BUILDING BLOCKS OF THE FLAVOURFUL SMEFT

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(based on `arXiv:2210.09316` w/ C. Machado and S. Renner)
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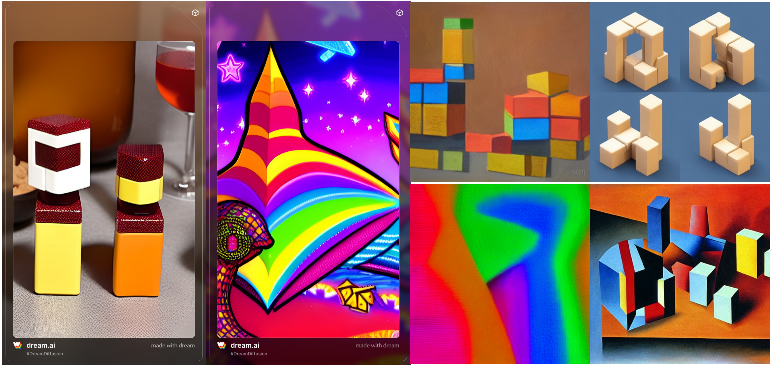
WHAT'S A BUILDING BLOCK?

Various AI text-to-image interpretations of the title



This talk is about organising the search for new physics by looking for RG invariant blocks in the EFT.

INTRODUCTION

SMEFT IS THE SHORT RANGE EFFECTS OF BSM PHYSICS

n-point BSM amplitudes are functions of the new physics scale M and scattering energy E

$$\mathcal{A}^n_{\text{BSM}} = f(E, M)$$

At low energies they can be expanded in $\frac{1}{M}$

$$\mathcal{A}^n_{\text{EFT}} = E^{4-n}\left(a_4 + a_5\left(\frac{E}{M}\right) + a_6\left(\frac{E}{M}\right)^2 + \ldots\right)$$

FROM MODEL SPACE TO WILSON COEFFICIENT SPACE

Build higher-dimension operators from the SM fields to span these effects (truncated to some dimension order)

$$\mathcal{L}_{\text{SMEFT}} = \frac{c_i^{(5)}}{M}\mathcal{O}_i^{(5)} + \frac{c_i^{(6)}}{M^2}\mathcal{O}_i^{(6)} + \dots$$

$$\Downarrow$$

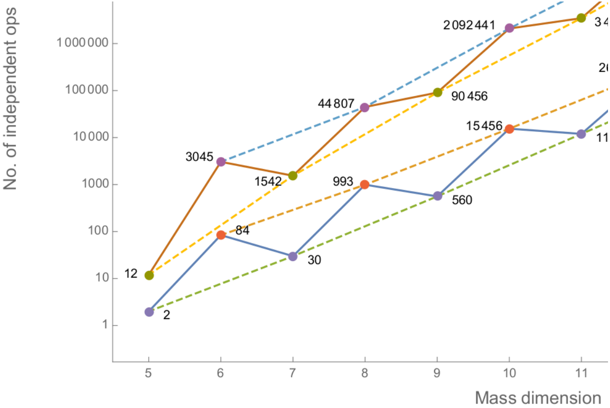
$$\frac{\mathcal{A}^n_{\text{SMEFT}}}{E^{4-n}} = \alpha_i^{(5)} c_i^{(5)} \left(\frac{E}{M}\right) + \left[\alpha_i^{(6)} c_i^{(6)} + \beta_{ij}^{(5)} c_i^{(5)} c_j^{(5)}\right] \left(\frac{E}{M}\right)^2 + \dots$$

New physics is mapped onto space of Wilson coefficients.

Important for future high energy data.

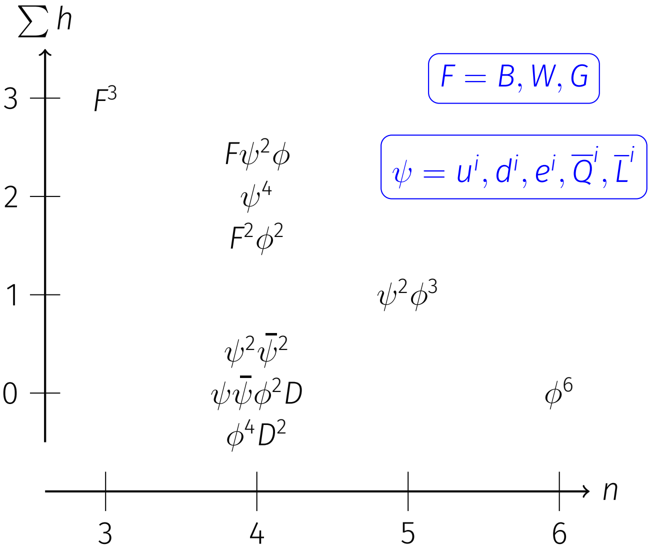
PROBLEM: THERE ARE MANY PARAMETERS

(Henning, Lu, Melia, and Murayama 2017)

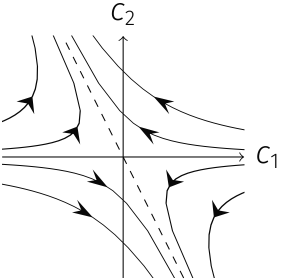


There are 2499 at leading order! Many of them flavourful

A MAP OF DIMENSION 6 OPERATORS



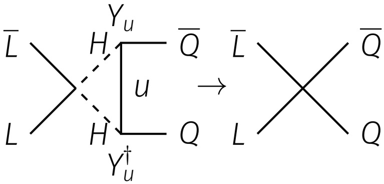
PROBLEM: THEY RUN



$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu}c_i = \frac{1}{16\pi^2}\gamma_{ij}c_j$$

Parameters mix via γ, populated by SM couplings.

Much of it is flavourful, e.g.



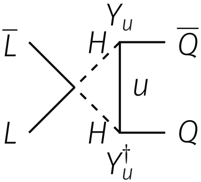
Calculated by (Alonso, Jenkins, Manohar, and Trott 2014), implemented in code

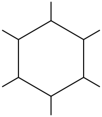
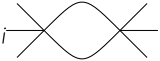
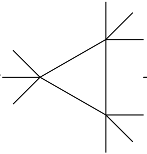
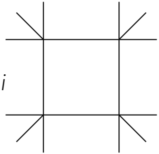
THE PLAN

- Structures in the RG due to helicity (Cheung and Shen 2015)
- Structures in the RG due to flavour (*arXiv:2210.09316*)
- Relevant directions in the IR (preliminary work)

BLOCKS FROM HELICITY

Consider the Passarino-Veltman decomposition of a one loop diagram, e.g.

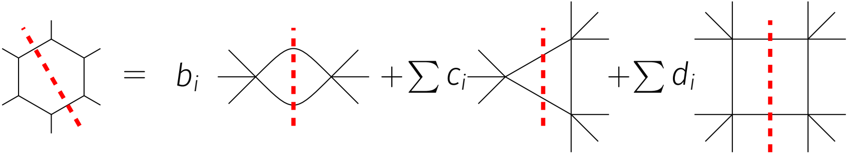


 $= \sum b_i$  $+ \sum c_i$  $+ \sum d_i$ 

It contains UV and IR divergences. Anomalous dimensions are encoded in the *b*s.

CUTTING THROUGH THE NOISE

"Cut" both sides by placing two propagators on-shell



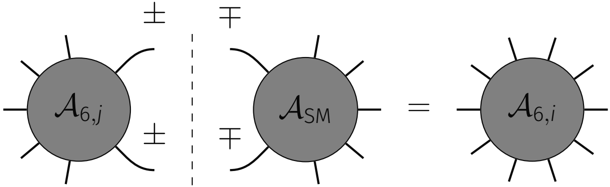
Take all possible cuts, obtain a set of linear equations for $\{b_i, c_i, d_i\}$.

For many SMEFT amplitudes, the LHS vanishes for all cuts, and therefore $b_i = c_i = d_i = 0$.

For how to calculate EFT RGs onshell, see (Caron-Huot and Wilhelm 2016), (Jiang, Ma, and Shu 2021), (Baratella, Fernandez, and Pomarol 2020)

HELICITY SELECTION RULES

LHSs vanish because SM ultra-helicity violating amplitudes vanish, e.g., $\mathcal{A}_{\mathrm{SM}}\left(g^+g^+g^+g^-\right)$.



$$\begin{pmatrix} n_j \\ \sum h_j \end{pmatrix} + \begin{pmatrix} -4 \\ 0 \end{pmatrix} + \begin{pmatrix} n_{\mathrm{SM}} \\ \sum h_{\mathrm{SM}} \end{pmatrix} = \begin{pmatrix} n_i \\ \sum h_i \end{pmatrix} \begin{matrix} \text{[\# legs]} \\ \text{[Tot. helicity]} \end{matrix}$$

Tree-level SM amplitudes satisfy

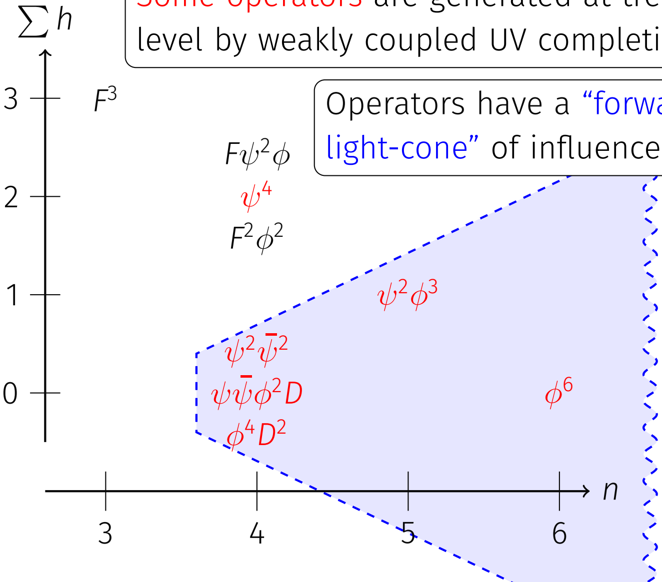
$$\left|\sum h_{\mathrm{SM}}\right| \leq n_{\mathrm{SM}} - 4$$

with the exception of $\mathcal{A}\left(Q^+u^+Q^+d^+\right) \propto Y_u \times Y_d$

A “CAUSAL” RG

Some operators are generated at tree level by weakly coupled UV completions

Operators have a “forward light-cone” of influence



FOCUS ON THE $(4,0)$ BLOCK

$$\begin{array}{ccc} & (4,0) & \text{other} \\ (4,0) & \left(\begin{array}{c} \\ \end{array}\right. & \left.\begin{array}{c} 0 \\ \end{array}\right) \\ \text{other} & & \end{array}$$

$$\gamma = \begin{array}{c|c} (4,0)\ \text{block} & 0 \\ \hline & \end{array}$$

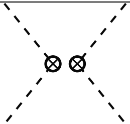
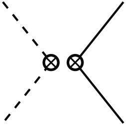
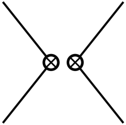
Nothing runs into it, except a few $(4,2)$ operators, but that's suppressed by $Y_u \times Y_d$. By the same token, drop $\mathcal{O}_{Hud}$ and $\mathcal{O}_{LedQ}$.

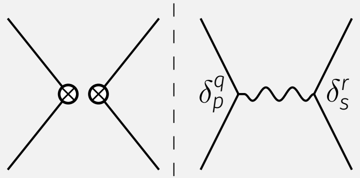
The block contains 1460 of 2499 parameters, all tree-level generated.

BLOCKS FROM FLAVOUR

THE CURRENT-CURRENT OPERATORS

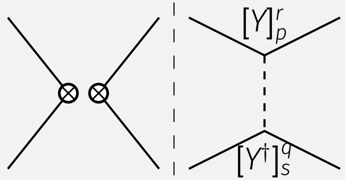
All considered operators are the product of two currents

Class	Example	Notation
$\phi^4 D^2$	$(H^\dagger i\overleftrightarrow{D}H)^2, (H^\dagger i\overleftrightarrow{D}\sigma^I H)^2$	
$\psi\bar{\psi}\phi^2 D$	$(H^\dagger i\overleftrightarrow{D}H)(\overline{u}_R\gamma u_R), (H^\dagger i\overleftrightarrow{D}\sigma^I H)(\overline{L}_L\gamma\sigma^I L_L)$	
$\psi^2\bar{\psi}^2$	$(\overline{Q}_L\gamma\lambda^A Q_L)(\overline{u}_R\gamma\lambda^A u_R), (\overline{L}_L\gamma L_L)^2$	



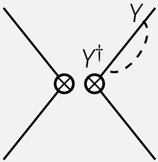
It is *flavourful* — it lifts flavour universal pieces relative to non-universal ones.

It can change operator type.



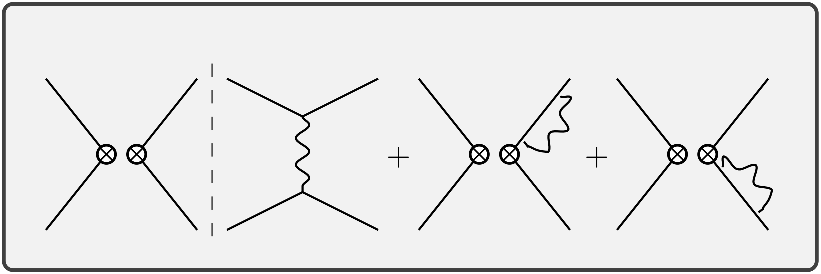
It is *flavourful* — it affects the third generation more than others.

It can change operator type.



It is *flavourful* — it affects third generation more than others.

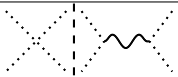
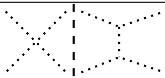
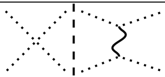
It *cannot* change operator type.



It is *flavourless*. It often vanishes due to non-renormalisation of number current.

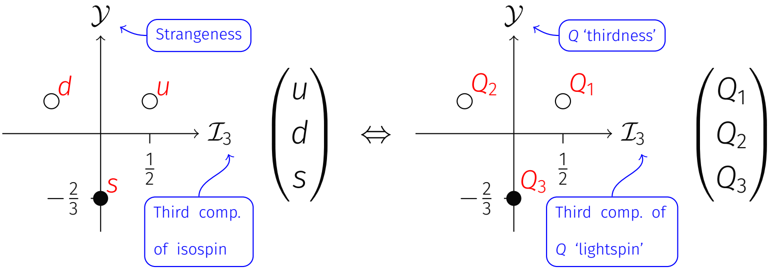
It *cannot* change operator type (other than mixing different gauge structures, e.g. $\mathcal{O}_{ud}^{(1)} \leftrightarrow \mathcal{O}_{ud}^{(8)}$).

THE FOUR TYPES OF RUNNING: SUMMARY

γ contribution	Cut topology	Flavour action
IR-finite gauge		singlets $\leftrightarrow$ singlets
IR-finite Yukawa		mixes irreps
IR-divergent gauge	 and collinear	blind
IR-divergent Yukawa	collinear	mixes irreps

(Also a couple flavourless Higgs quartic interactions.)

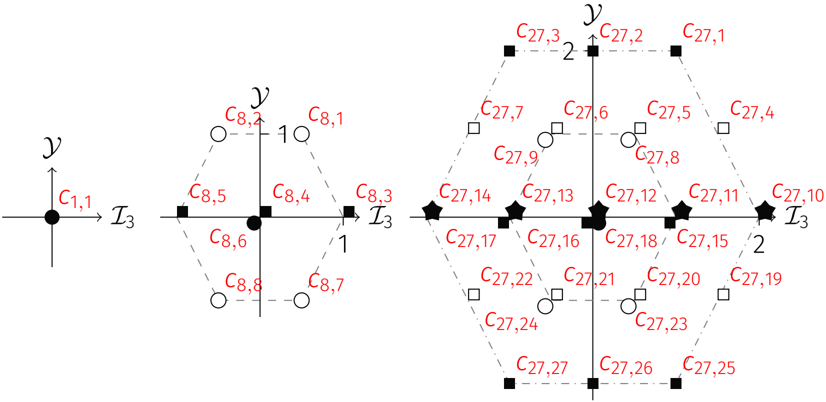
Cf. $SU(3)$ of uds: The SM Yukawas hierarchically break its $SU(3)_Q \times SU(3)_u \times SU(3)_d \times SU(3)_L \times SU(3)_e$ symmetry.



There are 20 flavour quantum numbers in total

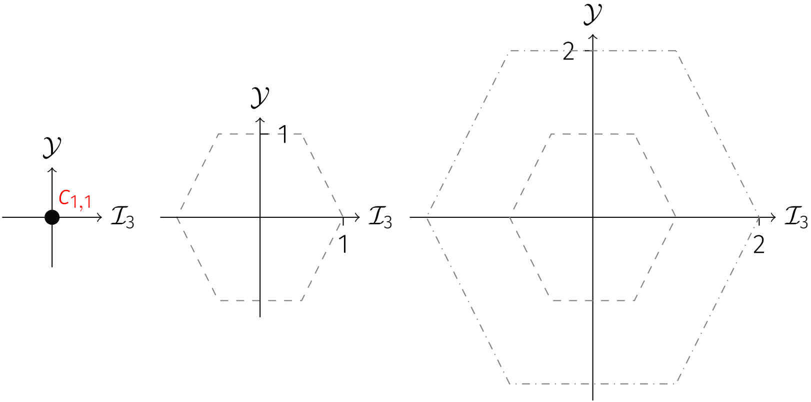
$$\{d, \mathcal{I}, \mathcal{I}_3, \mathcal{Y}\}_F \qquad \forall F \in \{Q, u, d, L, e\}$$

Irreps for current-current operators: $\mathbf{1}_F, \mathbf{8}_F, \mathbf{27}_F$ $(\mathbf{8}_{F_1} \otimes \mathbf{8}_{F_2})$



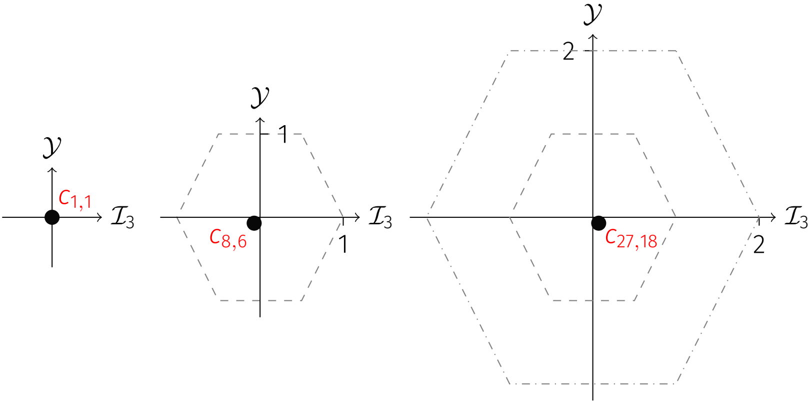
Total lightspin ($\mathcal{I}$) key: ● $= 0$, ○ $= \frac{1}{2}$, ■ $= 1$, □ $= \frac{3}{2}$, ⬟ $= 2$.

Flavour universal ($U(3)^5$ symmetric)



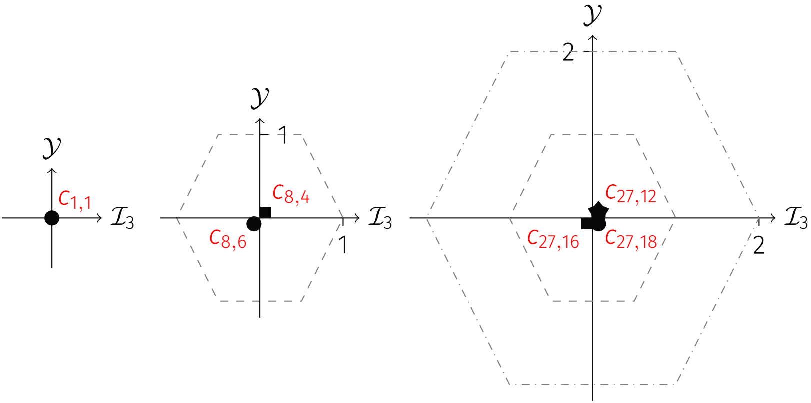
Total lightspin ($\mathcal{I}$) key: ● $= 0$, ○ $= \frac{1}{2}$, ■ $= 1$, □ $= \frac{3}{2}$, ⬟ $= 2$.

$U(2)^5$ symmetric



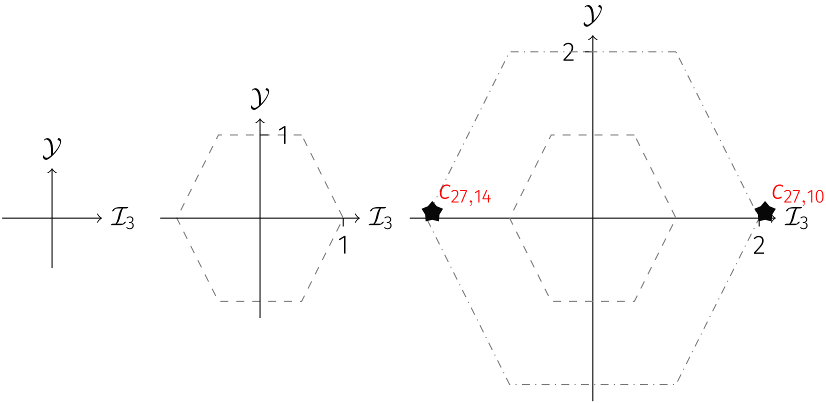
Total lightspin ($\mathcal{I}$) key: ● $= 0$, ○ $= \frac{1}{2}$, ■ $= 1$, □ $= \frac{3}{2}$, ⬟ $= 2$.

Flavour conserving



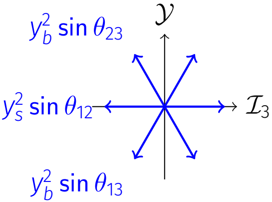
Total lightspin ($\mathcal{I}$) key: $\bullet = 0$, $\circ = \frac{1}{2}$, $\blacksquare = 1$, $\square = \frac{3}{2}$, $\bigstar = 2$.

Kaon mixing (where $F = d$)



Total lightspin ($\mathcal{I}$) key: $\bullet = 0$, $\circ = \frac{1}{2}$, $\blacksquare = 1$, $\square = \frac{3}{2}$, $\bigstar = 2$.

In the up basis, the Yukawas' flavour violation is small.



Flavour violation is through 'diagonal' y_t running

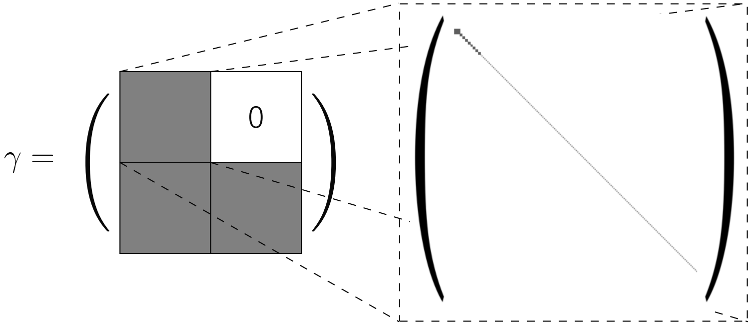
$$\overline{Q}^i \gamma \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}^{ij} Q^j \overset{\text{Run}}{\to} \overline{Q}^i \gamma \begin{pmatrix} a & 0 & 0 \\ 0 & a & 0 \\ 0 & 0 & b \end{pmatrix}^{ij} Q^j \overset{\text{Match}}{\to} (b-a)(V_{3i}^{\text{CKM}})^* V_{3j}^{\text{CKM}} \overline{d}^i \gamma d^j$$

y_t important: comparable to g_s and appears frequently

$$\alpha_t(m_Z) = \frac{y_t^2}{4\pi} \approx 0.08\,; \qquad \alpha_s(m_Z) = \frac{g_s^2}{4\pi} \approx 0.12\,.$$

FLAVOUR BLOCKS: GAUGE ONLY APPROX.

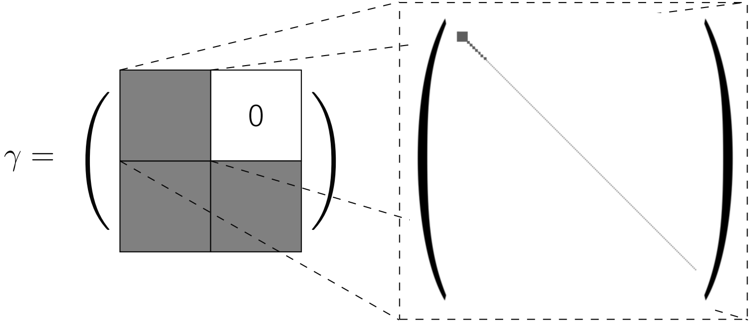
All numbers conserved: $\{d, \mathcal{I}, \mathcal{I}_3, \mathcal{Y}\}_{\{Q,u,d,L,e\}}$



Block size	34	13	9	6	2	1
Multiplicity	1	8	24	8	256	546

FLAVOUR BLOCKS: GAUGE AND y_t APPROX.

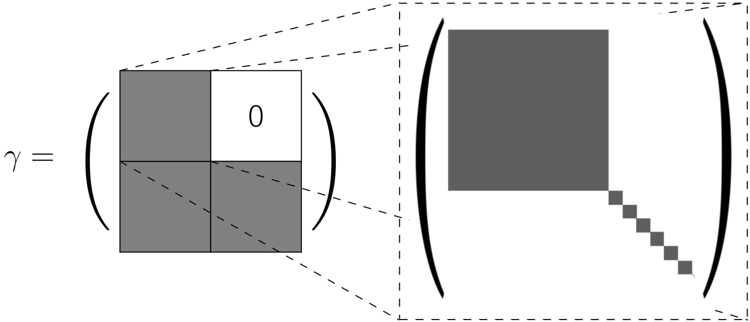
Conserved: $\{\mathcal{I}, \mathcal{I}_3, \mathcal{Y}\}_{\{Q,u\}}$, $\{d, \mathcal{I}, \mathcal{I}_3, \mathcal{Y}\}_{\{d,L,e\}}$



Block size	61	17	13	12	8	2	1
Multiplicity	1	7	8	15	8	217	498

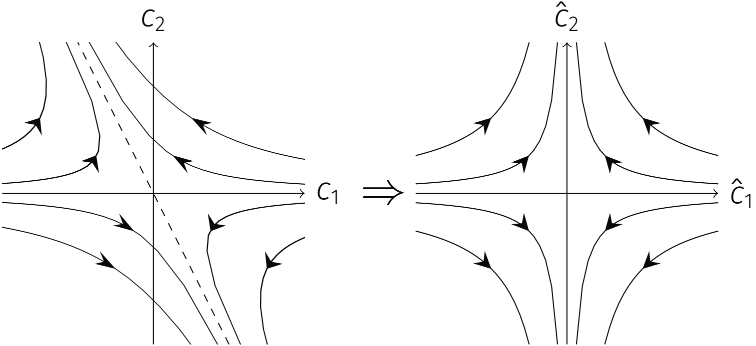
FLAVOUR BLOCKS: NO APPROX.

Lepton number conserved: $\mathcal{I}_{3,L} + \mathcal{I}_{3,e},\ \mathcal{Y}_L + \mathcal{Y}_e$



Block size	932	81	4	3
Multiplicity	1	6	6	6

IR RELEVANT DIRECTIONS

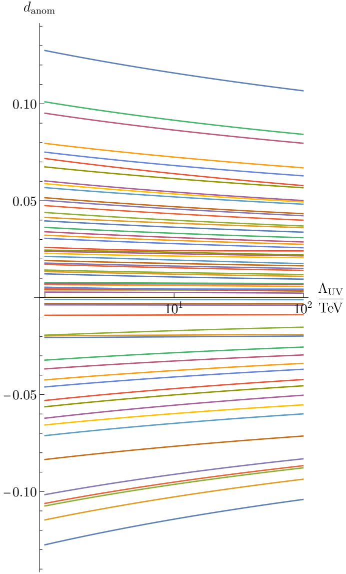


Diagonalise the anomalous dimension matrix

$$\frac{\mathrm{d}\hat{c}_i}{\mathrm{d}\ln\mu} = \frac{\hat{\gamma}_i \hat{c}_i}{16\pi^2} \implies \mathcal{A} \sim \hat{c}_i^{(6)}(E)\left(\frac{E}{M}\right)^2 = \hat{c}_i^{(6)}(M)\left(\frac{E}{M}\right)^{2+\frac{\hat{\gamma}_i}{16\pi^2}}$$

(To account for running of SM coeffs, $\gamma \to \langle\gamma\rangle_{\ln\mu}$.)

OPERATOR SPECTRUM IN GAUGE+y_t APPROX. (PRELIMINARY)



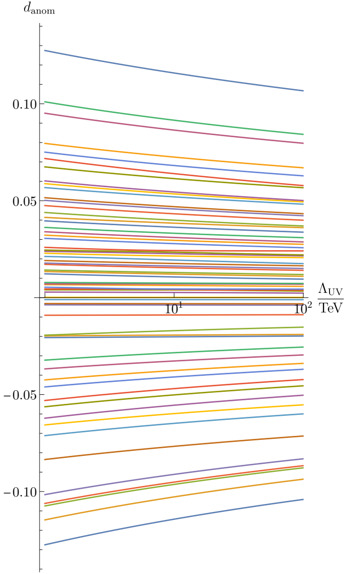
Diagonalise the 61×61 block.

Contains 533 y_t^2 entries, 138 g_s^2 entries.

Individual entries $\frac{g_s^2(m_Z)}{16\pi^2} = 0.01$ add up to $\pm\mathrm{O}(0.1)$ eigenvalues.

Directions double/halve from 50 TeV to 174 GeV.

OPERATOR SPECTRUM IN GAUGE+y_t APPROX. (PRELIMINARY)



Dimension 6.12

$\mathcal{O} \approx 0.94\mathcal{O}_{HD} + 0.23\mathcal{O}_{H\Box} - 0.19(\mathcal{O}_{Hu})_{8,6} + \ldots$

Dimension 5.88

$\mathcal{O} \approx 0.63(\mathcal{O}^{(8)}_{Qu})_{8,6,1,1} - 0.59(\mathcal{O}^{(8)}_{Qd})_{8,6,1,1} - 0.46(\mathcal{O}^{(8)}_{Qd})_{8,6,8,6} + \ldots$

SUMMARY

The RG of the SMEFT is not a black box, but a beautifully simple clockwork machine!

It is more flavourful than expected.

A flavour-symmetry-based decomposition reduces parameter space to manageable invariant blocks with distinct phenomenology.

This is a step towards finding the IR relevant directions of any heavy new physics, key for flavour physics.