# Higgs-fermion couplings & interplay with flavour

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# Outline

In the Standard Model, the Yukawa couplings between the Higgs and the fermions are the only source of flavour symmetry breaking

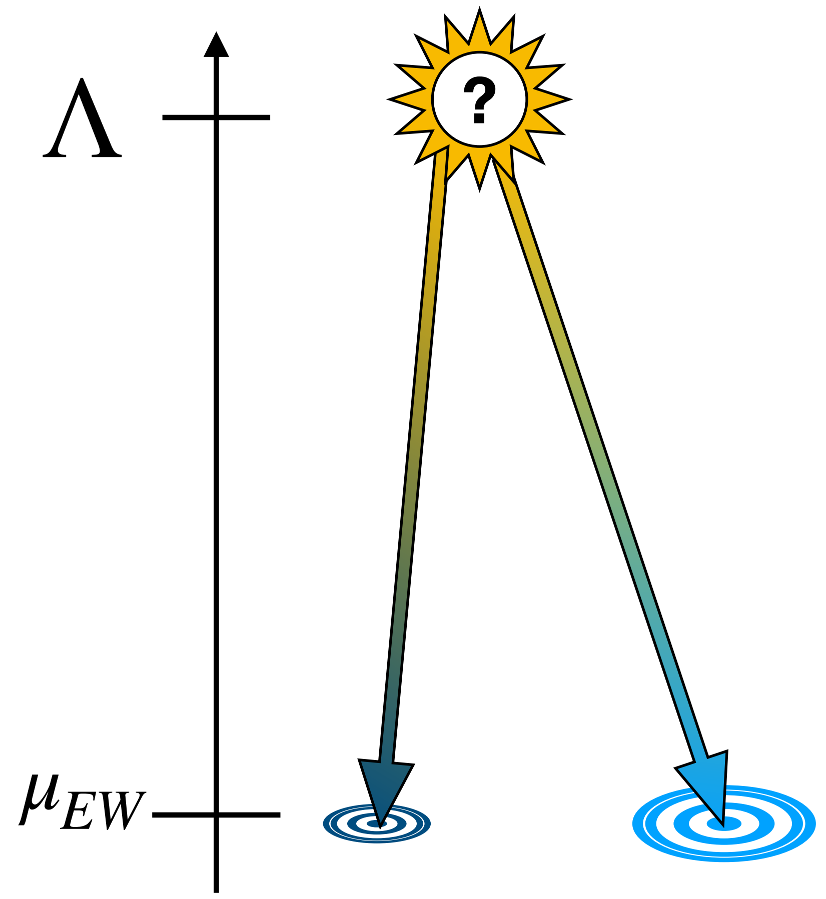
$$\mathscr{L}_{SM} = \mathscr{L}_{flavour\ symm} + \mathscr{L}_{Yukawa}$$

Currently, experimental limits on Higgs signal strengths allow for large deviations from SM in some Higgs-fermion couplings

**Question: model-independently, how large can these be without their effects being ruled out by other (particularly flavour) observables?**

# The Standard Model Effective Field Theory

Approximate the effects of all possible heavy particles by writing down all possible new interactions between SM particles




$$\mathscr{L}_{\mathrm{SMEFT}} = \frac{1}{\Lambda^2} \sum_i C_i O_i + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Operators are suppressed by BSM scale

$\Lambda$

Different classes of operators built from SM fields...

$$X^3 \quad H^6 \quad H^4D^2 \quad \psi\bar{\psi}H^2D \quad \psi\bar{\psi}H^3 \quad \psi\bar{\psi}XH \quad X^2H^2 \quad \bar{\psi}^2\psi^2$$

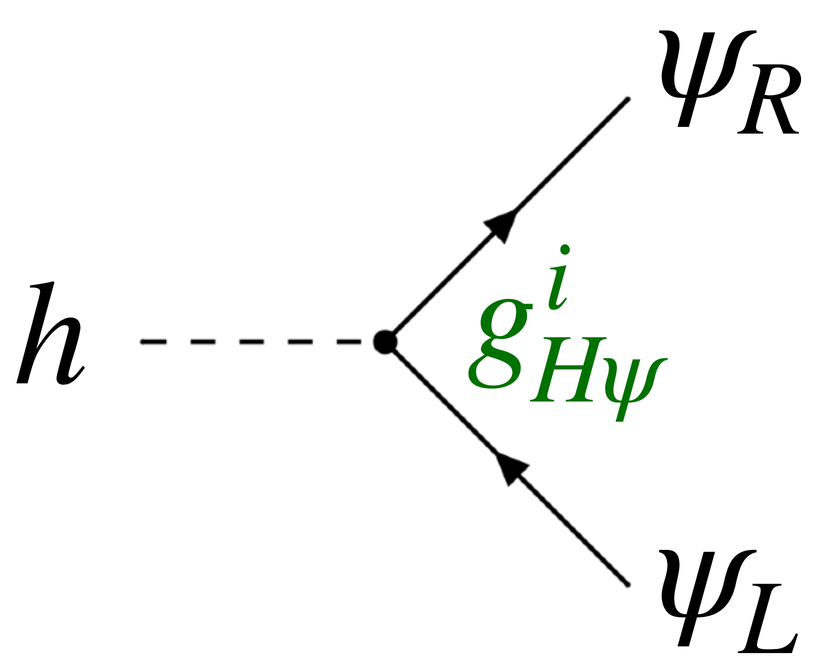
$X = B_{\mu\nu}, G^A_{\mu\nu}, W^I_{\mu\nu}$

$\psi = Q, u, d, L, e$

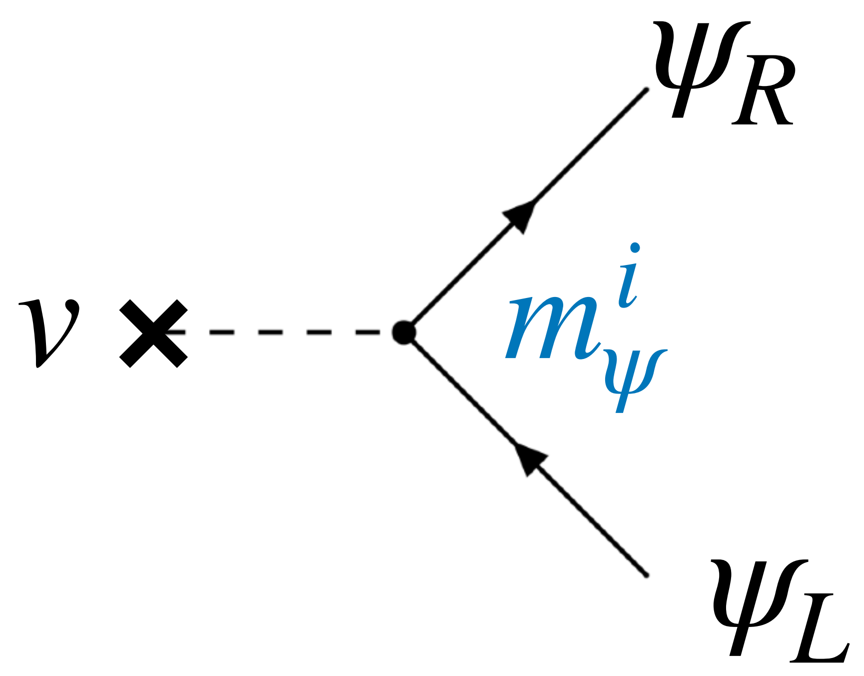
Parameters of the theory are contained in the Wilson coefficients

# Higgs – fermion couplings in the SMEFT

In SM, one-to-one relationship between masses and couplings

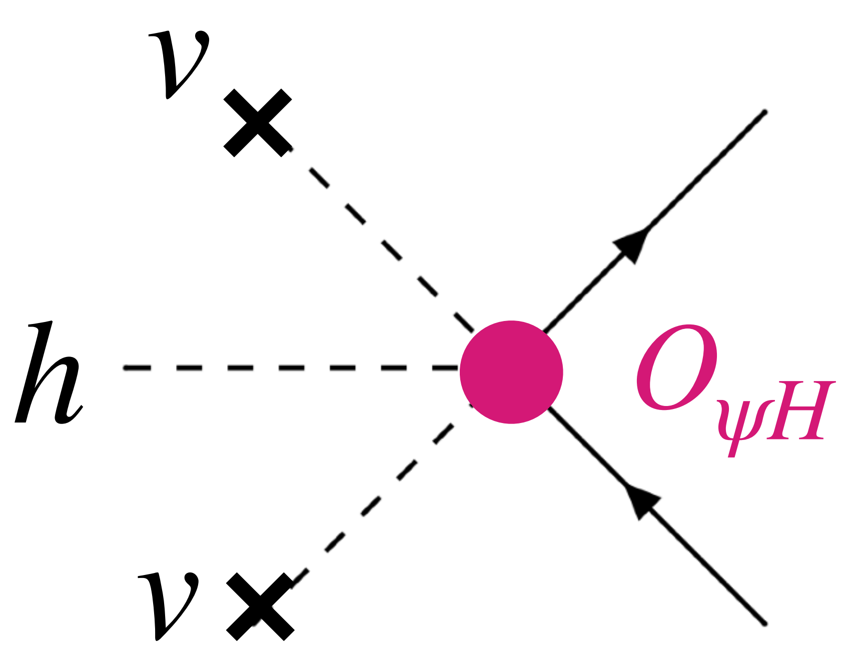



$$g^i_{H\psi} = \frac{1}{\sqrt{2}}[Y_f]_{ii} \iff m^i_\psi = \frac{v}{\sqrt{2}}[Y_f]_{ii}$$




Beyond SM, e.g. in SMEFT, that relationship is broken

$$\mathcal{L}_{\text{SMEFT}} \supset C_{\psi H}(H^\dagger H)\bar{\psi}_L \psi_R H$$




dimension 6 operator

$$m^{ij}_\psi = \frac{v}{\sqrt{2}}\left(Y^{ij}_\psi - \frac{v^2}{2}C^{ij}_{\psi H}\right)$$

$$g^{ij}_{H\psi} = \frac{1}{\sqrt{2}}\left(Y^{ij}_\psi(1 + v^2 c_{H,\text{kin}}) - \frac{3}{2}v^2 C^{ij}_{\psi H}\right)$$

$$c_{H,\text{kin}} = C_{H\Box} - \frac{1}{4}C_{HD}$$

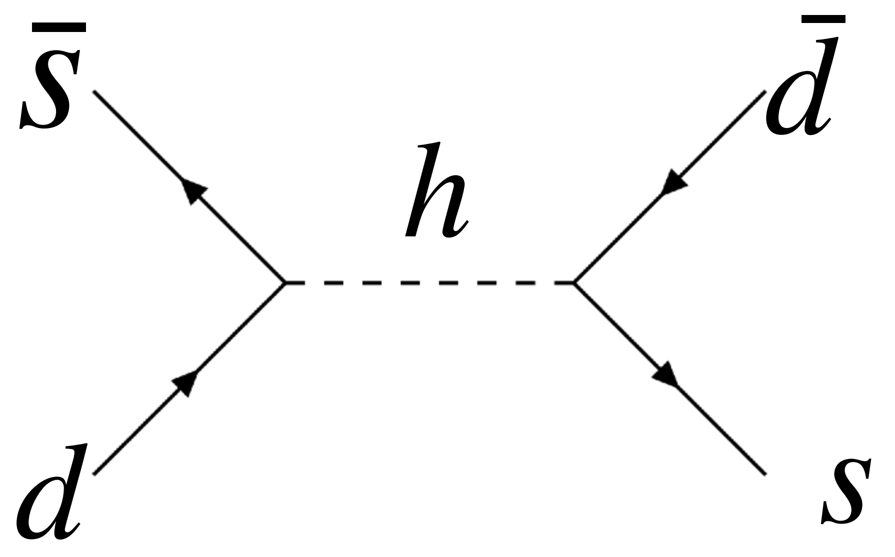
# Flavour off-diagonal Higgs couplings

In the SM, Higgs couplings are flavour-diagonal by construction

In SMEFT… $g^{ij}_{H\psi} = \frac{1}{v} m^{ij}_\psi (1 + v^2 c_{H,\mathrm{kin}}) - \frac{v^2}{\sqrt{2}} C^{ij}_{\psi H}$ Diagonalising $m_{ij}$ doesn't necessarily diagonalise $g^{ij}_{H\psi}$

**But: bounds on (flavour changing) Higgs decays are weak**

Best limits usually indirect, low energy




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

from N. Selimovic's slides

$|\kappa_c| < 1.2$

$|\kappa_s| < 13$

$|\kappa_u| < 260$

$|\kappa_d| < 156$

**HL-LHC @ 95% CL**

Exceptions: couplings involving $t$ or $\tau$

$BR(t \to Hu) < 0.019\,\%$
$BR(t \to Hc) < 0.043\,\%$ (CMS)

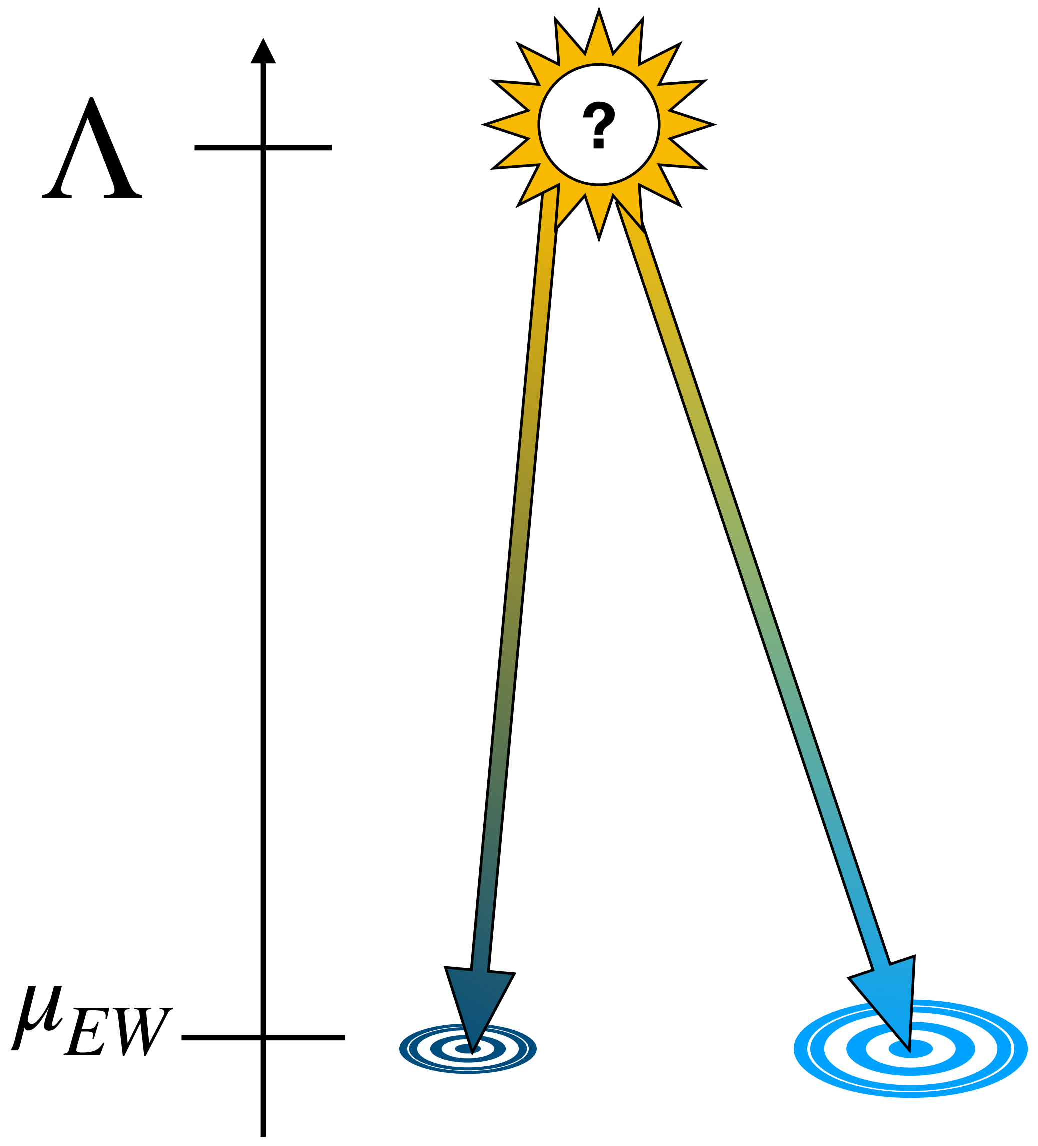
SM expectation: $O(10^{-17})$, $O(10^{-15})$

$BR(h \to \mu\tau) < 0.15\,\%$
$BR(h \to e\tau) < 0.22\,\%$ (CMS)

c.f. SM $B(h \to \mu\mu) = 0.02\,\%$

# Connecting Higgs couplings with other phenomena

**Any contribution to Higgs couplings breaks SM flavour group**




Under $U(3)^5$ flavour symmetry group,

$$(H^\dagger H)\bar{\psi}_L \psi_R H \sim \bar{3}_L \otimes 3_R$$

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

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

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

**Indirect constraints from other operators?**

# Flavour selection rules

**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

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

**Operators can only generate each other at loop level if:**

$a)$ They are of the same irrep under $SU(3)^5$

**OR**

$b)$ There are factors of SM Yukawas in the RGEs

Higgs couplings: $O_{\psi H} = (H^\dagger H)\bar{\psi}_L \psi_R H \sim \bar{3}_L \otimes 3_R$

Dipoles: $O_{\psi X} = \bar{\psi}_L \psi_R X H \sim \bar{3}_L \otimes 3_R$

Only dipole operators, e.g. $O_{dW}$ etc

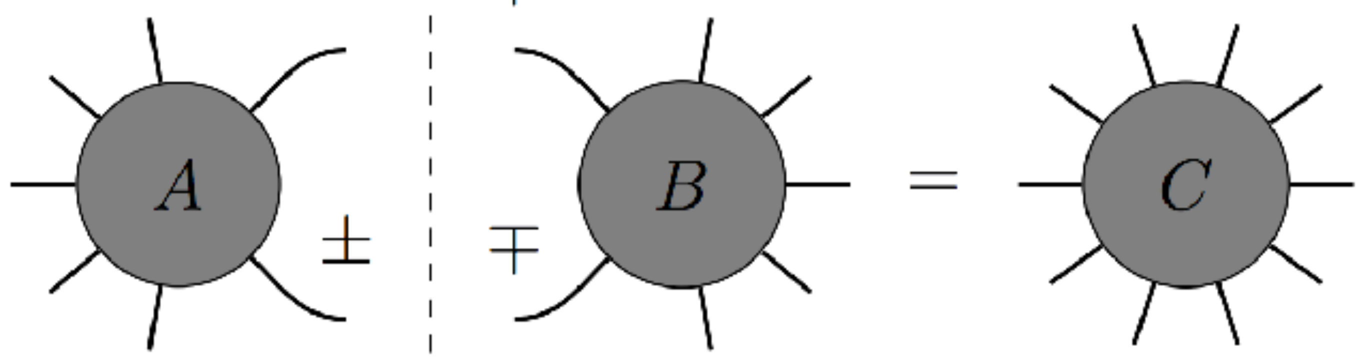
e.g.

$$O^{(1)}_{quqd} = (\bar{Q}u)(\bar{Q}d) \sim \underbrace{\bar{3}_Q \otimes 3_u}_{\sim Y_u^\dagger} \otimes \underbrace{\bar{3}_Q \otimes 3_d}_{\sim O_{dH}}$$

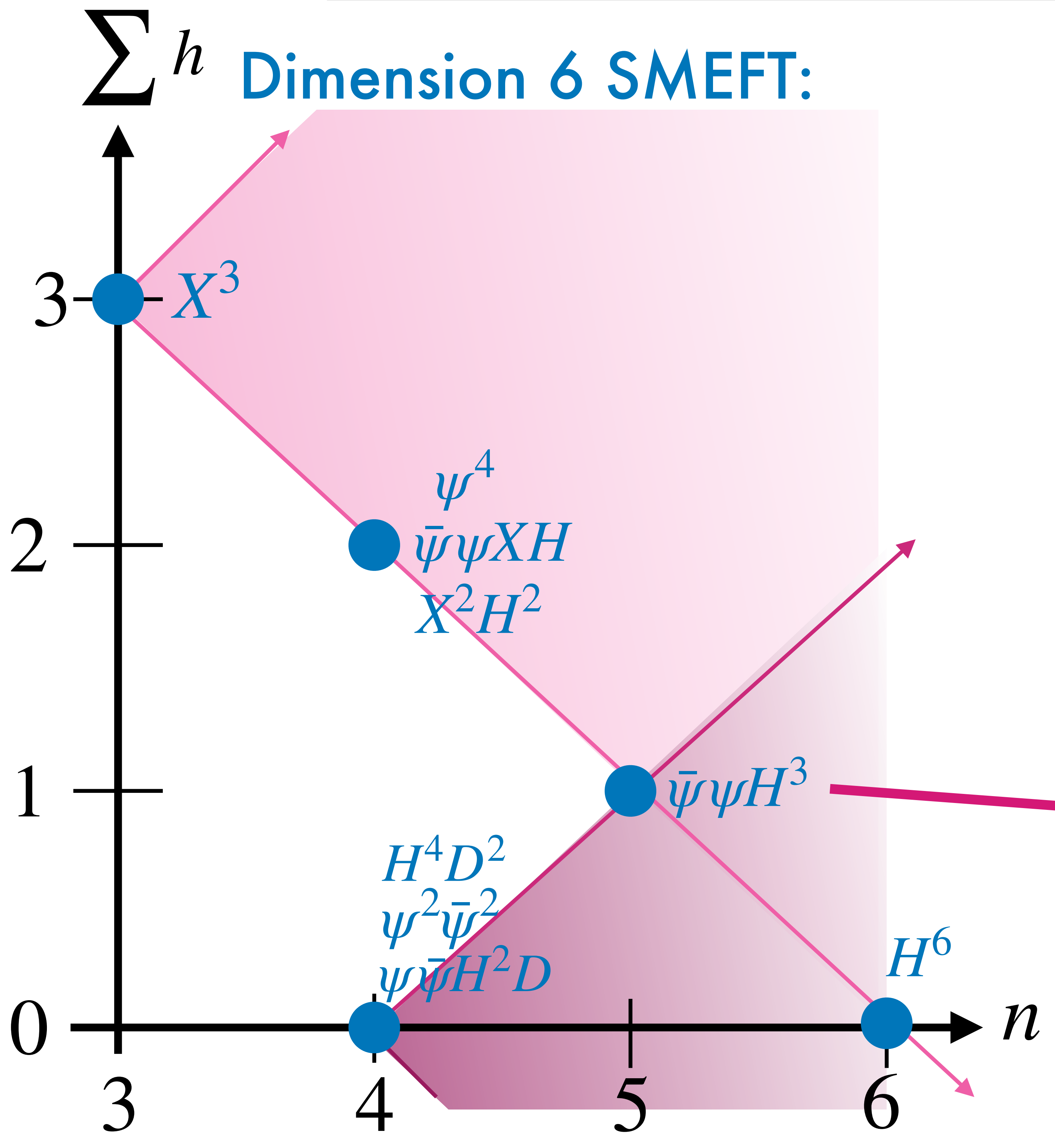
Only important for large Yukawas ($y_t$)

# Helicity and non-renormalisation

Label amplitudes by number of legs $n$ and total helicity $\sum h$




$$n_C = n_A + n_B - 4 \quad \text{and} \quad \sum h_C = \sum h_A + \sum h_B$$




All SM amplitudes (*) lie in the cone defined by

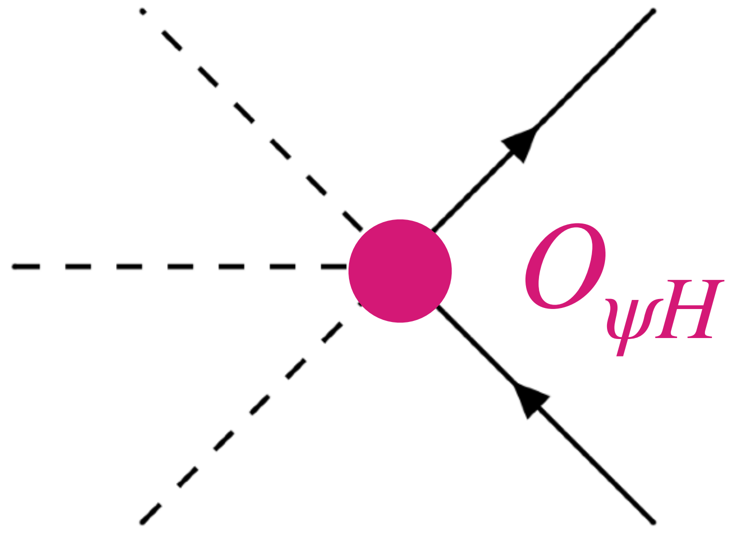
(*)exceptions suppressed by small Yukawas

$$\left|\sum h\right| \leq n - 4$$

Alonso, Jenkins, Manohar 1409.0868
Cheung, Shen 1505.01844

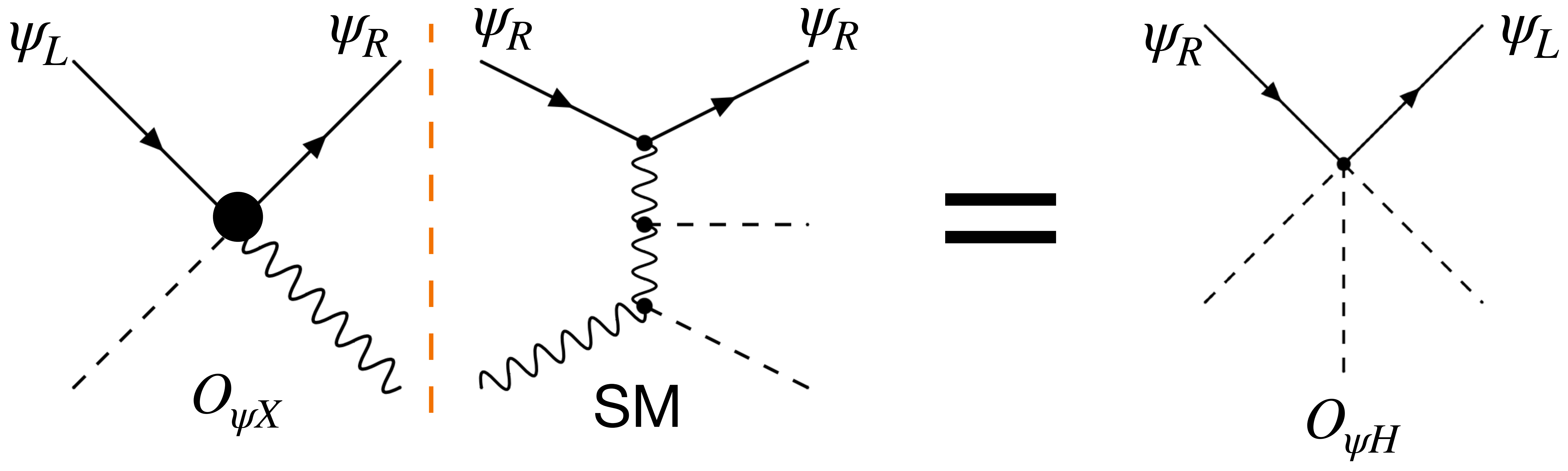
From any operator, can only run into operators on or within its cone **at one loop**

**Yukawa-like operators: Higgs-fermion couplings**



# Overall: few connections

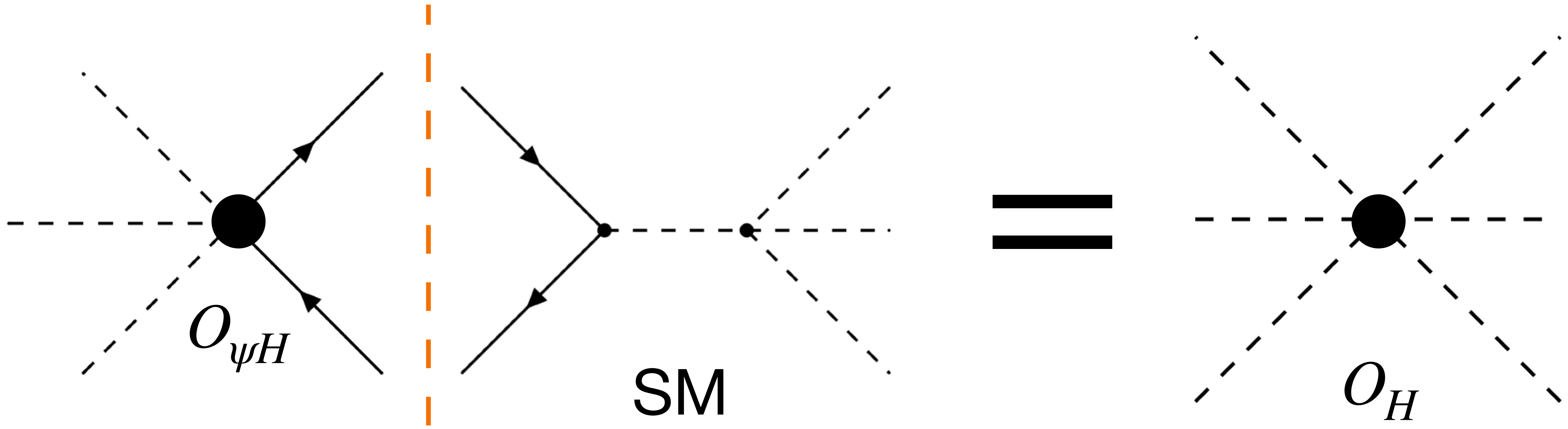
e.g. **Dipoles → Higgs-fermion couplings BUT Higgs-fermion couplings ↛ dipoles**




**Flavour:** $\bar{3}_R \otimes 3_L$ $\otimes$ $1$ $\bar{3}_R \otimes 3_L$ ✔

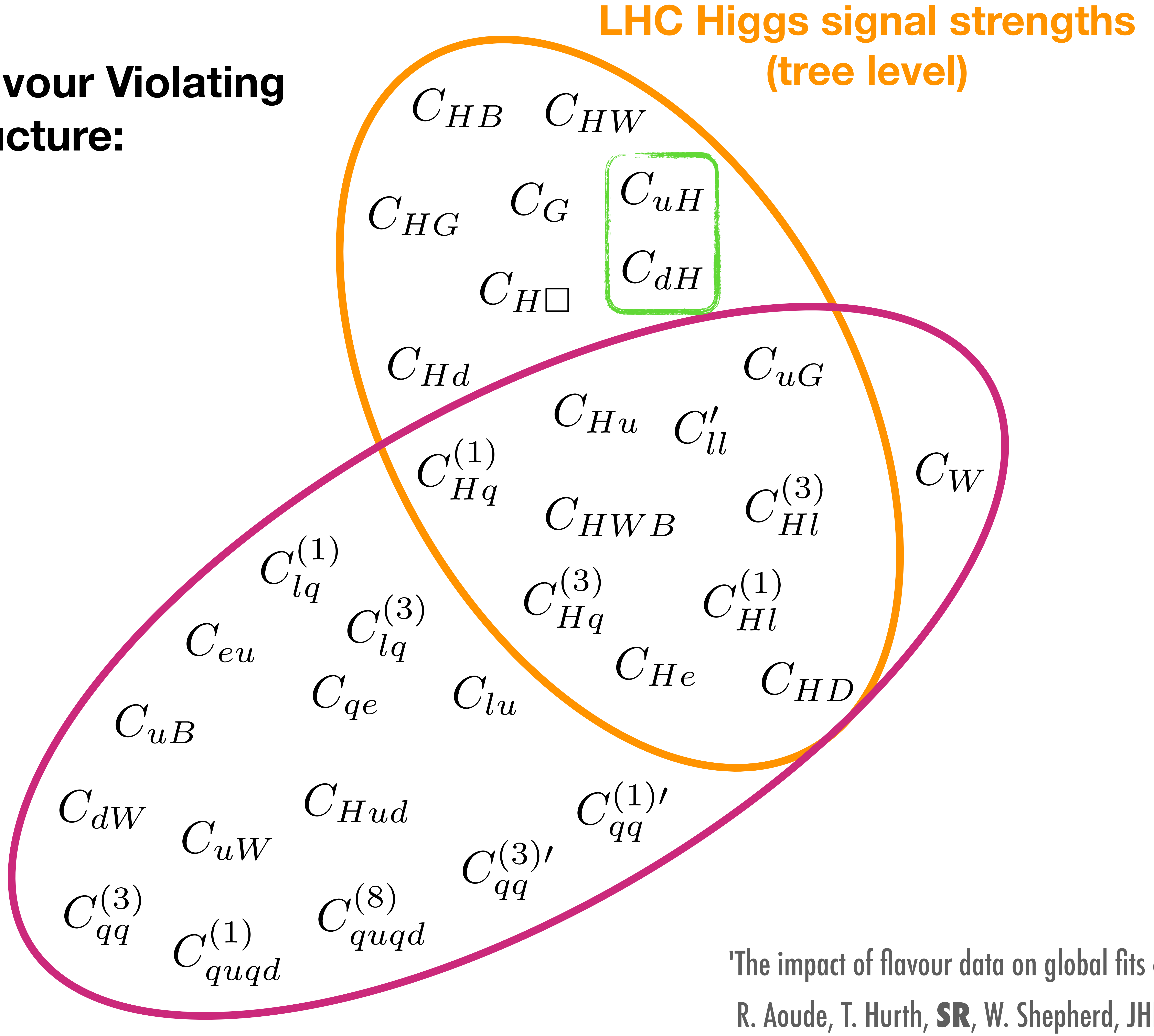
$\left(n, \sum h\right)$**:** $(4,2)$ $+(-4,0)+$ $(5,-1)$ $(5,1)$ ✔

**Only operator that $O_{\psi H}$ runs into:**




**Not well constrained, lose flavour information**

## Assuming a Minimally Flavour Violating (MFV) flavour structure:




**FCNCs at one loop**

$b \to s\gamma$

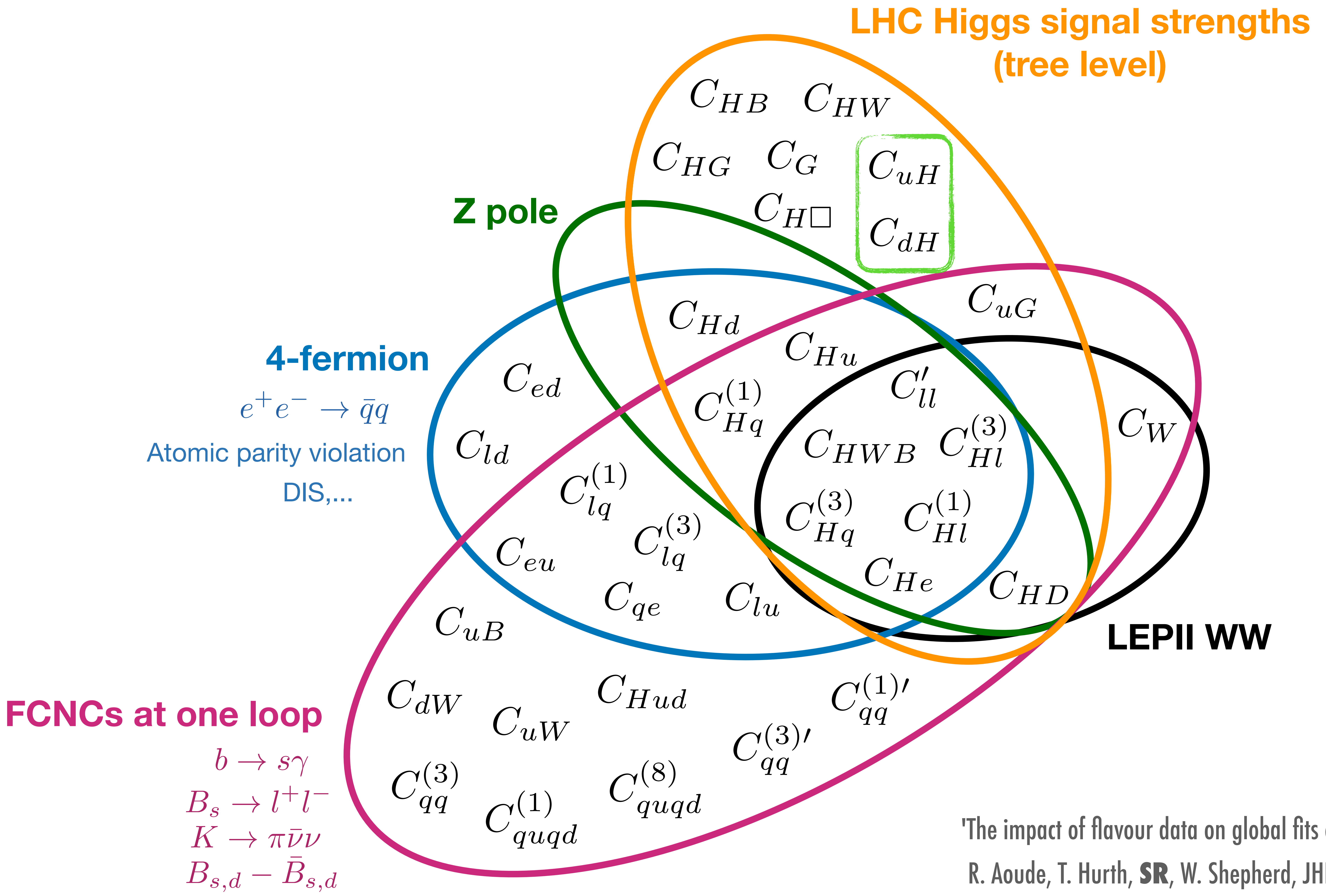
$B_s \to l^+ l^-$

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

$B_{s,d} - \bar{B}_{s,d}$

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

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




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

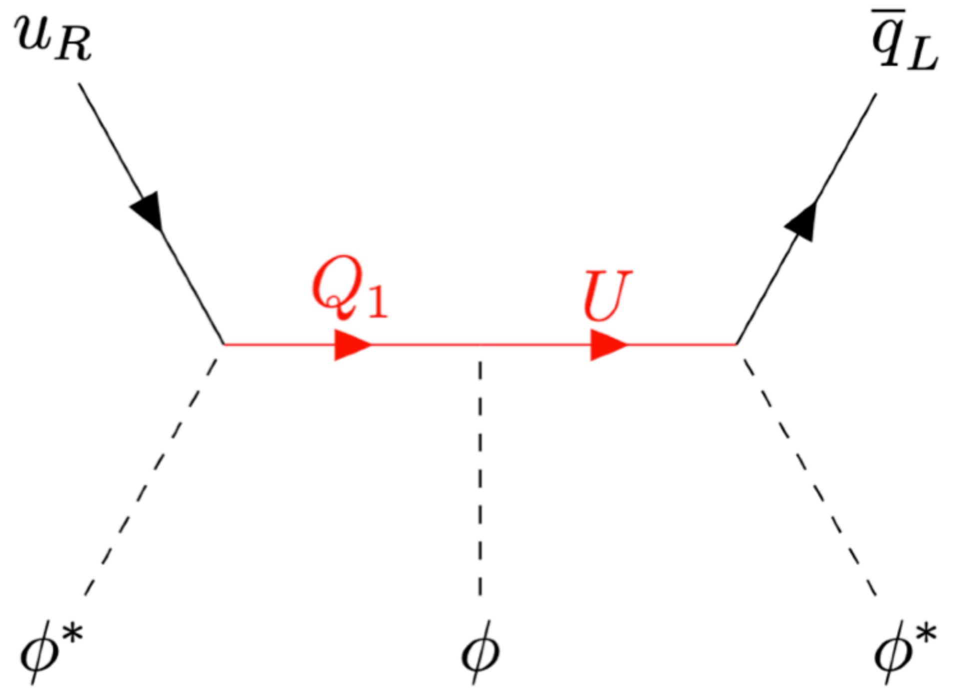
R. Aoude, T. Hurth, **SR**, W. Shepherd, JHEP 12 (2020) 113

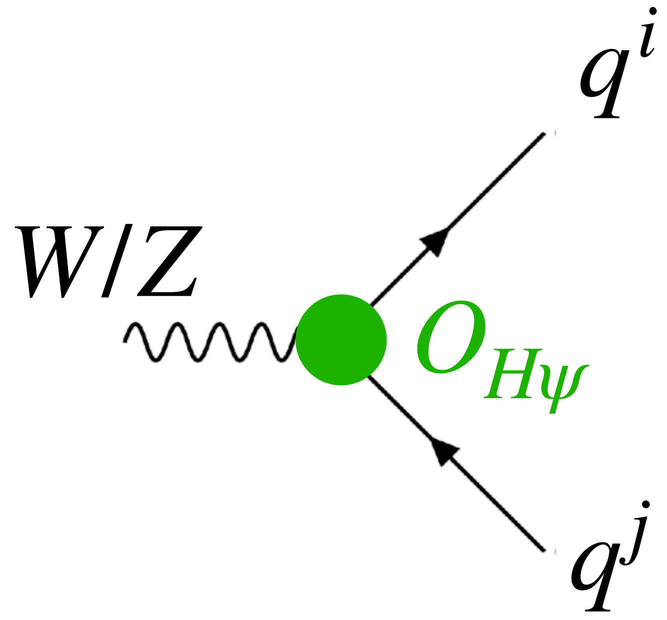
# Beyond the SMEFT

UV models which can generate modified Higgs couplings will also generate correlated effects in other SMEFT operators & flavour and collider physics

## A pair of vector-like fermions

Erdelyi, Grober, Selimovic 2410.08272



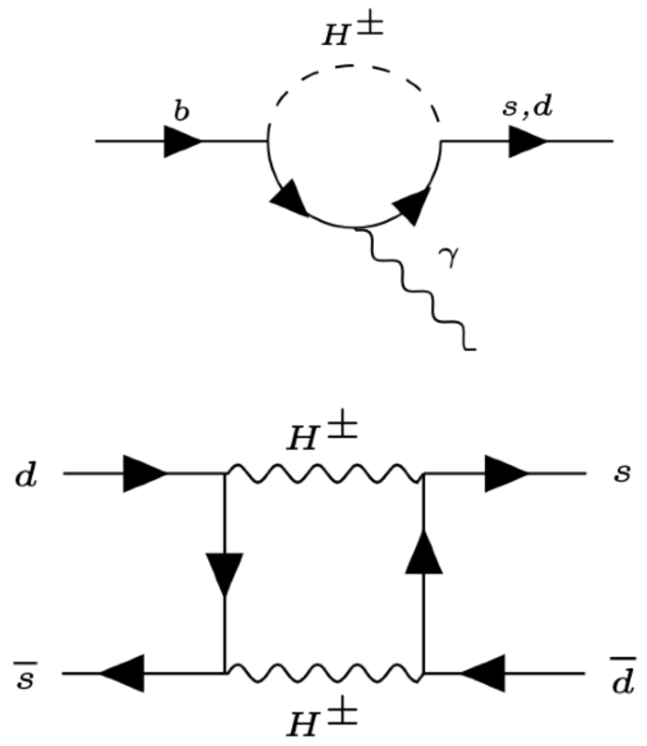

Constraints from FCNCs, and CKM unitarity

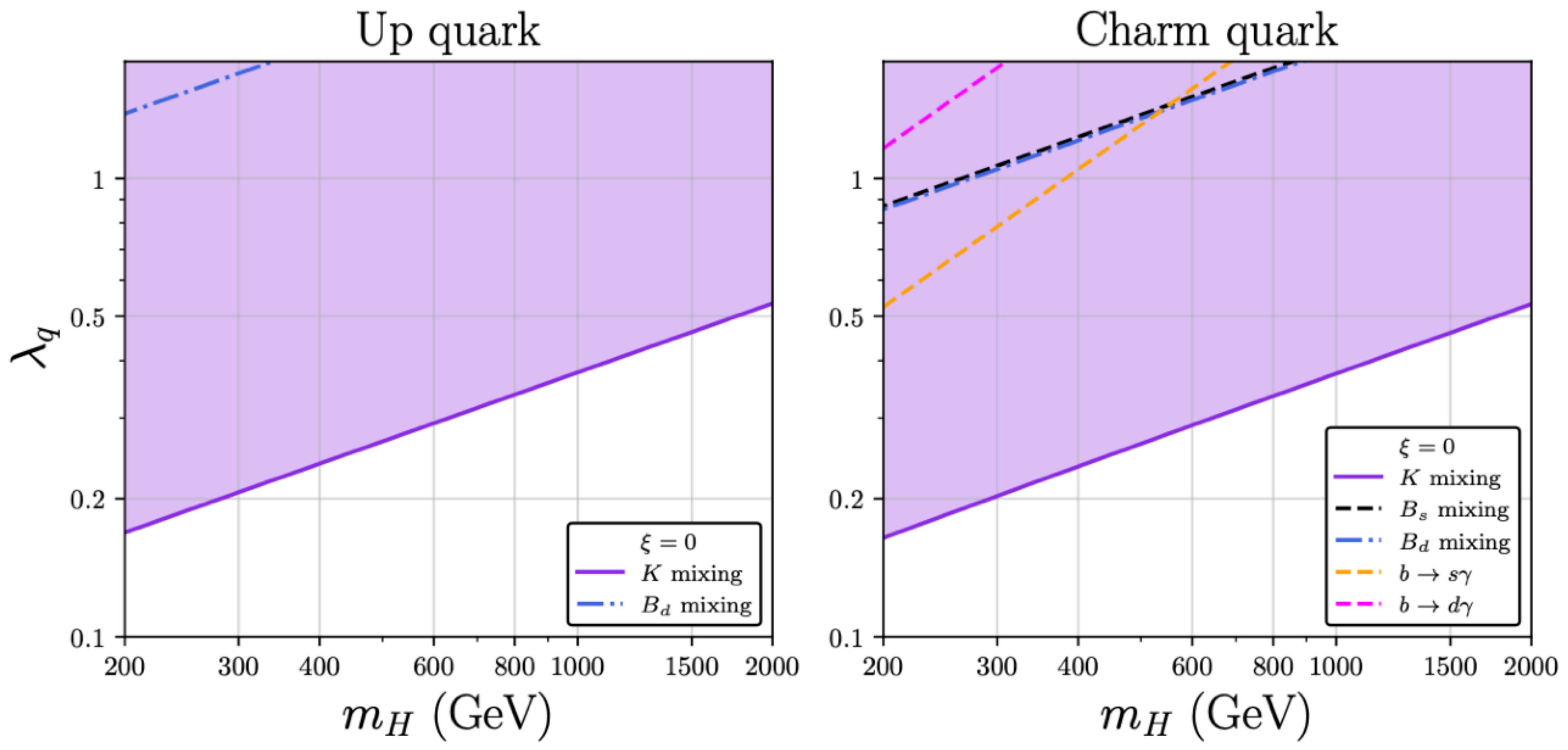
Also EWPTs, Higgs physics, direct searches

see N. Selimović's talk yesterday!

## 2HDM with Spontaneous Flavour Violation

Giannakopoulou, Meade, Valli 2410.05236




Strongest flavour constraints from K mixing

Also direct collider constraints for new Higgs bosons

# Summary & outlook

- Modified Higgs-fermion couplings occupy a special place in SMEFT parameter space
- Due to flavour and helicity structure, few model-independent connections to other (e.g. better measured) observables
- Model-building opportunities to identify correlated observables, experimental targets

# Backup

# Future of Higgs couplings

**Projected precision (%):**

FCC Snowmass report, 2203.06520

| Collider | HL-LHC | FCC-ee$_{240\to365}$ | FCC-ee + HL-LHC | FCC-INT | FCC-INT + HL-LHC |
|---|---|---|---|---|---|
| Int. Lumi (ab$^{-1}$) | 3 | 5 + 0.2 + 1.5 | – | 30 | – |
| Years | 10 | 3 + 1 + 4 | – | 25 | – |
| $g_{\mathrm{Hbb}}$ (%) | 5.1 | 0.69 | 0.64 | 0.48 | 0.48 |
| $g_{\mathrm{Hcc}}$ (%) | SM | 1.3 | 1.3 | 0.96 | 0.96 |
| $g_{\mathrm{H}\tau\tau}$ (%) | 1.9 | 0.74 | 0.66 | 0.49 | 0.46 |
| $g_{\mathrm{H}\mu\mu}$ (%) | 4.4 | 8.9 | 3.9 | 0.43 | 0.43 |
| $g_{\mathrm{Htt}}$ (%) | 3.4 | – | 3.1 | 1.0 | 0.95 |

FCC-ee matters most { $g_{\mathrm{Hbb}}$, $g_{\mathrm{Hcc}}$, $g_{\mathrm{H}\tau\tau}$

FCC-hh matters most { $g_{\mathrm{H}\mu\mu}$, $g_{\mathrm{Htt}}$

In the SMEFT at dim 6, each of these decays is modified by a single operator:

| $5 : \psi^2 H^3 + \mathrm{h.c.}$ | |
|---|---|
| $Q_{eH}$ | $(H^\dagger H)(\bar{l}_p e_r H)$ |
| $Q_{uH}$ | $(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$ |
| $Q_{dH}$ | $(H^\dagger H)(\bar{q}_p d_r H)$ |

$$\frac{v^2}{2\sqrt{2}}(v + 3h + \ldots)\,\bar{q}_L u_R$$

These operators can be generated at tree level in some models, e.g. 2HDM

$\Longrightarrow$ test of the Yukawa sector