Università degli Studi di Padova

INFN Padova
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

How large can the light Yukawa couplings be?

Barbara Anna Erdelyi

based on JHEP 05 (2025) 135 and JHEP 05 (2025) 189

with Ramona Gröber and Nudžeim Selimović

Flavour for New Physics at Present and Future Colliders, MITP

June 18, 2025

Higgs boson couplings

✓ couplings to EW gauge bosons;

✓ couplings to the third generation massive fermions;

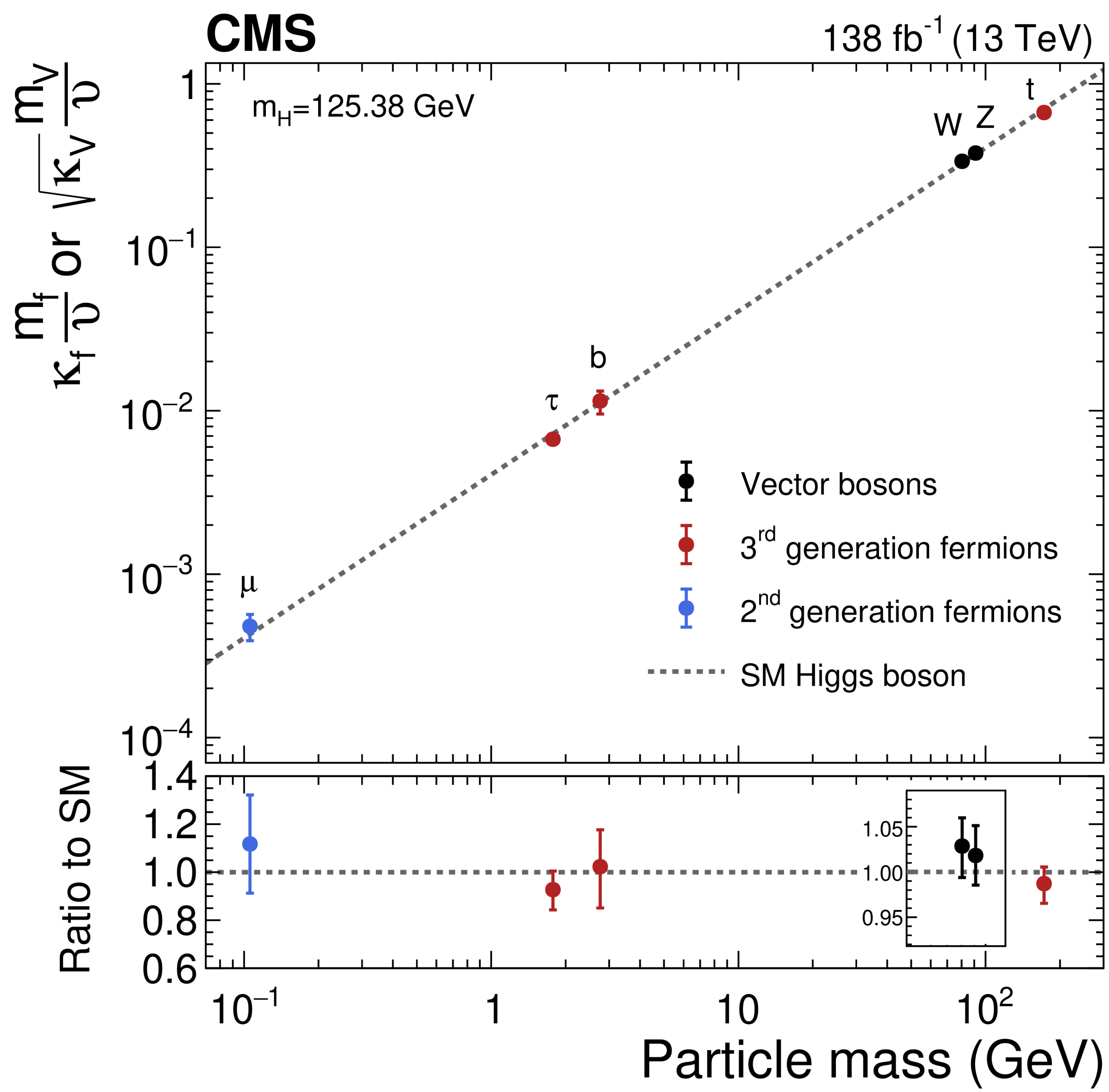
✓ coupling to the muon;

✗ Higgs self couplings;

✗ coupling to the electron;

✗ couplings to the light quarks.

κ -parametrisation: $\kappa_f = \dfrac{g_{hff}}{g_{hff}^{SM}}$



[CMS Collaboration, 2022]

General Overview

Light fermion Yukawa couplings

Current constraints

- Higgs + photon: $|\kappa_u| < 2.3 \cdot 10^3, \quad -42 < \kappa_s < 44$; $|\kappa_d| < 9.7 \cdot 10^2, \quad -4.0 < \kappa_c < 3.5$ at $95\,\%$ C.L. [CMS Collaboration, 2025]
- Higgs decay to electrons: $|\kappa_e| < 260$ at $95\,\%$ C.L. [ATLAS Collaboration, 2019]

Proposals for light quark Yukawa couplings:

- $W^{\pm}h$ charge asymmetry [Yu, 2016]
- Higgs p_T spectrum [Bishara, Haisch, Monni, Re, 2016]
- Higgs pair production [Alasfar, Corral Lopez, Gröber, 2019], [Alasfar, Gröber, Grojean, Paul, Qian, 2022]
- Global fits on Higgs data [de Blas et al., 2019]
- Triboson production [Falkowski et al, 2020]
- Higgs plus photon [Aquilar-Saavedra, Cano, No, 2020]
- Higgs off-shell production [Balzani, Gröber, Vitti, 2023]

HL-LHC at $95\,\%$ C.L.

$|\kappa_u| < 260$
$|\kappa_d| < 156$ [Balzani, Gröber, Vitti, 2023]

$|\kappa_c| < 1.2$
$|\kappa_s| < 13$ [de Blas et al., 2019]

$|\kappa_e| < 120$ [Cepeda et al., 2019]

Standard Model Effective Field Theory

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_{d>4} \sum_{i=1}^{n_d} \mathscr{C}_i^{(d)}(\mu)\ \mathscr{O}_i^{(d)}\,, \qquad \left[\mathscr{C}_i^{(d)}\right] = 4 - d\,.$$

1. Identify deviations from SM predictions:

   $$\mathscr{O}_\alpha^{theo} = \mathscr{O}_\alpha^{SM} + \delta\mathscr{O}_\alpha^{SMEFT}\,;$$

2. Compare with experimental results, obtaining constraints in terms of Wilson Coefficients;

3. Introduce UV model dependence by matching procedure [Fuentes-Martín, König, Pagès, Thomsen, Wilsch, 2022], [Guedes, Olgoso, Santiago, 2023] and [Guedes, Olgoso, 2024].

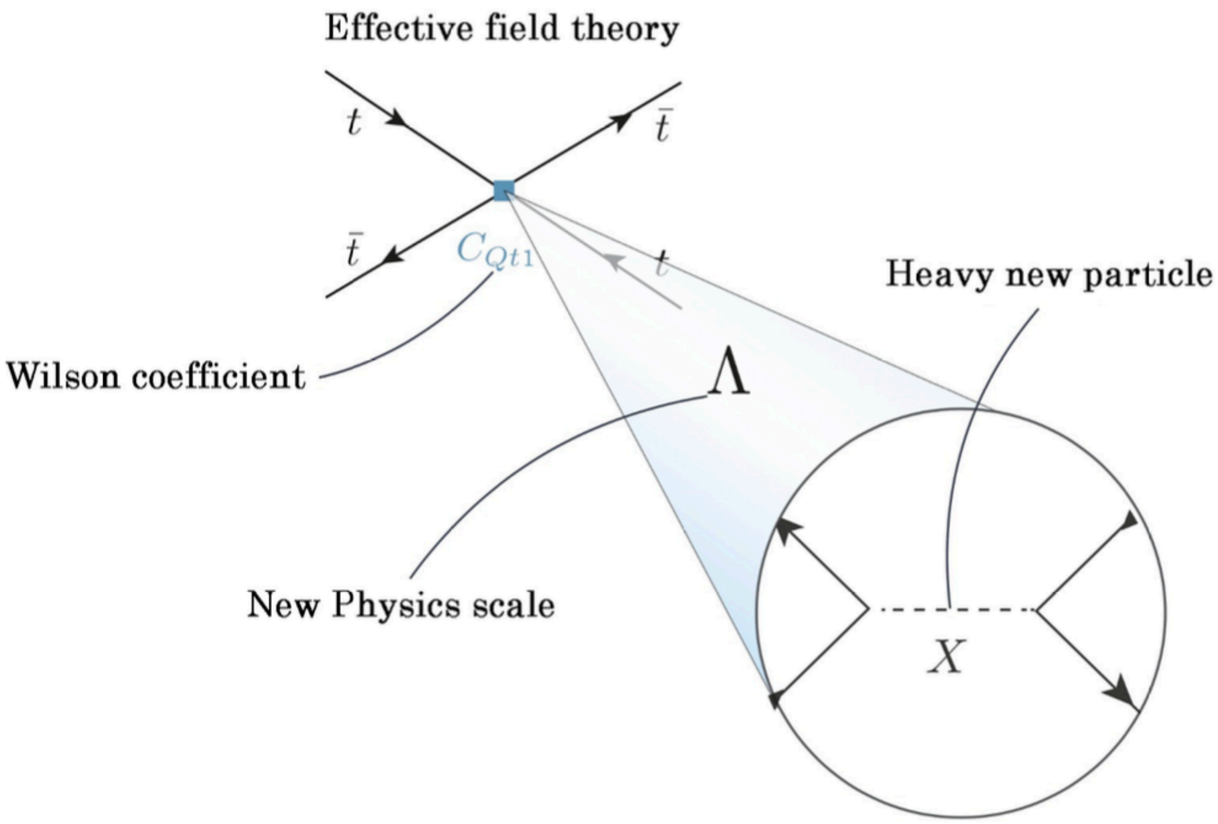


Figure courtesy of L. Alasfar

Identification of dimension-six SMEFT operators

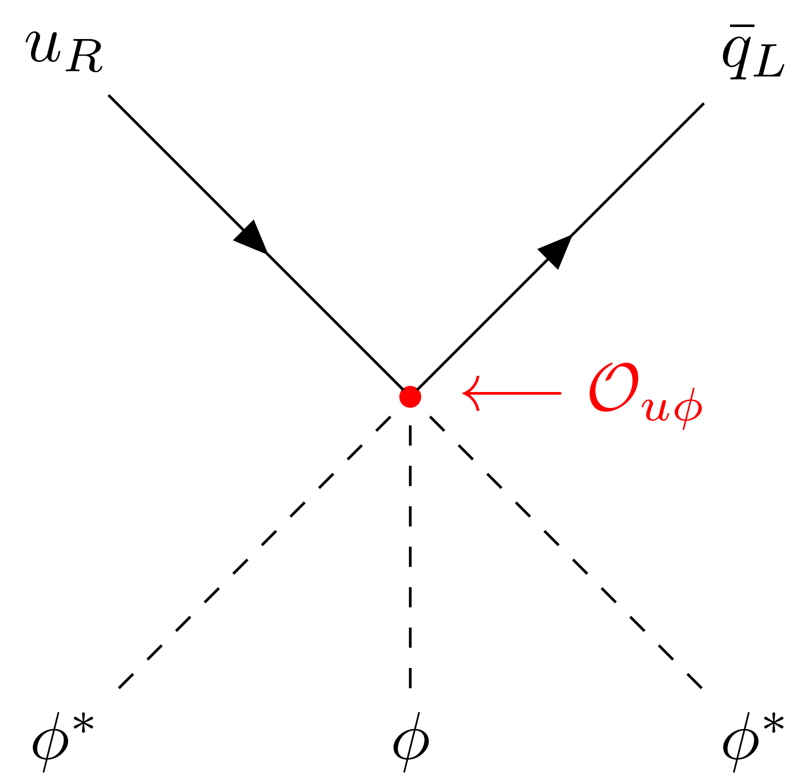
$$\mathscr{L}^{d=6}_{SMEFT} = \mathscr{L}_{SM} + \sum_{i=1}^{n_6} \mathscr{C}_i^{(6)}(\mu)\ \mathscr{O}_i^{(6)}, \qquad \left[\mathscr{C}_i^{(6)}\right] = -2\,.$$

Identify three Warsaw basis [Grzadkowski, Iskrzyński, Misiak, Rosiek, 2010] operators:

$$\mathscr{O}_{u\phi} = \left(\phi^\dagger\phi\right)\left(\bar{q}_L\tilde{\phi}u_R\right),$$

$$\mathscr{O}_{d\phi} = \left(\phi^\dagger\phi\right)\left(\bar{q}_L\phi d_R\right),$$

$$\mathscr{O}_{e\phi} = \left(\phi^\dagger\phi\right)\left(\bar{l}_L\phi e_R\right).$$



Broken phase

$$\begin{cases} m_f = \frac{v}{\sqrt{2}}\left(y_f - \frac{v^2}{2}\mathscr{C}_{f\phi}\right) \\ g_{hff} = \frac{1}{\sqrt{2}}\left(y_f - \frac{3v^2}{2}\mathscr{C}_{f\phi}\right) \end{cases}$$

m_f → Fine tuning — *E.g.*: for $\kappa_u \approx 1000$ order per mille tuning between $[y_u]_{11}$ and $v^2[\mathscr{C}_{u\phi}]_{11}/2$

g_{hff} → $$\kappa_f = 1 - \frac{v^3}{\sqrt{2}m_f}\mathscr{C}_{f\phi}$$

Model Identification

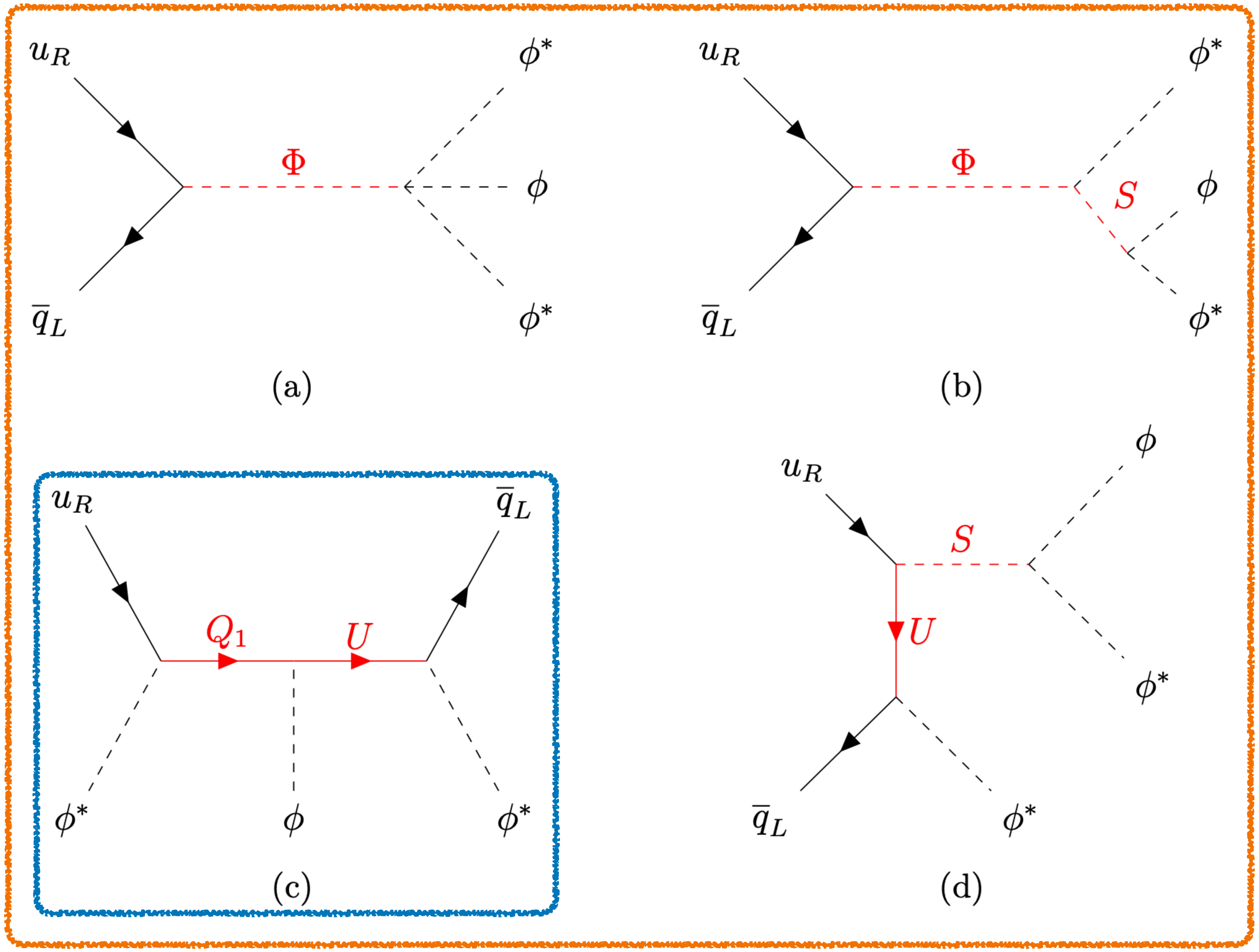
Goal: identify UV models generating unsuppressed contributions to $\mathcal{O}_{f\phi}$:

(a) Single scalar mediator models;

(b) Two scalars models;

(c) Models with a pair of vector-like fermions (VLQs and VLLs);

(d) Models with a VLQ / VLL + scalar.



[de Blas, Criado, Perez-Victoria, Santiago, 2018]

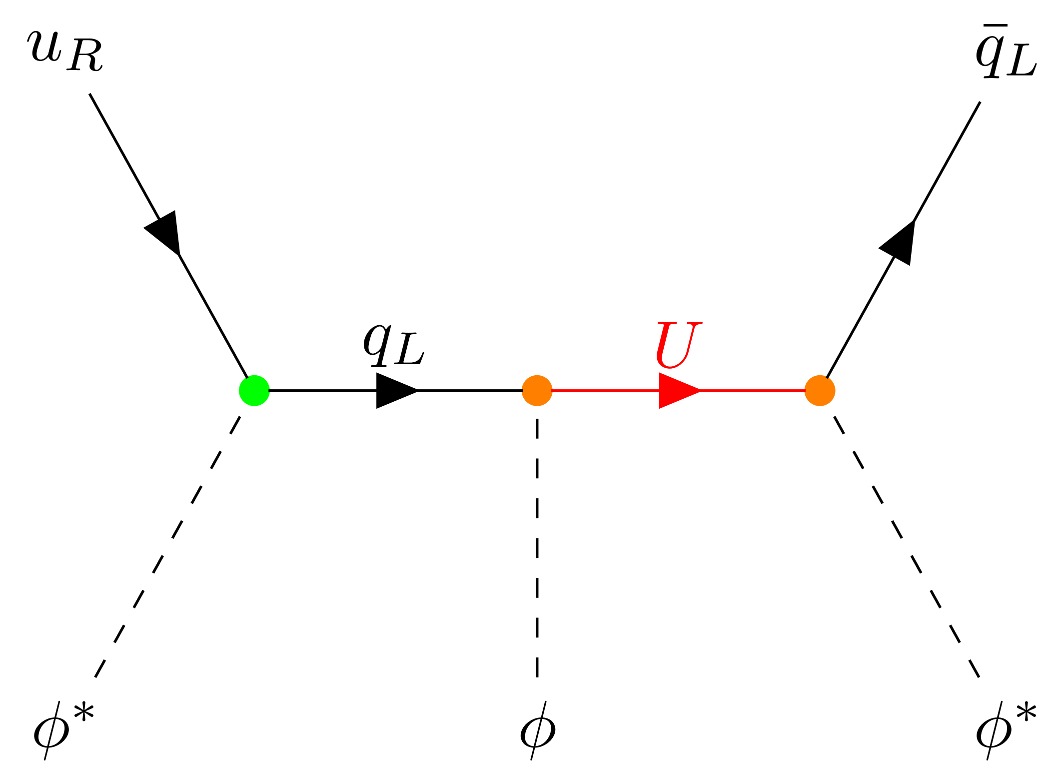
UV models with one vector-like fermion

If only one VLF is included, matching results in $\mathscr{C}_{f\phi} \sim y_f \lambda^2_{\mathrm{UV}} \Rightarrow \kappa_f - 1 \sim \frac{v^2}{M^2}\lambda^2_{\mathrm{UV}}$

E.g.: model with only $U \sim (3,1)_{\frac{2}{3}}$

$$\mathscr{L} \supset -(\lambda_U \bar{U}_R \tilde{\phi}^\dagger q_L + \text{h.c.}) - M_u \bar{U}U$$

$$[\mathscr{C}_{u\phi}]_{ij} = \frac{[y_u^*]_{jk}[\lambda_U]_k[\lambda_U^*]_i}{2M_U^2}$$



$\kappa_u - 1 \sim v^2 \frac{|[\lambda_U]_1|^2}{2M_U^2} = -\sqrt{2}\delta g_{Zu}$, constrained by EWPOs.

Models with Vector-like quark pairs

VLQs and Irreps. under $G_{\rm SM}$

Singlets	Doublets	Triplets
$U \sim (3,1)_{\frac{2}{3}}$	$Q_1 \sim (3,2)_{\frac{1}{6}}$	$T_1 \sim (3,3)_{-\frac{1}{3}}$
$D \sim (3,1)_{-\frac{1}{3}}$	$Q_5 \sim (3,2)_{-\frac{5}{6}}$	$T_2 \sim (3,3)_{\frac{2}{3}}$
	$Q_7 \sim (3,2)_{\frac{7}{6}}$	

Models

Doublet + Singlet	Doublet + Triplet
$Q_1 + U$	$Q_1 + T_1$
$Q_1 + D$	$Q_5 + T_1$
$Q_7 + U$	$Q_1 + T_2$
$Q_5 + D$	$Q_7 + T_2$

Yukawa-like interactions with SM light quarks

$$\mathscr{L}_{\rm UV} \supset \sum_{i=1,2} \lambda_{Q_i}\phi\, Q_i\, q + \lambda_{Q_1 Q_2}\phi\, Q_1\, Q_2$$

Yukawa-like pair interaction

Prediction: $\kappa_q - 1 \approx \frac{v^3}{\sqrt{2}m_q}\mathscr{C}_{q\phi} \sim \frac{1}{M_{Q_1}M_{Q_2}}\lambda_{Q_1}\lambda_{Q_2}\lambda_{Q_1Q_2}$ $\Rightarrow$ No Yukawa suppression

[de Blas, Criado, Perez-Victoria, Santiago, 2018]

VLLs and Irreps. under G_{SM}

Singlets	Doublets	Triplets
$E \sim (1,1)_{-1}$	$\Delta_1 \sim (1,2)_{-\frac{1}{2}}$	$\Sigma \sim (1,3)_0$
	$\Delta_3 \sim (3,2)_{-\frac{3}{2}}$	$\Sigma_1 \sim (1,3)_{-1}$

Yukawa-like interactions with SM electron

$$\mathscr{L}_{\text{UV}} \supset \lambda_R \phi \, L_{1L} \, e_R + \lambda_L \phi \, L_{2R} l_L + \lambda_{L_1 L_2} \phi \, L_1 \, L_2$$

Models

Doublet + Singlet	Doublet + Triplet
$\Delta_1 + E$	$\Sigma_1 + \Delta_3$
$\Delta_3 + E$	$\Sigma_1 + \Delta_1$
	$\Sigma + \Delta_1$

Yukawa-like pair interaction

Prediction: $\kappa_e - 1 \approx \frac{v^3}{\sqrt{2} m_e} \mathscr{C}_{e\phi} \sim \frac{1}{M_{L_1} M_{L_2}} \lambda_{L_1} \lambda_{L_2} \lambda_{L_1 L_2}$ $\Rightarrow$ No Yukawa suppression

[de Blas, Criado, Perez-Victoria, Santiago, 2018]

SMEFT operators from UV Models with VLF pairs

We focus on the following Warsaw basis operators [Grzadkowski, Iskrzyński, Misiak, Rosiek, 2010], generated by integrating out the heavy particles:

- Operators generated at the tree level ($f = e, u, d$):

$\mathcal{O}_{u\phi}$	$(\phi^\dagger\phi)\,(\bar{q}_L\tilde{\phi}u_R)$	$\mathcal{O}_{d\phi}$	$(\phi^\dagger\phi)\,(\bar{q}_L\phi d_R)$	$\mathcal{O}_{e\phi}$	$(\phi^\dagger\phi)\,(\bar{l}_L\phi e_R)$
$\mathcal{O}_{\phi f}$	$(i\phi^\dagger \overleftrightarrow{D}_\mu\phi)(\bar{f}_R\gamma^\mu f_R)$	$\mathcal{O}^{(1)}_{\phi f}$	$(i\phi^\dagger \overleftrightarrow{D}_\mu\phi)(\bar{f}_L\gamma^\mu f_L)$	$\mathcal{O}^{(3)}_{\phi f}$	$(i\phi^\dagger \overleftrightarrow{D}^I_\mu\phi)(\bar{f}_L\gamma^\mu\sigma^I f_L)$

- Operators generated at the one loop level:

$\mathcal{O}_{\phi\Box}$	$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$\mathcal{O}_{\phi G}$	$(\phi^\dagger\phi)\,(G^A_{\mu\nu}G^{\mu\nu A})$	$\mathcal{O}_{\phi B}$	$(\phi^\dagger\phi)\,(B_{\mu\nu}B^{\mu\nu})$
$\mathcal{O}_{\phi D}$	$\lvert\phi^\dagger D_\mu\phi\rvert^2$	$\mathcal{O}_{\phi W}$	$(\phi^\dagger\phi)\,(W^I_{\mu\nu}W^{\mu\nu I})$	$\mathcal{O}_{\phi WB}$	$(\phi^\dagger\sigma^I\phi)\,(W^I_{\mu\nu}B^{\mu\nu})$

SMEFT operators from UV Models with VLF pairs

These operators cause deviations in the theoretical predictions for Higgs Physics Observables and for ElectroWeak Precision Observables :

- Operators generated at the tree level ($f = e, u, d$):

$\mathcal{O}_{u\phi}$	$(\phi^\dagger\phi)\,(\bar{q}_L\tilde{\phi}u_R)$	$\mathcal{O}_{d\phi}$	$(\phi^\dagger\phi)\,(\bar{q}_L\phi d_R)$	$\mathcal{O}_{e\phi}$	$(\phi^\dagger\phi)\,(\bar{l}_L\phi e_R)$
$\mathcal{O}_{\phi f}$	$(i\phi^\dagger \overleftrightarrow{D}_\mu\phi)(\bar{f}_R\gamma^\mu f_R)$	$\mathcal{O}_{\phi f}^{(1)}$	$(i\phi^\dagger \overleftrightarrow{D}_\mu\phi)(\bar{f}_L\gamma^\mu f_L)$	$\mathcal{O}_{\phi f}^{(3)}$	$(i\phi^\dagger \overleftrightarrow{D}^I_\mu\phi)(\bar{f}_L\gamma^\mu\sigma^I f_L)$

- Operators generated at the one loop level:

$\mathcal{O}_{\phi\Box}$	$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$\mathcal{O}_{\phi G}$	$(\phi^\dagger\phi)\,(G^A_{\mu\nu}G^{\mu\nu A})$	$\mathcal{O}_{\phi B}$	$(\phi^\dagger\phi)\,(B_{\mu\nu}B^{\mu\nu})$
$\mathcal{O}_{\phi D}$	$\lvert\phi^\dagger D_\mu\phi\rvert^2$	$\mathcal{O}_{\phi W}$	$(\phi^\dagger\phi)\,(W^I_{\mu\nu}W^{\mu\nu I})$	$\mathcal{O}_{\phi WB}$	$(\phi^\dagger\sigma^I\phi)\,(W^I_{\mu\nu}B^{\mu\nu})$

Light quark Yukawa coupling enhancements

Constraints: Overview

Flavour Physics

$\lambda_Q^i, i = 1,2$

CKM

EWPOs

quark couplings to $W^\pm$

and Z

$$\chi^2_{\text{tot}} < \chi^2_{\text{tot, min}} + \Delta\chi^2(n_{\text{dofs}}, \text{CL})$$

Direct Searches

$M_Q > \Lambda^{\text{exp}}$

Higgs Physics

Observables:

Higgs boson production

and decays

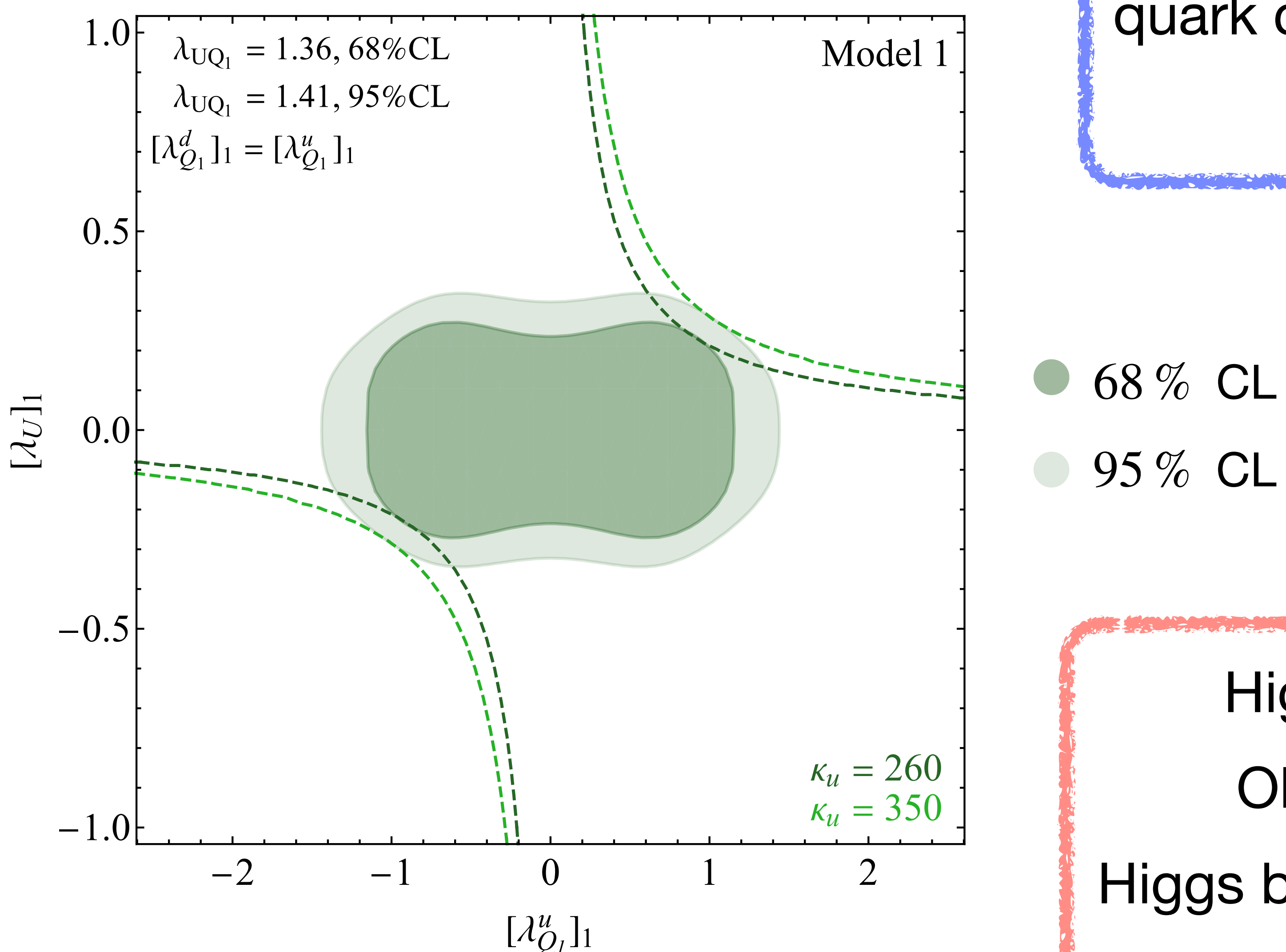
Flavour Physics

$\lambda_Q^i, i = 1{,}2$

CKM

EWPOs

quark couplings to $W^{\pm}$ and Z



Direct Searches

$M_Q > \Lambda^{\rm exp}$

Higgs Physics Observables:

Higgs boson production and decays

Plot made using current experimental constraints

Constraints: Flavour Physics Bounds

- Flavour changing neutral currents constrain models to very high scales if couplings to first and second generation couplings are allowed:

E.g.: For $D \sim (3,1)_{-\frac{1}{3}}$, $K^+ \to \pi^+ \nu \bar{\nu}$ sets $M_D > \sqrt{[\lambda_D]^1 \, [\lambda_D]^2} \, 126$ TeV.

[Ishiwata, Ligeti, Wise, 2015]

⇒NP couples to one generation at a time

- Presence of $\mathcal{O}^{(3)}_{\phi q}$ induces deviations in W boson couplings, in particular deviations from CKM unitarity

$$S_{11} = |V_{i1}|^2 + |V_{i2}|^2 + |V_{i3}|^2 = 0.9984 \pm 0.0007$$

[Particle Data Group, 2024]

Lower bounds on masses

Particle	CKM unitarity
$U \sim (\mathbf{3}, \mathbf{1})_{2/3}$	$3.2 \times \lvert[\lambda_U]_1\rvert$
$D \sim (\mathbf{3}, \mathbf{1})_{-1/3}$	$3.2 \times \lvert[\lambda_D]_1\rvert$
$T_1 \sim (\mathbf{3}, \mathbf{3})_{-1/3}$	$1.6 \times \lvert[\lambda_{T_1}]_1\rvert$
$T_2 \sim (\mathbf{3}, \mathbf{3})_{2/3}$	$1.6 \times \lvert[\lambda_{T_2}]_1\rvert$

Constraints: Direct searches for Vector-like Quarks

Production of VLQs coupled to the light quarks at the Large Hadron Collider.

- Current searches:

  In the limit Br$(Q \to qW) = 1$,

  [ATLAS Collaboration, 2024] sets

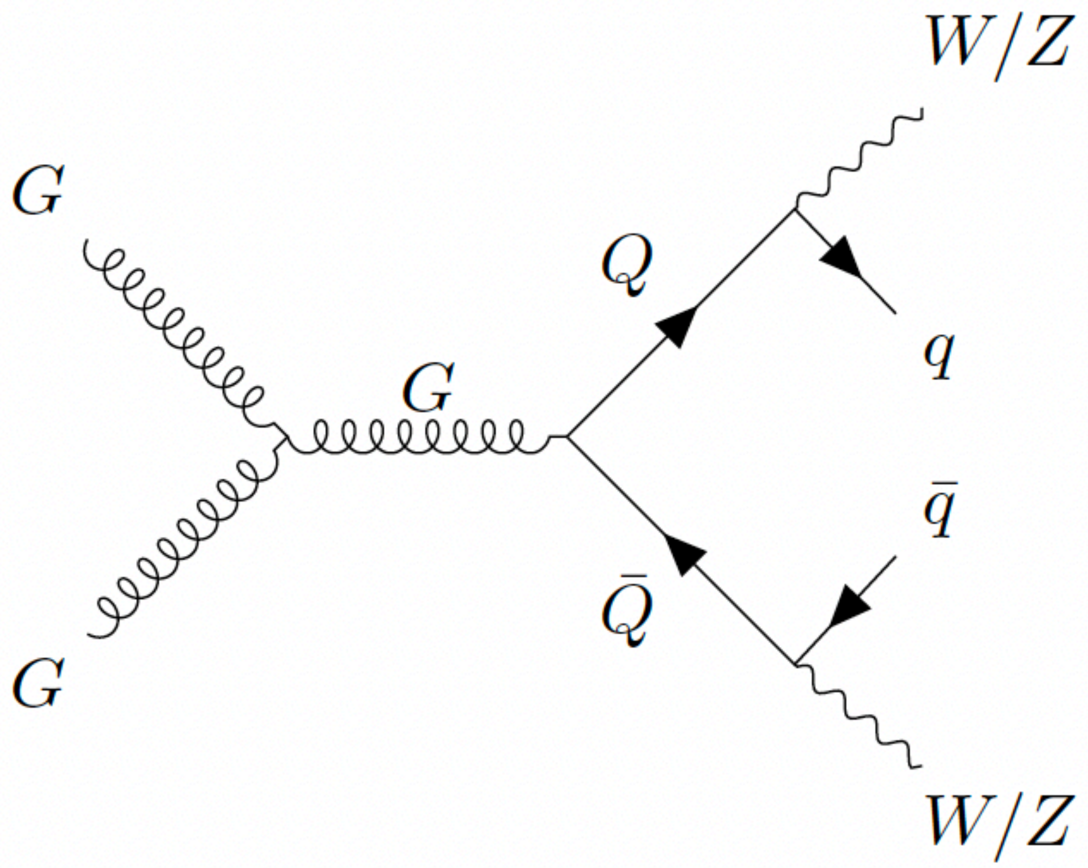
  $M_Q > 1.53$ TeV $\Rightarrow M_Q = \Lambda = 1.6$ TeV;

- Future Colliders:

  [Freitas, Gonçalves, Morais, Pasechnik, 2022] provides

  projections for HL-LHC.

  Sets $M_Q = \Lambda = 2.4$ TeV.



Constraints: ElectroWeak Precision Observables

$$\chi^2 = \sum_{\alpha,\beta} \left(\mathcal{O}_\alpha^{exp} - \mathcal{O}_\alpha^{theo}\right)\sigma_{\alpha\beta}^{-2}\left(\mathcal{O}_\beta^{exp} - \mathcal{O}_\beta^{theo}\right), \qquad \mathcal{O}_\alpha^{theo} = \mathcal{O}_\alpha^{SM} + \delta\mathcal{O}_\alpha^{SMEFT}.$$

$\mathcal{O}_\alpha^{exp}$ → W-pole and Z-pole observables:

- $m_W = 80.379(12)$ GeV;
- $\Gamma_W = 2.085(42)$ GeV;
- $\Gamma_Z = 2.4955(23)$ GeV;
- $\ldots$

$\delta\mathcal{O}_\alpha^{SMEFT}$ → Deviations due to $\mathcal{O}_{\phi q}^{(1)}, \mathcal{O}_{\phi q}^{(3)}, \mathcal{O}_{\phi u}, \mathcal{O}_{\phi d}, \mathcal{O}_{\phi ud}, \mathcal{O}_{\phi D}$ and $\mathcal{O}_{\phi WB}$.

E.g.: $\delta m_W = -v^2 \frac{g_L^2}{4(g_L^2 - g_Y^2)}\mathcal{C}_{\phi D} - v^2 \frac{g_L g_Y}{g_L^2 - g_Y^2}\mathcal{C}_{\phi WB}$.

[de Blas et al, 2019], [Bresó-Pla, Falkowksi, González-Alonso, 2021], [Bernardi et al, 2022], [Allwicher, Isidori, Lizana, Selimović, Stefanek, 2023]

Constraints: Higgs Physics Observables

Current LHC results and HL-LHC projections

$$\chi^2 = \sum_{\alpha,\beta} \left(\mathcal{O}_\alpha^{exp} - \mathcal{O}_\alpha^{theo} \right) \sigma_{\alpha\beta}^{-2} \left(\mathcal{O}_\beta^{exp} - \mathcal{O}_\beta^{theo} \right), \qquad \mathcal{O}_\alpha^{theo} = \mathcal{O}_\alpha^{SM} + \delta\mathcal{O}_\alpha^{SMEFT}.$$

Observable is the Signal Strength : $\mu_\alpha = \dfrac{\sigma_h^{SMEFT}\ \mathrm{BR}^{SMEFT}(h \to \alpha)}{\sigma_h^{SM}\ \mathrm{BR}^{SM}(h \to \alpha)}$

$$= \frac{\sigma_h^{SMEFT}}{\sigma_h^{SM}} \frac{\Gamma_h^{SM}}{\Gamma_h^{SMEFT}} \frac{\Gamma_{h\to\alpha}^{SMEFT}}{\Gamma_{h\to\alpha}^{SM}}$$

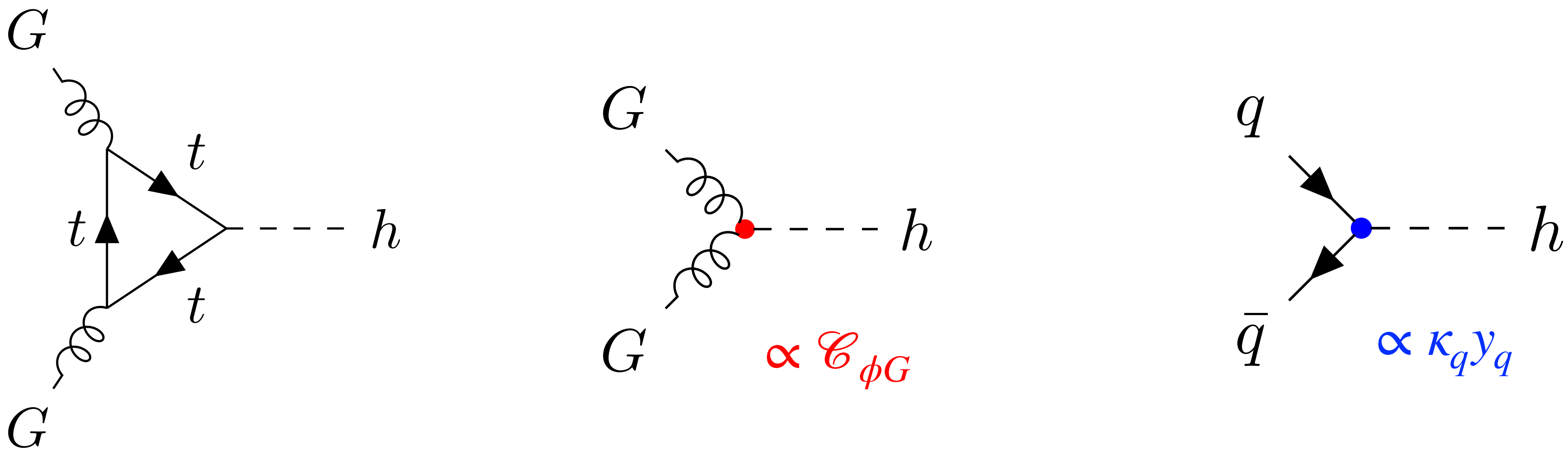
$$\alpha = \gamma\gamma,\ ZZ,\ W^+W^-,\ \mu^+\mu^-,\ \tau^+\tau^-,\ \bar{b}b.$$

[Brivio, Corbett, Trott, 2019], [Alasfar, Corral Lopez, Gröber, 2019], [Cepeda et al, 2019], [Spira, 2021], [CMS Collaboration, 2022]

Constraints: Higgs Physics Observables

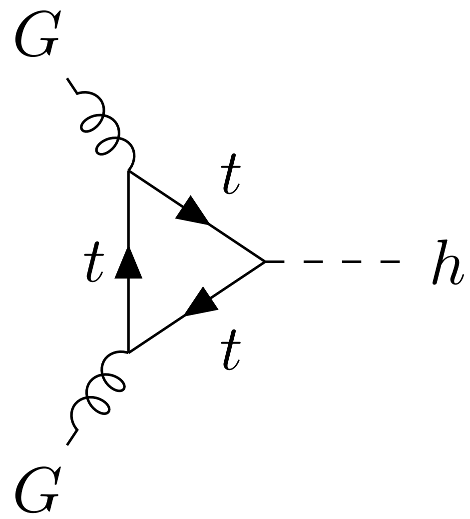
Higgs boson production in SMEFT:

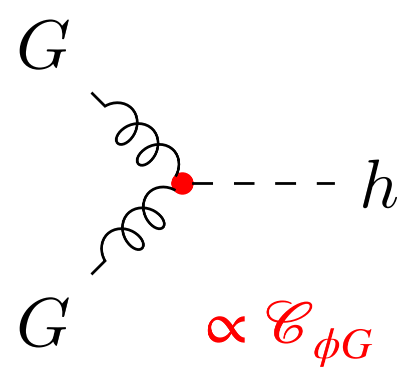
$$\sigma_h^{SMEFT} = \sigma_h^{SM} + \sigma_{GGh}^{SMEFT} + \kappa_u^2\,\sigma_{uuh}^{SM} + \kappa_d^2\,\sigma_{ddh}^{SM}\,.$$

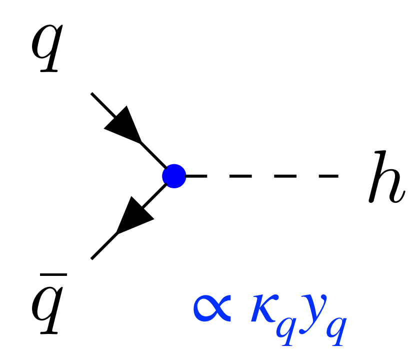


Higgs boson production in SMEFT:

$$\sigma_h^{SMEFT} = \sigma_h^{SM} + \sigma_{GGh}^{SMEFT} + \kappa_u^2\ \sigma_{uuh}^{SM} + \kappa_d^2\ \sigma_{ddh}^{SM}\,.$$







Higgs boson decays in the SMEFT:

$$\Gamma_h^{SMEFT} = \Gamma_h^{SM}(1 + \text{[Brivio, Corbett, Trott, 2019]} + 2v^2\left(\mathrm{BR}(h \to \gamma\gamma) + \mathrm{BR}(h \to GG)\right)\mathscr{C}_h^{kin}) +$$

$$+\Gamma_d^r\kappa_d^2 + \Gamma_u^r\kappa_u^2 + \Gamma_c^{SM}(\kappa_c^2 - 1) + \Gamma_s^{SM}(\kappa_s^2 - 1)$$

Constraints: Higgs Physics Observables

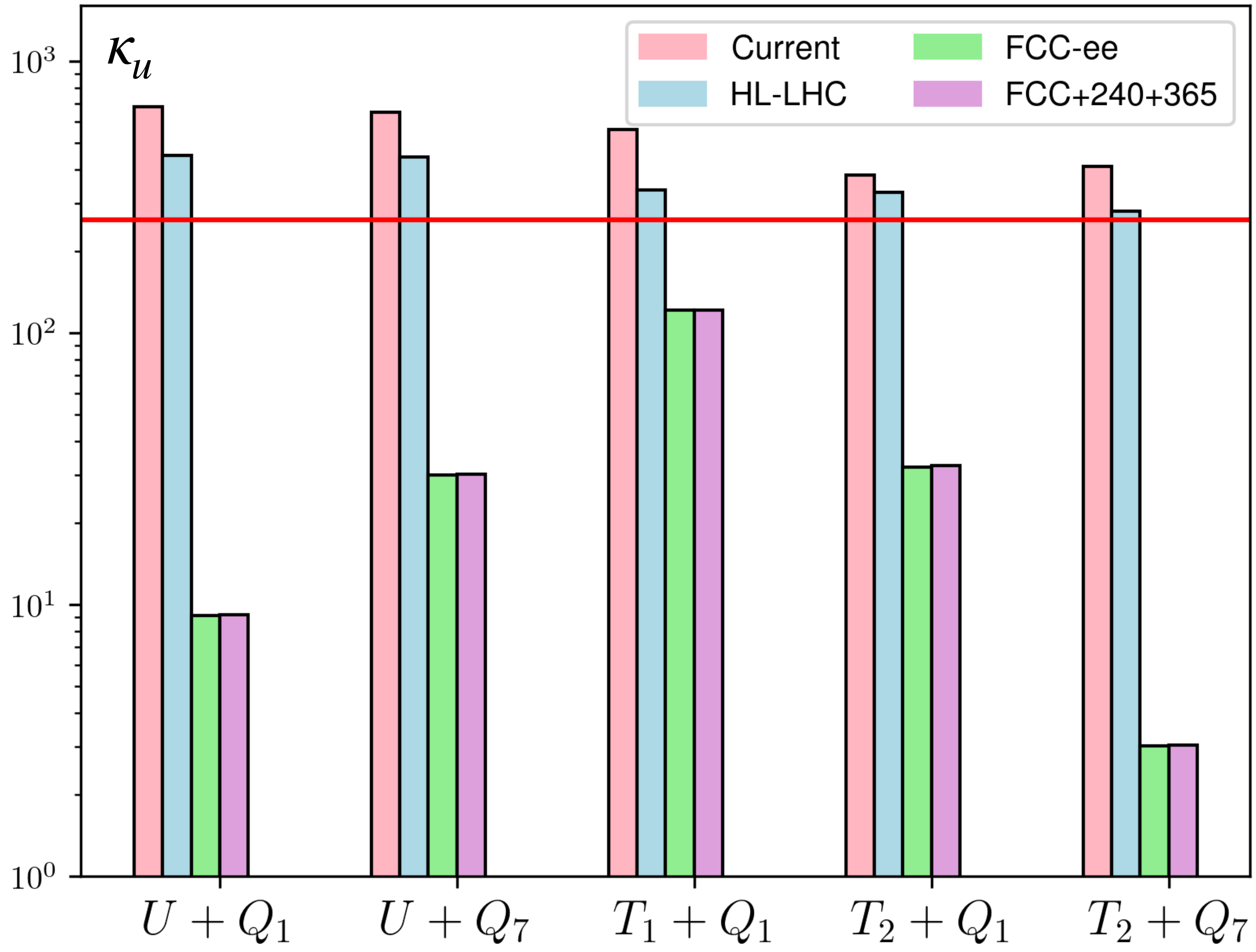
FCC - ee projections

$$\chi^2 = \sum_{\alpha,\beta} \left(\mathcal{O}_\alpha^{exp} - \mathcal{O}_\alpha^{theo} \right) \sigma_{\alpha\beta}^{-2} \left(\mathcal{O}_\beta^{exp} - \mathcal{O}_\beta^{theo} \right), \qquad \mathcal{O}_\alpha^{theo} = \mathcal{O}_\alpha^{SM} + \delta\mathcal{O}_\alpha^{SMEFT} .$$

Quantity	Precision reach [%]	Quantity	Precision reach [%]
$\frac{g_{hZZ}^{\mathrm{SMEFT}}}{g_{hZZ}^{\mathrm{SM}}} - 1$	0.17	$\frac{g_{h\tau\tau}^{\mathrm{SMEFT}}}{g_{h\tau\tau}^{\mathrm{SM}}} - 1$	0.74
$\frac{g_{hWW}^{\mathrm{SMEFT}}}{g_{hWW}^{\mathrm{SM}}} - 1$	0.43	$\frac{g_{h\mu\mu}^{\mathrm{SMEFT}}}{g_{h\mu\mu}^{\mathrm{SM}}} - 1$	9.0
$\frac{g_{h\gamma\gamma}^{\mathrm{SMEFT}}}{g_{h\gamma\gamma}^{\mathrm{SM}}} - 1$	3.9	$\frac{\Gamma_h^{\mathrm{SMEFT}}}{\Gamma_h^{\mathrm{SM}}} - 1$	1.3
$\frac{g_{hbb}^{\mathrm{SMEFT}}}{g_{hbb}^{\mathrm{SM}}} - 1$	0.61		

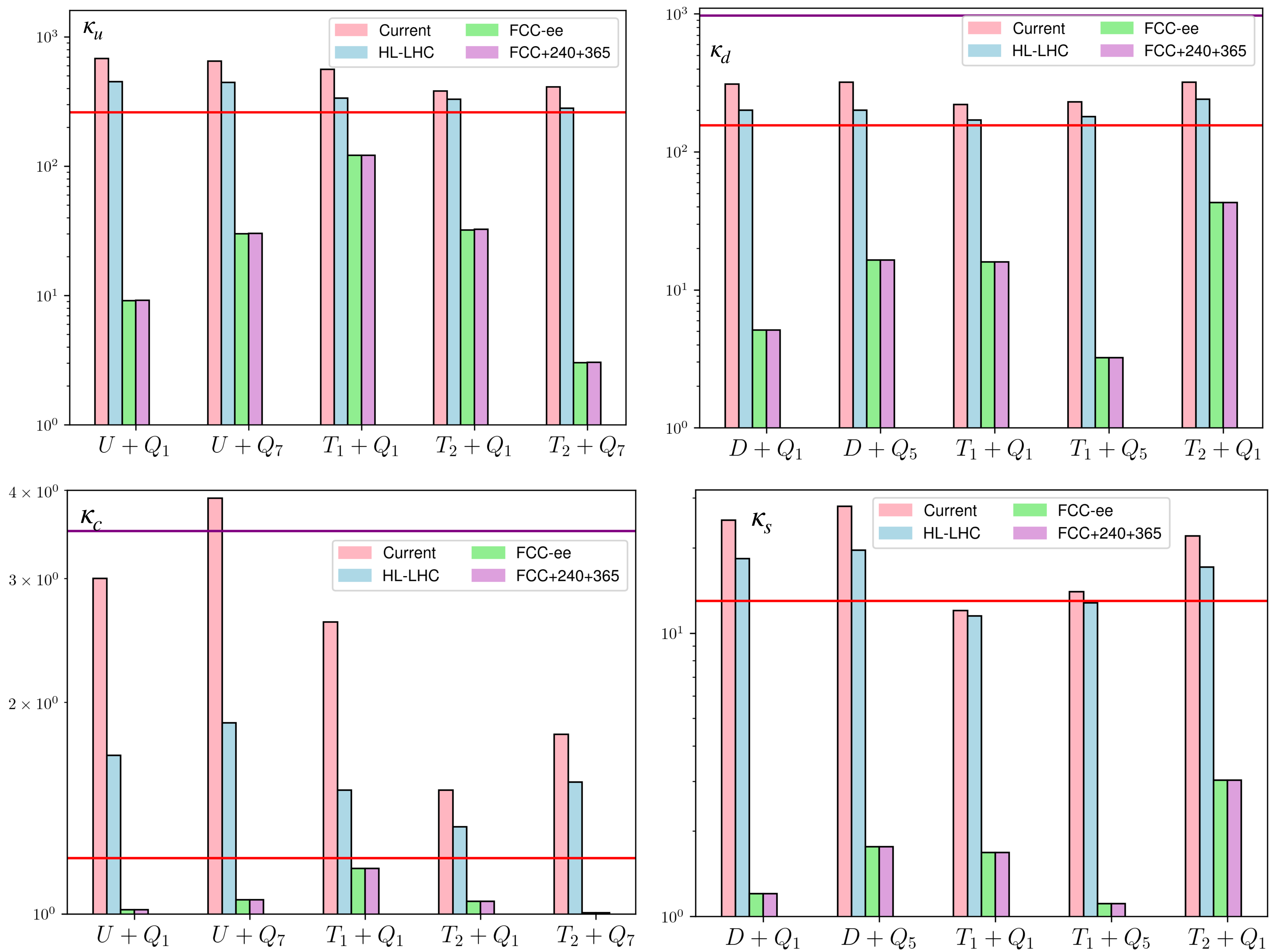
Precision reach on effective Higgs couplings at 240 GeV and 365 GeV runs at FCC-ee [FCC Collaboration, 2018].

Results: up quarks



$\kappa_u = 260$ [Balzani, Gröber, Vitti, 2023]

Results: light quark Yukawa couplings



HL-LHC projections @ 95 % CL

$\kappa_u = 260$

$\kappa_d = 156$

$\kappa_c = 1.2$

$\kappa_s = 13$

[de Blas et al., 2019], [Balzani, Gröber, Vitti, 2023]

Exp. constraints @ 95 % CL

$|\kappa_u| < 2.3 \cdot 10^3$

$|\kappa_d| < 9.7 \cdot 10^2$

$-42 < \kappa_s < 44$

$-4.0 < \kappa_c < 3.5$

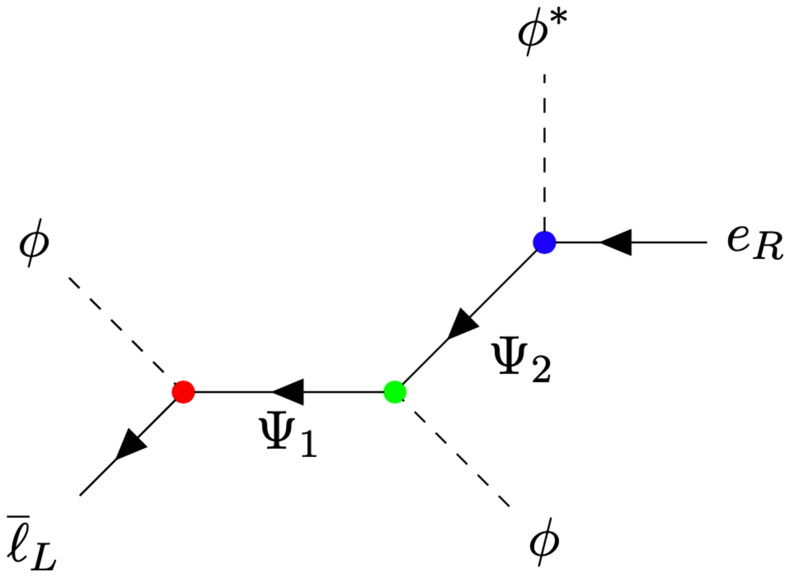
[CMS Collaboration, 2025]

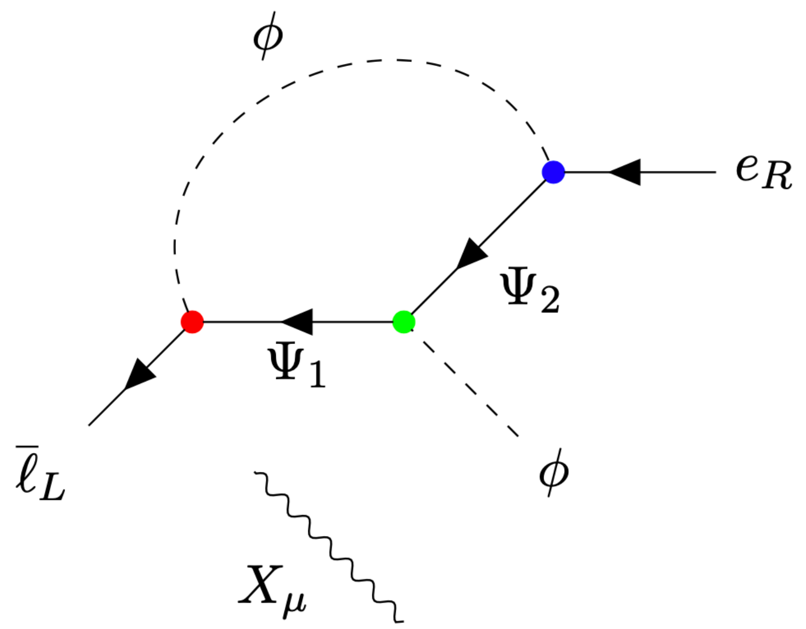
Electron Yukawa coupling enhancements

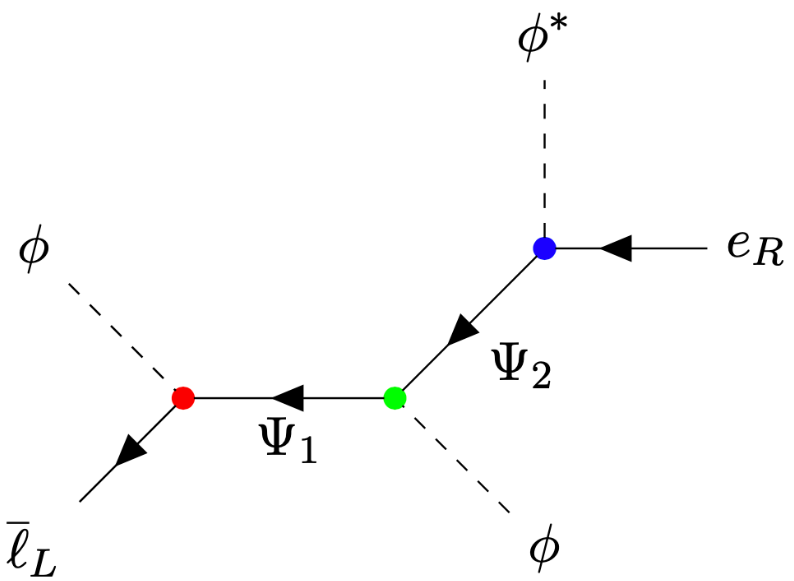
Constraints: Overview

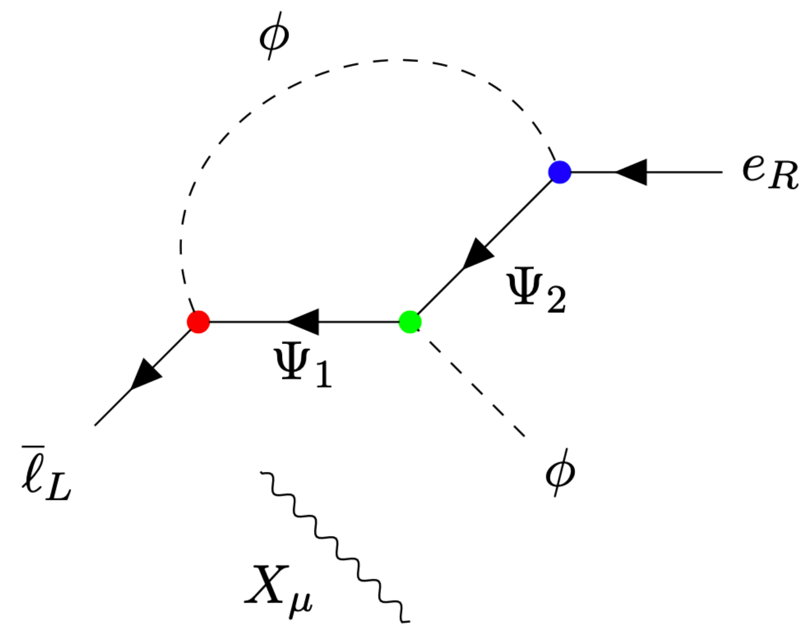
- Current constraints: electron g-2 experiments
- Constraints from future experiments
  - Future electron g-2
  - FCC-ee Tera-Z run
  - FCC-ee Tera-Z plus 240 GeV run

Constraints: Electron g-2









$$a_e = \frac{g_e - 2}{2}$$

Dipoles: $\mathscr{L}_{SMEFT} \supset \mathscr{C}_{eB}(\bar{l}_L \sigma^{\mu\nu} e_R)\phi B_{\mu\nu} + \mathscr{C}_{eW}(\bar{l}_L \sigma^{\mu\nu} e_R)\sigma^I \phi W^I_{\mu\nu}$ + h.c. .

$$\Delta a_e = \eta \frac{m_e^2}{16\pi^2 v^2}(\kappa_e - 1)$$

Current Constraints $\Delta a_e < 5 \cdot 10^{-13}$ [Fan, Myers, Sukra, Gabrielse, 2022]

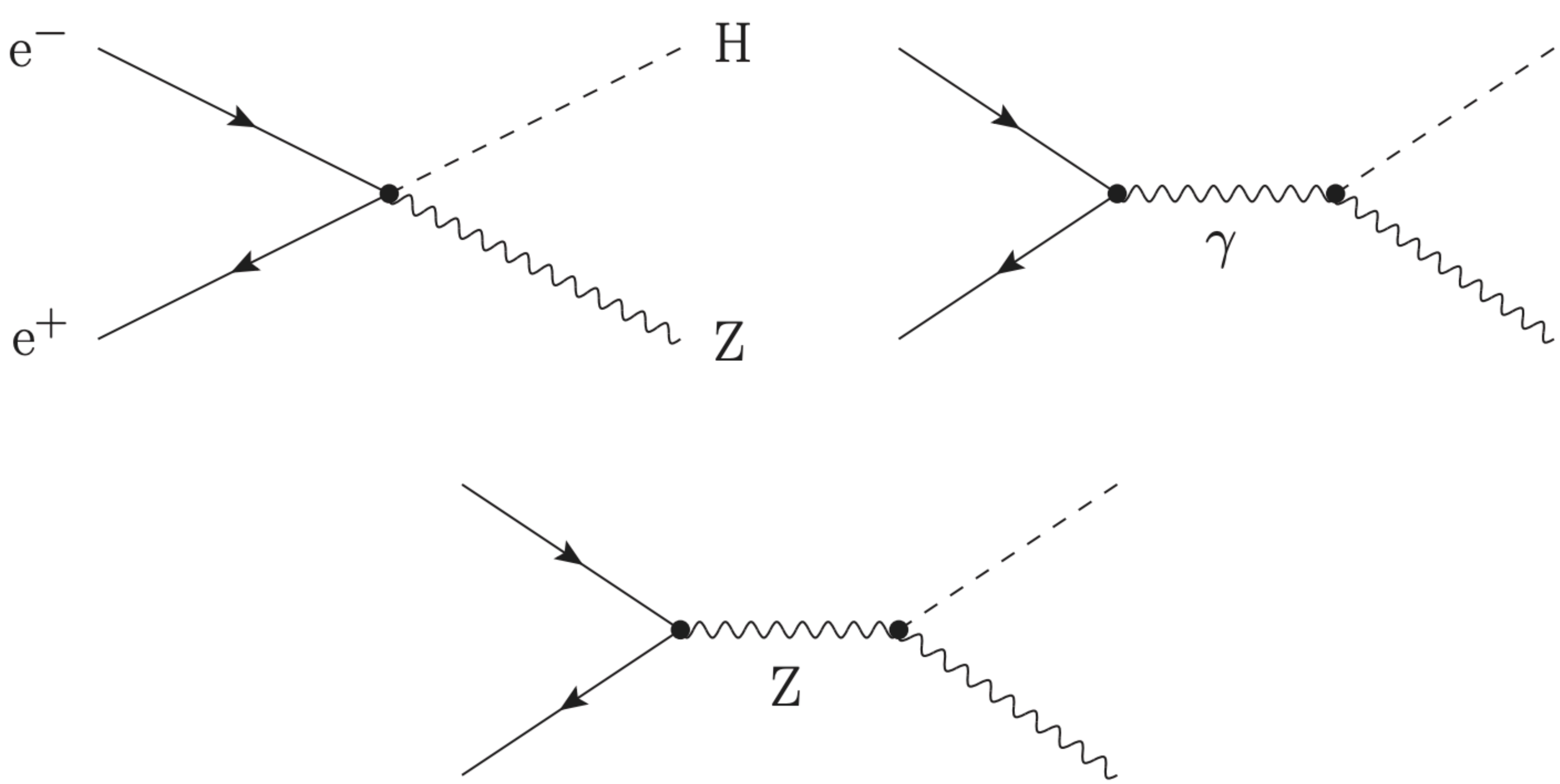
Future Constraints $\Delta a_e < 5 \cdot 10^{-14}$ [Di Luzio, Keshavarzi, Masiero, Paradisi, 2024]

Constraints: FCC-ee

$$\chi^2 = \sum_{\alpha,\beta} \left(\mathcal{O}_\alpha^{exp} - \mathcal{O}_\alpha^{theo} \right) \sigma_{\alpha\beta}^{-2} \left(\mathcal{O}_\beta^{exp} - \mathcal{O}_\beta^{theo} \right), \qquad \mathcal{O}_\alpha^{theo} = \mathcal{O}_\alpha^{SM} + \delta \mathcal{O}_\alpha^{SMEFT}.$$

Electroweak Physics fit: same construction as the one previously shown.

Higgs Physics fit: based on modifications from SMEFT to Zh production and h decays.



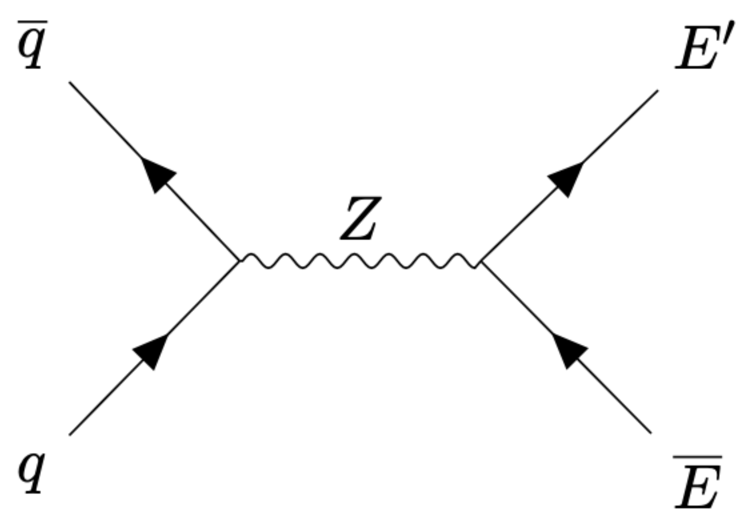
- Uncertainties on $\sigma_{Zh}^{@\,240\,\mathrm{GeV}} \cdot \mathrm{BR}(h \to \alpha)$ from [FCC Collaboration, 2022]
- $\sigma_{Zh}^{@\,240\,\mathrm{GeV}}$ in SMEFT at NLO studied in [Asteriadis, Dawson, Giardino, Szafron, 2024]

LO diagrams from [Asteriadis, Dawson, Giardino, Szafron, 2024]

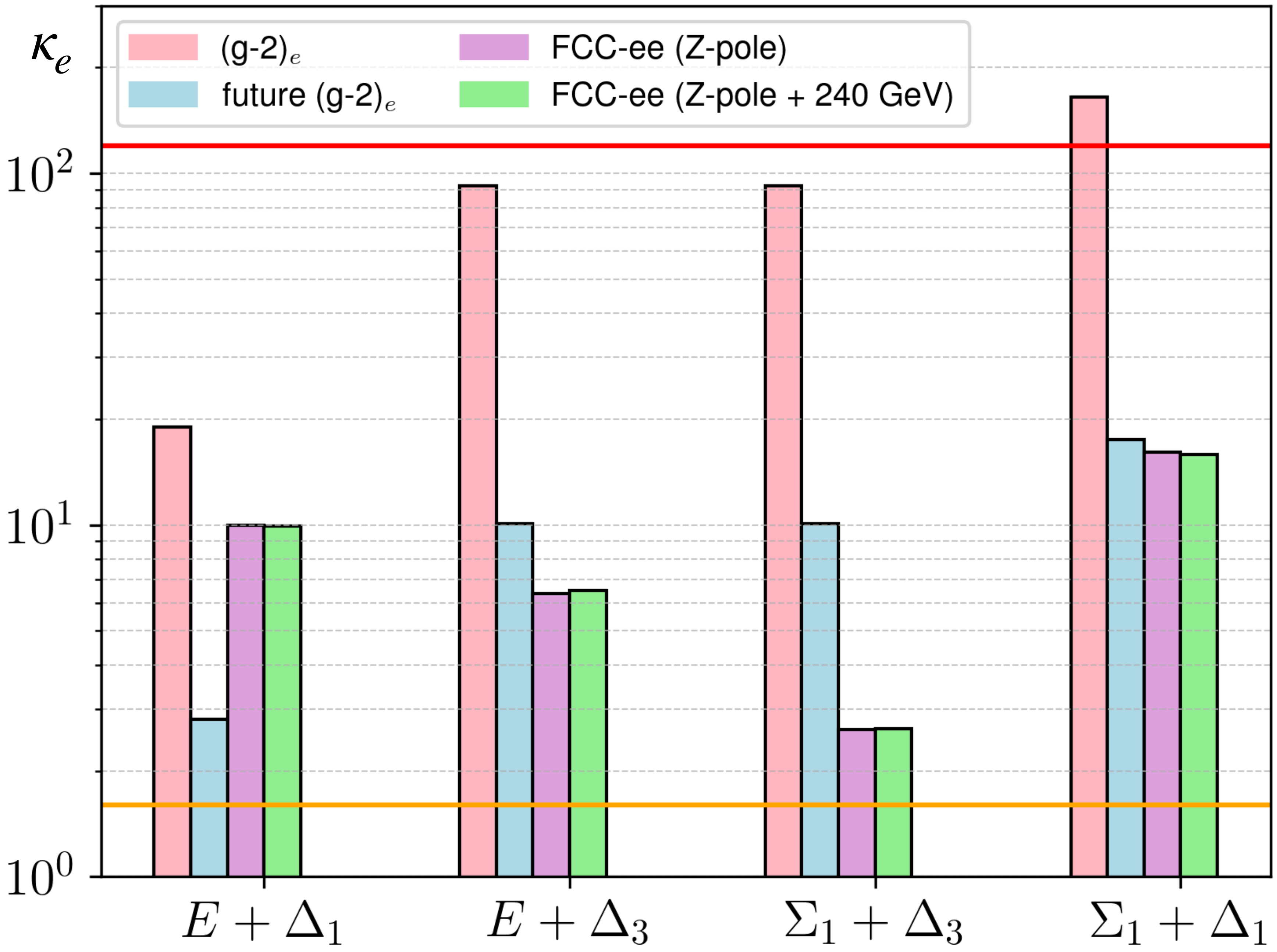
[CMS Collaboration, 2024]: Provides exclusion limits expected for HL-LHC for VLLs coupled to the first generation leptons, as a function of the VLL mass.

Setting $M_{L_1} = M_{L_2} = \Lambda$, we obtain:

Model	$\Delta_1 + E$	$\Delta_3 + E$	$\Sigma_1 + \Delta_3$	$\Sigma_1 + \Delta_1$
Mass [TeV]	1.8	1.9	2.2	2.1



Results: electron



$\kappa_e = 120$ Projections for HL-LHC [Cepeda et al, 2019]

$\kappa_e = 1.6$ Projection for Higgs pole run at FCC-ee [d'Enterria, Poldaru, Wojcik, 2021]

Conclusions and Outlook

- Existence of interplay between light fermion Yukawa enhancements and limits on other SMEFT operators → to be accounted for in future global fits;

- Large enhancements in the light Yukawa couplings are possible given current and future experimental data, even using simplified UV models

	κ_u	κ_d	κ_c	κ_s	κ_e
Current	$\mathcal{O}(600)$	$\mathcal{O}(300)$	$\mathcal{O}(3)$	$\mathcal{O}(20)$	$\mathcal{O}(100)$
FCC-ee proj.	$\mathcal{O}(30)$	$\mathcal{O}(20)$	$\mathcal{O}(1.04)$	$\mathcal{O}(1.8)$	$\mathcal{O}(10)$

- Motivation for dedicated experimental searches.

Thank you!

Back - Up Slides

Formulae

- To guarantee canonical normalisation of the Higgs boson's kinetic term, redefine

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h\left(1 + v^2 \mathscr{C}_\phi^{\text{kin}}\right) \end{pmatrix}, \quad \mathscr{C}_\phi^{\text{kin}} = \left(\mathscr{C}_{\phi\Box} - \frac{1}{4}\mathscr{C}_{\phi D}\right);$$

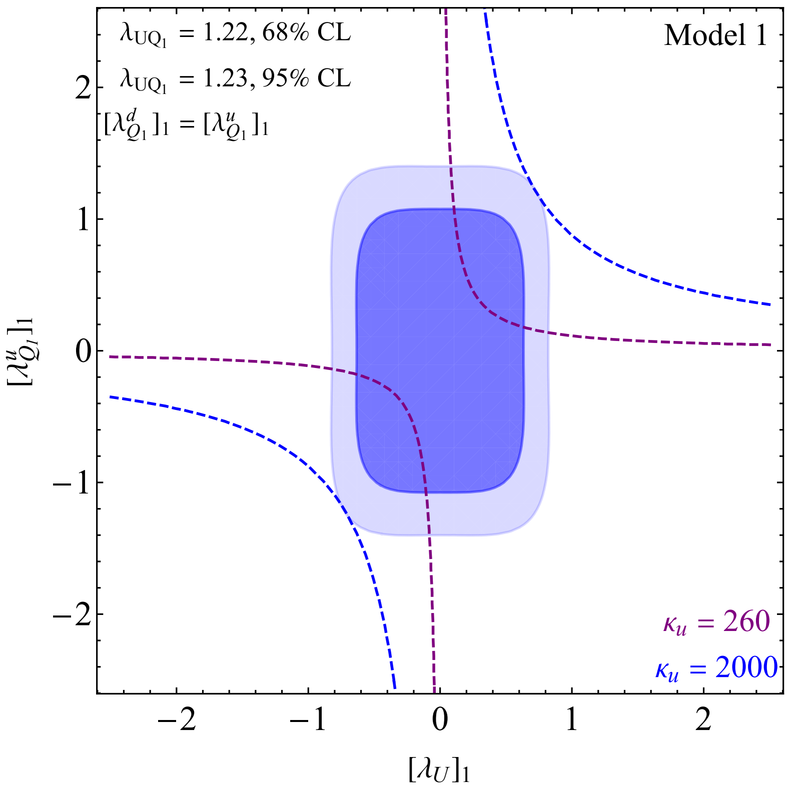
- Complete expression for the coupling deviation:

$$[g_{hf_if_j}] = \frac{m_f}{v}\delta_{ij}\left(1 + v^2 \mathscr{C}_\phi^{\text{kin}}\right) - \frac{v^2}{\sqrt{2}}[\mathscr{C}_{f\phi}]_{ij} \Rightarrow \kappa_{f_i} = 1 + v^2\mathscr{C}_\phi^{\text{kin}} - \frac{v^3}{\sqrt{2}m_{f_i}}[\mathscr{C}_{f\phi}]_{ii}.$$

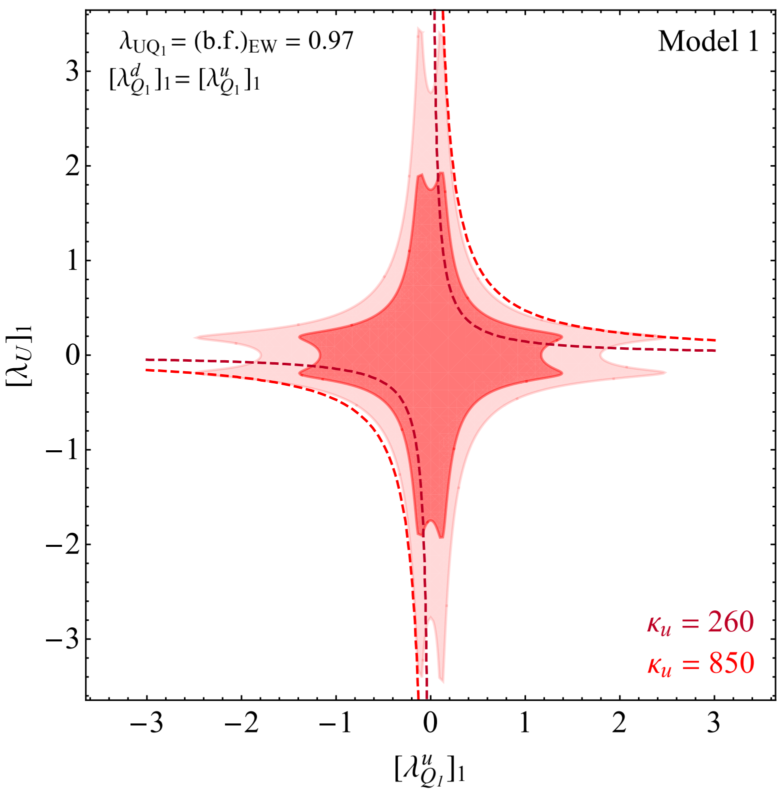
Suppression from
- One-loop generated operators;
- Would modify also heavy particle couplings;
- No $1/m_q$ enhancement.

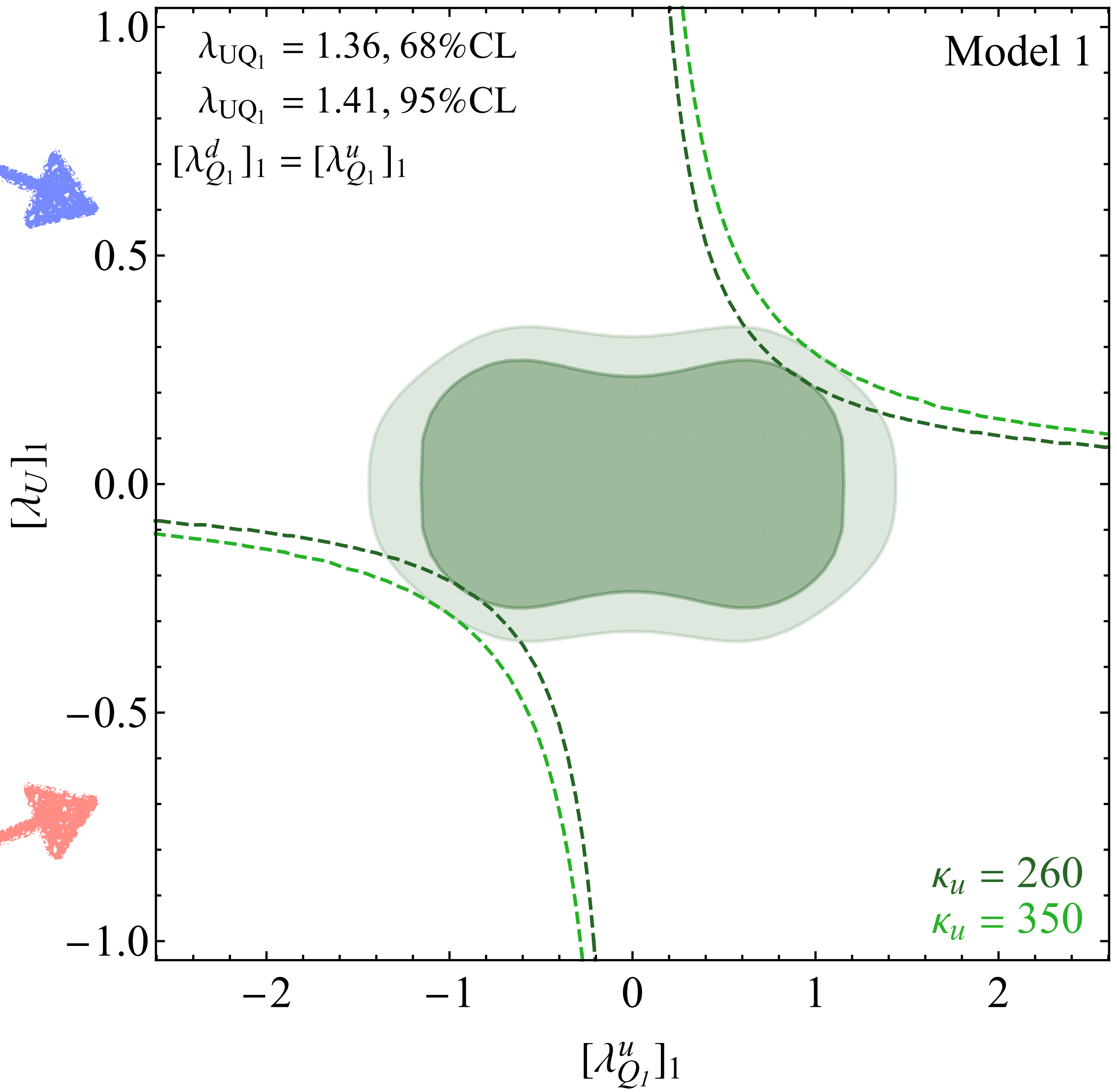
Allowed Parameter Space (Model 1)

EWPOs
+
Flavour



Higgs
Physics
Fit



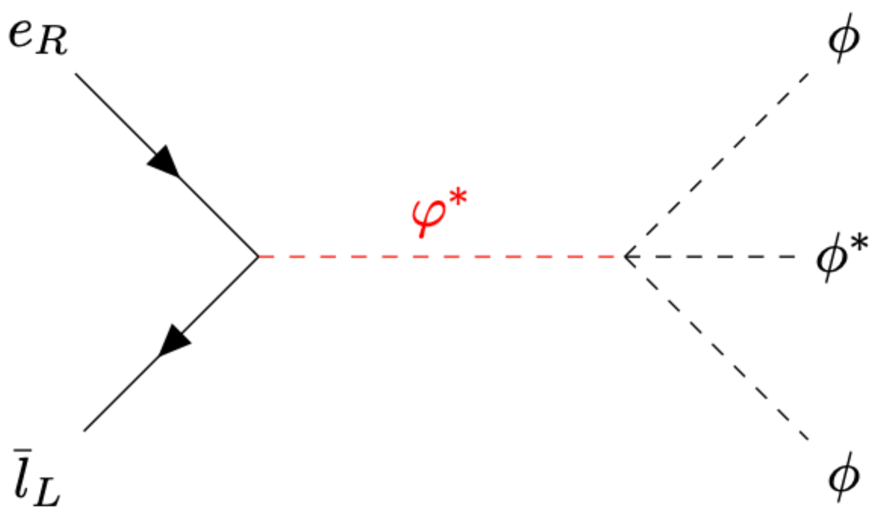


UV models involving only scalars

Singlets	Doublets	Triplets
$S \sim (1,1)_0$	$\varphi \sim (1,2)_{\frac{1}{2}}$	$\Xi \sim (1,3)_0$
		$\Xi_1 \sim (1,3)_1$

[de Blas, Criado, Perez-Victoria, Santiago, 2018]

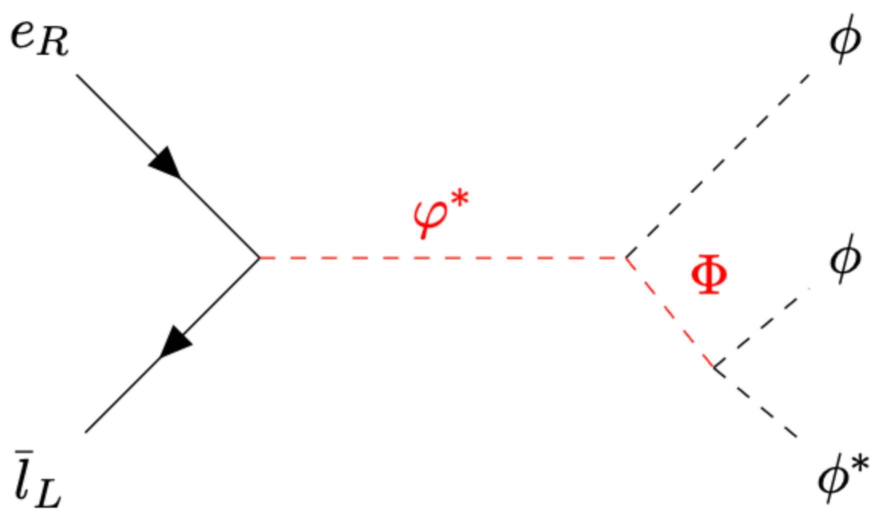
Generates $\mathcal{O}_{\nu\nu}$ ⇒ Not considered



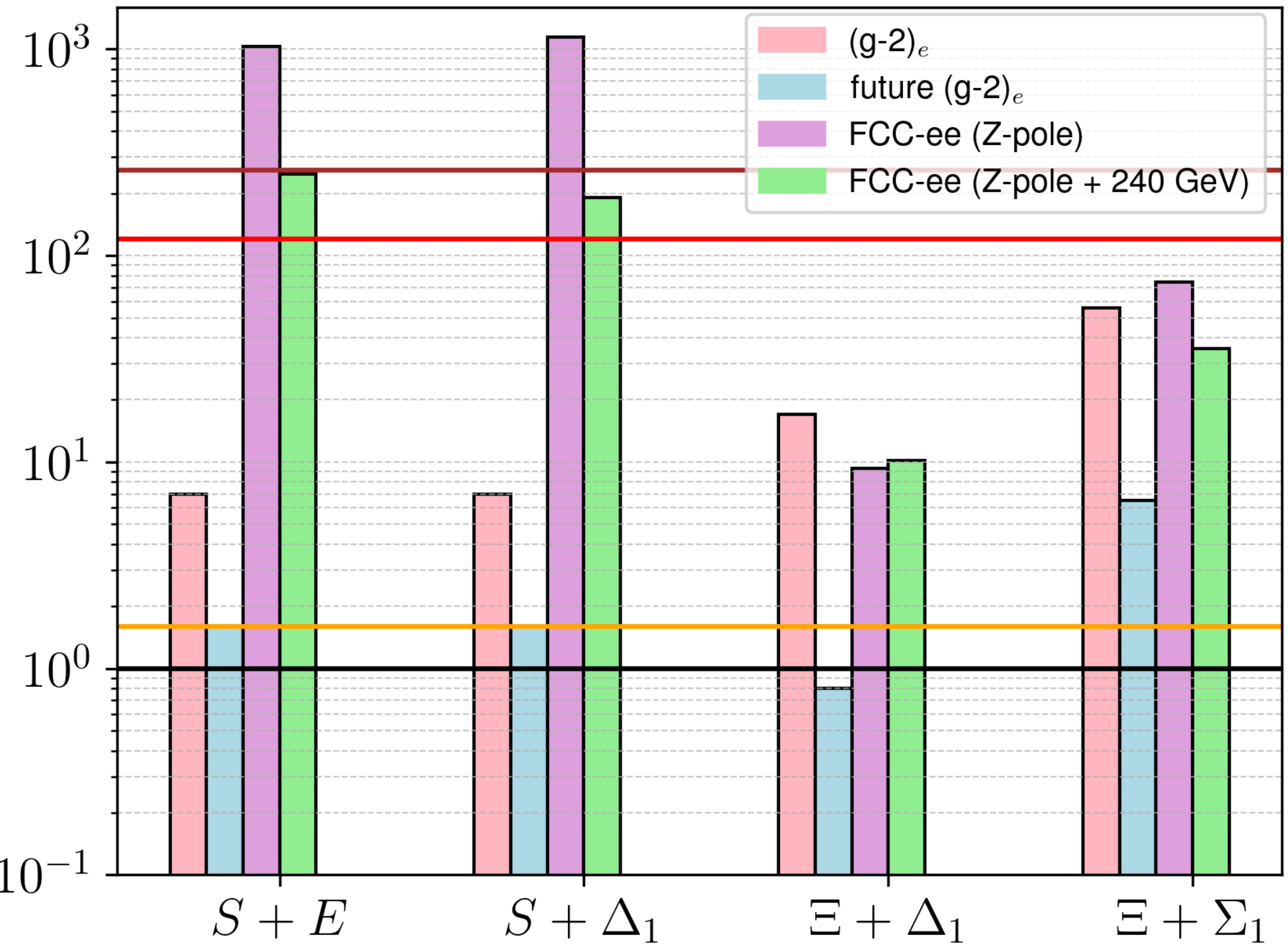
Three available models:

- Single scalar extensions with φ
- Scalar pair extensions with $\varphi + S$ and $\varphi + \Xi_1$

Particle content	φ	$\varphi + S$	$\varphi + \Xi$
κ_e	266	925	323



UV models involving one scalar and one VLL



$\kappa_e = 260$ Current constraint [ATLAS Collaboration, 2019]

$\kappa_e = 120$ Projections for HL-LHC [Cepeda et al., 2019]

$\kappa_e = 1.6$ Projection for Higgs pole run at FCC-ee [d'Enterria, Poldaru, Wojcik, 2021]

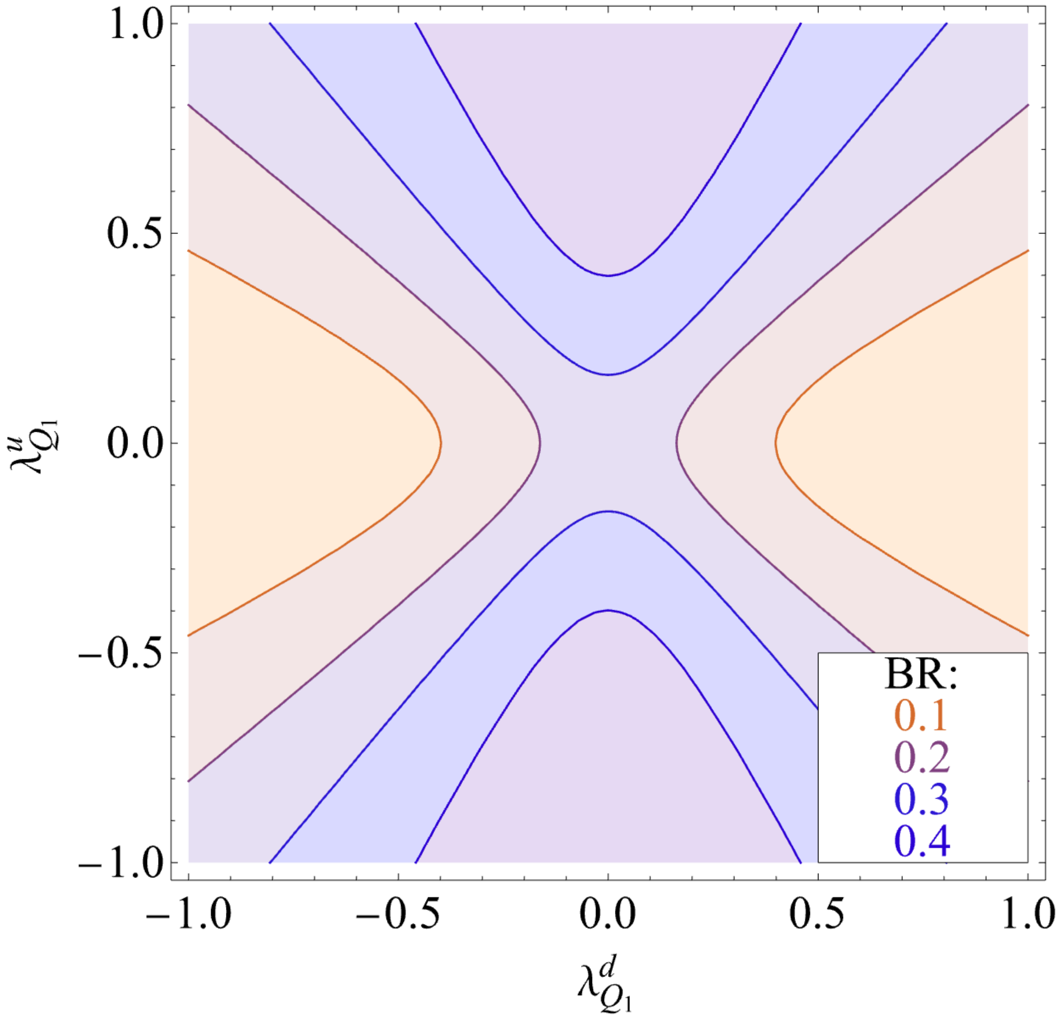
In some models the branching ratios in an appropriate limit can reproduce

$$\text{BR}\left(Q \to Wq : Zq : hq\right) = 0.5 : 0.25 : 0.25$$

E.g., Model 1 with $Q_1 = \begin{pmatrix} T \\ B \end{pmatrix}$ and U :

$$\text{BR}\left(T/U \to hu\right) = \text{BR}\left(T/U \to Zu\right) = \frac{1}{2}\frac{\lambda_U^2 + \lambda_{Q_1}^{u2}}{\lambda_{Q_1}^{u2} + \lambda_{Q_1}^{d2} + 2\lambda_U^2}$$

$$\xrightarrow{\lambda_{Q_1}^{u2} \to \lambda_{Q_1}^{d2}} \frac{1}{4}$$



Branching Ratios

In some models the branching ratios in an appropriate limit can reproduce

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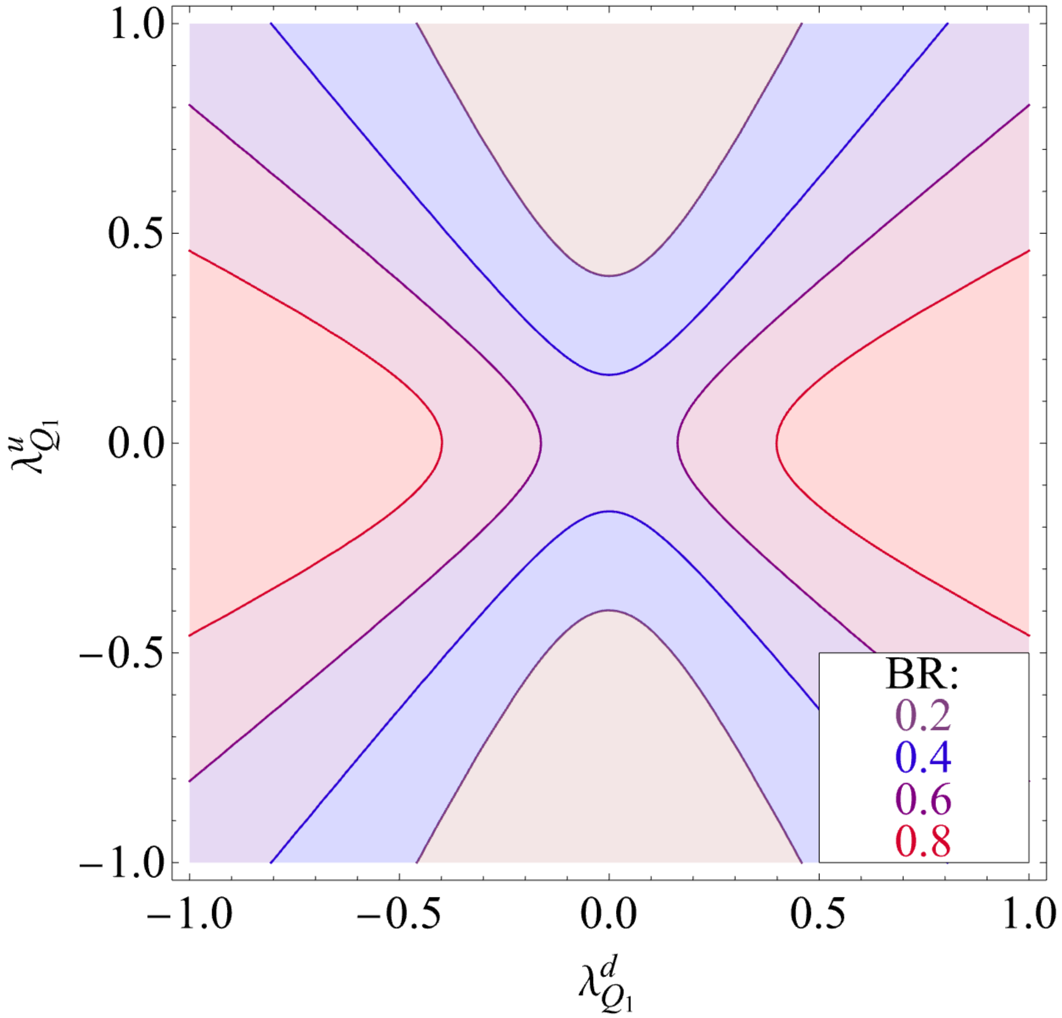
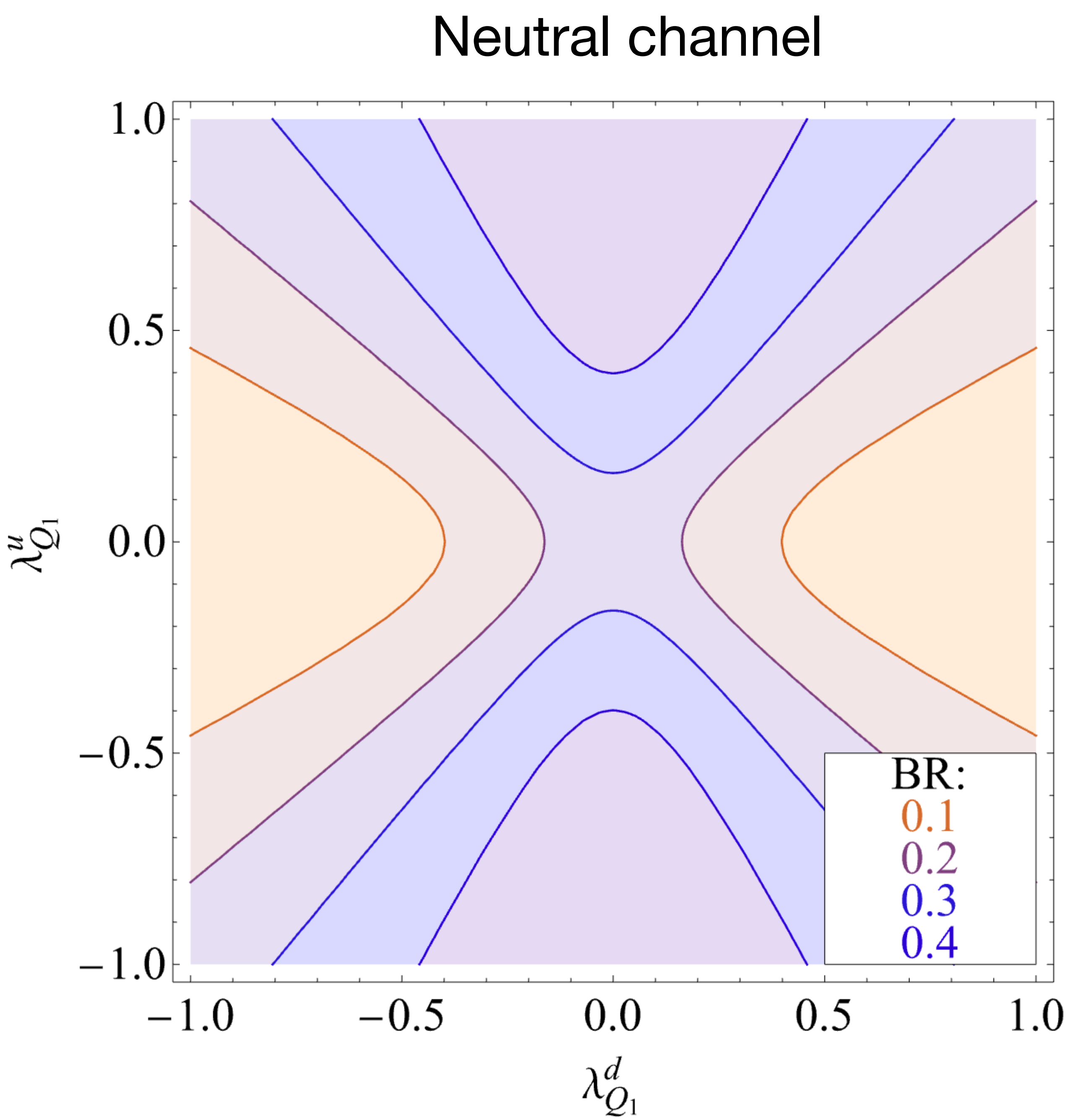
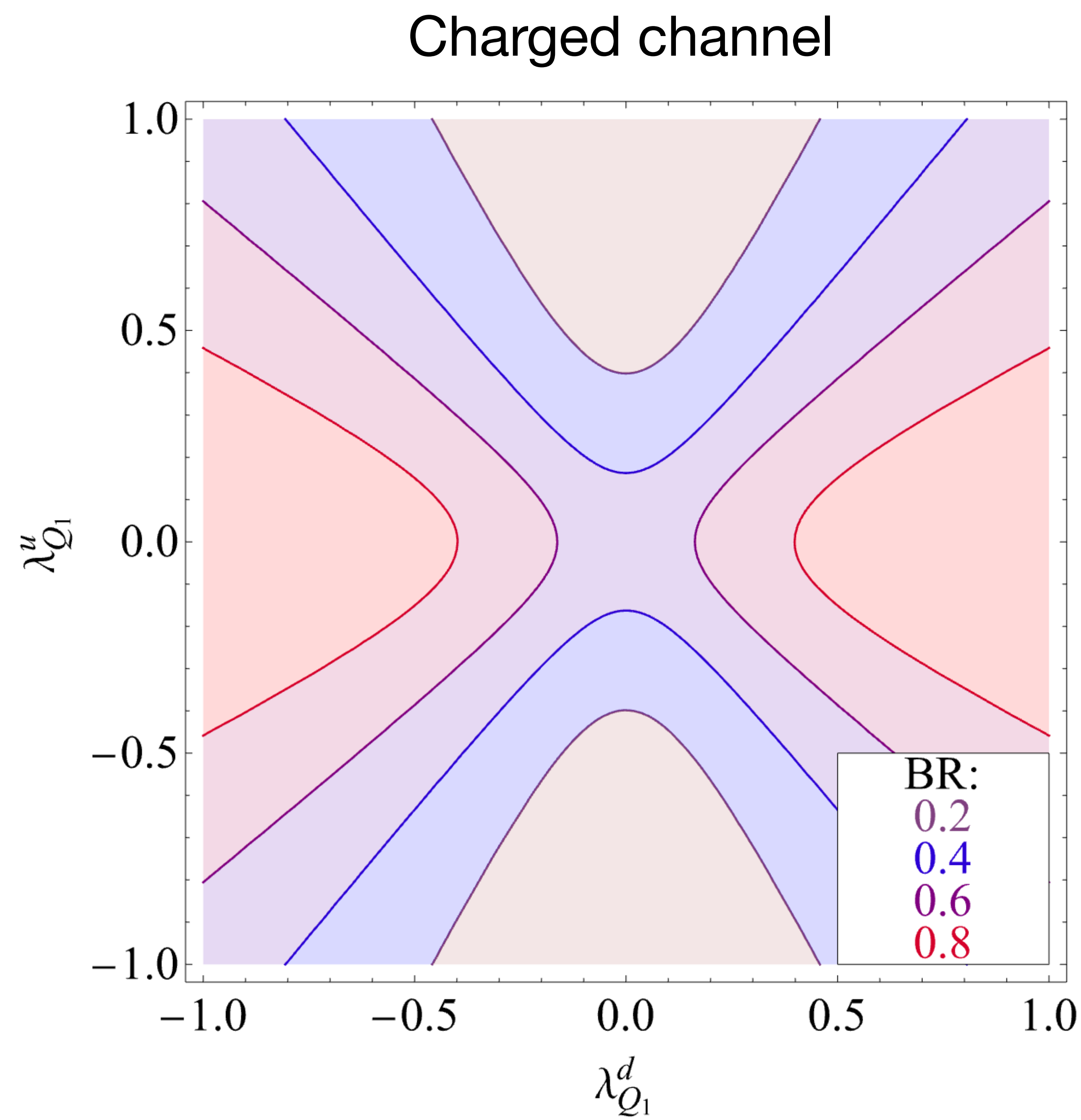
E.g., Model 1 with $Q_1 = \begin{pmatrix} T \\ B \end{pmatrix}$ and U :

$$\text{BR}\left(T/U \to W^+ d\right) = \frac{\lambda_U^2 + \lambda_{Q_1}^{d\,2}}{\lambda_{Q_1}^{u\,2} + \lambda_{Q_1}^{d\,2} + 2\lambda_U^2} \xrightarrow{\lambda_{Q_1}^{u2} \to \lambda_{Q_1}^{d2}} \frac{1}{2}$$




Neutral channel
1.0
0.5
0.0
−0.5
−1.0
$\lambda^u_{Q_1}$
−1.0
−0.5
0.0
0.5
1.0
$\lambda^d_{Q_1}$
BR:
0.1
0.2
0.3
0.4


Charged channel
1.0
0.5
0.0
−0.5
−1.0
$\lambda^u_{Q_1}$
−1.0
−0.5
0.0
0.5
1.0
$\lambda^d_{Q_1}$
BR:
0.2
0.4
0.6
0.8