour-changing Z couplings & Wilson coefficients



$$C_9{}^{\text{NP}} \propto (1-4s_w^2)\delta g_L \qquad C_{10}{}^{\text{NP}} \propto -\delta g_L \qquad (C_L^\nu)^{\text{NP}} \propto -\delta g_L$$
$$(C_9')^{\text{NP}} \propto (1-4s_w^2)\delta g_R \qquad (C_{10}')^{\text{NP}} \propto -\delta g_R \qquad (C_R^\nu)^{\text{NP}} \propto -\delta g_R$$

Note that $(1-4s_w^2) \approx 0.08$ is accidentally small $\Rightarrow$ FC Z couplings mostly affect C_{10}, C_{10}' and C_L^ν, C_R^ν

$B_s \to \mu\mu$ vs. $B_d \to \mu\mu$



triplet + anarchy

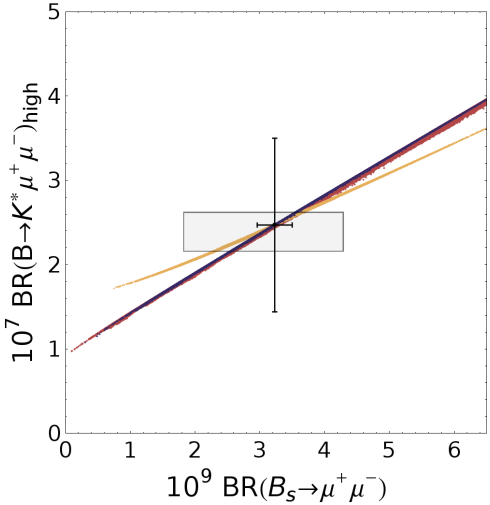
bidoublet + anarchy

bidoublet + $U(2)^3$

- LHCb **starts** to probe the models
- MFV-like $B_d \leftrightarrow B_s$ correlation in $U(2)^3$

[Straub 1302.4651]

$B_s \to \mu\mu$ vs. $B \to K^*\mu\mu$

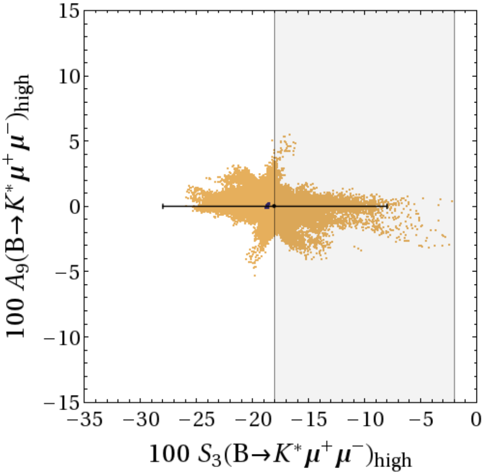


triplet + anarchy
bidoublet + anarchy
bidoublet + $U(2)^3$

- Correlation due to protection of LH *or* RH coupling

[Straub 1302.4651]

$B \to K^* \mu\mu$ angular observables



triplet + anarchy

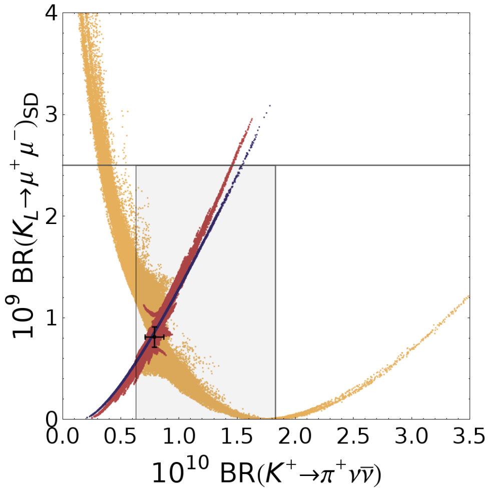
bidoublet + anarchy

bidoublet + $U(2)^3$

- S_3, A_9 probe RH currents: effects only in triplet model
- only small effects

[Straub 1302.4651]

$K^+ \to \pi^+ \nu\bar{\nu}$ vs. $K_L \to \mu^+\mu^-$



triplet + anarchy

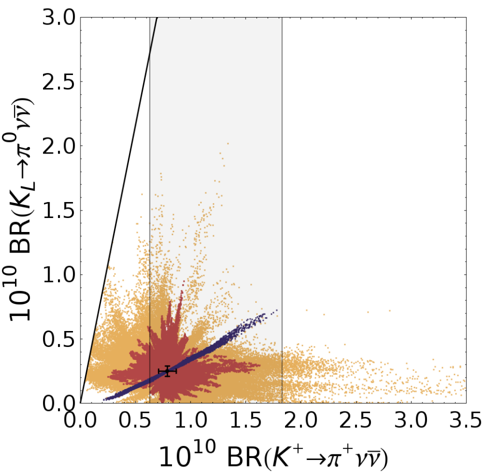
bidoublet + anarchy

bidoublet + $U(2)^3$

- triplet: RH coupling
- bidoublet: LH coupling

[Straub 1302.4651]

$K^+ \to \pi^+ \nu\bar{\nu}$ vs. $K_L \to \pi^0 \nu\bar{\nu}$



triplet + anarchy

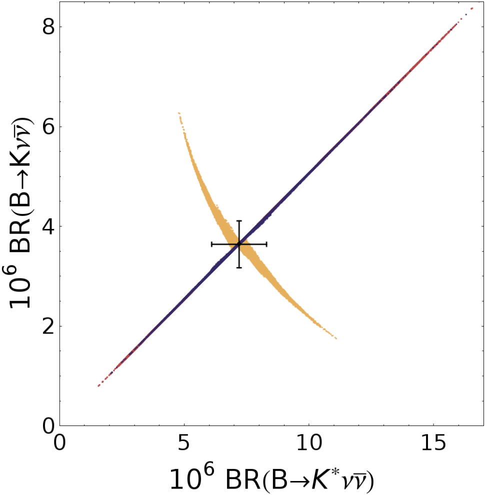
bidoublet + anarchy

bidoublet + $U(2)^3$

- Visible effects in both modes
- $U(2)^3$: aligned in phase with the SM

[Straub 1302.4651]

$B \to K\nu\bar{\nu}$ vs. $B \to K^*\nu\bar{\nu}$



triplet + anarchy

bidoublet + anarchy

bidoublet + $U(2)^3$

- triplet: RH coupling
- bidoublet: LH coupling

[Straub 1302.4651]

Summary of Part II

- Many good reasons for going **beyond MFV**:
  - addressing the **flavour puzzle**
  - split families in **natural SUSY**
- $U(2)^3$ flavour symmetry
  - no new operators in rare decays, but Wilson coefficients become **complex**
  - imaginary parts of C_i much less constrained $\rightarrow$ **CP asymmetries**!
  - correlation between B and K decays **broken**
- $U(1)^9$ flavour symmetry
  - **chirality-flipped** operators are generated
  - **new observables relevant**, like $S_{K^*\gamma}$, S_3, A_9
- Rare decays in **Composite Higgs** Models
  - Flavour-changing ***Z* couplings** can generate effects in rare B and K decays
  - Custodial protection of $Z \rightarrow b\bar{b}$ leads to characteristic **patterns** that allow to distinguish between models