New physics on the run from precision tests

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UK Research and Innovation

University of Glasgow

Outline

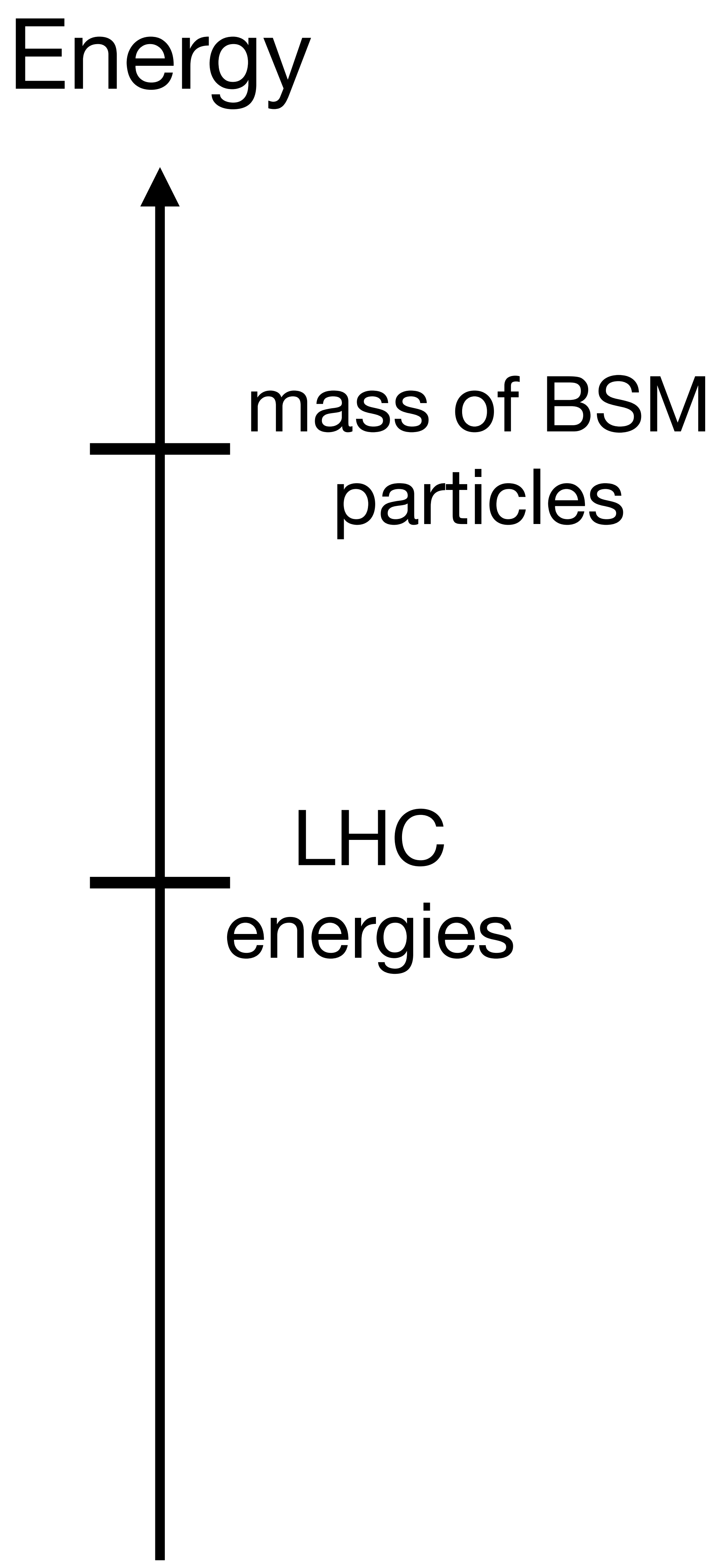
- Variety of increasingly precise data from current and upcoming experiments
- Possible new Z pole measurements at FCC-ee will contain lots of indirect info about new physics beyond the Standard Model
- How to quantify the power of this and make sense of this in a model-independent way?
- Via some more general thoughts on how to deal with the large parameter space of heavy new physics

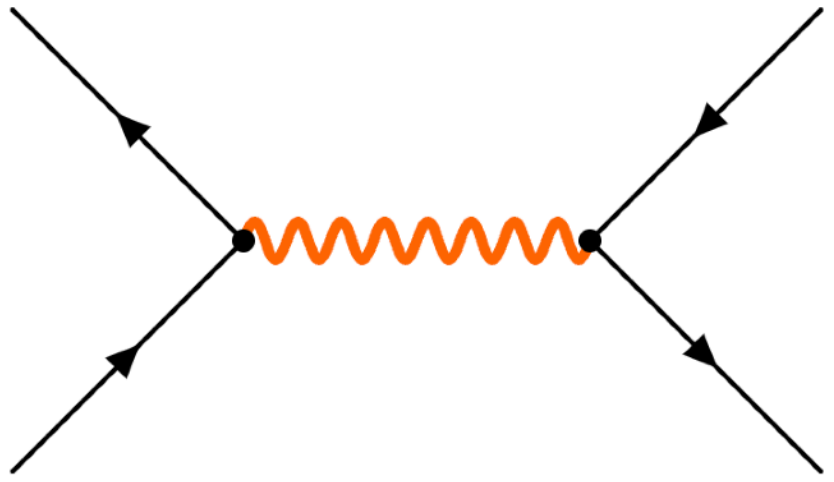
Based mostly on:

2210.09316 Camila Machado, SR, Dave Sutherland

Work in progress with Lukas Allwicher & Matthew McCullough

The Standard Model Effective Field Theory

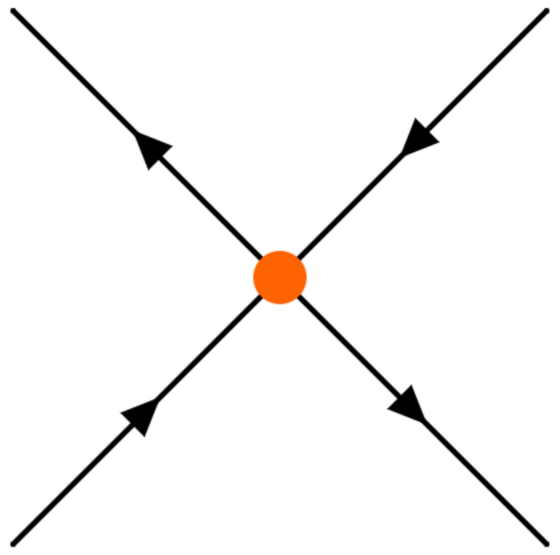




$$\propto \frac{1}{s - M^2}$$

New resonance

$$s \ll M^2$$



$$\propto \frac{s}{M^2}$$

New interaction between SM particles

SMEFT for BSM physics

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

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

ADVANTAGES

Can reproduce effects of heavy new physics at low energies

Model independent

Language to interpret experimental results

Can connect scales via anomalous dimension matrix

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

CHALLENGES

Too many parameters to deal with (2499 at dimension 6)

Sometimes opaque connection between operators and observables

Flavour in the SMEFT

Flavour is responsible for most of the parameters…

If there were one generation… **76 real parameters** (baryon number conserving)

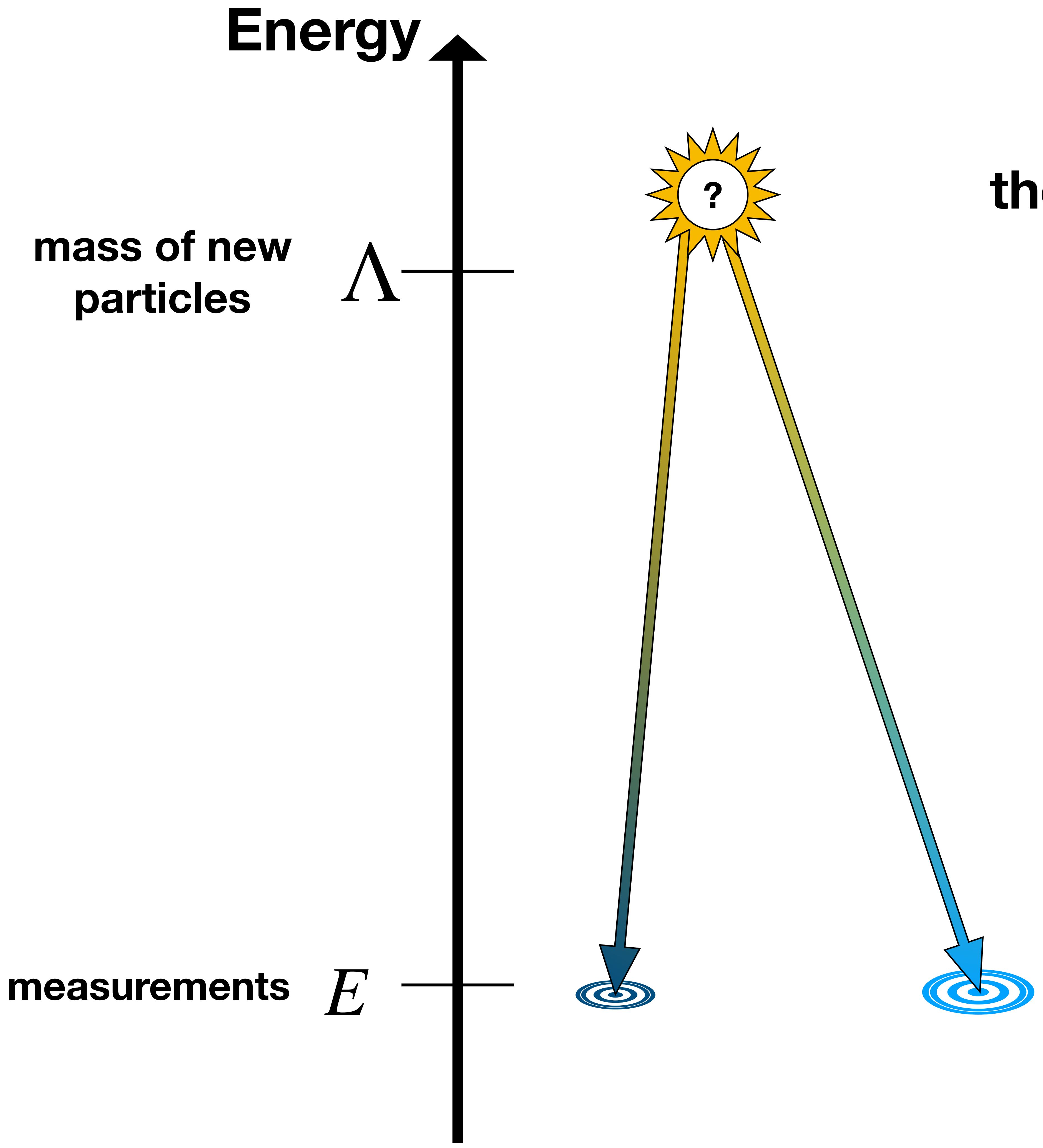
e.g. $C_{qe}\,(\bar{Q}\gamma^{\mu}Q)(\bar{e}\gamma_{\mu}e)$ Only one real parameter in C_{qe}

With three generations… **2499 real parameters** (baryon number conserving)

e.g. $C_{qe}^{ijkl}\,(\bar{Q}^{i}\gamma^{\mu}Q^{j})(\bar{e}^{k}\gamma_{\mu}e^{l})$ Now 81 real parameters in C_{qe}

(of which some CP odd)

Scale distortions



Some effect may be zero at the high scale of the new theory, but regenerates by the scale of the measurements

$$\frac{dC_i}{d\log\mu} = \frac{1}{16\pi^2}\sum_j \gamma_{ij} C_j$$

$N \times N$ matrix involving SM parameters

Renormalization Group equation (RGE) for EFT of N operators (at a given dimension)

This mixing of operators happens due to loop diagrams involving SM interactions

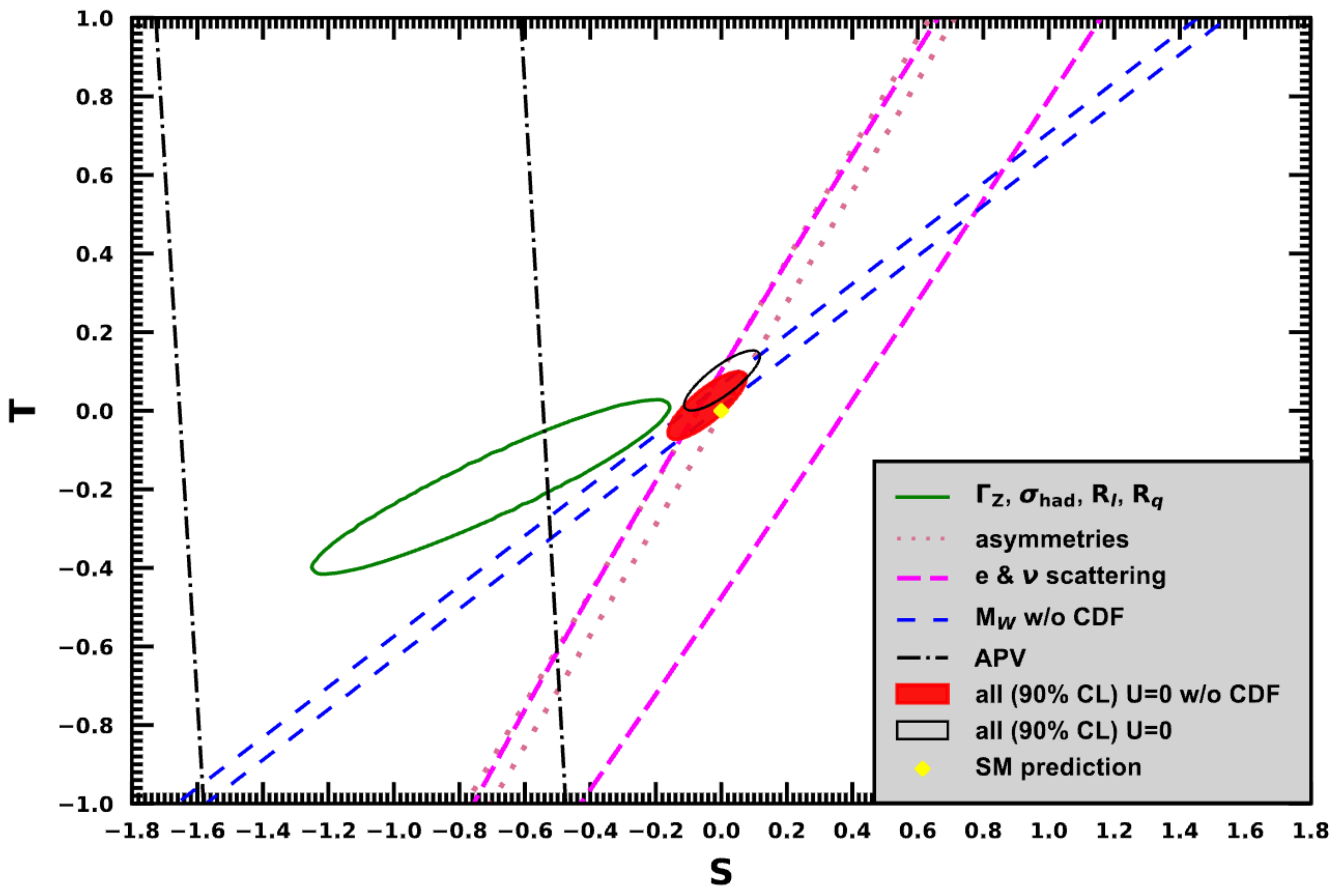
Precision tests

Flavour measurements
e.g. meson mixing

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

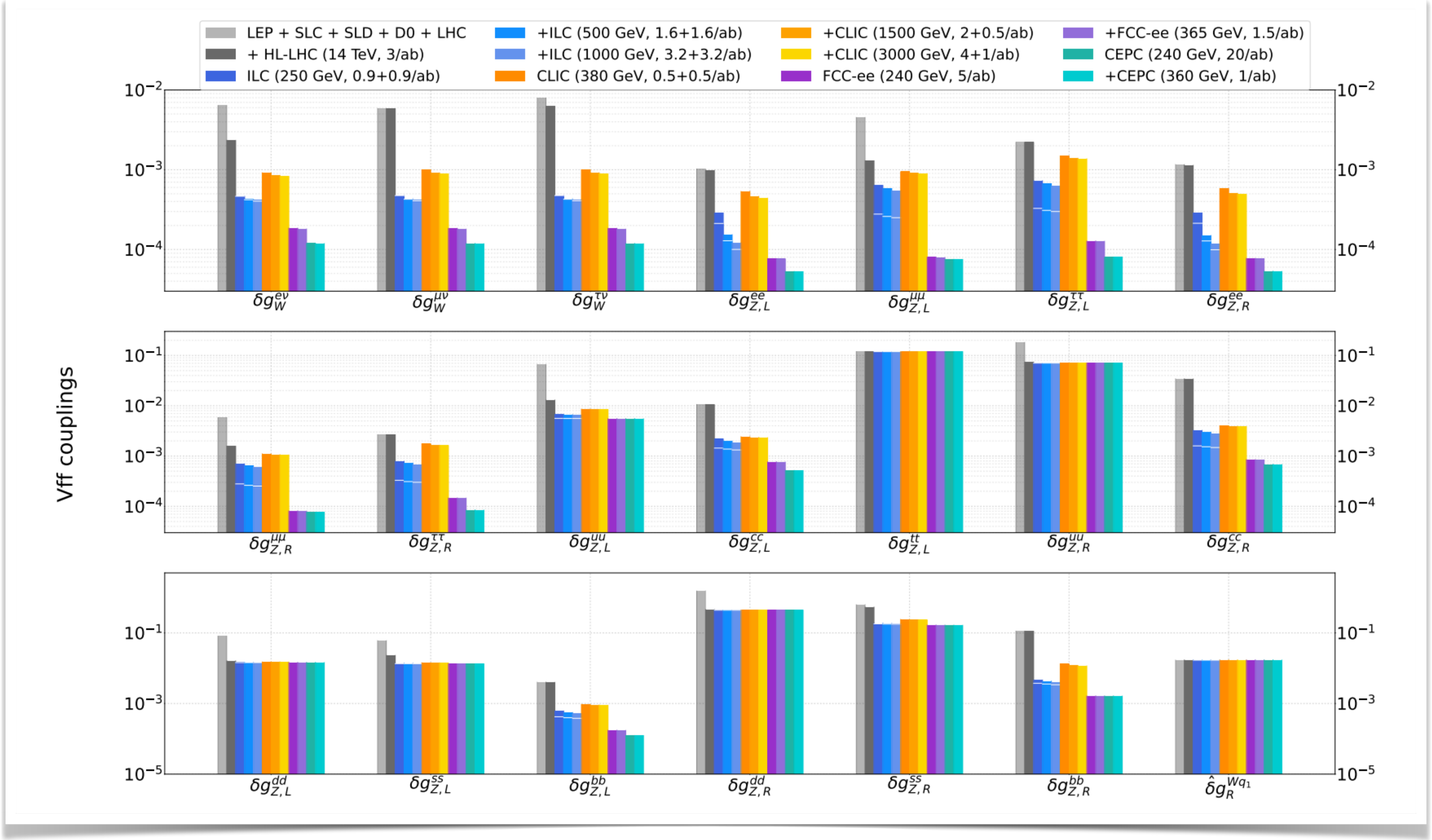
[Isidori, 1507.00867]

Z pole measurements



What are the scope of these bounds on the space of new physics?

Z pole at FCC-ee



De Blas et al, 2206.08326

LEP: 17 million Zs

FCC-ee: 5×10^{12} Zs

Bounds at better than per-mille level on most Z coupling deviations

SMEFT on the Z pole

Out of 2499 coefficients in dimension 6 SMEFT, 23 enter Z pole at tree level

Han, Skiba hep-ph/0412166
Berthier, Trott 1502.02570, ...

$\bar{\psi}\psi HD$

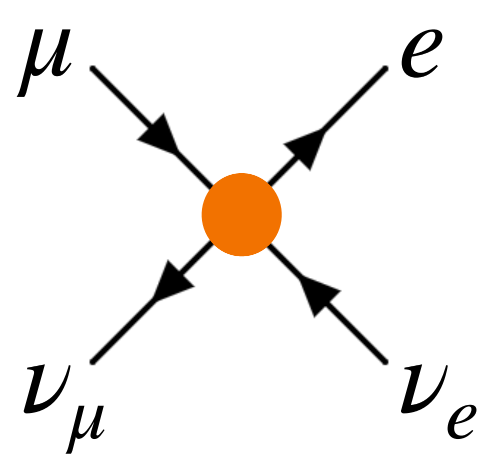
$$\{C_{HWB}, C_{HD}, C_{Hl}^{(1)}, C_{Hl}^{(3)}, C_{Hq}^{(1)}, C_{Hq}^{(3)}, C_{Hu}, C_{Hd}, C_{He}, C'_{ll}\}$$

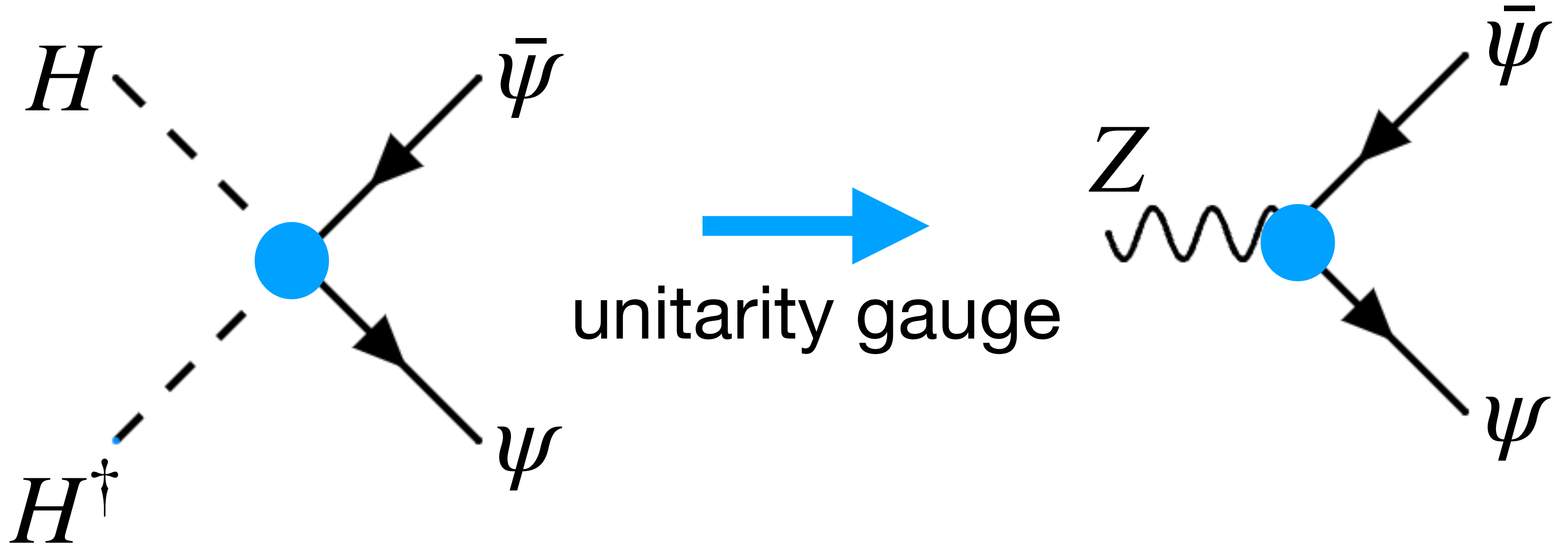
$\propto S$

$\propto T$

shift Z-fermion couplings

induces muon decay
$\Longrightarrow$ shifts G_F





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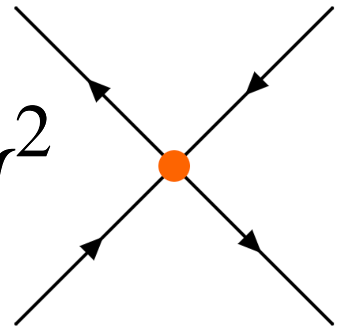
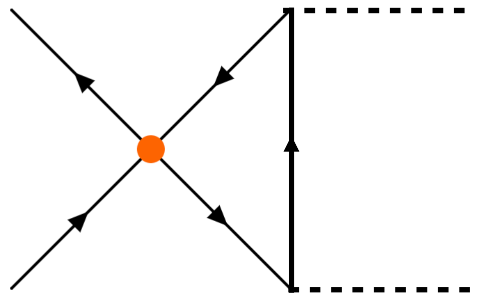
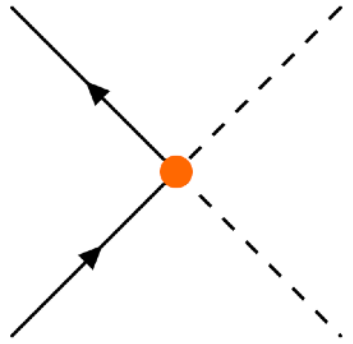
induces muon decay $\implies$ shifts G_F

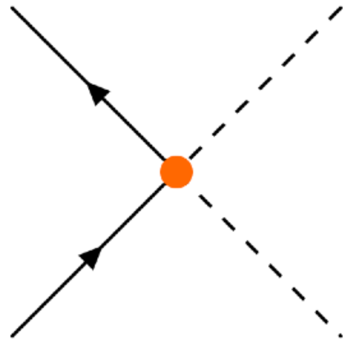
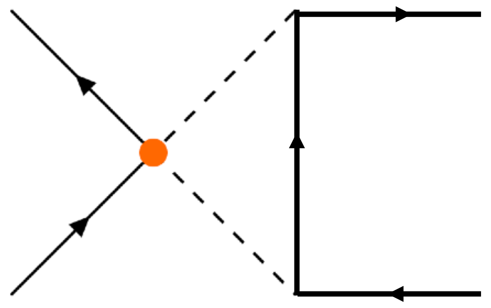
$\propto S$ $\propto T$ shift Z-fermion couplings

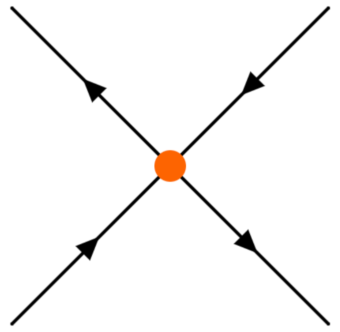
But any particular set of coefficients is not scale invariant in general

e.g. $\bar\psi^2\psi^2$  can be put into a loop: 

Which gives a divergent contribution to:  $\bar\psi\psi HD$

4-fermion operators can generate Z-pole

e.g. $\bar\psi\psi HD$  can be put into a loop: 

Which gives a divergent contribution to:  $\bar\psi^2\psi^2$

…and vice versa

Flat directions

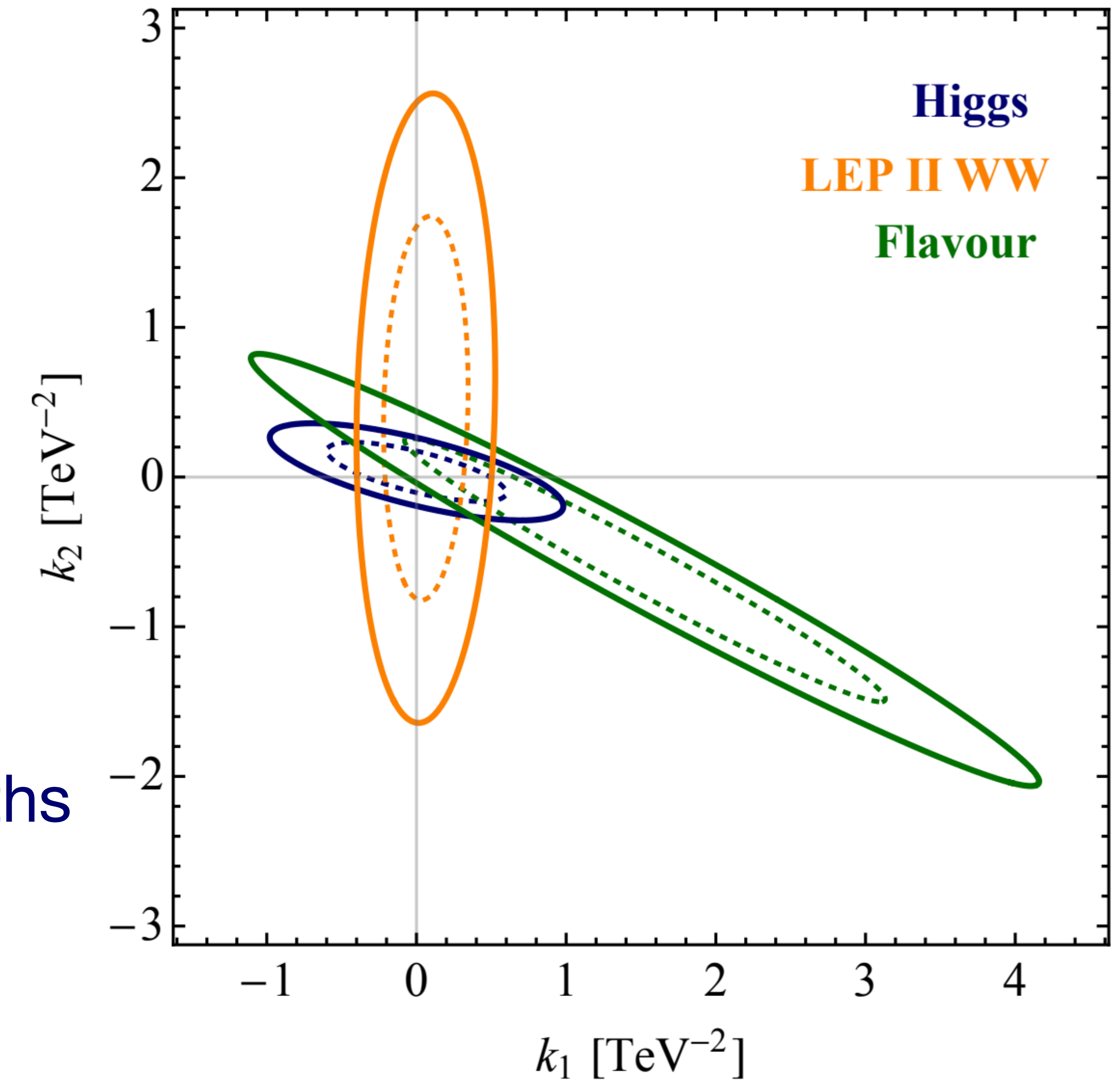
From the 23 Z-pole coefficients there are 3 flat directions

$$\mathcal{C}_0^{(1)} \propto [\mathcal{C}_{Hq}^{(1)}]_{33} - [\mathcal{C}_{Hq}^{(3)}]_{33},$$

$$\mathcal{C}_0^{(2)} \propto -\frac{g_Y}{g_L}\mathcal{C}_{HWB} + \sum_{i=1}^{3}\left([\mathcal{C}_{H\ell}^{(3)}]_{ii} + [\mathcal{C}_{Hq}^{(3)}]_{ii}\right),$$

$$\mathcal{C}_0^{(3)} \propto 2\,\mathcal{C}_{HD} - \frac{1}{2}\frac{g_L}{g_Y}\mathcal{C}_{HWB} + \sum_{\psi}\sum_{i} Y_\psi \mathcal{C}_{H\psi},$$

Aoude, Hurth, SR, Shepherd., 2003.05432



Tree level: Run I Higgs signal strengths

Tree level: LEP II $e^+e^- \to W^+W^-$

Loop level: meson decays/mixing

Origin of flat directions can be understood in terms of : EOM relations on TGC operators [Grojean, Skiba, Terning hep-ph/0602154] or a reparameterisation invariance in $\psi\psi \to \psi\psi$ processes [Brivio, Trott 1701.06424]

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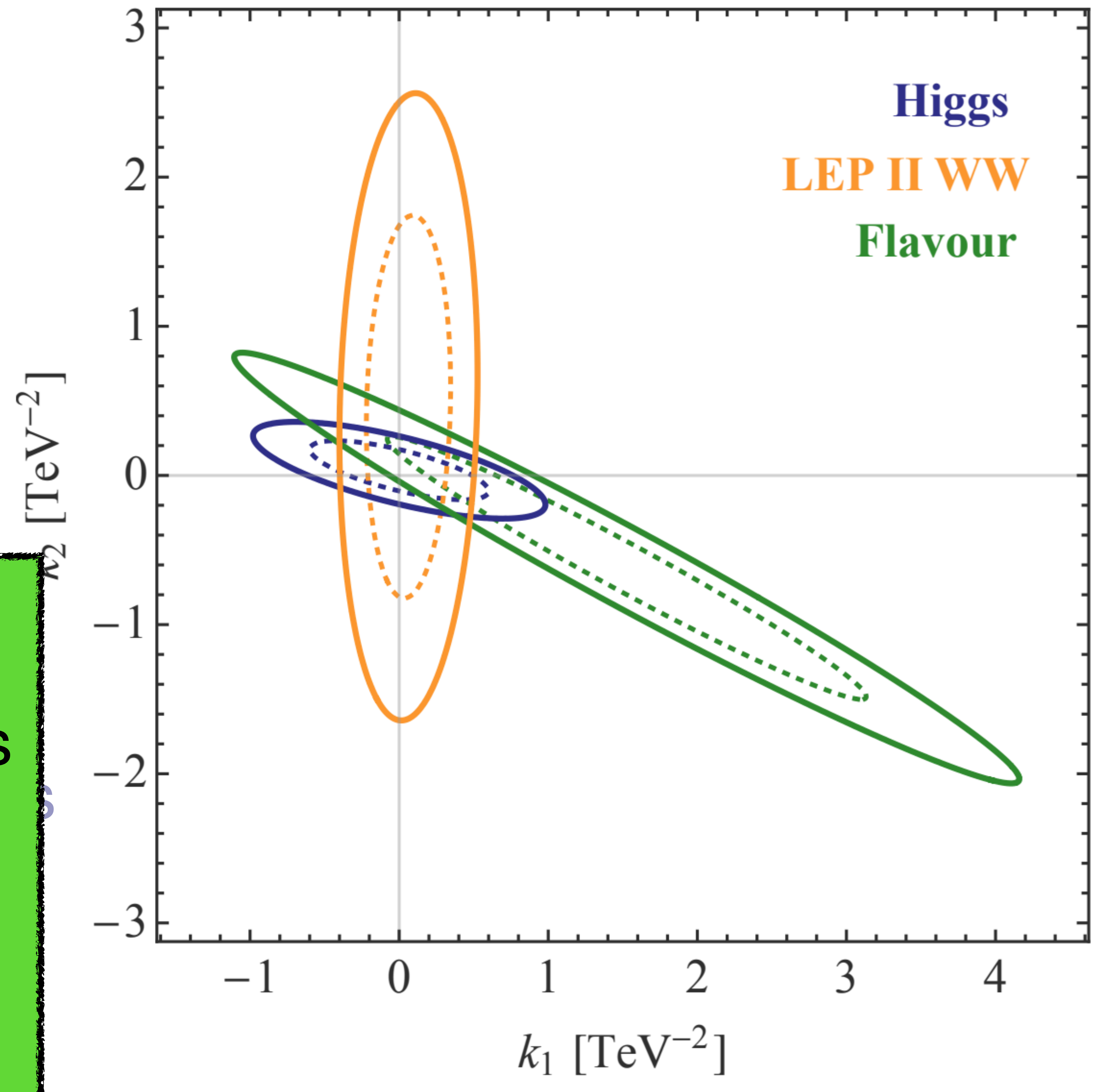


Three issues at play here:

Operators do not correspond straightforwardly to observables

Mixing of operators

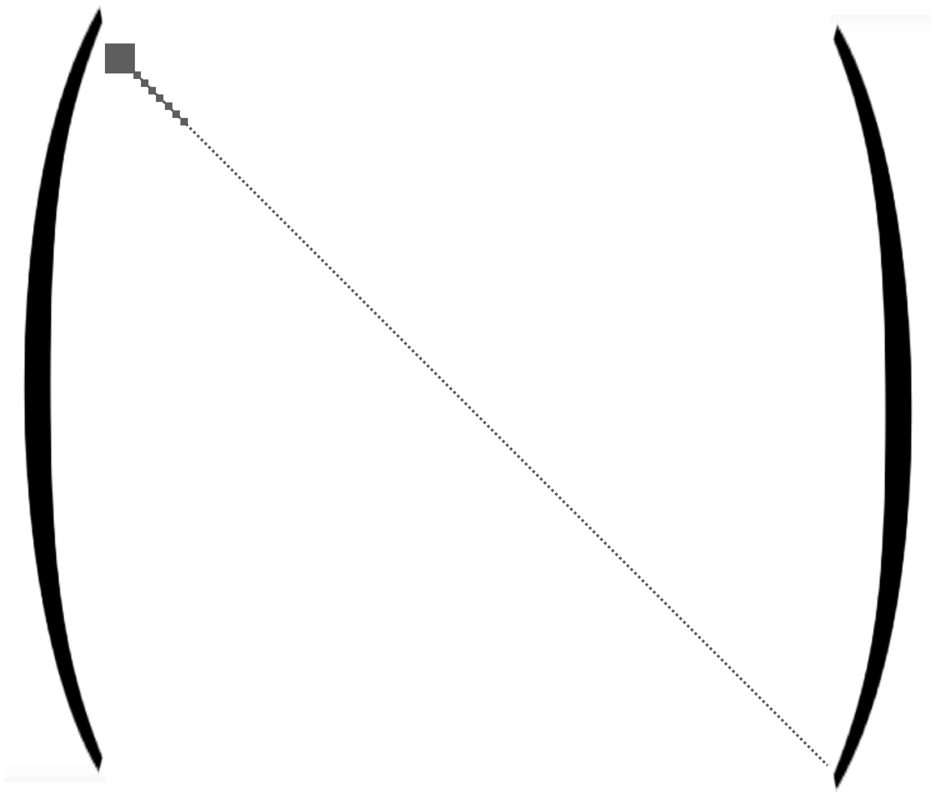
Hierarchy of precision in measurements

processes [Brivio, Trott 1701.06424]

How to simplify the problem?

A couple of directions:

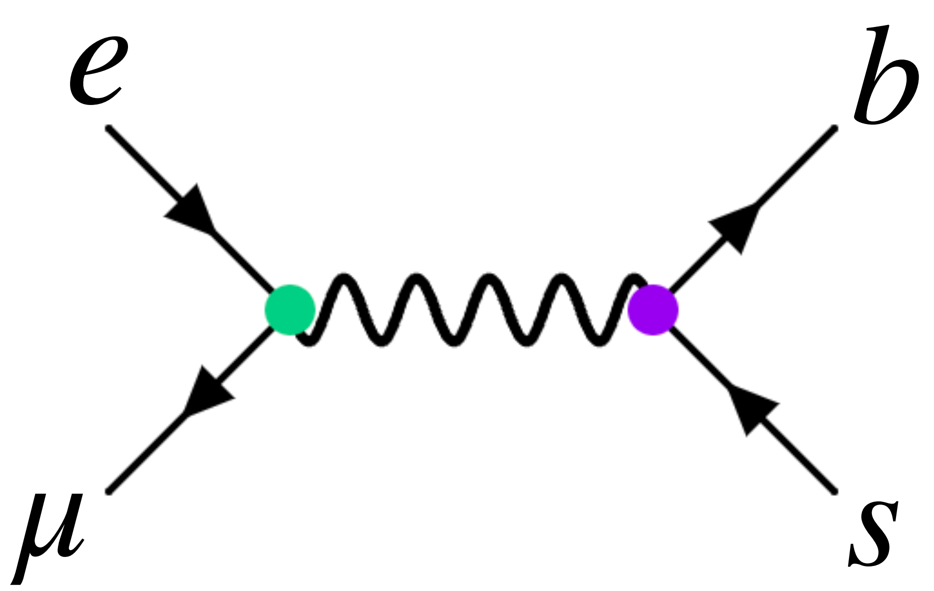
Non-renormalisation theorems

$\gamma_{ij} =$ 

Identify consistent categories of operators preserved over scales

Categories can then be studied separately

Studying simple UV completions



Identify generic correlations & connections between operator coefficients

Non renormalisation theorems

Is it possible to isolate particular operators/phenomenology within EFTs in a scale-invariant way?

$$\frac{dC_i}{d\log\mu} = \frac{1}{16\pi^2}\sum_j \gamma_{ij} C_j$$

γ_{ij} is an $N \times N$ matrix dependent only on SM parameters

[(Alonso), Jenkins, Manohar, Trott, 2013]

If a particular entry of γ is zero, one operator will not generate another (much)

Some of these zeroes can be understood on a general level
e.g. using kinematic properties of EFT and SM amplitudes

[Elias-Miro, Espinosa, Pomarol 2014]
[Cheung & Shen, 2015]

Most of the N parameters are elements of flavour matrices: any way of understanding flavoured aspects?

Flavour selection rules

More zeroes can be understood from SM flavour structure

[Machado, SR, Sutherland, JHEP 03 (2023) 226]

$$\mathscr{L}_{SM} = \mathscr{L}_{flavour\ symm} + \mathscr{L}_{Yukawa}$$

Yukawa terms: breaking in a controlled way

Gauge terms: global flavour symmetry

$$SU(3)_Q \times SU(3)_u \times SU(3)_d \times SU(3)_L \times SU(3)_e$$

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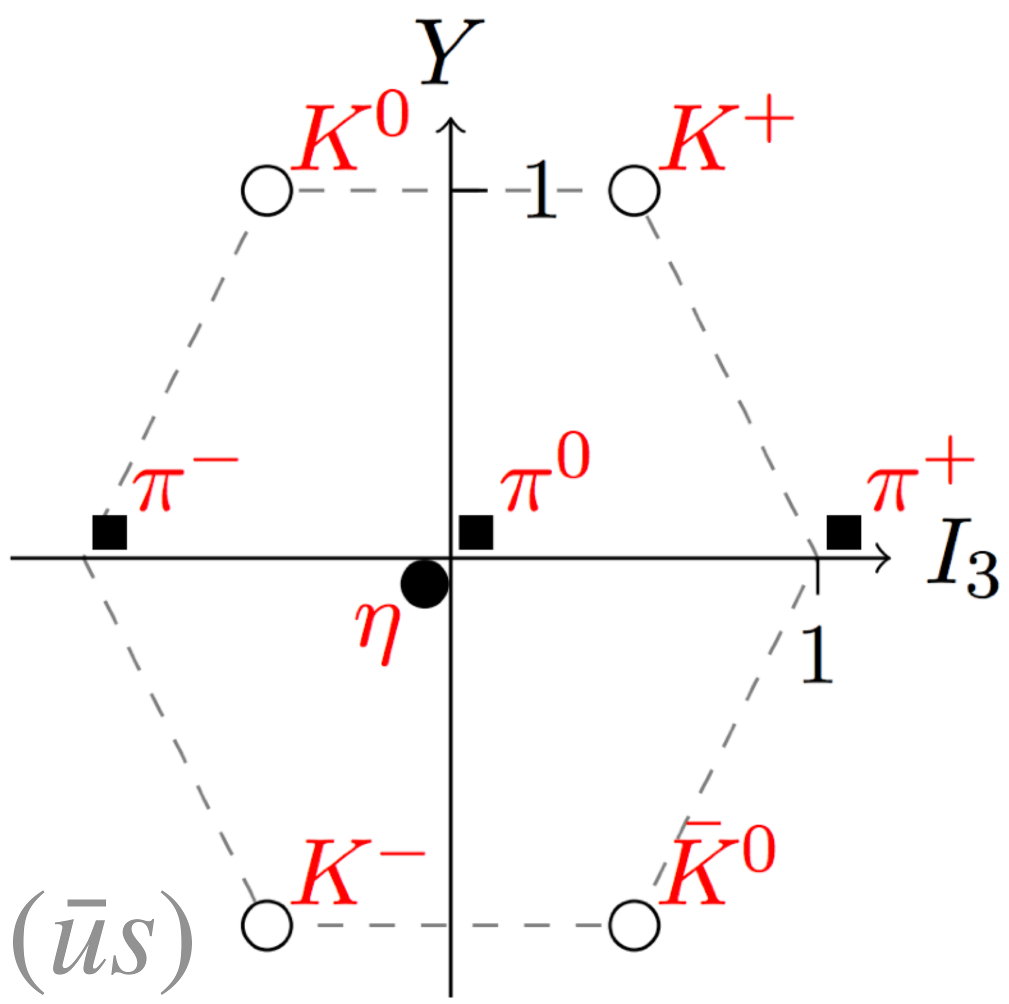
$$\mathscr{L}_{SM} = \mathscr{L}_{flavour\ symm} + \mathscr{L}_{Yukawa}$$

At low energies, approx $SU(3)$ symmetry

$$q_i = \begin{pmatrix} u \\ d \\ s \end{pmatrix}$$

Meson octet



$K^- \sim (\bar{u}s)$

Symmetry forbids transitions between different types of mesons

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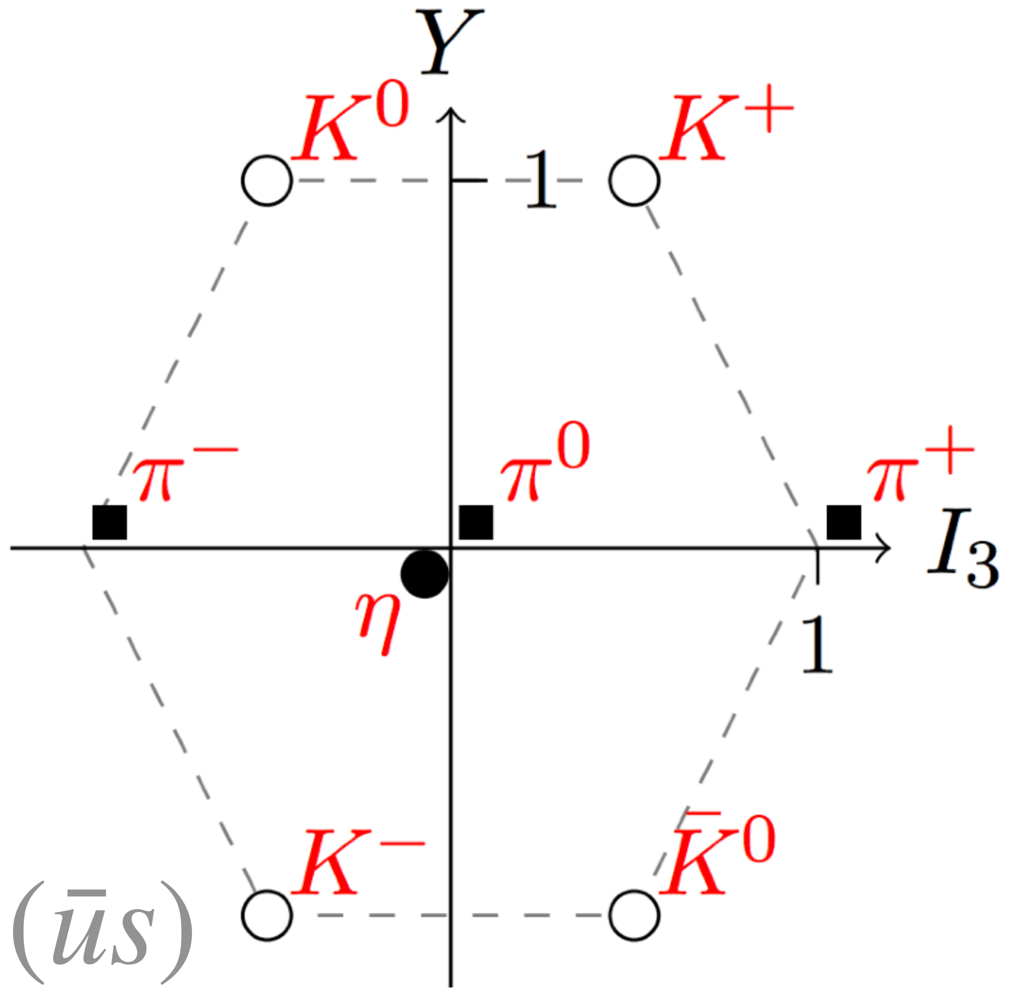


$K^- \sim (\bar{u}s)$

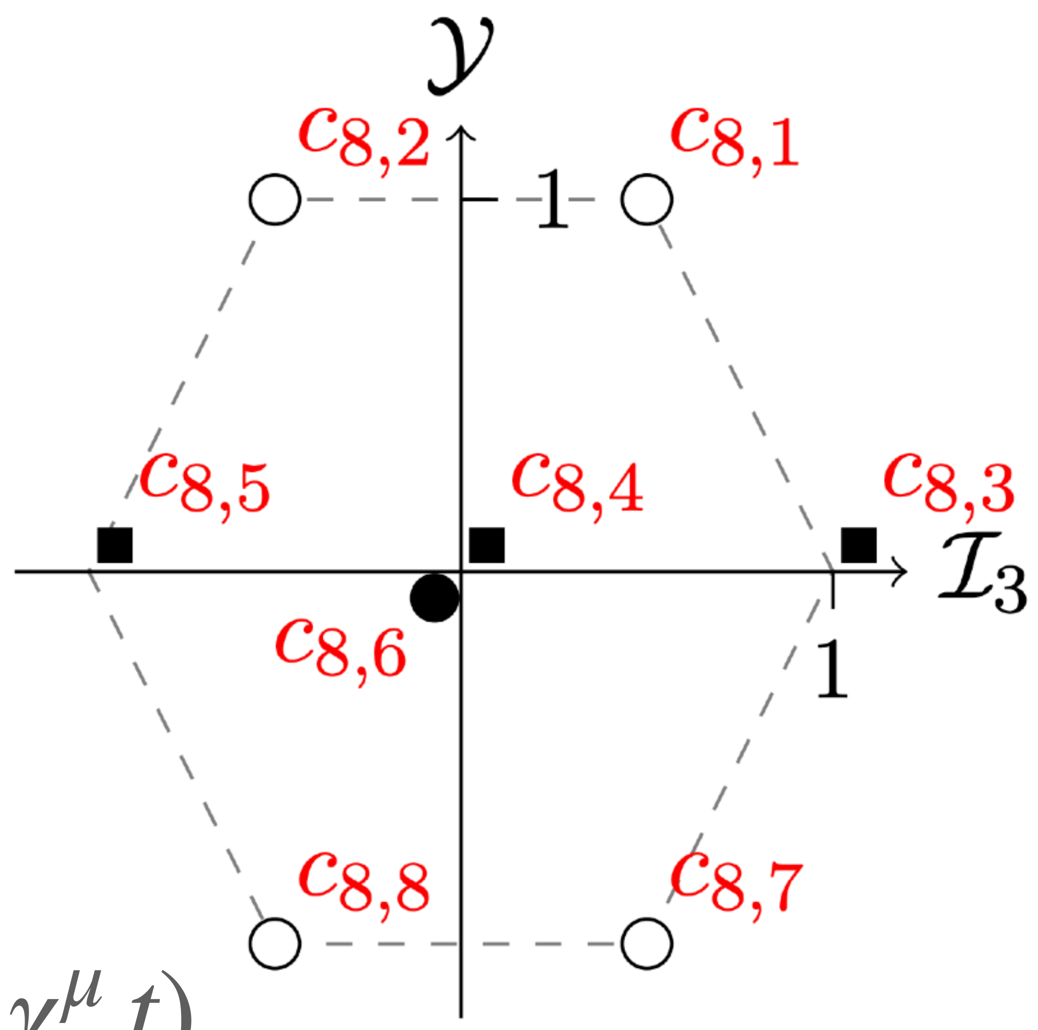
Symmetry forbids transitions between different types of mesons

In SM, approx $SU(3)$ symmetry for each fermion species

$$u_i = \begin{pmatrix} u \\ c \\ t \end{pmatrix}$$

Operator

$$(H^\dagger i D_\mu H)(\bar{u}_i \gamma^\mu u_j)$$



$O_{8,8} \sim (H^\dagger i D_\mu H)(\bar{u}\, \gamma^\mu\, t)$

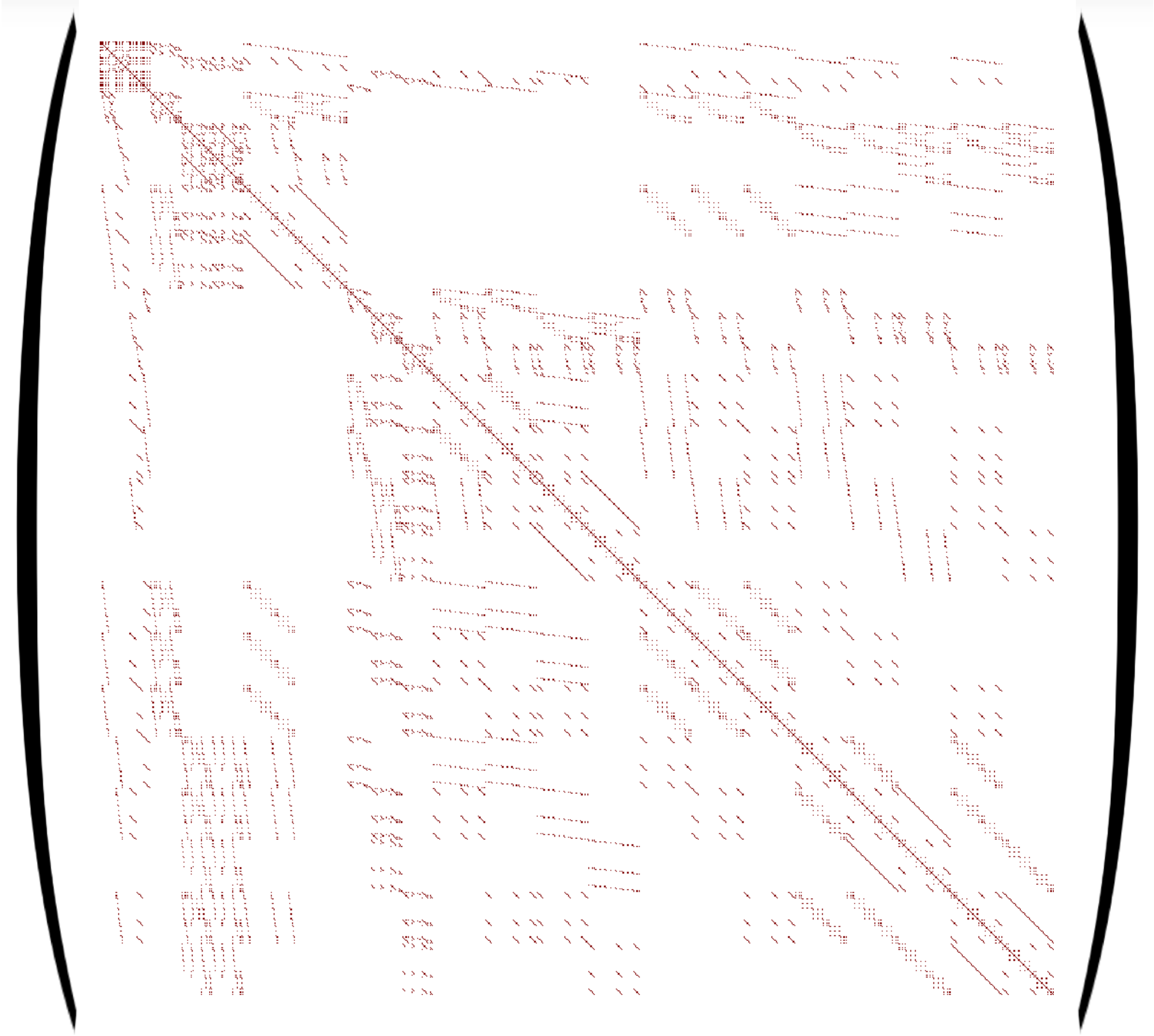
Symmetry forbids transitions between different types of operators

Block diagonalisation

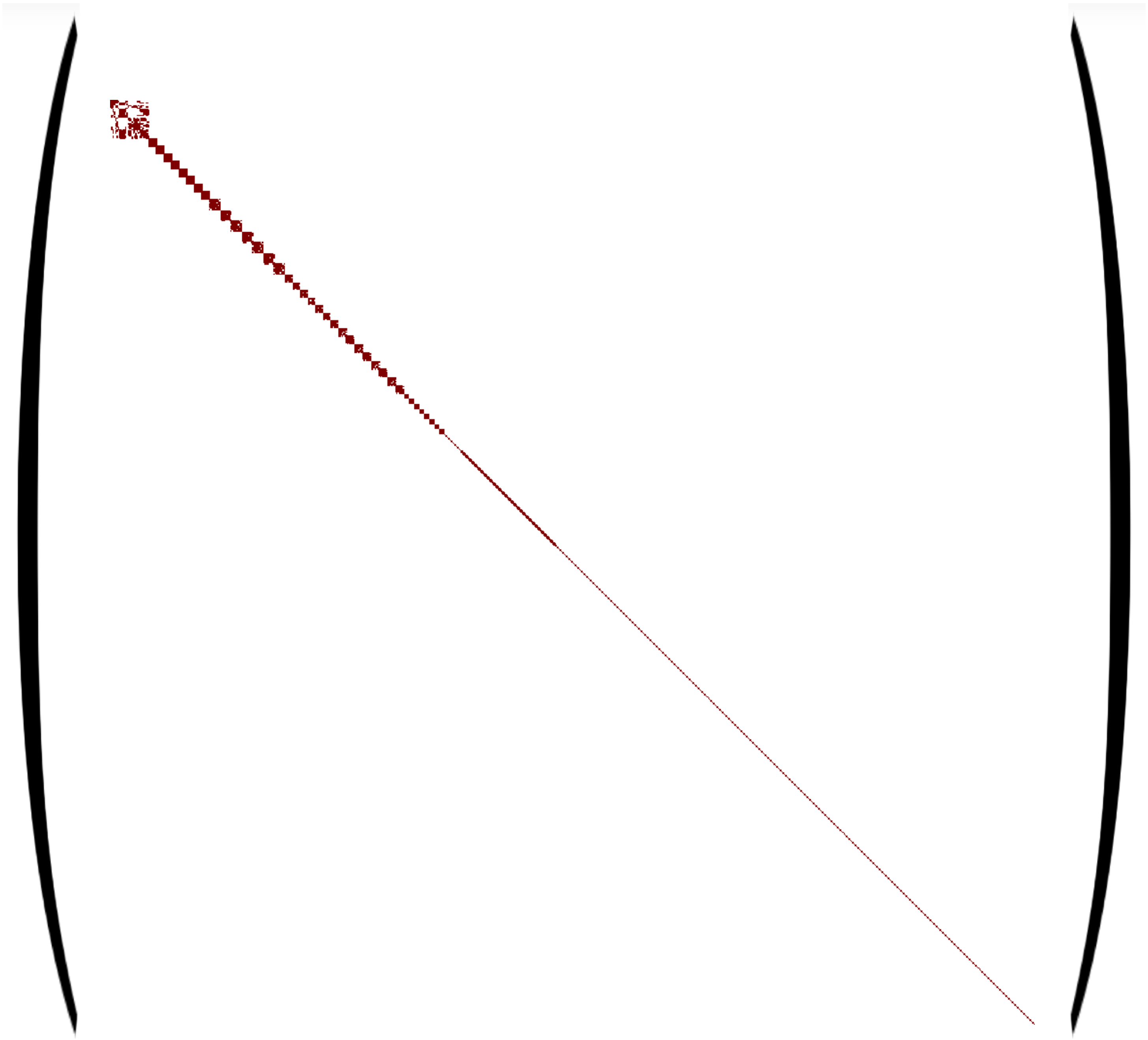
[Machado, SR, Sutherland, JHEP 03 (2023) 226]

Usual basis (gauge + y_t)

Flavour symmetry basis (gauge + y_t)



Lots of zeroes, but no block diagonalisation



Block-diagonalised

Can now see at a glance which operators can generate which via RG running

Flavour categorisation of Z pole operators

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

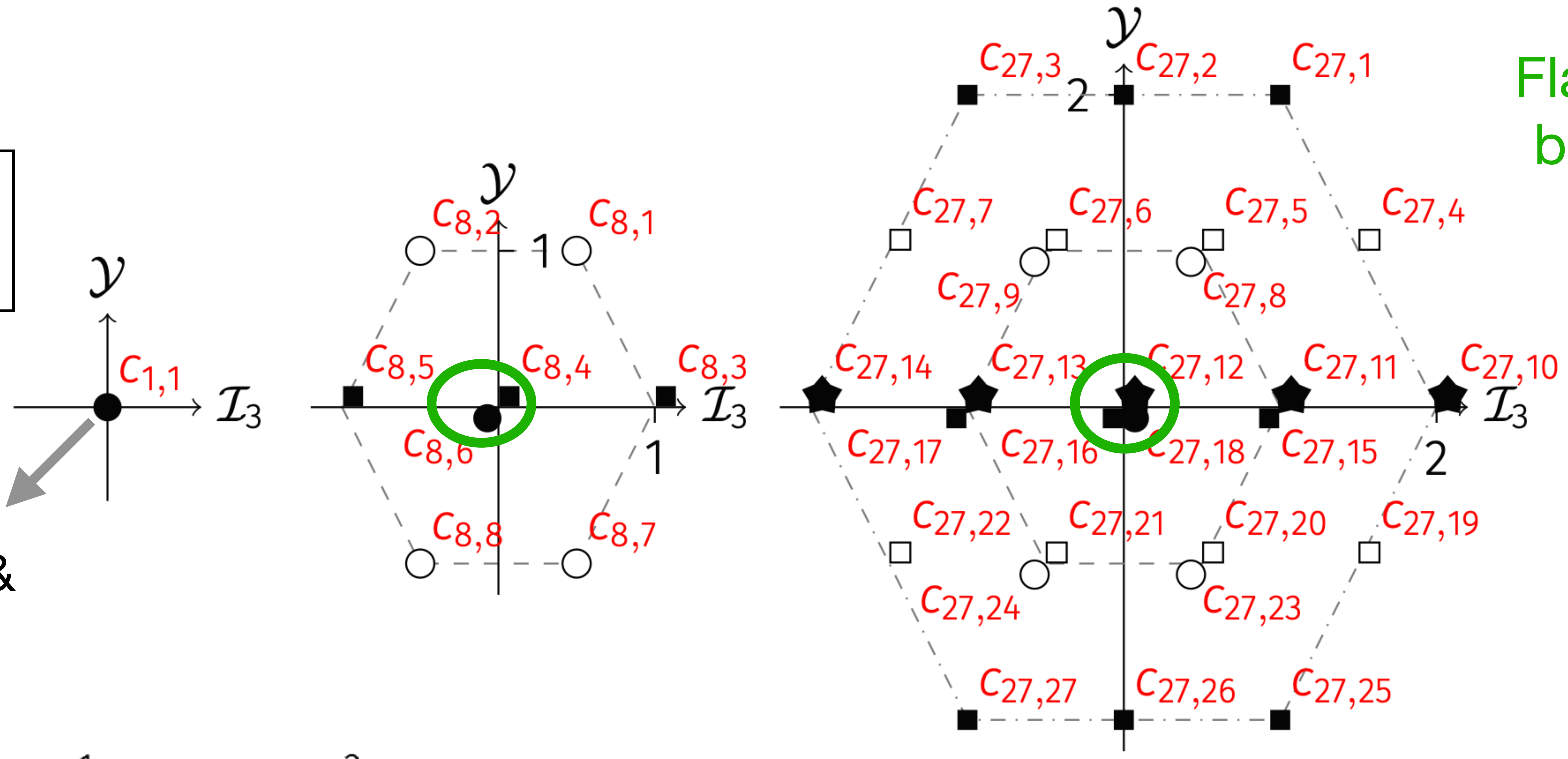
Components of $3_l \otimes \bar{3}_l \otimes 3_l \otimes \bar{3}_l = 1_l \oplus 1_l \oplus 8_l \oplus 8_l \oplus 27_l$

Fully bosonic: trivially singlets under $SU(3)^5$

Components of $3_F \otimes \bar{3}_F = 1_F \oplus 8_F$

Flavour diagonal $\implies$ at the origin

Flavour conserving but non-universal

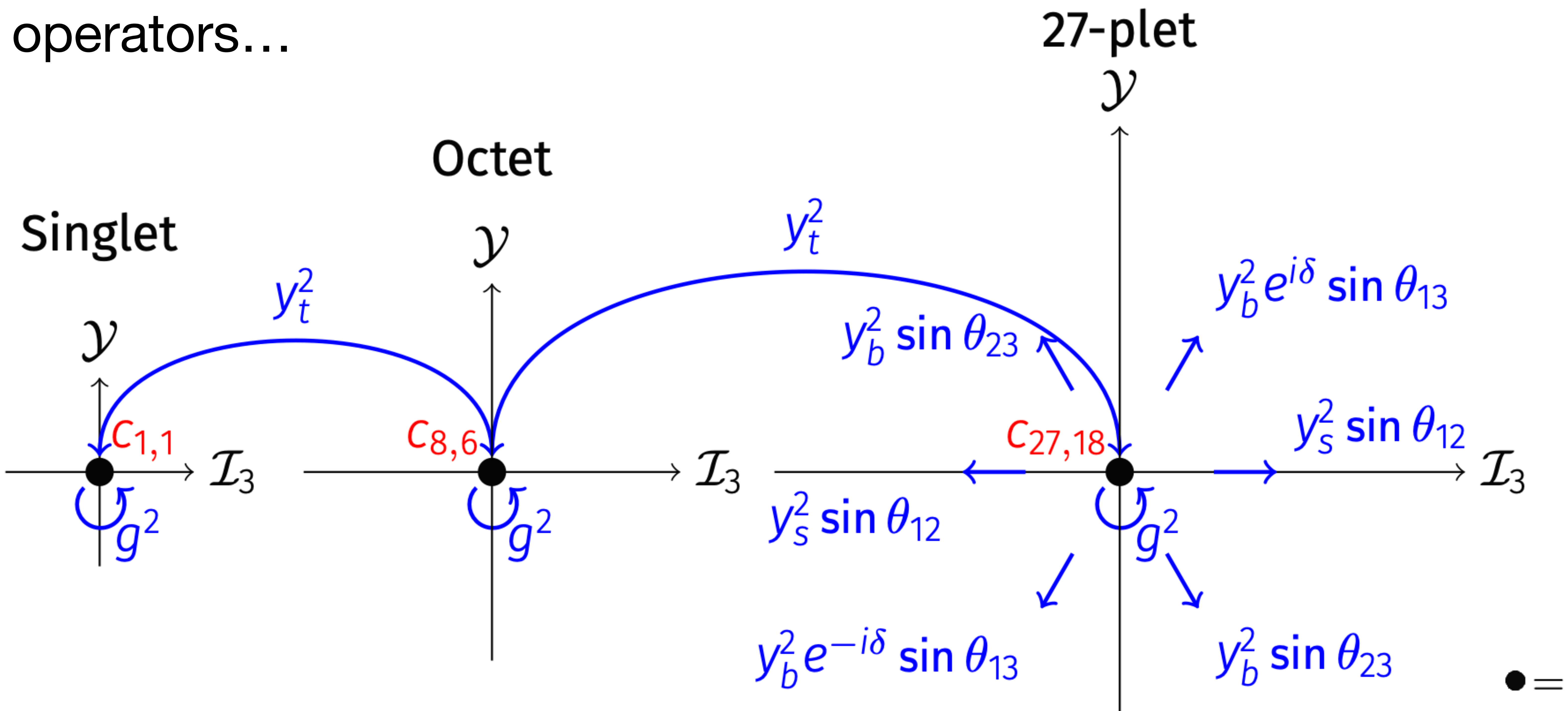


Singlet:
flavour conserving &
flavour universal

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

Gauge and y_t running

For Q charged operators…



Total $\mathcal{I}$ key:

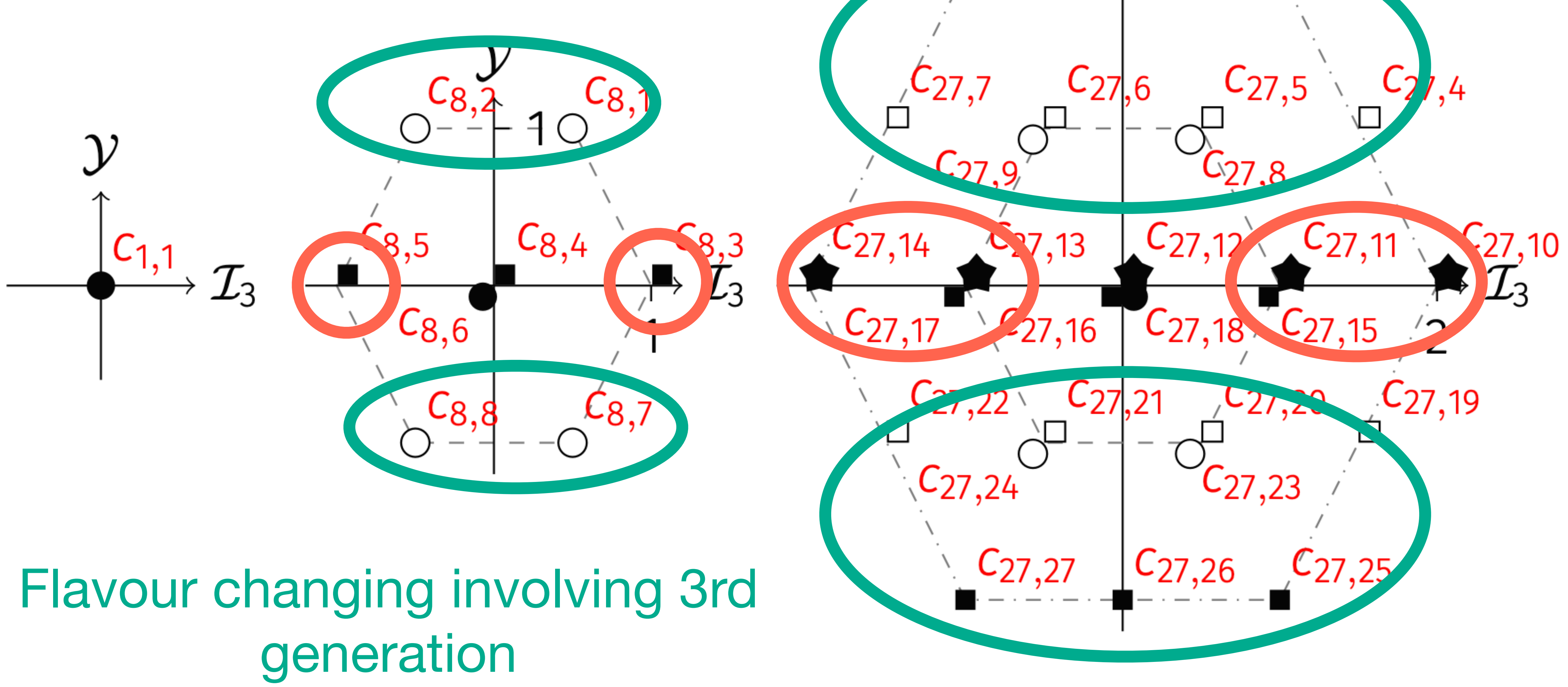
● $= 0$, ○ $= \frac{1}{2}$, ■ $= 1$, □ $= \frac{3}{2}$, ★ $= 2$

$$V_{\rm CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Relatively small number of operators connected to Z pole operators by gauge $+y_t$ running!
Only about 6% (164) of the total 2499 parameters at dim 6

Flavourful operators: Z-pole safe?

Flavour changing in first two generations only

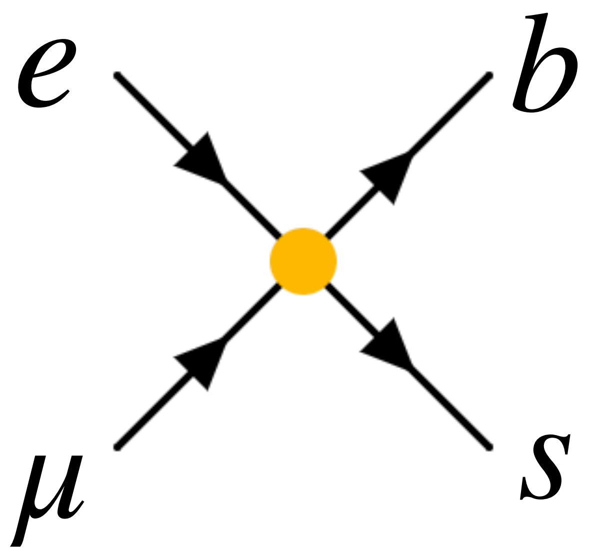


Flavour changing involving 3rd generation

Any operators away from the origin cannot run into Z pole operators

These are flavour off-diagonal operators

e.g.



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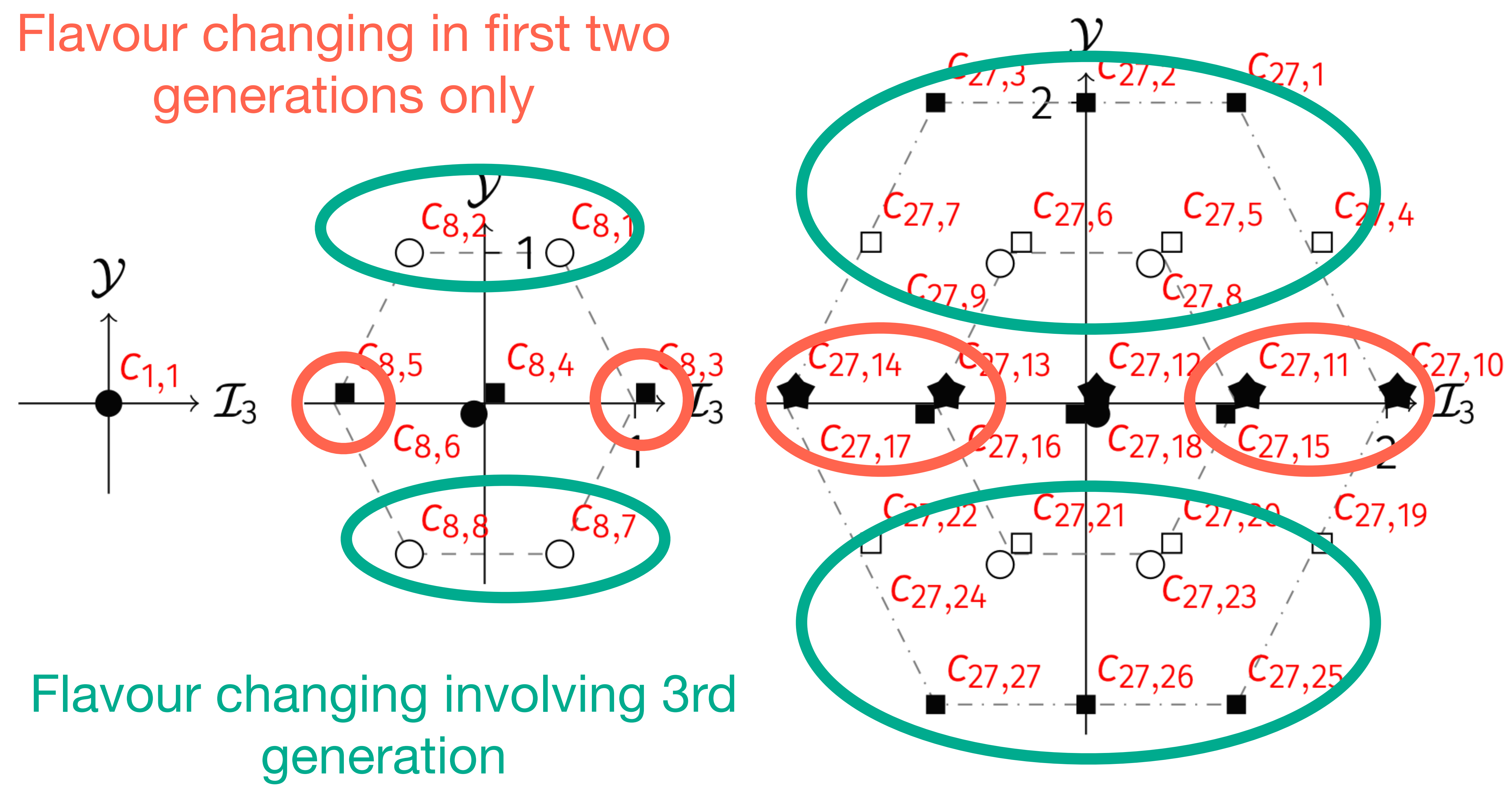

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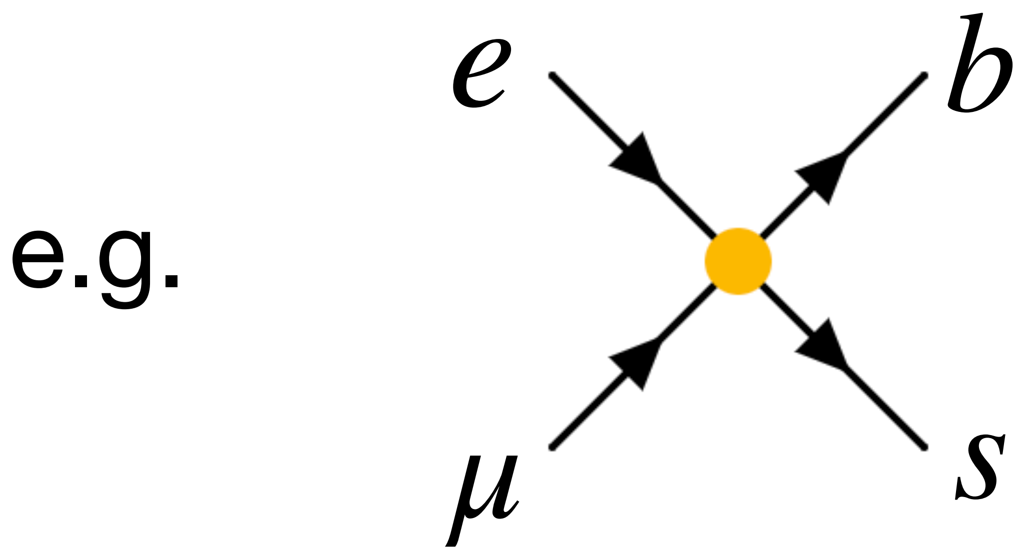
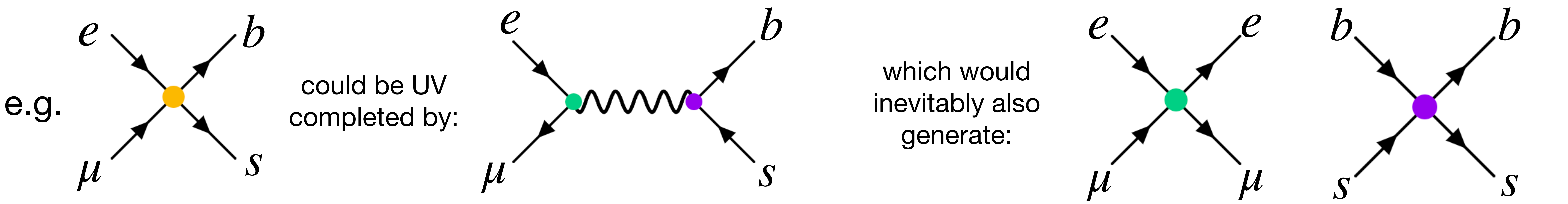


But in (tree level) UV completions, not generally possible to create flavourful operators on their own



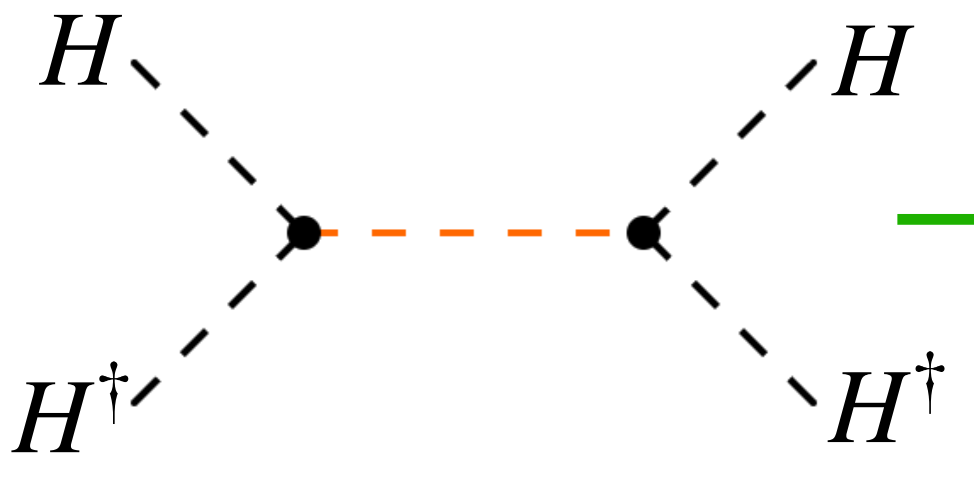
More general arguments can be made from sum rules, e.g. Remmen & Rodd 2010.04723

Explicit mediators

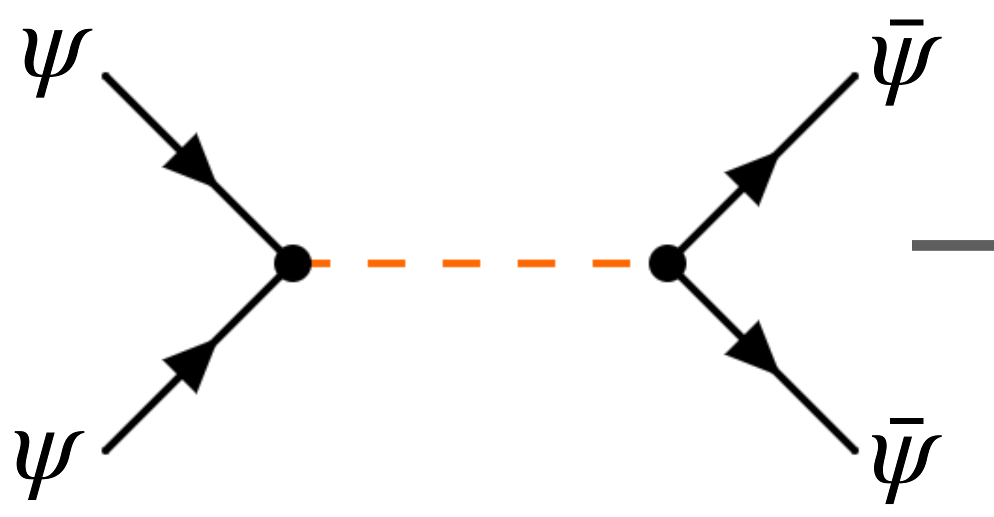
Can study the full space of tree-level mediators using the “Granada dictionary”

Criado et al., 1711.10391

Scalars



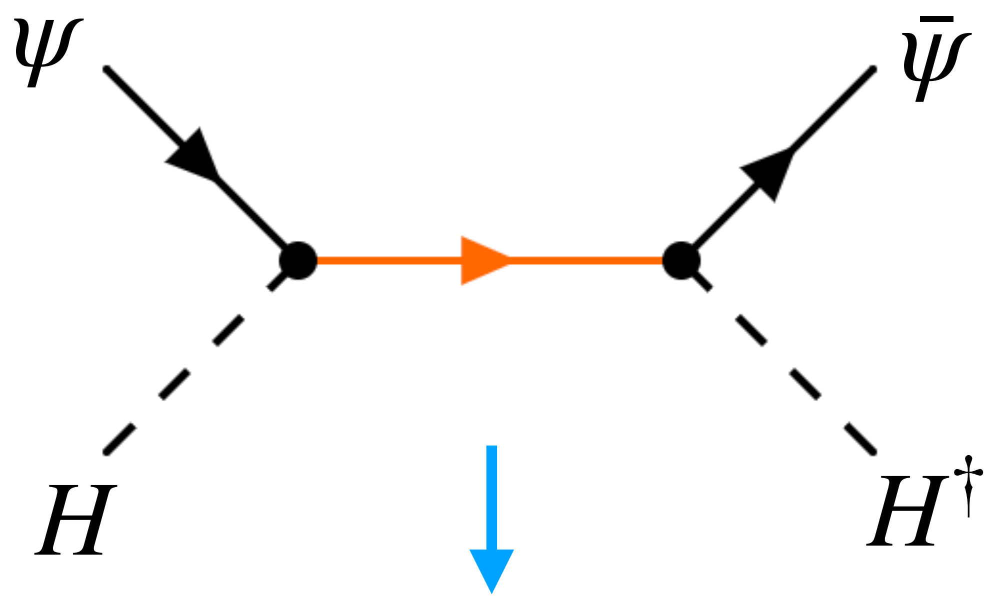
$\rightarrow C_{HD}$ (T parameter)



$\rightarrow C_{\psi\bar{\psi}}$

Many do not generate Z pole operators at tree level

Fermions



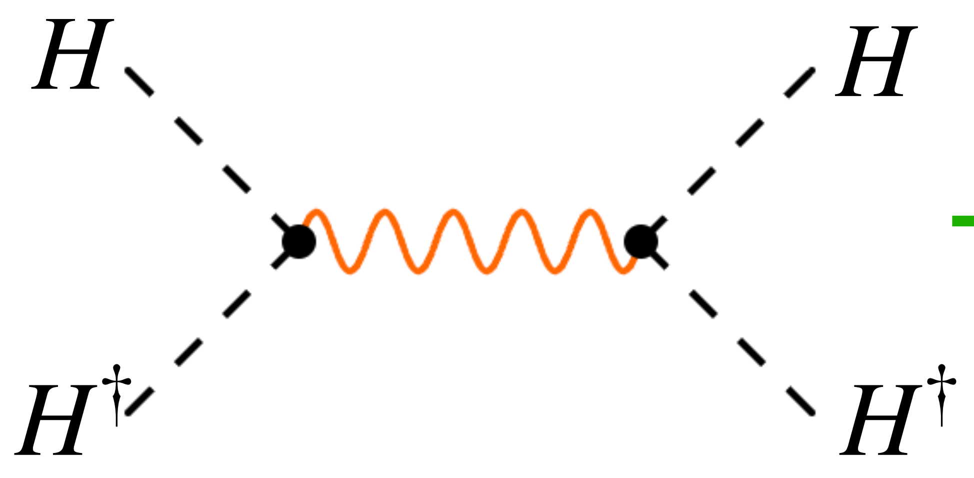
$\downarrow$

$C_{H\psi}$

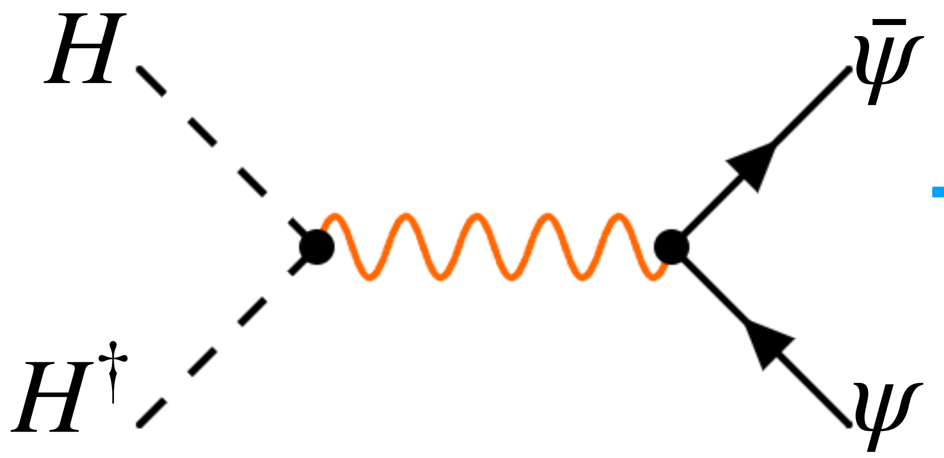
(shifts Z couplings to SM fermions)

Always generate Z pole operators at tree level (unless couple only to tops)

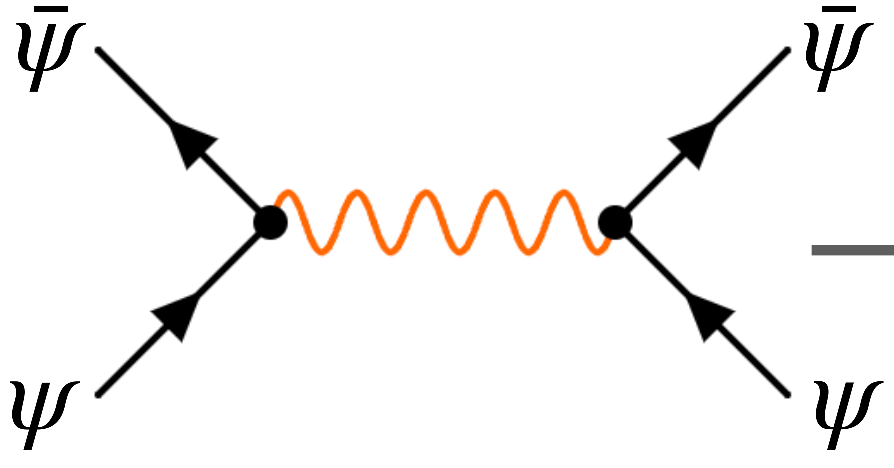
Vectors



$\rightarrow C_{HD}$ (T parameter)



$\rightarrow C_{H\psi}$ (shifts Z couplings to SM fermions)



$\rightarrow C_{\psi\bar{\psi}}$

Many do not generate Z pole operators at tree level

Z pole RGEs

$$\dot{C}_{HD} = -8N_c y_t^2 C_{Hu}^{33},$$
$$\dot{C}_{Hf_1}^{(1)jj} = 2N_c y_t^2 \left(-S_{f_1u} C_{uf_1}^{33jj} + S_{f_1q} C_{qf_1}^{33jj}\right),$$
$$\dot{C}_{Hl}^{(3)jj} = -2N_c y_t^2 C_{lq}^{(3)jj33},$$
$$\dot{C}_{Hq}^{(3)jj} = -2y_t^2 \left(2N_c C_{qq}^{(3)jj33} + C_{qq}^{(1)j33j} - C_{qq}^{(3)j33j}\right),$$

$\propto y_t^2$

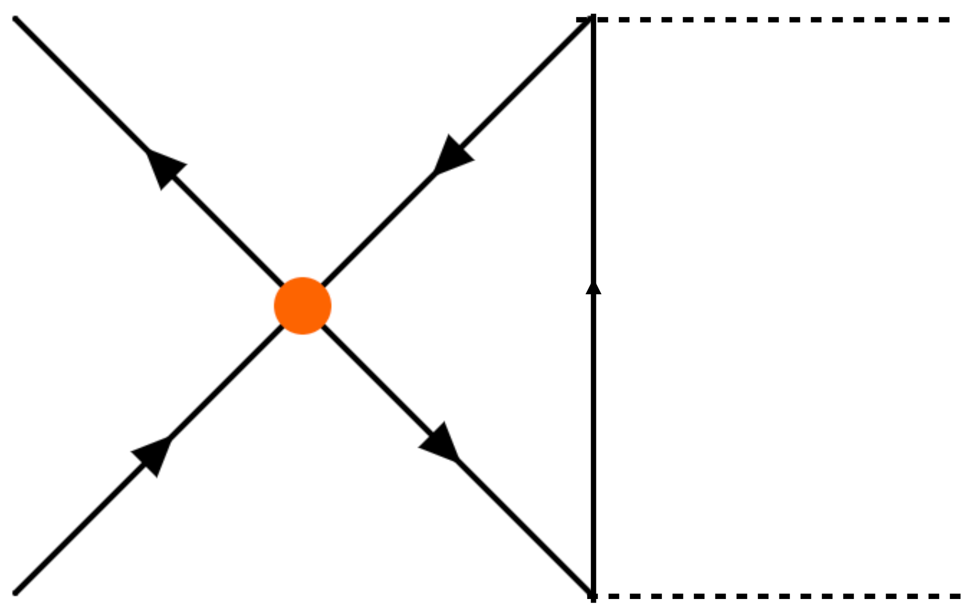
$$\dot{C}_{Hf_1}^{(1)jj} = \frac{4}{3} g_1^2 Y_h \sum_k \Big[Y_e S_{f_1e} C_{f_1e}^{jjkk} + 2Y_l S_{f_1l} C_{f_1l}^{jjkk} + N_c \left(Y_u S_{f_1u} C_{f_1u}^{jjkk} + Y_d S_{f_1d} C_{f_1d}^{jjkk} + 2Y_q S_{f_1q} C_{f_1q}^{jjkk} \right) \Big],$$

$\propto g_1^2$

$$\dot{C}_{Hl}^{(3)jj} = \frac{2}{3} g_2^2 \sum_k \left(C_{ll}^{jkkj} + N_c C_{lq}^{(3)jjkk} \right),$$
$$\dot{C}_{Hq}^{(3)jj} = \frac{2}{3} g_2^2 \sum_k \left(C_{lq}^{(3)kkjj} + 2N_c C_{qq}^{(3)kkjj} + C_{qq}^{(1)jkkj} - C_{qq}^{(3)jkkj} \right),$$
$$\dot{C}_{ll}^{1221} = \frac{2}{3} g_2^2 \Big[C_{ll}^{2222} + C_{ll}^{2332} + C_{ll}^{1111} + C_{ll}^{1331} + N_c \sum_k \left(C_{lq}^{(3)22kk} + C_{lq}^{(3)11kk} \right) \Big]$$

$\propto g_2^2$

Given expected precision at FCC-ee, how many models run into Z pole operators?



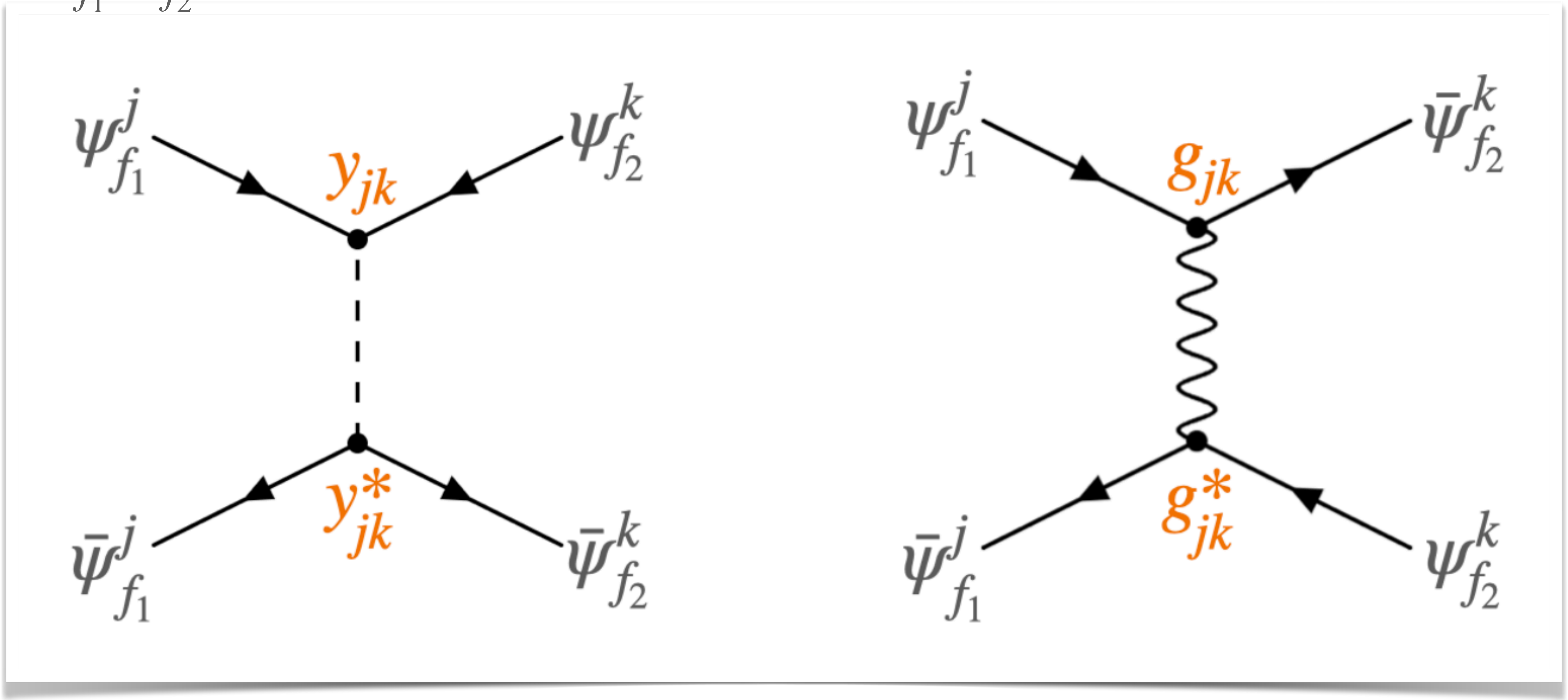
All states(*) produce 4 fermion operators

(*) a few scalar exceptions which couple to Higgs

In order to avoid producing effects at 1 loop, need to additionally produce zeroes in each of these equations…

Cancellations within the RGEs?

$\psi_{f_1}, \psi_{f_2} \in \{Q, u, d, L, e\}$



If a scalar or vector UV completion carries hypercharge:

$$C^{jjkk}_{\psi_{f_1}\psi_{f_2}} \propto |y_{jk}|^2 \quad \text{or} \quad \propto |g_{jk}|^2$$

Then the gauge-dependent RGEs become of the form:

$$\dot{C}^{jj}_{Hf_1} \propto \sum_k |y_{jk}|^2$$

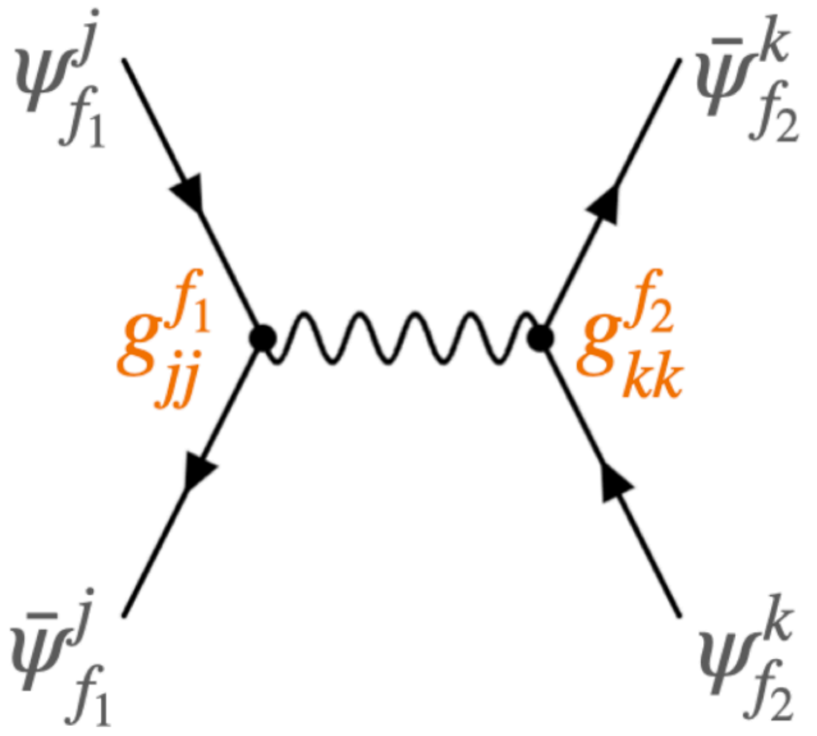
i.e. no zero solution unless all couplings are zero

Cancellations within the RGEs

What about zero hypercharge states?

Zero hypercharge scalars don't produce 4-fermion operators: their effects depend on their coupling to Higgs

Vectors:



Now $C^{jjkk}_{\psi_{f_1}\psi_{f_2}} \propto g^{f_1}_{jj}\, g^{f_2}_{kk}$ no definite sign

$\mathcal{B} \sim (1,0,0)$

$$(g^q_{\mathcal{B}})_{33} - (g^u_{\mathcal{B}})_{33} \stackrel{!}{=} 0,$$

$$\sum_k (-(g^e_{\mathcal{B}})_{kk} + (g^l_{\mathcal{B}})_{kk} + 2(g^u_{\mathcal{B}})_{kk} - (g^d_{\mathcal{B}})_{kk} - (g^q_{\mathcal{B}})_{kk}) \stackrel{!}{=} 0.$$

Works for some familiar anomaly-free $U(1)\, Z'$ models e.g. $B_i - L_j$, $L_\mu - L_\tau$

$\mathcal{W} \sim (1,3,0)$

$$(g^l_{\mathcal{W}})_{ij} \stackrel{!}{=} 0, \quad (g^q_{\mathcal{W}})_{3j} \stackrel{!}{=} 0, \quad (g^q_{\mathcal{W}})_{22} \stackrel{!}{=} \pm(g^q_{\mathcal{W}})_{11}, \quad |(g^q_{\mathcal{W}})_{12}| \stackrel{!}{=} (g^q_{\mathcal{W}})_{11}\sqrt{4N_c - 1}$$

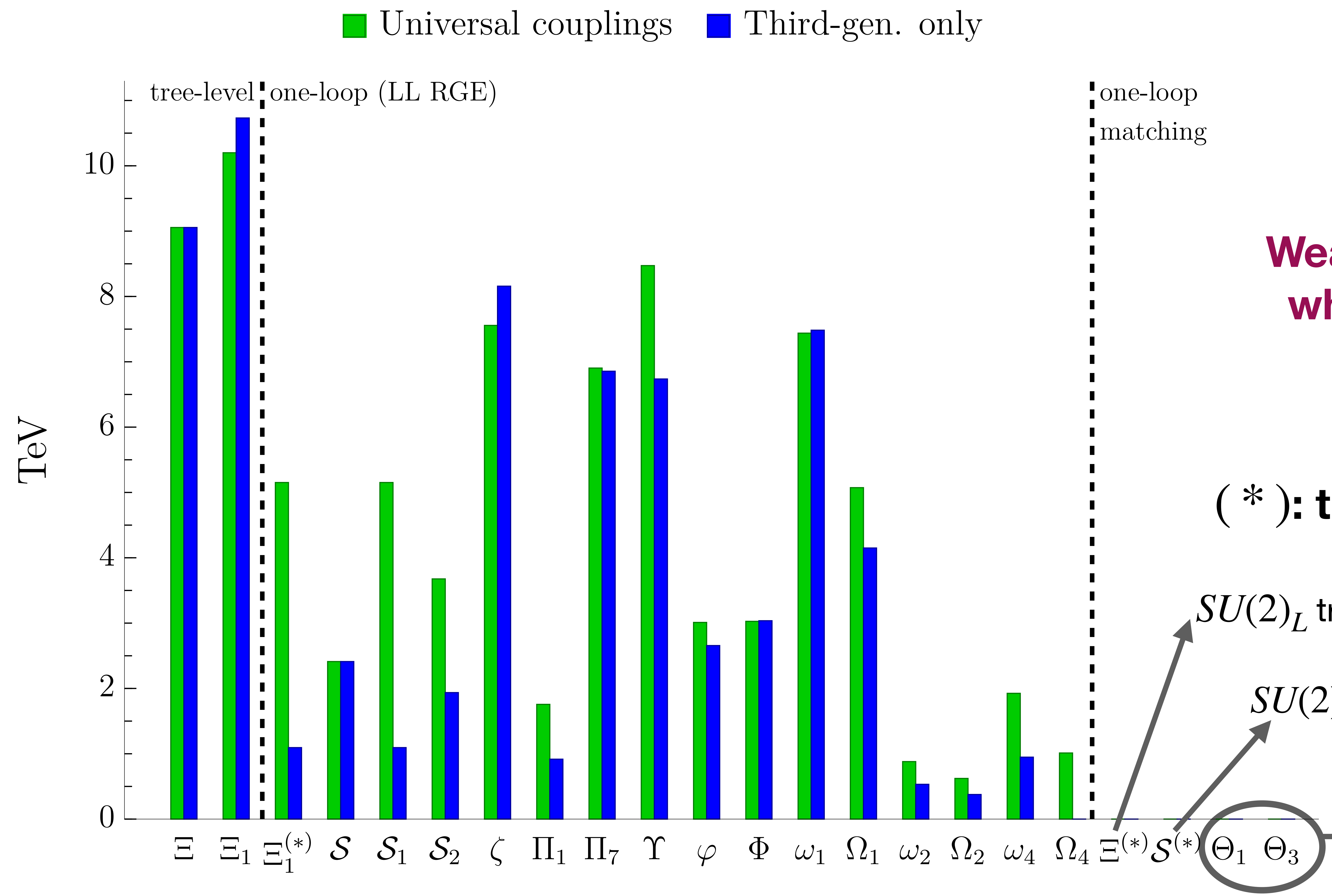
Strong complementary constraints from kaon mixing

$\mathcal{G} \sim (8,1,0)$ No cancellations, but zero at 1 loop if couples only to RH tops

$\mathcal{H} \sim (8,3,0)$ No solutions

FCC-ee projections: scalars

Allwicher, McCullough, SR, w.i.p



Weakest constraints on states which couple only to quarks

(*): turning off a coupling to Higgs

$SU(2)_L$ triplet: ?

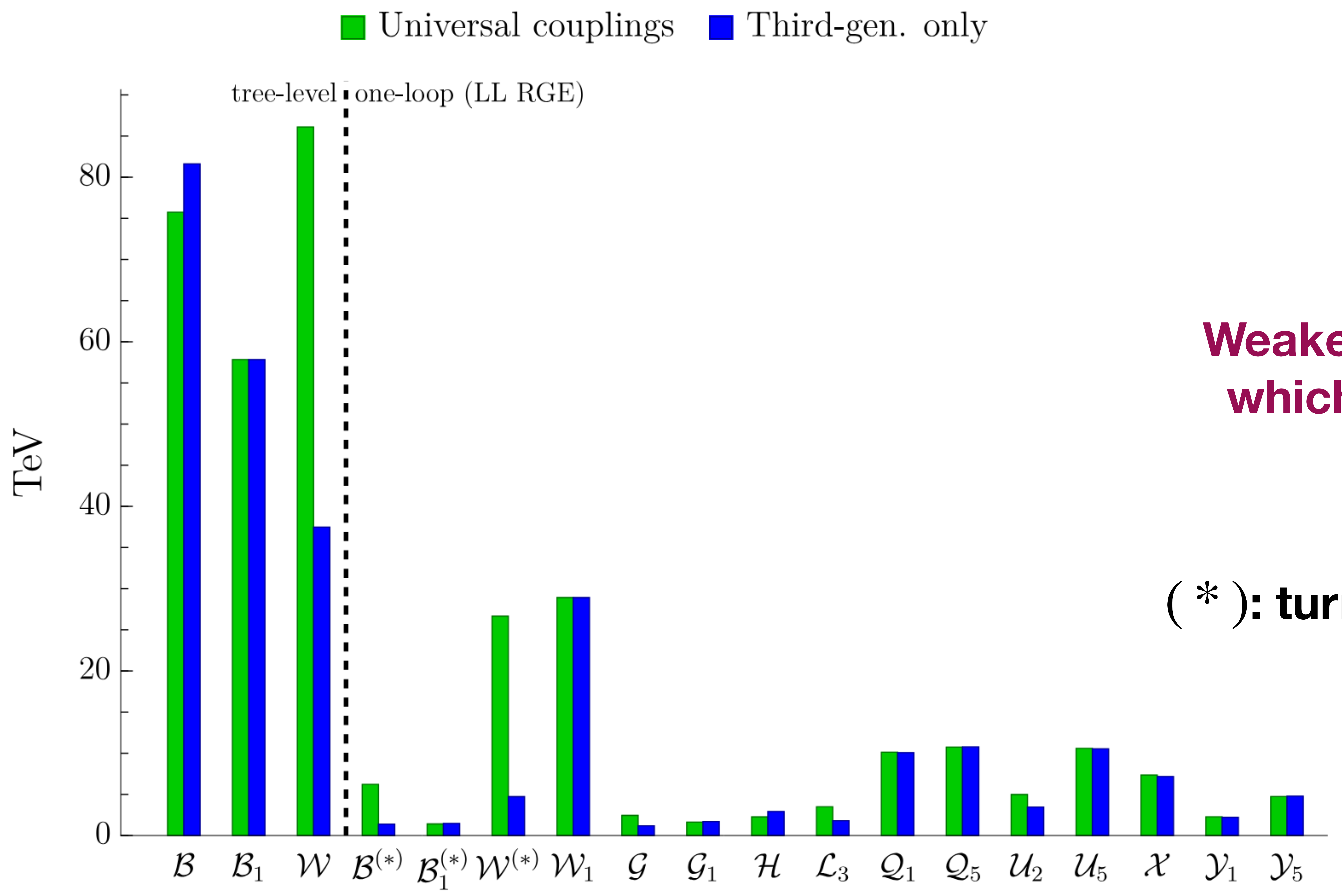
$SU(2)_L$ singlet: no finite 1-loop contributions

S. Ellis & al, 1706.07765
Jiang & al, 1811.08878
Haisch & al, 2003.05936

$SU(2)_L$ quartets: finite one-loop contributions to T parameter

Durieux, McCullough, Salvioni, 2209.00666

FCC-ee projections: vectors



Weakest constraints on states which couple only to quarks

(*): turning off a coupling to Higgs

Summary & outlook

EFTs: best way to deal with scale-separated new physics entering a variety of precision observables

But large no. of parameters and opaque connection to observables makes life complicated

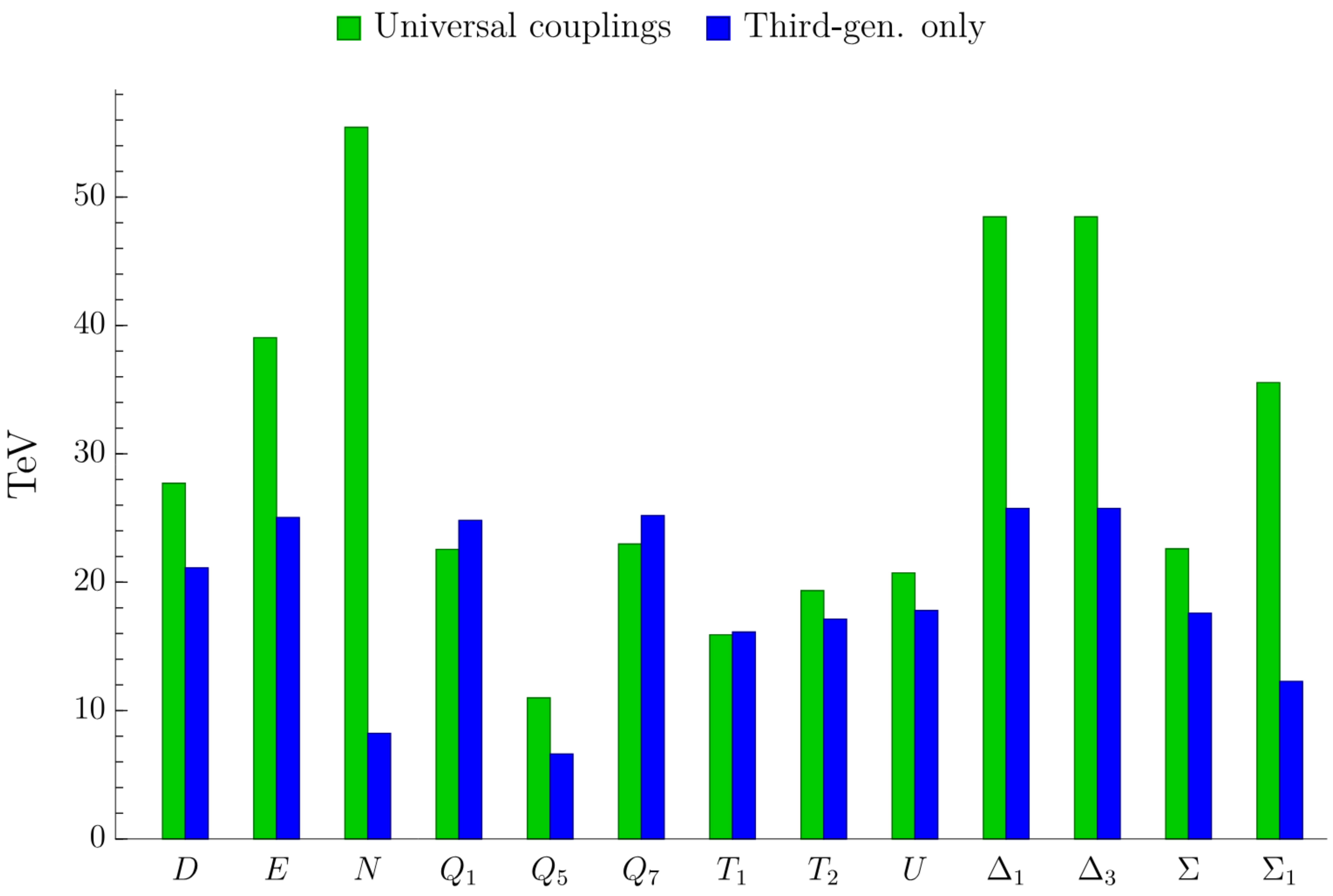
In this talk, explored simplifying things with non-renormalisation theorems and simple UV completions

Pheno message: ~all heavy NP enters in Z pole observables at one loop or better

FCC-ee can tell us a lot about heavy NP!

Backup

FCC-ee projections: fermions



Cancellations within the RGEs

What about zero hypercharge states?

Allwicher, McCullough, SR, w.i.p

e.g. if no contribution to $C^{(1)}_{Hf_1}$ coefficients at tree level:

$\propto y_t^2$

$$\dot{C}^{(1)jj}_{Hf_1} = 2N_c y_t^2 \left(-S_{f_1u} C^{33jj}_{uf_1} + S_{f_1q} C^{33jj}_{qf_1}\right)$$

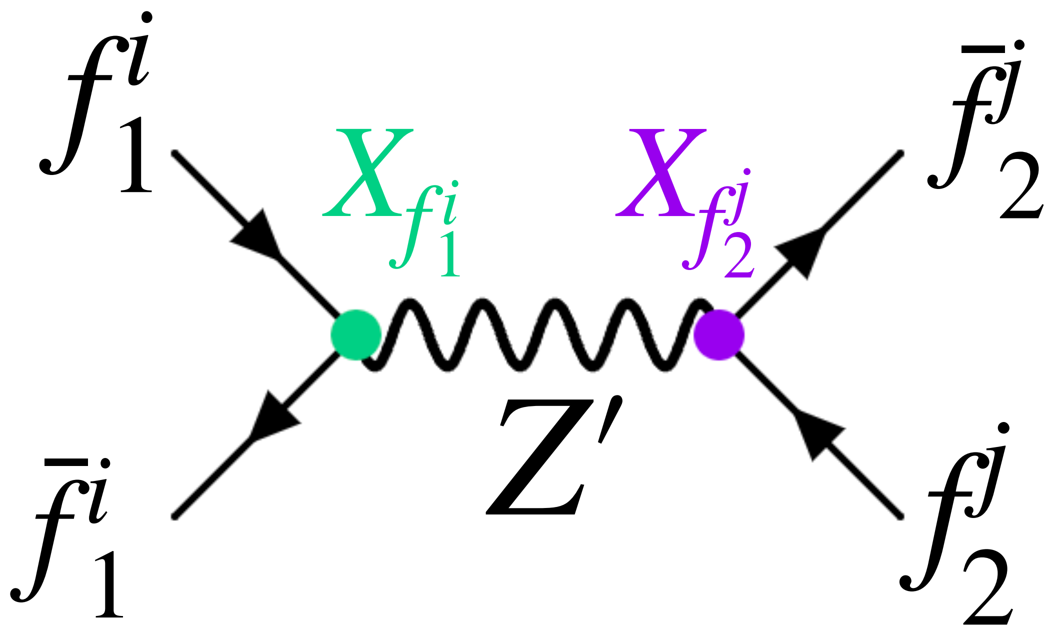
$S_{f_1f_2} = 1 + \delta_{f_1f_2}$ is a symmetry factor

$\propto g_1^2$

$$\dot{C}^{(1)jj}_{Hf_1} = \sum_k \frac{4}{3} g_1^2 Y_h \Big[Y_e S_{f_1e} C^{jjkk}_{f_1e} + 2Y_l S_{f_1l} C^{jjkk}_{f_1l} + N_c \left(Y_u S_{f_1u} C^{jjkk}_{f_1u} + Y_d S_{f_1d} C^{jjkk}_{f_1d} + 2Y_q S_{f_1q} C^{jjkk}_{f_1q}\right)\Big]$$

If a model generates a particular linear combination of Wilson coefficients, RGEs for Z pole operators can be zero

e.g. singlet vector Z'



Matching to SMEFT gives

$$C^{iijj}_{f_1f_2} = -\frac{X_{f_1^i} X_{f_2^j}}{m^2_{Z'}}$$

Criado et al., 1711.10391

$\dot{C}^{(1)}_{Hf_1} = 0$ if:

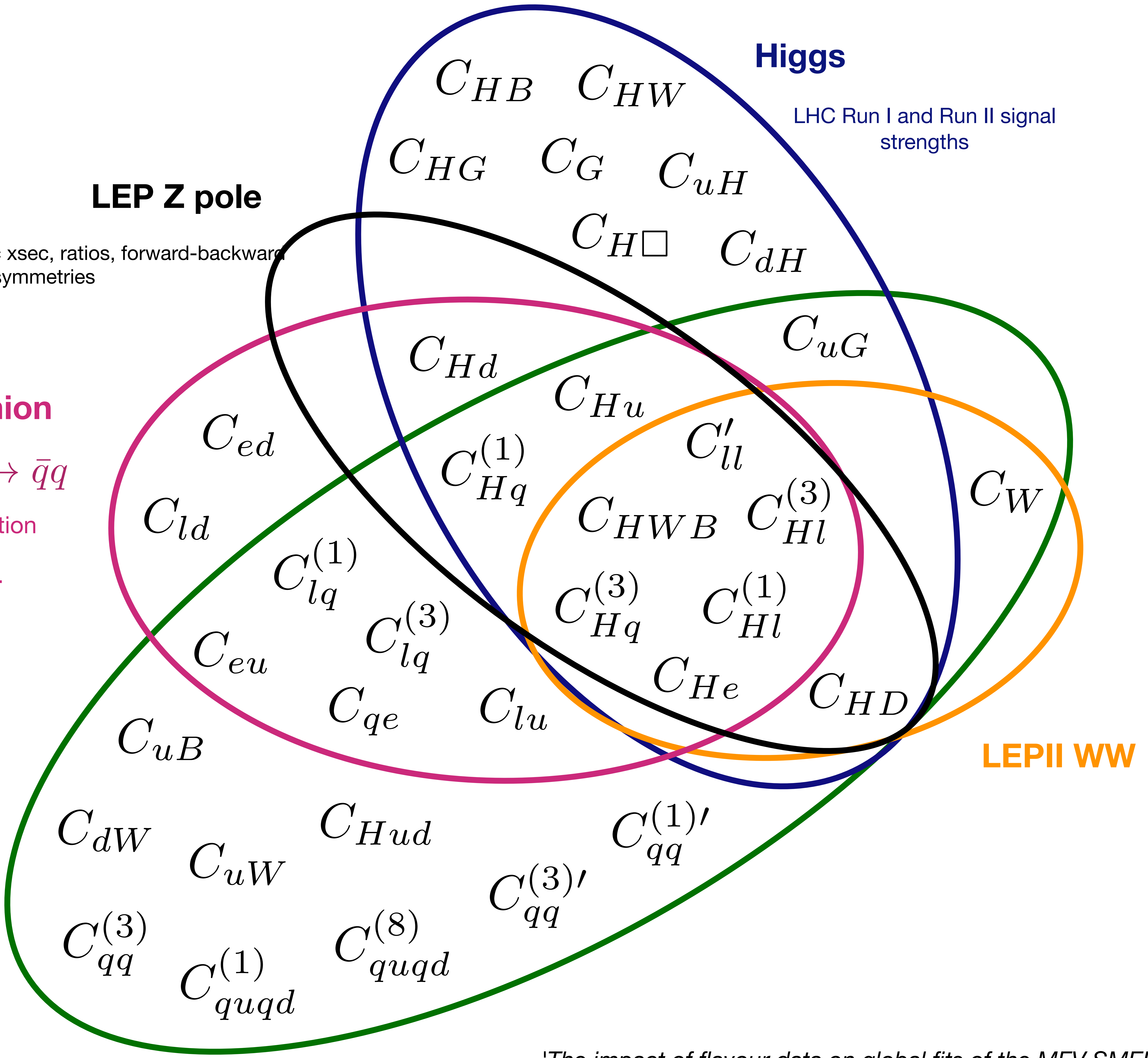
$$X_{q^3} - X_{u^3} = 0$$

$$\sum_k \left(-X_{e^k} + X_{l^k} + 2X_{u^k} - X_{d^k} - X_{q^k}\right) = 0$$

Works for some familiar anomaly-free $U(1)\ Z'$ models!

e.g. $B - L$, $L_\mu - L_\tau$, …

(Warsaw basis)



LEP Z pole

Partial widths, hadronic xsec, ratios, forward-backward asymmetries

4-fermion

$e^+e^- \to \bar{q}q$

Atomic parity violation

DIS,...

Flavour

$K \to \mu\nu$

$b \to s\gamma$

$b \to s l^+ l^-$

$K \to \pi\bar{\nu}\nu$

$B \to K^{(*)}\bar{\nu}\nu$

$B_s - \bar{B}_s$

$K^0 - \bar{K}^0$

'The impact of flavour data on global fits of the MFV SMEFT'

R. Aoude, T. Hurth, **SR**, W. Shepherd, JHEP 12 (2020) 113