Flavour constraints on flavourless new physics

Sophie Renner, SISSA

Based on:

Matching for FCNCs in the flavour symmetric SMEFT [1903.00500] with T Hurth, W Shepherd,
The impact of flavour data on global fits of the MFV SMEFT [2003.05432] with T Hurth, W Shepherd, R Aoude

Cambridge remote seminar, October 2020

Introduction and motivation

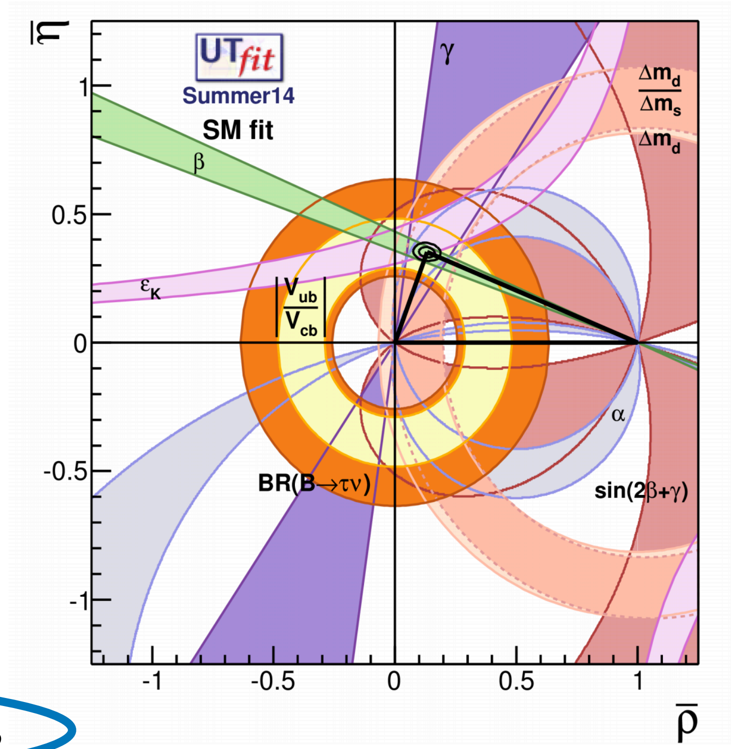
- BSM particles with new tree level flavour-violating interactions: clearly flavour observables will be sensitive
- What about the other extreme? What if BSM physics is flavour symmetric? Does flavour still have something to say?
- If TeV scale new physics exists, it must have suppressed FCNCs
- SMEFT global fits often done assuming $U(3)^5$ flavour symmetry, or MFV. In this context is flavour data irrelevant?

Flavour in the SM

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

$\Downarrow$

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

$\Downarrow$

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 new sources of flavour violation

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

$\Downarrow$

Flavour symmetries and/or FCNCs connected to fermion masses

eg MFV — eg partial compositenesss

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

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

The Standard Model Effective Field Theory (SMEFT)

Effective theory parameterising effects of heavy new physics respecting the full SM gauge group, and containing a Higgs doublet

$$\mathcal{L}_{\rm NP} = \frac{1}{\Lambda^2}\sum_i C_i^{(6)}\mathcal{O}_i^{(6)} + \frac{1}{\Lambda^4}\sum_i C_i^{(8)}\mathcal{O}_i^{(8)} + \ldots$$

Series of higher dimensional operators respecting SM gauge symmetries

- Any* model of heavy new physics can be matched to the SMEFT
- Experimental data can be used to constrain SMEFT coefficients

Flavour in the SMEFT

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

Large hierarchy of constraints on different Wilson coefficients...

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

[SMEFT tree level flavour constraints: Silvestrini & Valli 1812.10913]

For Λ close to the TeV scale, need:

Flavour symmetries and/or FCNCs connected to fermion masses

eg MFV

eg partial compositenesss

Suppression of tree level FCNCs, and more manageable number of parameters

$U(3)^5$

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

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

Plus spurionic Yukawas ("MFV")

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

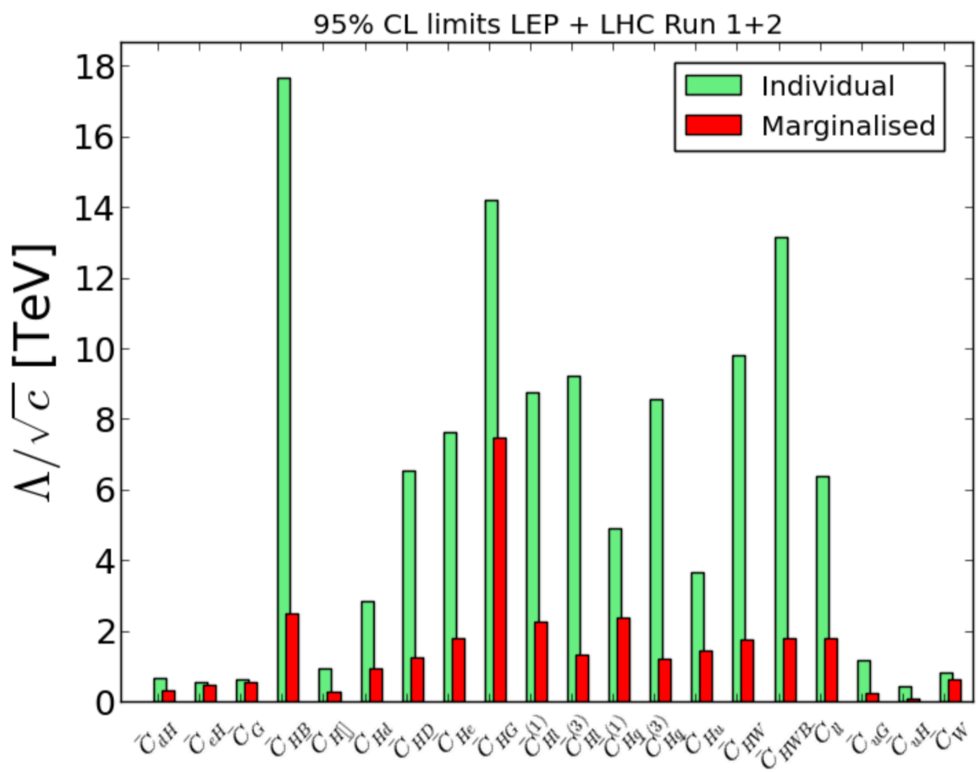
Implications for the SMEFT:

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

The flavour symmetric SMEFT

- $U(3)^5$
- Cuts down number of parameters
- "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:

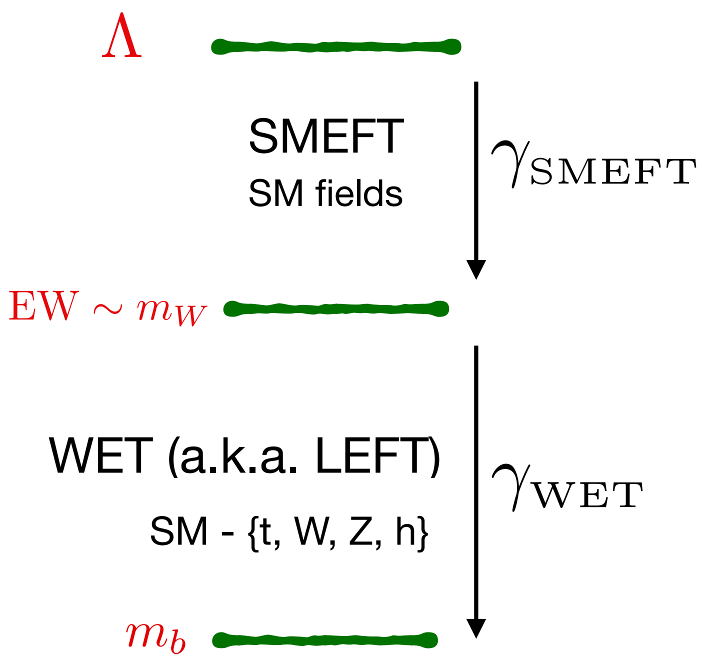
LEP: EW precision data and WW production

LHC: Higgs data and WW production

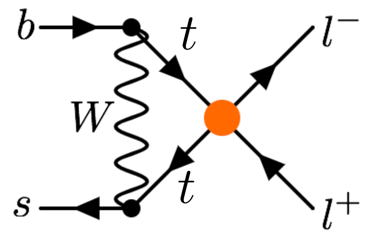
Still many flat directions

Flavour in the flavour symmetric SMEFT

$U(3)^5$ ***Plus lowest order in spurionic Yukawas*** $\Longrightarrow$ **No tree level FCNCs**



Loop level matching at mW:
Integrate out loops of Ws, tops



Below mW: contribution to WET operator

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

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

Observables and operators

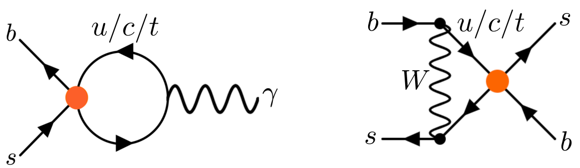
Down-type FCNC processes

$B_{s,d}$ **mixing** $\quad B \to K^{(*)}\bar{\nu}\nu \quad K^0 - \bar{K}^0$

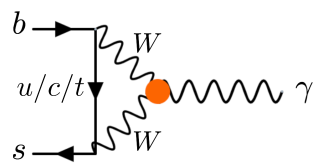
$b \to s\gamma \quad b \to s l^+ l^- \quad K \to \pi\bar{\nu}\nu$

These depend on a total of 27 Warsaw basis coefficients, through diagrams like these:

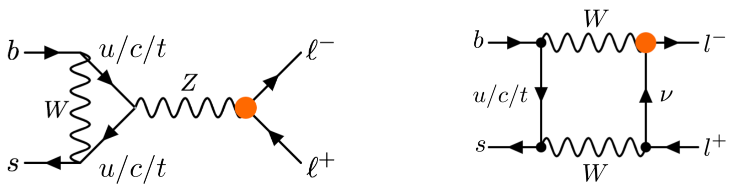
4 quark operators



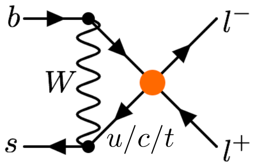
Purely bosonic operators



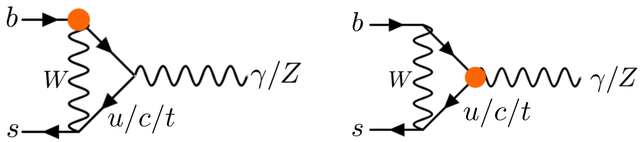
Higgs-lepton operators



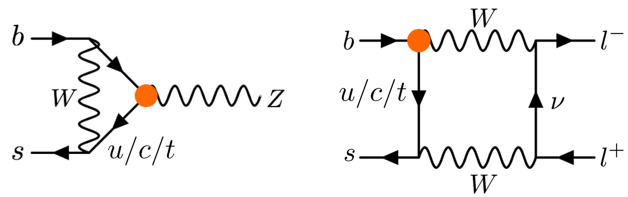
2 quark, 2 lepton operators



Dipole operators



Higgs-quark operators



[Other matching refs: Aebischer & al 1512.02830, Dekens & Stoffer 1908.09295]

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 measured inputs to fix parameters of the theory...

We chose
2 different schemes

Brivio & Trott 1701.06424

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

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

In the SM, these are used to assign numerical values to SM parameters

e.g. from measurement of $G_F = \frac{1}{\sqrt{2}v^2} \implies v = 246\,\mathrm{GeV}$

Inputs

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

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

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

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

These coefficients therefore modify the SM-like (dim 4) amplitude

Inputs

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

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CKM

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The CKM matrix in the SM

The CKM matrix depends on 4 parameters

$$\begin{bmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + O(\lambda^4)$$

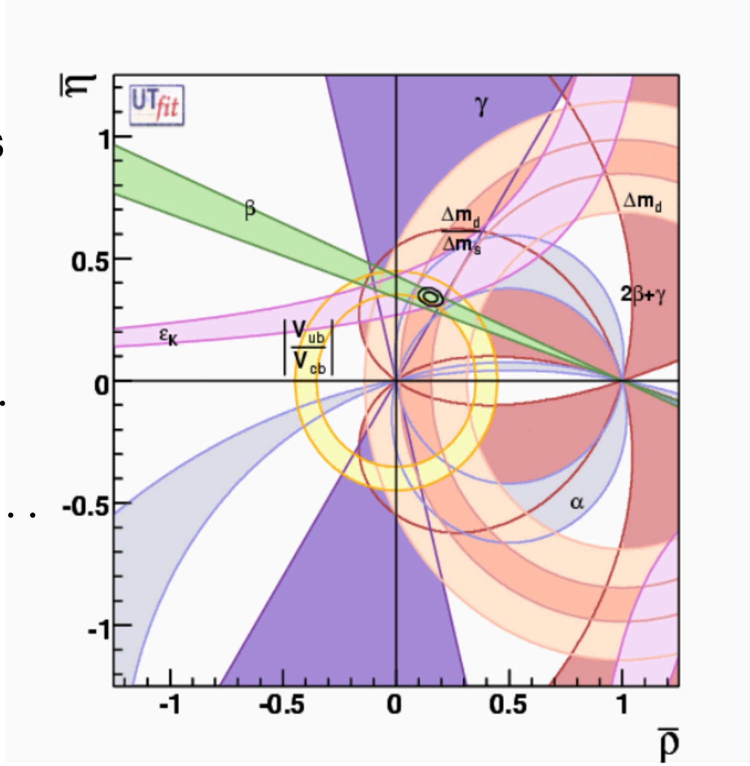
SM CKM fits are done to many measurements

Leptonic decays e.g. $K \to \mu\bar{\nu},\ \pi \to e\bar{\nu},\ldots$

Semileptonic decays e.g. $K \to \pi e\bar{\nu},\ B \to De\bar{\nu},\ldots$

CP asymmetries, e.g. in $B \to J/\psi K^{(*)}, B \to \pi\pi,\ldots$

Neutral meson mixing, e.g. $\Delta M_d, \epsilon\ \ldots$



If there is NP, need to understand how it contributes to the observables used to fix the CKM

The CKM matrix in the SMEFT

Pick 4 measurements which can fix the 4 parameters

Fix the CKM taking account of SMEFT contributions to the processes involved in the fit

This will give a $O(\Lambda^{-2})$ shift compared to the SM determination, which must be included in the SMEFT predictions for other processes

The CKM parameters in the SMEFT

[arXiv:1812.08163]

Sébastien Descotes-Genon[a], Adam Falkowski[a], Marco Fedele[b], Martín González-Alonso[c] and Javier Virto[d,e]

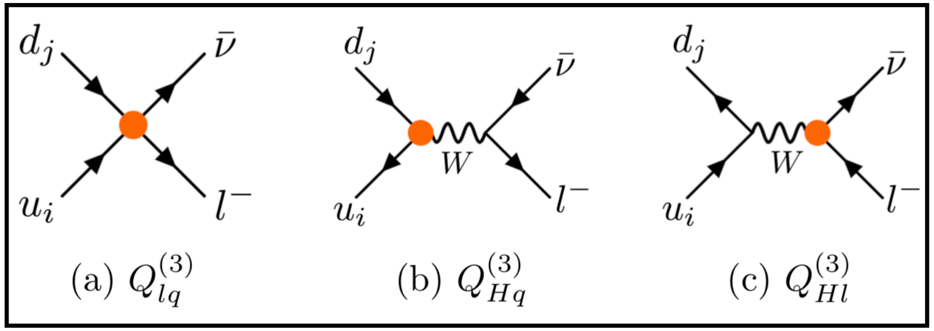
The CKM matrix in the MFV SMEFT

Under our flavour assumptions, the SMEFT contributions to any process are proportional to the same CKM factors as in the SM

$$\text{Amplitude}_{ij} \sim (\text{SM+NP})\, V_{ij}$$

No flavour indices here

e.g. charged-current (semi)leptonic decays



So appropriate ratios of processes are unchanged, still proportional to SM CKM ratios

e.g. schematically $\dfrac{b \to c l \nu}{s \to u l \nu} \propto \left| \dfrac{V_{cb}}{V_{us}} \right|^2$

$$\frac{\Delta M_s}{\Delta M_d}, \quad S_{\psi K_S}, \quad \frac{\Gamma(K^- \to \mu^- \bar{\nu}_\mu)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)}, \quad \frac{\Gamma(B \to D l \nu)}{\Gamma(K \to \pi l \nu)}$$

$$\left| \frac{V_{td}}{V_{ts}} \right|, \quad \sin 2\beta, \quad \left| \frac{V_{us}}{V_{ud}} \right|, \quad \left| \frac{V_{cb}}{V_{us}} \right|$$

$$\begin{pmatrix} \lambda = & 0.2254 \pm 0.0005 \\ A = & 0.80 \pm 0.013 \\ \bar{\rho} = & 0.187 \pm 0.020 \\ \bar{\eta} = & 0.33 \pm 0.05 \end{pmatrix}$$

A little less precise than full fits

This can be used for theory predictions when fitting to the MFV SMEFT

Results of matching calculations

Expressions for WET coeffs in terms of SMEFT coeffs
+ flavour constraints as bounds on those WET coeffs

New constraints for SMEFT fits

Example: ΔM_s observable in B_s mixing

Constrains BSM coefficient of WET operator $(\bar{s}_L \gamma^\mu b_L)^2$

$$C^{bs}_{1,mix}(m_W) = 0.07^{+0.17}_{-0.15}$$

Matching result:

$$C^{b(s,d)}_{1,\mathrm{mix}}(m_W) = 0.25\, C_{uW} + 0.61\, (C^{(3)}_{Hq} + C'_{ll} - 2C^{(3)}_{Hl}) + 0.28\, (C^{(3)\prime}_{qq} - C^{(1)\prime}_{qq} - 2C^{(3)}_{qq})$$

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Linear combination of SMEFT coeffs, in units of 1/TeV²
(defined at Lambda=1 TeV)

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} **New constraints for global SMEFT fits**

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Constrained WET coefficient

Linear combination of SMEFT coeffs, in units of 1/TeV²

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

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

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

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

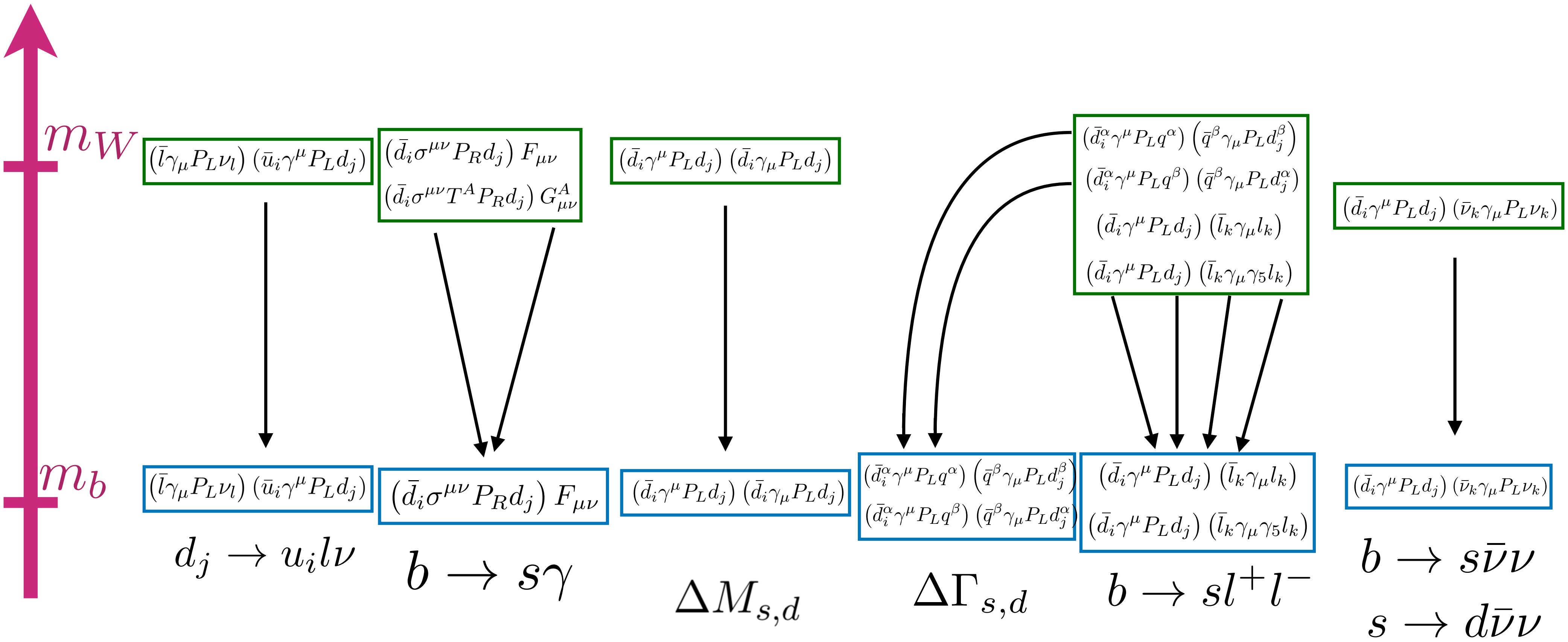
- No right handed currents
- Same CKM factors
- GIM mechanism

$$C_7 = \frac{3}{2} g_2 v^2 C_W \left(-\frac{x_t^2 + x_t}{2(x_t-1)^2} + \frac{x_t^2}{(x_t-1)^3} \log x_t \right),$$
$$C_9 = \frac{3}{2} g_2 v^2 C_W \left(\frac{3x_t^2 - x_t}{2(x_t-1)^2} - \frac{x_t^3}{(x_t-1)^3} \log x_t \right).$$

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

Running below weak scale

[Anomalous dim matrix: Aebischer & al 1704.06639, Jenkins & al 1711.05270]



Effects of the MFV SMEFT only appear in particular WET operators

Limited number of new constraints

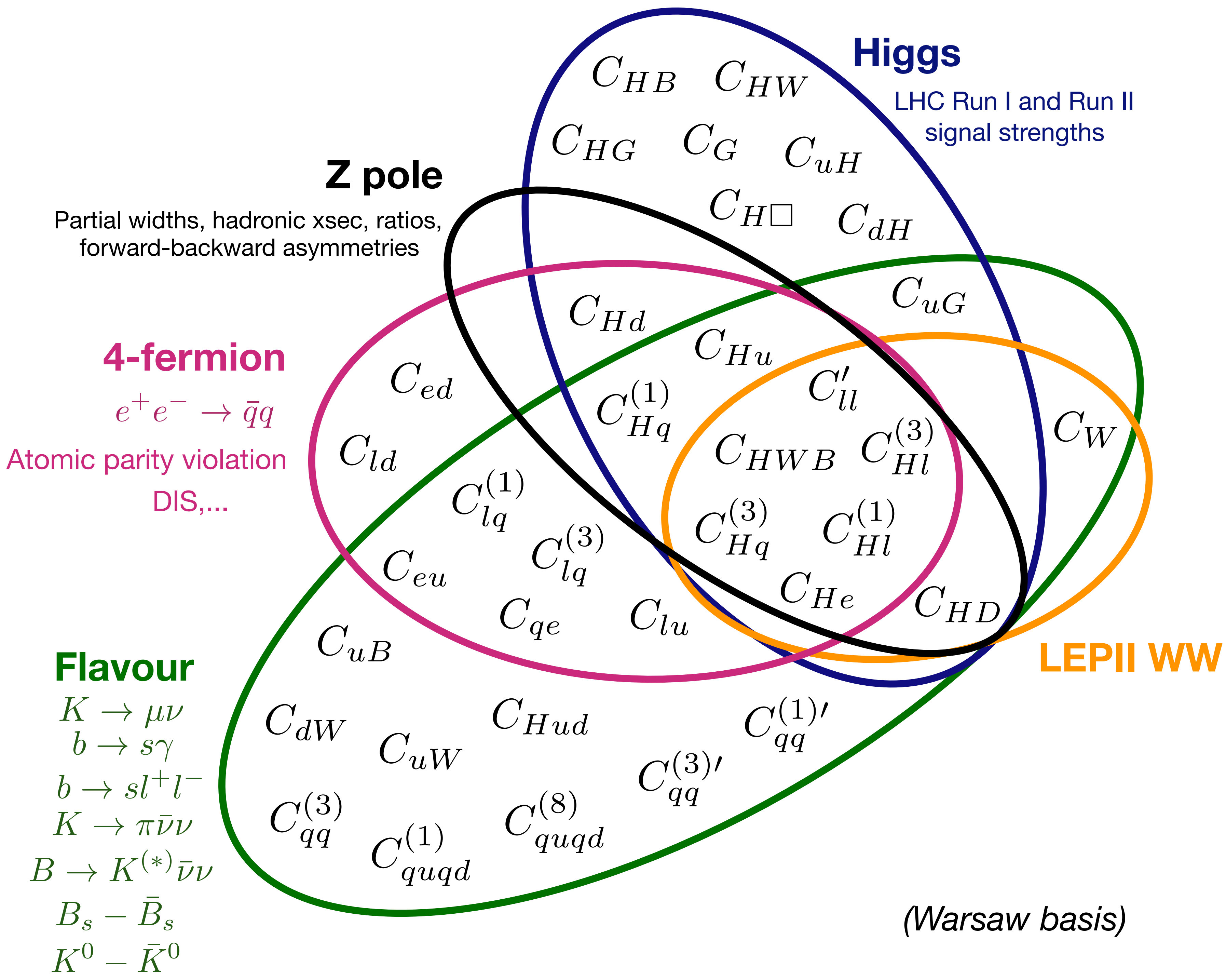
Flavour vs existing constraints

Many operator directions are already well constrained by electroweak data

But there are flat directions in global fits: more operators than independent constraints

To get a full picture...

- Allow all operators at once
- Constrain with many different observables


Higgs
LHC Run I and Run II signal strengths
Z pole
Partial widths, hadronic xsec, ratios, forward-backward asymmetries
4-fermion
$e^+e^- \to \bar{q}q$
Atomic parity violation
DIS,...
Flavour
$K \to \mu\nu$
$b \to s\gamma$
$b \to s l^+ l^-$
$K \to \pi\bar{\nu}\nu$
$B \to K^{(*)}\bar{\nu}\nu$
$B_s - \bar{B}_s$
$K^0 - \bar{K}^0$
LEPII WW
C_{HB} C_{HW} C_{HG} C_G C_{uH} $C_{H\Box}$ C_{dH}
C_{Hd} C_{uG} C_{Hu} C'_{ll} $C^{(1)}_{Hq}$ C_{HWB} $C^{(3)}_{Hl}$ C_W
C_{ed} C_{ld} $C^{(1)}_{lq}$ $C^{(3)}_{lq}$ C_{eu} C_{qe} C_{lu}
$C^{(3)}_{Hq}$ $C^{(1)}_{Hl}$ C_{He} C_{HD}
C_{uB} C_{dW} C_{uW} C_{Hud} $C^{(1)\prime}_{qq}$ $C^{(3)\prime}_{qq}$
$C^{(3)}_{qq}$ $C^{(1)}_{quqd}$ $C^{(8)}_{quqd}$
(Warsaw basis)

Global fit

Observables: Higgs, Z-pole, LEPII WW, $e^+e^- \to \bar{q}q$ off the Z pole, low energy precision measurements, flavour } **187 observables**

$$\{C_{H\Box}, C_{HWB}, C_{HD}, C_{HW}, C_{HB}, C_{HG}, C_W, C_G, C_{Hl}^{(1)}, C_{Hl}^{(3)}, C_{Hq}^{(1)}, C_{Hq}^{(3)}, C_{Hu}, C_{Hd}, C_{He}, C_{Hud}, C_{uH}, C_{dH}, C_{uW}, C_{dW}, C_{uB}, C_{uG}, C'_{ll}, C_{lq}^{(3)}, C_{lq}^{(1)}, C_{qe}, C_{lu}, C_{ld}, C_{eu}, C_{ed}, C_{qq}^{(1)\prime}, C_{qq}^{(3)}, C_{qq}^{(3)\prime}, C_{quqd}^{(1)}, C_{quqd}^{(8)}, C_{quqd}^{(1)\prime}, C_{quqd}^{(8)\prime}\}.$$

} **36 coefficients**

Method of least squares

[PDG Statistics review]

$$\boldsymbol{\mu}(\boldsymbol{\theta}) = \boldsymbol{\mu}_{SM} + \mathbf{H} \cdot \boldsymbol{\theta}$$

matrix

vector of SMEFT coeffs

vector of SMEFT predictions for the observables

Global fit

Observables: Higgs, Z-pole, LEPII WW, $e^+e^- \to \bar{q}q$ off the Z pole, low energy precision measurements, flavour } **187 observables**

$$\{C_{H\Box}, C_{HWB}, C_{HD}, C_{HW}, C_{HB}, C_{HG}, C_W, C_G, C_{Hl}^{(1)}, C_{Hl}^{(3)}, C_{Hq}^{(1)}, C_{Hq}^{(3)}, C_{Hu}, C_{Hd}, C_{He}, C_{Hud}, C_{uH}, C_{dH}, C_{uW}, C_{dW}, C_{uB}, C_{uG}, C'_{ll}, C_{lq}^{(3)}, C_{lq}^{(1)}, C_{qe}, C_{lu}, C_{ld}, C_{eu}, C_{ed}, C_{qq}^{(1)\prime}, C_{qq}^{(3)}, C_{qq}^{(3)\prime}, C_{quqd}^{(1)}, C_{quqd}^{(8)}, C_{quqd}^{(1)\prime}, C_{quqd}^{(8)\prime}\}.$$

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Method of least squares

[PDG Statistics review]

$$\boldsymbol{\mu}(\boldsymbol{\theta}) = \boldsymbol{\mu}_{SM} + \mathbf{H} \cdot \boldsymbol{\theta}$$

matrix

covariance matrix of measurements

Fisher matrix

$$\mathbf{F} = \mathbf{H}^T \mathbf{V}^{-1} \mathbf{H} = \mathbf{U}^{-1}$$

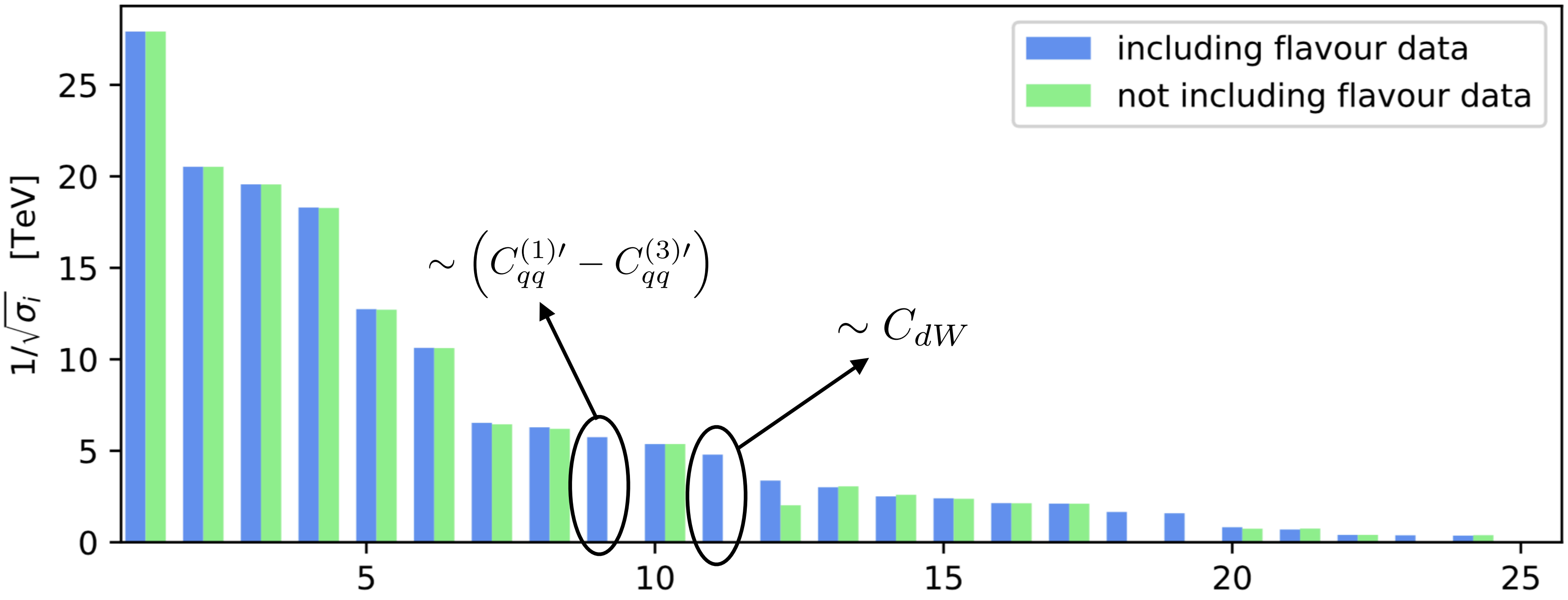
Output of the fit: covariance matrix in Wilson coeff space

Eigenvectors of the Fisher matrix: linear combinations of SMEFT coeffs

Eigenvalues of the Fisher matrix: $1/\sigma_i^2$

Constraints

Observables: Higgs, Z-pole, LEPII WW, $e^+e^- \to \bar{q}q$ off the Z pole, low energy precision measurements, flavour



Without flavour: 12 flat directions
With flavour: 7 flat directions

Flavour in Z pole flat directions

In the Wilson coeff space of Z pole data...

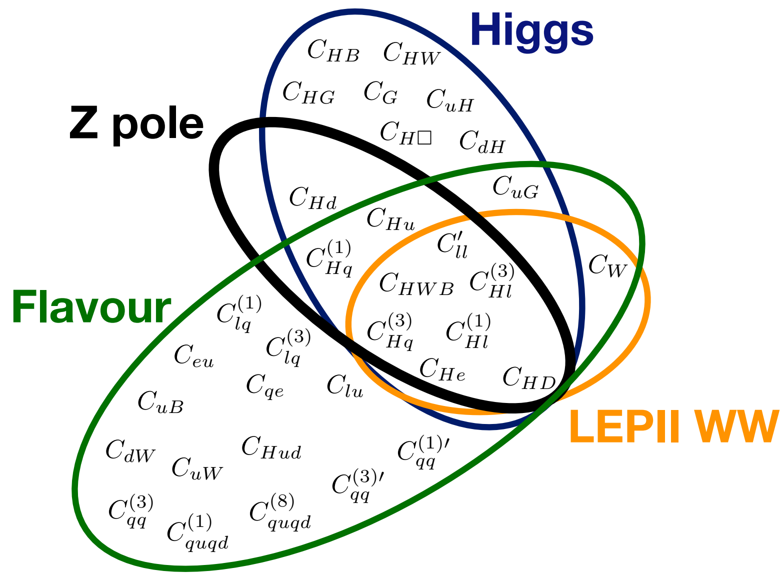
$$\{C_{HWB}, C_{HD}, C_{Hl}^{(1)}, C_{Hl}^{(3)}, C_{Hq}^{(1)}, C_{Hq}^{(3)}, C_{Hu}, C_{Hd}, C_{He}, C_{ll}'\}$$

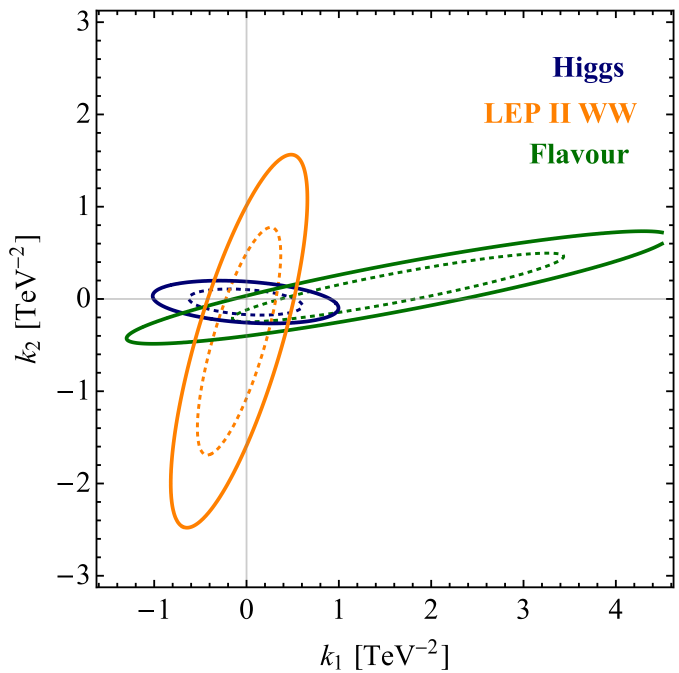
there are *two directions* that are unconstrained

$$k_1 = 0.388\left(\frac{1}{3}C_{Hd} - 2C_{HD} + C_{He} + \frac{1}{2}C_{Hl}^{(1)} - \frac{1}{6}C_{Hq}^{(1)} - \frac{2}{3}C_{Hu}\right) + 0.22(C_{Hq}^{(3)} + C_{Hl}^{(3)}) + 0.895 C_{HWB}$$

$$k_2 = -0.664(C_{Hq}^{(3)} + C_{Hl}^{(3)}) + 0.344 C_{HWB}$$

Fit to this space of 10 coefficients and plot contours in the plane of the flat directions, profiling over the 8 orthogonal directions





[SMEFT predictions for Z pole observables from Brivio & Trott 1701.06424,
SMEFT predictions for LEPII WW from Berthier, Bjorn, Trott 1606.06693,
SMEFT predictions for Higgs signal strengths from Ellis, Murphy, Sanz, You 1803.03252]

Flavour in Z pole flat directions

In the Wilson coeff space of Z pole data...

$$\{C_{HWB}, C_{HD}, C^{(1)}_{Hl}, C^{(3)}_{Hl}, C^{(1)}_{Hq}, C^{(3)}_{Hq}, C_{Hu}, C_{Hd}, C_{He}, C'_{ll}\}$$

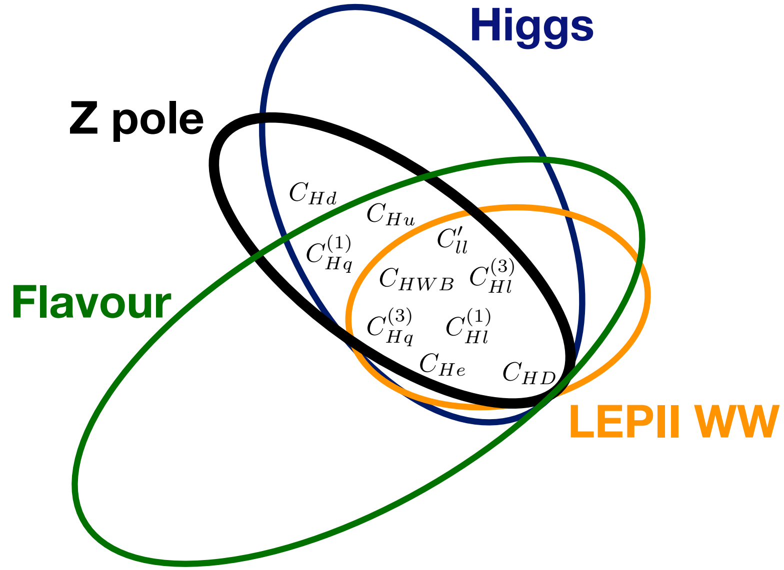
there are *two directions* that are unconstrained

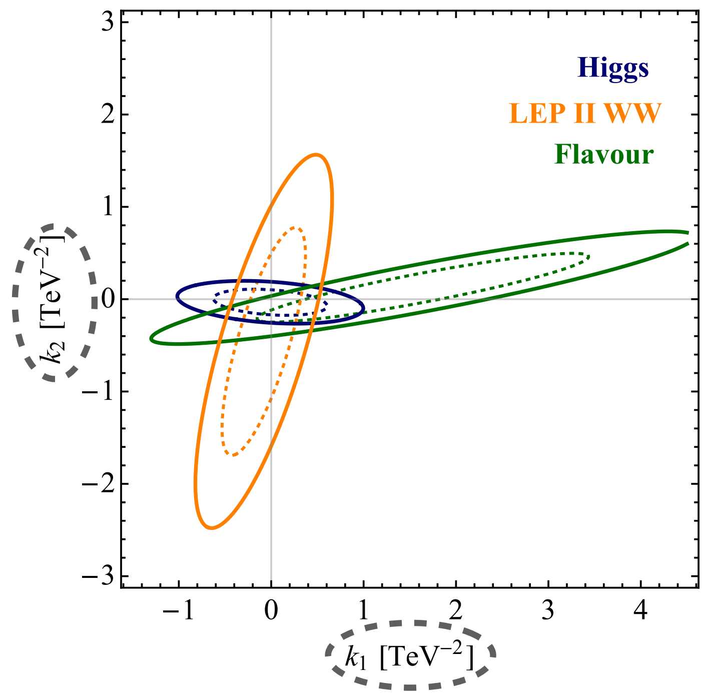
$$k_1 = 0.388\left(\frac{1}{3}C_{Hd} - 2C_{HD} + C_{He} + \frac{1}{2}C^{(1)}_{Hl} - \frac{1}{6}C^{(1)}_{Hq} - \frac{2}{3}C_{Hu}\right) + 0.22(C^{(3)}_{Hq} + C^{(3)}_{Hl}) + 0.895C_{HWB}$$

$$k_2 = -0.664(C^{(3)}_{Hq} + C^{(3)}_{Hl}) + 0.344C_{HWB}$$

Fit to this space of 10 coefficients and plot contours in the plane of the flat directions, profiling over the 8 orthogonal directions

[SMEFT predictions for Z pole observables from Brivio & Trott 1701.06424, SMEFT predictions for LEPII WW from Berthier, Bjorn, Trott 1606.06693, SMEFT predictions for Higgs signal strengths from Ellis, Murphy, Sanz, You 1803.03252]





Thoughts

Flavour constraints clearly depend sensitively on the assumed flavour structure

...Can we learn anything from this if we don't believe that BSM physics follows this particular flavour symmetry?

- The $U(3)^5$ flavour symmetry is the largest one available. Can be thought of as "baseline" effects expected

- Loop effects are dominated by top contribution. If a theory doesnt have tree level FCNCs, and couples to the top, effects will be similar (but not identical: will break some GIM cancellations)

- If a theory's largest FCNC effects are loop induced, get similar qualitative patterns of deviations (CKM suppressions, lorentz structure)

Clearly a lot more work to do!

Summary

- Flavour measurements suggest possibility of NP with flavour symmetries

  What information can be extracted in this case?

- Calculated the loop level matching for SMEFT with MFV flavour symmetry to WET operators responsible for down type FCNCs

- Obtained explicit expressions for predictions of $U(3)^5$ SMEFT in flavour observables

- Flavour can now be included on the same footing as EW/higgs data in global fits and provide new constraints

- Lots of flavour data to come, how can we use it best?