Matching the flavour symmetric SMEFT to flavour observables

Sophie Renner, JGU Mainz

with T Hurth, W Shepherd, R Aoude

SMEFT-Tools, Durham, 12 June 2019

995g

Flavour in the SM

SM Lagrangian: only the Yukawa terms break $U(3)^5$ flavour symmetry

⇓

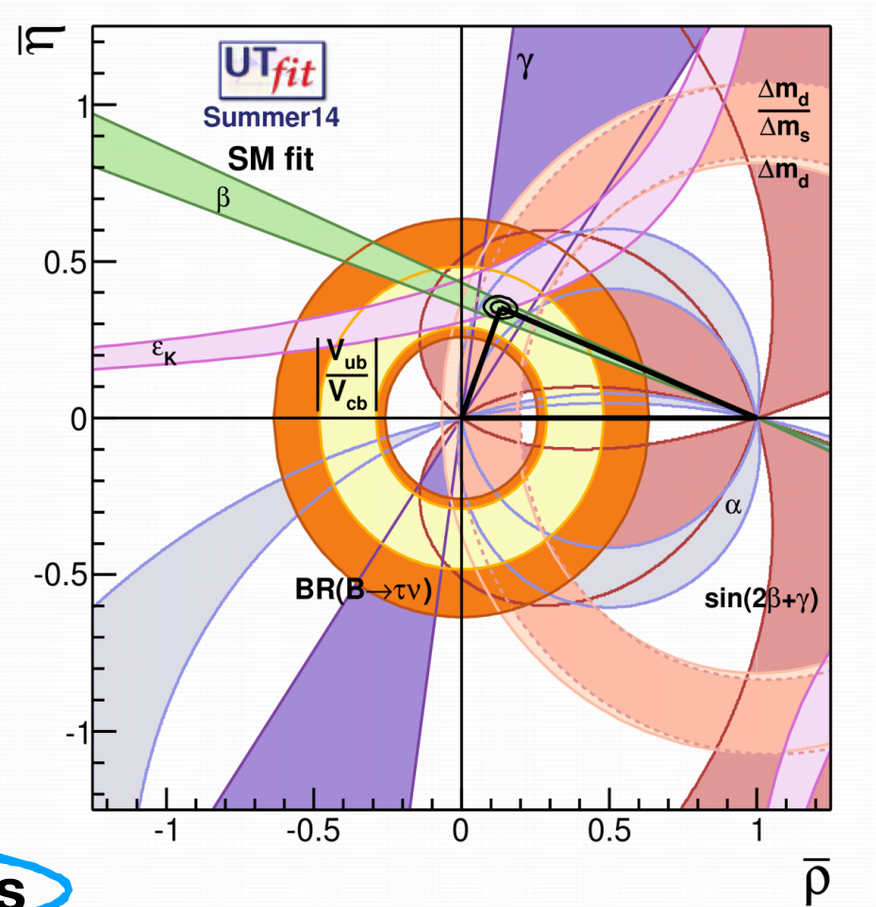
No tree level FCNCs

$$V = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\varrho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\varrho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

CKM ~ 1 and unitary

⇓

FCNCs at one loop suppressed by small CKM elements



A challenge and an opportunity for BSM...

Flavour beyond the SM

Flavour observables are extremely sensitive to NP

Tree level FCNCs strongly constrained

Operator	Λ in TeV ($c_{\rm NP}=1$) Re	Im
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2

[Isidori, 1507.00867]

For TeV(+) scale NP

⇓

Flavour symmetries **and/or** **FCNCs connected to fermion masses**

eg MFV — eg partial compositenesss

Tree level analyses of MFV, PC etc: strong limits even on these

Even NP with no explicit flavour violation will produce FCNCs via loops of SM particles

Flavour in the SMEFT

2499 parameters, nearly all of which are elements of flavour matrices

In general, large tree level FCNCs

Large hierarchy of constraints on different WCs

For TeV scale NP, have to assume that many WCs are suppressed way below O(1)

For TeV(+) scale Λ

$\Downarrow$

Flavour symmetries eg MFV

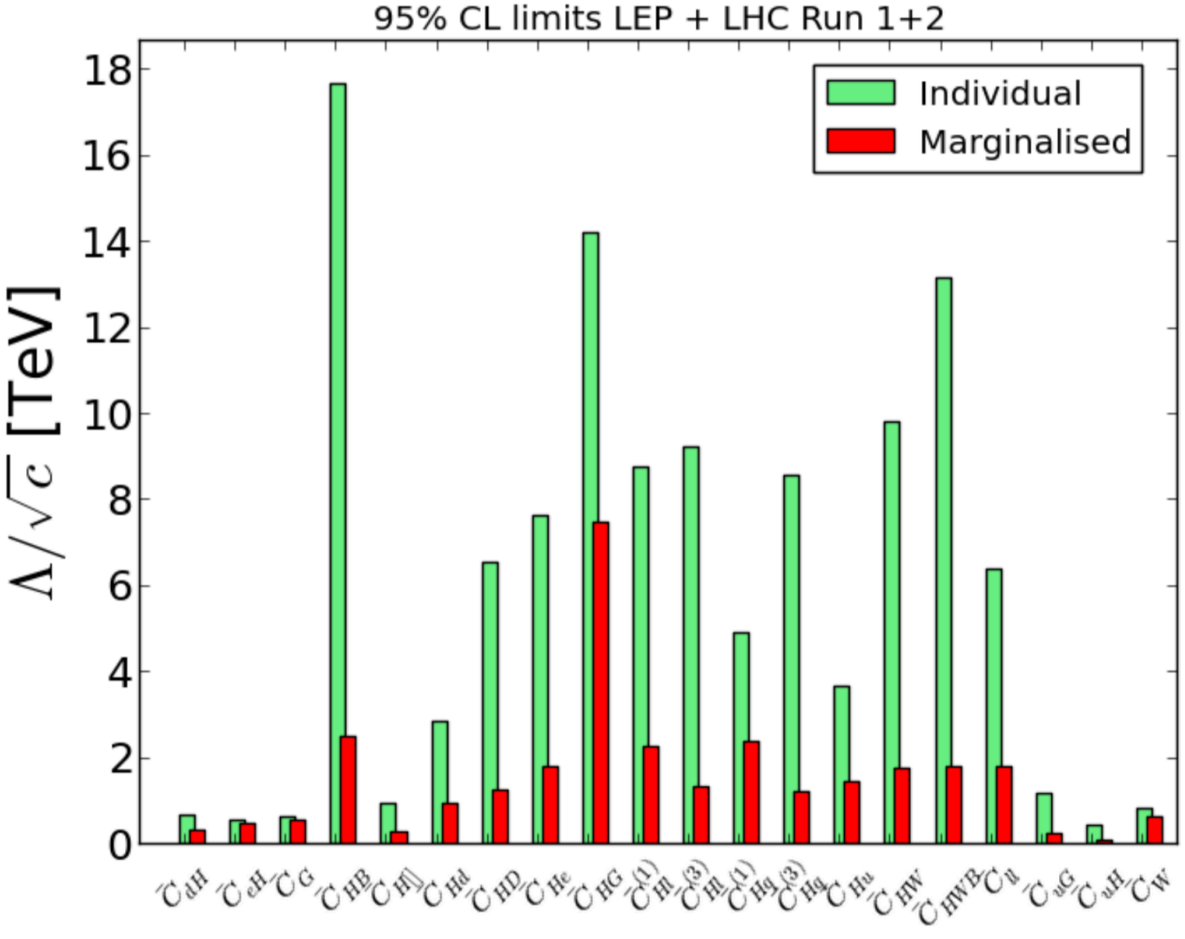
and/or

FCNCs connected to fermion masses eg partial compositenesss

The flavour symmetric SMEFT

- Can impose $U(3)^5$ flavour symmetry on the SMEFT
- Cuts down number of parameters to 59 (CP-even)
- (Almost) no tree level FCNCs... "Flavour safe"?

Often used in global fits, e.g. 1803.03252



Updated Global SMEFT Fit to Higgs, Diboson and Electroweak Data

John Ellis[a,b], Christopher W. Murphy[c], Verónica Sanz[d] and Tevong You[e]

20 WCs constrained by:

LEP: EW precision data and WW production

LHC: Higgs data and WW production

Still many flat directions

$U(3)^5$

$$U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$$

$$q \sim (3,1,1,1,1), \quad u \sim (1,3,1,1,1), \quad d \sim (1,1,3,1,1),$$
$$l \sim (1,1,1,3,1), \quad e \sim (1,1,1,1,3).$$

Implications for the SMEFT:

Some operators forbidden	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W^I_{\mu\nu}$	$C_{dW} = 0$
Many operators must have identity-like Wilson coefficient matrices	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	$C^{(1)}_{Hq} \sim \delta_{pr}$
	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	$C_{eu} \sim \delta_{pr}\delta_{st}$
A few operators have two possible symmetric combinations	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	$C_{ll} \sim \delta_{pr}\delta_{st}$ $C'_{ll} \sim \delta_{pt}\delta_{sr}$

Flavour in the flavour symmetric SMEFT

"Worst case scenario" $U(3)^5$ flavour symmetry

Easily incorporated into traditional SMEFT fits

Analysis of "irreducible" flavour effects

Baseline and starting point for other flavour symmetries or less restrictive MFV (many calculations in common)

- Calculated full one-loop matching from SMEFT to operators below weak scale mediating $d_i \to d_j \gamma$, $d_i \to d_j l^+ l^-$ and meson mixing

- Included all operators invariant under $U(3)^5$ and CP

- Consistently included effects of operators which effect shifts in input parameters, eg G_F, so results are expressed directly in terms of measured (PDG) quantities

Matching

UV theory

SM fields + ??

Λ

SMEFT

SM fields

γ_{SMEFT}
(1308.2627, 1310.4838, 1312.2014)

$\mathrm{EW} \sim m_W$

WET

SM - {t, W, Z, h}

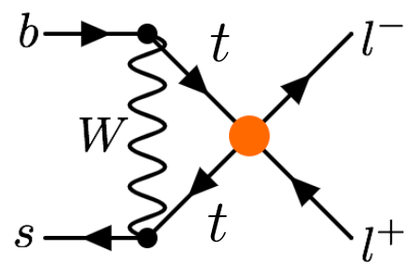
γ_{WET}
(1711.05270)

m_b

Loop level matching at mW:

Integrate out loops of W, tops

Above mW: no FCNC vertices



Below mW: contribution to WET operator

$$(\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu P_L l)$$

Related work

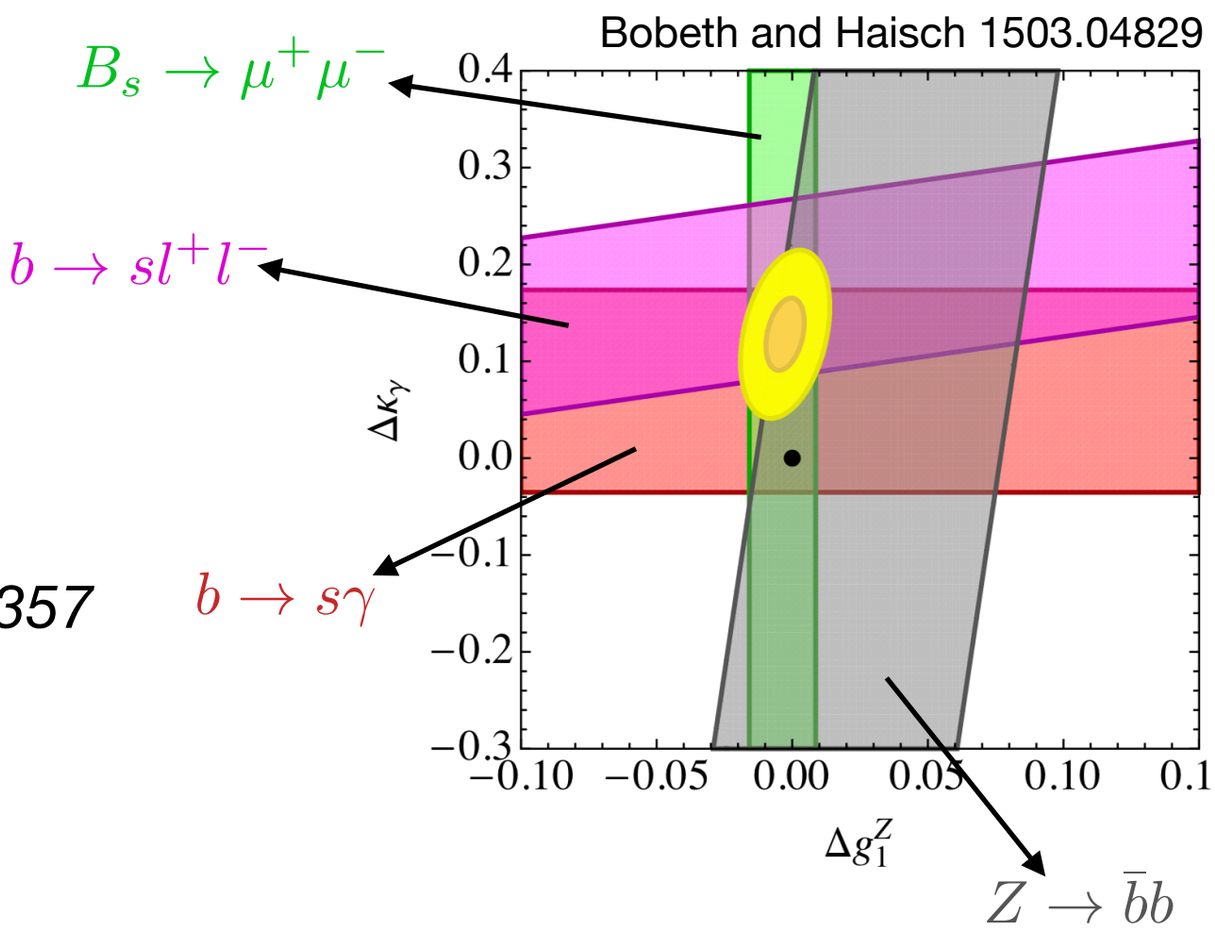
Some previous work has calculated the loop effects of SMEFT operators on flavour observables...

Grzadkowski & Misiak, 0802.1413
Operators: operators giving a tWb vertex
Observables: $B \to X_s \gamma$

Drobnak, Fajfer, Kamenik 1102.4347, 1109.2357
Operators: operators giving a tWb vertex
Observables: B decays, B mixing

Bobeth & Haisch 1503.04829
Operators: triple gauge operators
Observables: B, K decays, ϵ'/ϵ

Endo, Kitahara, Ueda 1811.04961
Operators: operators containing top quarks
Observables: B, K mixing



(c.f LEP II $e^+e^- \to W^+W^-$

$$\Delta g_1^Z = -0.06 \pm 0.03$$

$$\Delta\kappa_\gamma = 0.06 \pm 0.04$$ 1411.06699)

$$\mathcal{L}_{WWV} = -ig_{WWV}\left[g_1^V\left(W^+_{\mu\nu}W^{-\mu}V^\nu - W^+_\mu V_\nu W^{-\mu\nu}\right)\right.$$

$$\left. + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W^+_{\mu\nu} W^{-\nu\rho} V_\rho{}^\mu\right]$$

Related work

Matching of gauge invariant dimension-six operators for $\mathrm{b} \to \mathrm{s}$ and $\mathrm{b} \to \mathrm{c}$ transitions

---

Jason Aebischer[a] Andreas Crivellin[b] Matteo Fael[a] Christoph Greub[a]

1512.02830

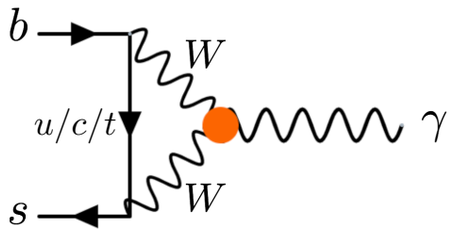
Different (complementary) approach/assumptions:

- Tree level FCNCs allowed: tree level matching for many operators
- Loop level matching only for operators containing right-handed up type quarks
- Many of the operators they include are forbidden by our flavour assumption
- Many of our loop level calculations are not covered by their work

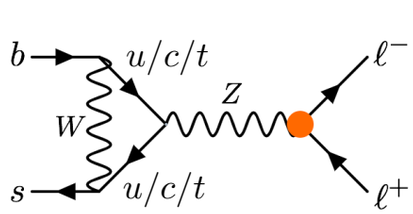
Observables and operators

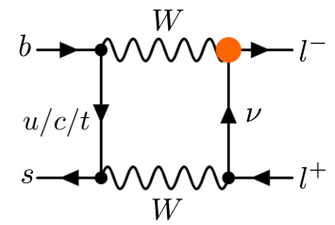
Name	Operator	$d_i \to d_j\gamma$	$d_i \to d_j\, l^+l^-$	Meson mixing
Q_G	$f^{ABC}G^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$	-	-	-
Q_W	$\epsilon^{IJK}W^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$	✔	✔	-
Q_H	$(H^\dagger H)^3$	-	-	-
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	-	-	-
Q_{HD}	$\left(H^\dagger D_\mu H\right)^*\left(H^\dagger D_\mu H\right)$	✔	✔	-
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	-	-	-
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$	-	-	-
Q_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	-	-	-
Q_{HWB}	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$	✔	✔	-
$Q^{(1)}_{H\ell}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$	-	✔	-
$Q^{(3)}_{H\ell}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$	✔*	✔	✔*
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$	-	✔	-
$Q^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$	-	✔	-
$Q^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$	✔	✔	✔
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$	-	✔	-
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$	-	-	-

Purely bosonic operators

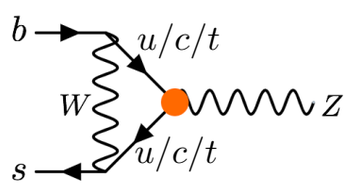


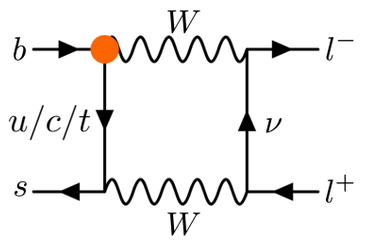
Higgs-lepton operators





Higgs-quark operators

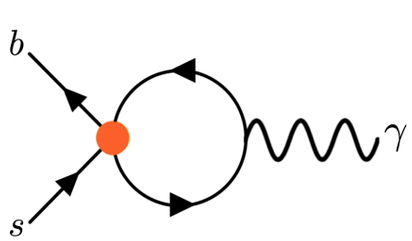


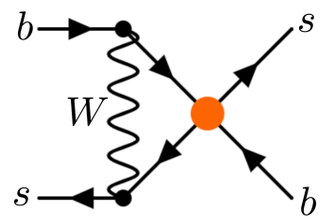


Observables and operators

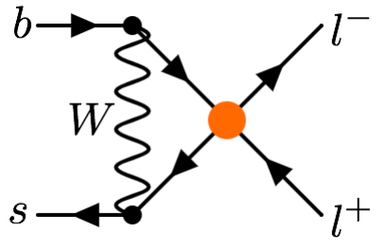
Name	Operator	$d_i \to d_j \gamma$	$d_i \to d_j\, l^+ l^-$	Meson mixing
$Q_{\ell\ell}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	✔*	✔*	✔*
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	-	✔	✔
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	-	✔	✔
$Q_{\ell q}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	-	✔	-
$Q_{\ell q}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	-	✔	-
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	-	-	-
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	-	-	-
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	-	-	-
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	-	✔	-
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	-	-	-
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	-	-	-
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	-	-	-
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$	-	-	-
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$	-	✔	-
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$	-	-	-
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$	-	✔	-
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$	-	-	-
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$	-	-	-
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$	-	-	-
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$	-	-	-

4 quark operators





2 quark, 2 lepton operators



Inputs

SMEFT operators enter into observables whose measurements fix the inputs of the theory

e.g. Alonso & al 1312.2014
Berthier & Trott 1502.02570
Han & Skiba hep-ph/0412166
Brivio & Trott 1701.06424
+ others

Need to pick a set of inputs to fix parameters of the theory...

We chose

Brivio & Trott 1701.06424

$$\left\{\hat{m}_W, \hat{m}_Z, \hat{G}_F, \hat{m}_t, \hat{m}_b, \hat{\alpha}_s, \hat{V}_{CKM}\right\}$$

$U(3)^5$: no change to CKM
(but see 1812.08163 for more general case)

In the SMEFT, EW parameters are (re)defined:

$$-\frac{4\mathcal{G}_F}{\sqrt{2}} = -\frac{2}{v_T^2} + \left(C^{ll}_{\mu ee\mu} + C^{ll}_{e\mu\mu e}\right) - 2\left(C^{(3)}_{Hl\,ee} + C^{(3)}_{Hl\,\mu\mu}\right)$$

$$\bar{M}_Z^2 = \frac{\bar{v}_T^2}{4}(\bar{g}_1{}^2 + \bar{g}_2{}^2) + \frac{1}{8}\,\bar{v}_T^4 C_{HD}(\bar{g}_1{}^2 + \bar{g}_2{}^2) + \frac{1}{2}\,\bar{v}_T^4 \bar{g}_1 \bar{g}_2 C_{HWB}$$

$$\bar{M}_W^2 = \frac{\bar{g}_2^2 \bar{v}_T^2}{4}$$

These operators modify the SM amplitude

Other details of the calculations

- **Used Feynman rules in R_ξ gauge from Dedes & al 1704.03888**

  Used ξ independence as a check of results

- **Where possible compared our results with existing results in the literature**

  (Grzadkowski & Misiak 0802.1413, Drobnak, Fajfer, Kamenik 1102.4347 & 1109.2357, Bobeth & Haisch 1503.04829, Aebischer & al 1512.02830)

- **Coefficients of divergent pieces compared with anomalous dimension matrices**

  ((Alonso), Jenkins, Manohar & Trott 1308.2627, 1310.4838, 1312.2014)

Aspects of results

Low energy (WET) Hamiltonian

$$\mathcal{H}_{\text{eff}}^{|\Delta B|=|\Delta S|=1} = \frac{4\hat{G}_F}{\sqrt{2}}\left[-\frac{1}{(4\pi)^2}\hat{V}_{ts}^*\hat{V}_{tb}\sum_{i=3}^{10} C_i\mathcal{O}_i + \sum_{q=u,c}\hat{V}_{qs}^*\hat{V}_{qb}\left(C_1\mathcal{O}_1^q + C_2\mathcal{O}_2^q\right)\right]$$

Canonically defined with CKM elements, in anticipation of SM results

$$\begin{aligned}
\mathcal{O}_7 &= \hat{e}\hat{m}_b\left(\bar{s}\sigma^{\mu\nu}P_R b\right)F_{\mu\nu},\\
\mathcal{O}_8 &= \hat{g}_s\hat{m}_b\left(\bar{s}\sigma^{\mu\nu}T^A P_R b\right)G^A_{\mu\nu},\\
\mathcal{O}_9 &= \hat{e}^2\left(\bar{s}\gamma^\mu P_L b\right)\left(\bar{\ell}\gamma_\mu\ell\right),\\
\mathcal{O}_{10} &= \hat{e}^2\left(\bar{s}\gamma^\mu P_L b\right)\left(\bar{\ell}\gamma_\mu\gamma_5\ell\right).
\end{aligned}$$

In SM, only non negligible contributions are to operators with left handed s

$U(3)^5$ **flavour symmetry** $\Longrightarrow$ **similar structure for our results**

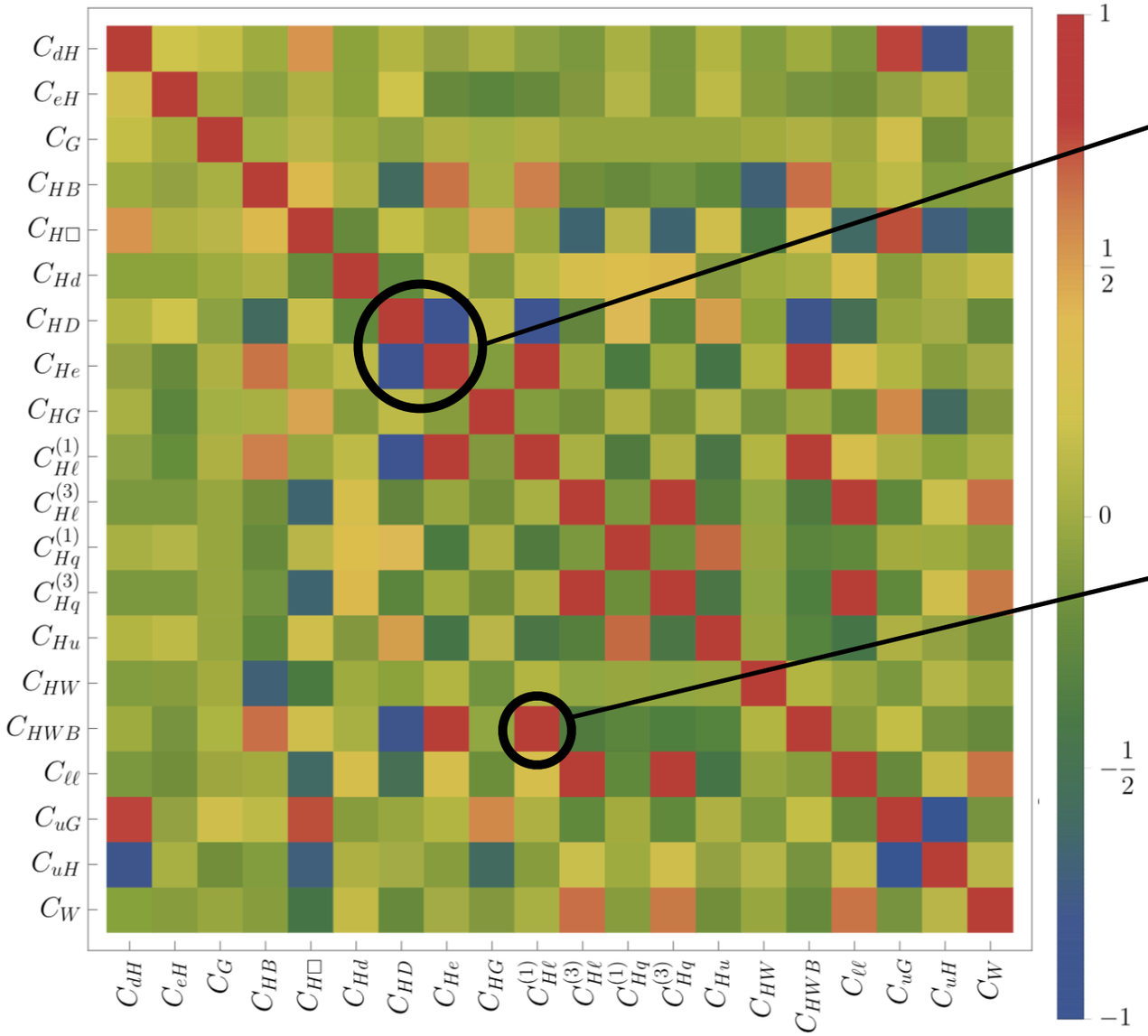
- No right handed currents
- Same CKM factors
- GIM mechanism

$$\begin{aligned}
C_7 &= \frac{3}{2}g_2v^2C_W\left(-\frac{x_t^2+x_t}{2(x_t-1)^2}+\frac{x_t^2}{(x_t-1)^3}\log x_t\right),\\
C_9 &= \frac{3}{2}g_2v^2C_W\left(\frac{3x_t^2-x_t}{2(x_t-1)^2}-\frac{x_t^3}{(x_t-1)^3}\log x_t\right).
\end{aligned}$$

$$x_t \equiv \frac{m_t^2}{m_W^2}$$

Pheno directions (preliminary)

Are the highly correlated/anticorrelated directions the same for the flavour observables?



Correlation matrix for LEP/LHC fit from Ellis & al, 1803.03252

$C_{HD},\ C_{He}$ fully anticorrelated

We find:

C_{HD} contributes to $b \to s\gamma$,
C_{He} doesn't

$C_{HWB}, C_{Hl}^{(1)}$ fully correlated

We find:

C_{HWB} contributes to $b \to s\gamma$,
$C_{Hl}^{(1)}$ doesn't

Should be able to close some flat directions

Summary + future directions

- **Flavour measurements are pointing us towards NP with flavour symmetries**
- **Calculated the loop level matching for SMEFT with $U(3)^5$ flavour symmetry to WET operators responsible for down type FCNCs**
- **Future plans: pheno eg new constraints for global fits**
- **Many other extensions, new observables (eg. D mixing), CPV, other motivated flavour symmetries**