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

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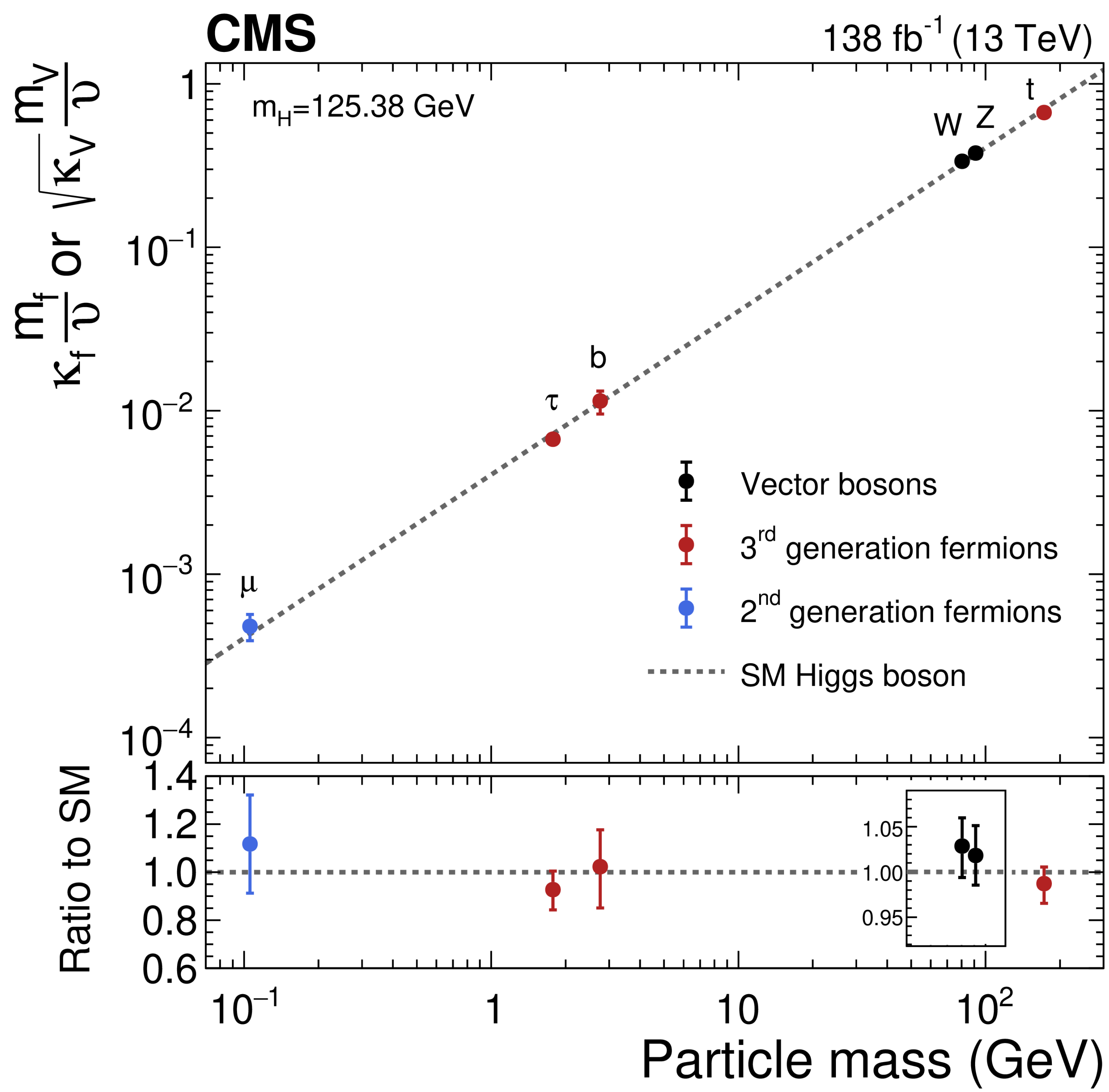
Higgs boson couplings

- ✓ 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: $\kappa_f = \frac{g_{hff}}{g_{hff}^{SM}}$



[CMS Collaboration, 2022]

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

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

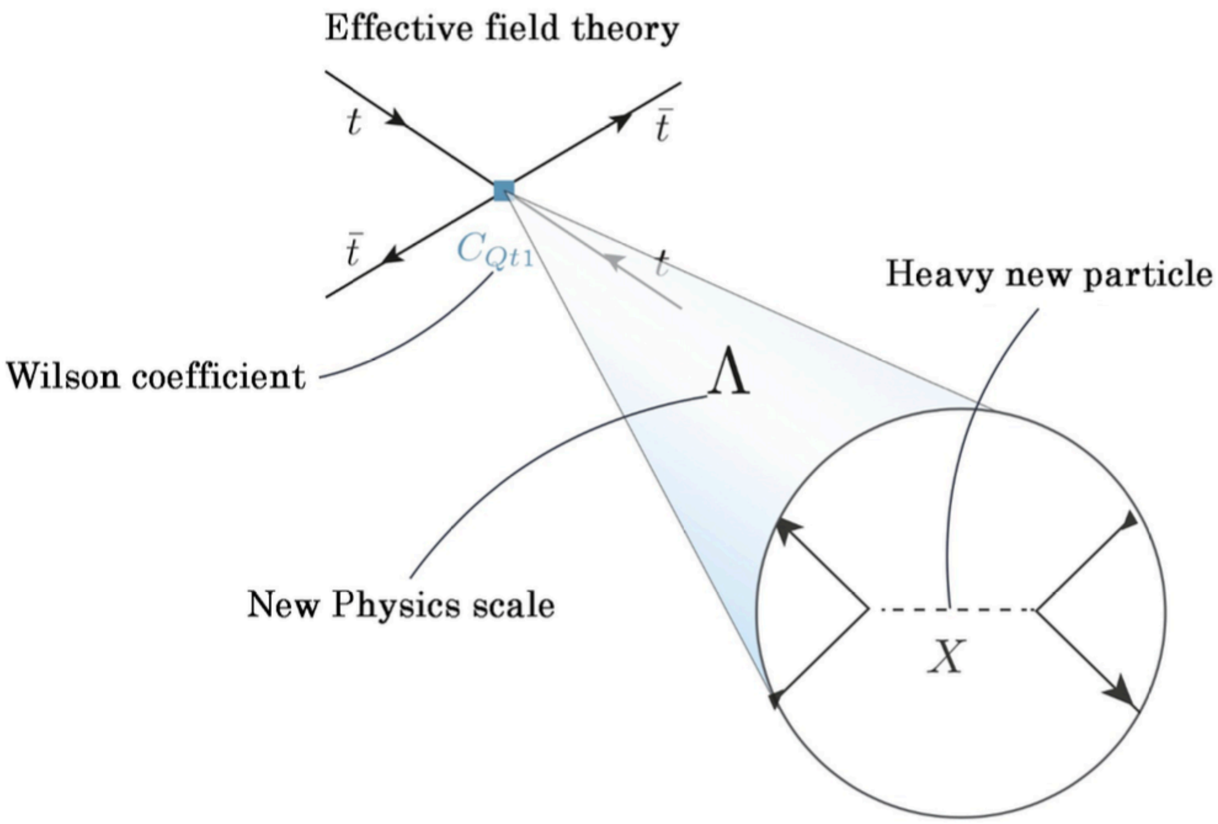


Figure courtesy of L. Alasfar

Standard Model Effective Field Theory

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

1. Identify deviations from SM predictions:

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

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].

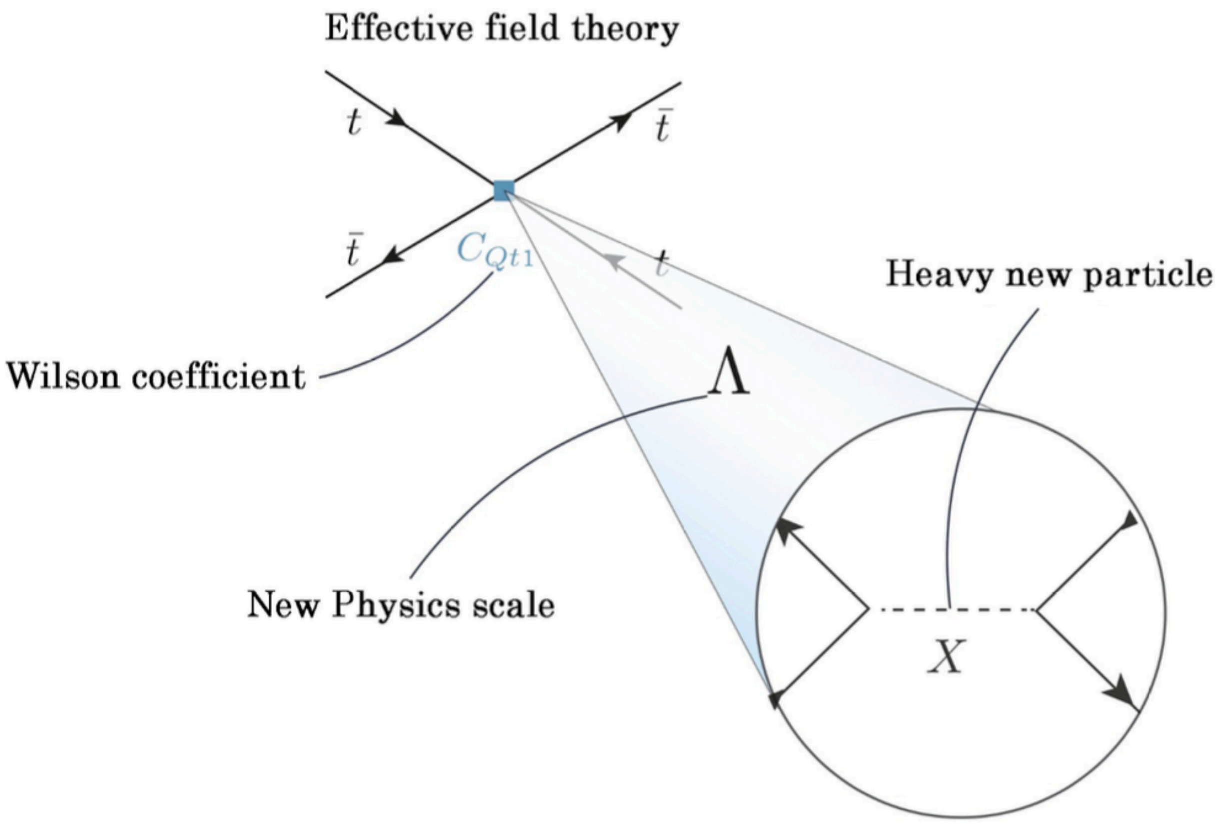


Figure courtesy of L. Alasfar

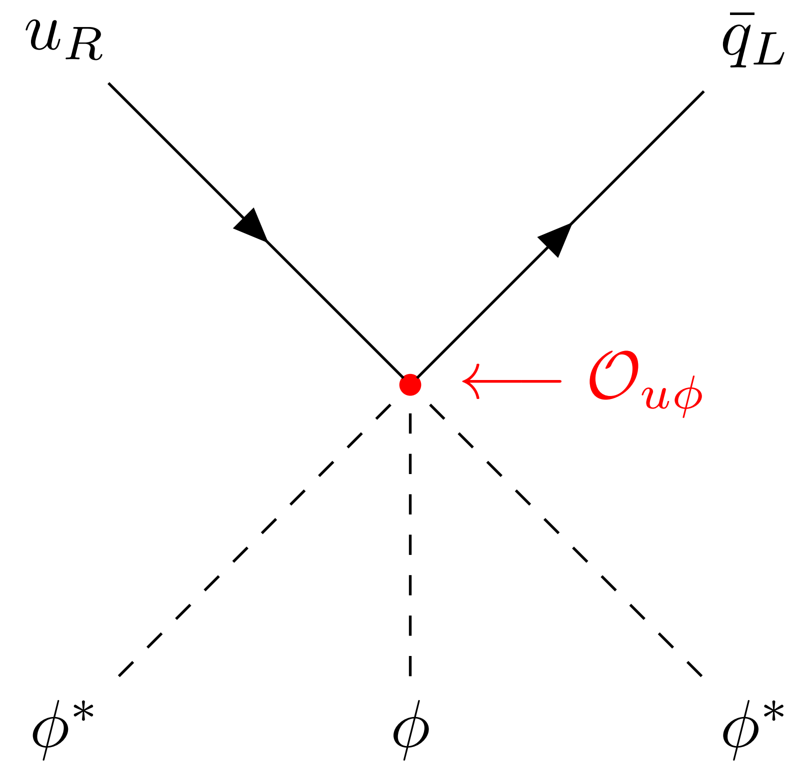
$$\mathscr{L}^{d=6}_{SMEFT} = \mathscr{L}_{SM} + \sum_{i=1}^{n_6} \mathscr{C}_i^{(6)}(\mu)\ \mathscr{O}_i^{(6)}\,, \qquad \left[\mathscr{C}_i^{(6)}\right] = -2\,.$$

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

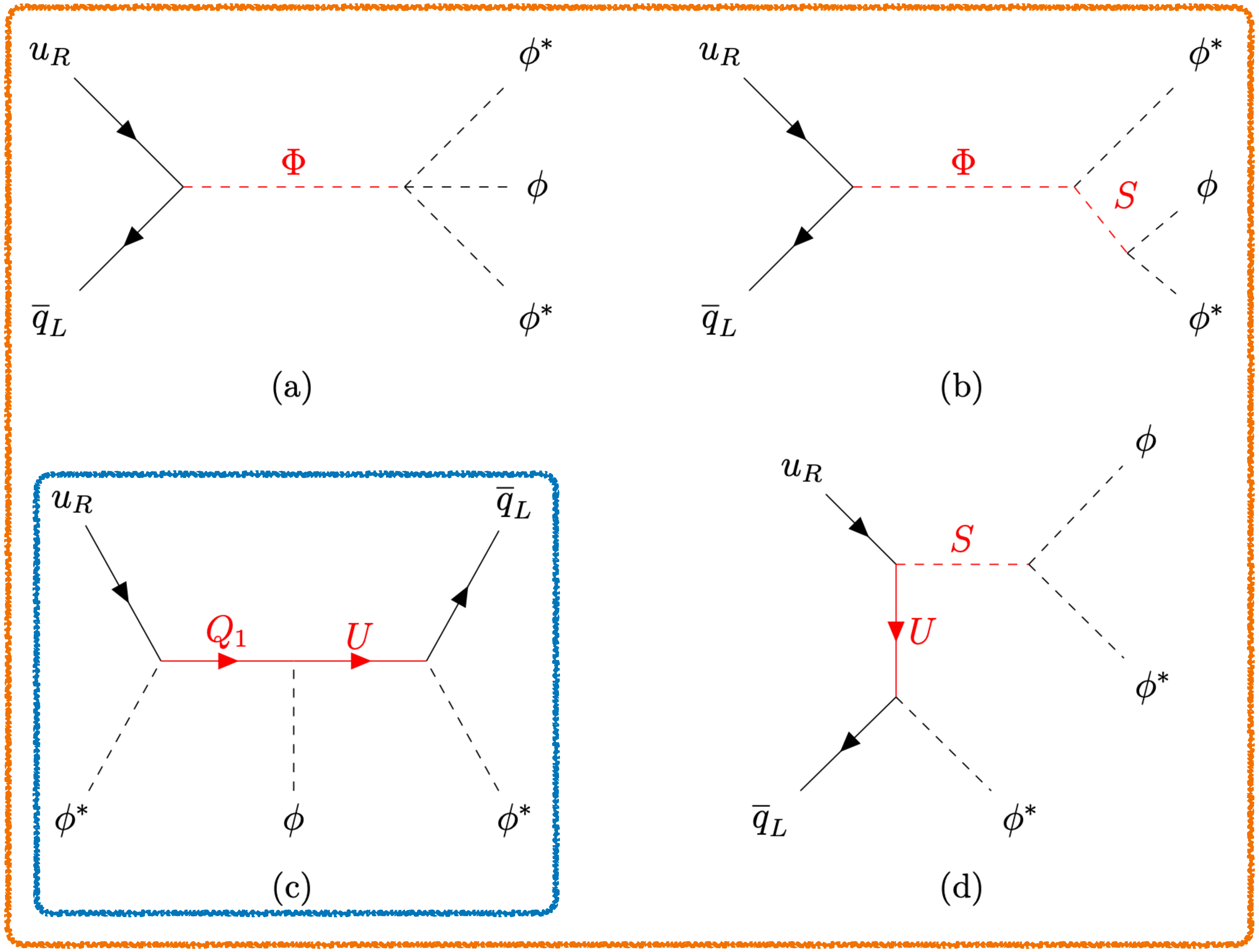
Goal: identify UV models generating unsuppressed contributions to $\mathcal{O}_{f\phi}$:

(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]

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

$$\mathscr{L}_{\rm UV} \supset \sum_{i=1,2} \lambda_{Q_i}\phi\, Q_i\, q + \lambda_{Q_1Q_2}\phi\, Q_1\, Q_2$$

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]

SMEFT operators from UV Models with VLF pairs

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

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

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

- Operators generated at the one loop level:

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

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 ($f = e, u, d$):

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

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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

$M_Q > 1.53$ TeV

Higgs Physics

Observables:

Higgs boson production

and decays

Constraints: Overview

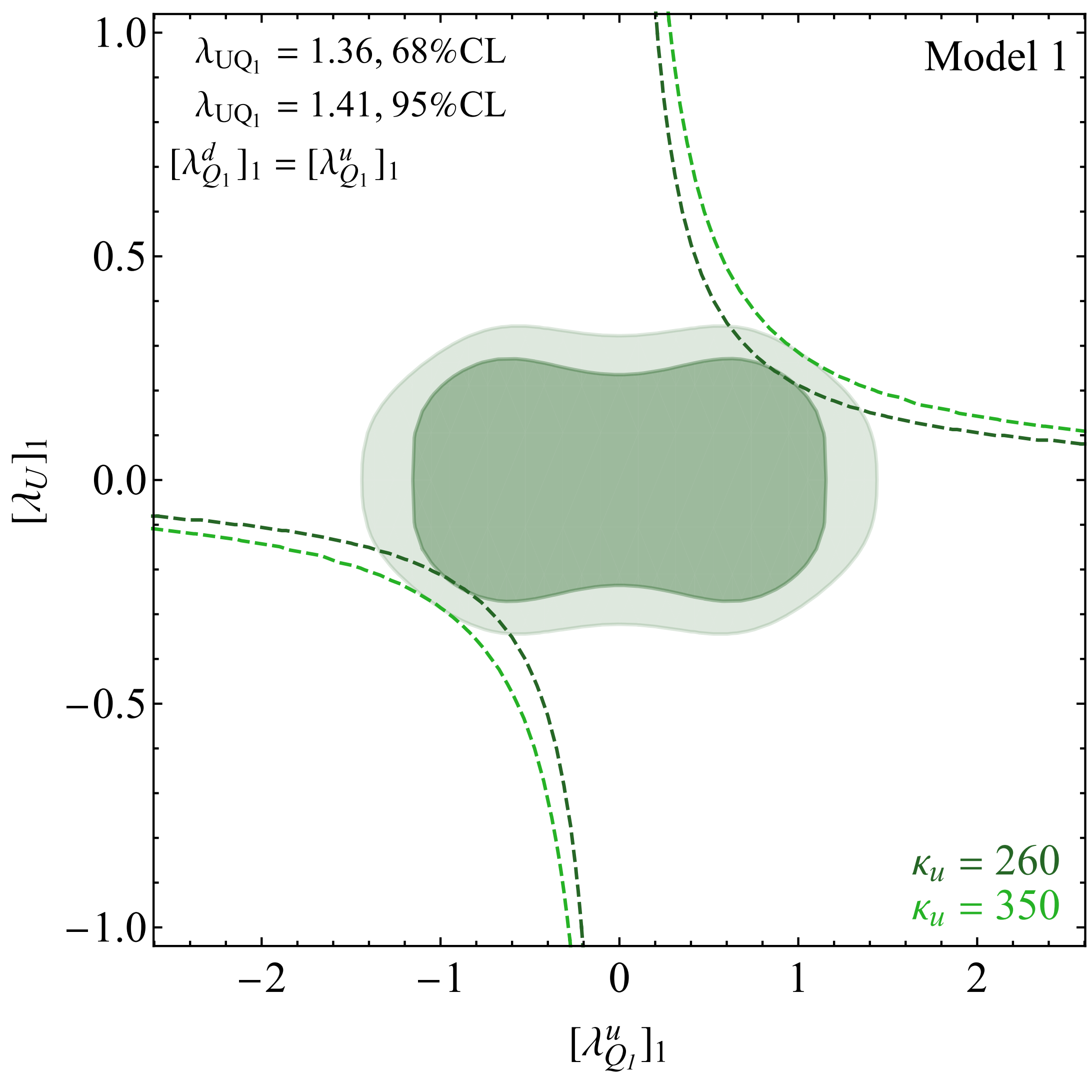
Flavour Physics

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

CKM

EWPOs

quark couplings to $W^\pm$ and Z



68 % CL

95 % CL

Direct Searches

$M_Q > 1.53$ TeV

Higgs Physics Observables:

Higgs boson production and decays

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

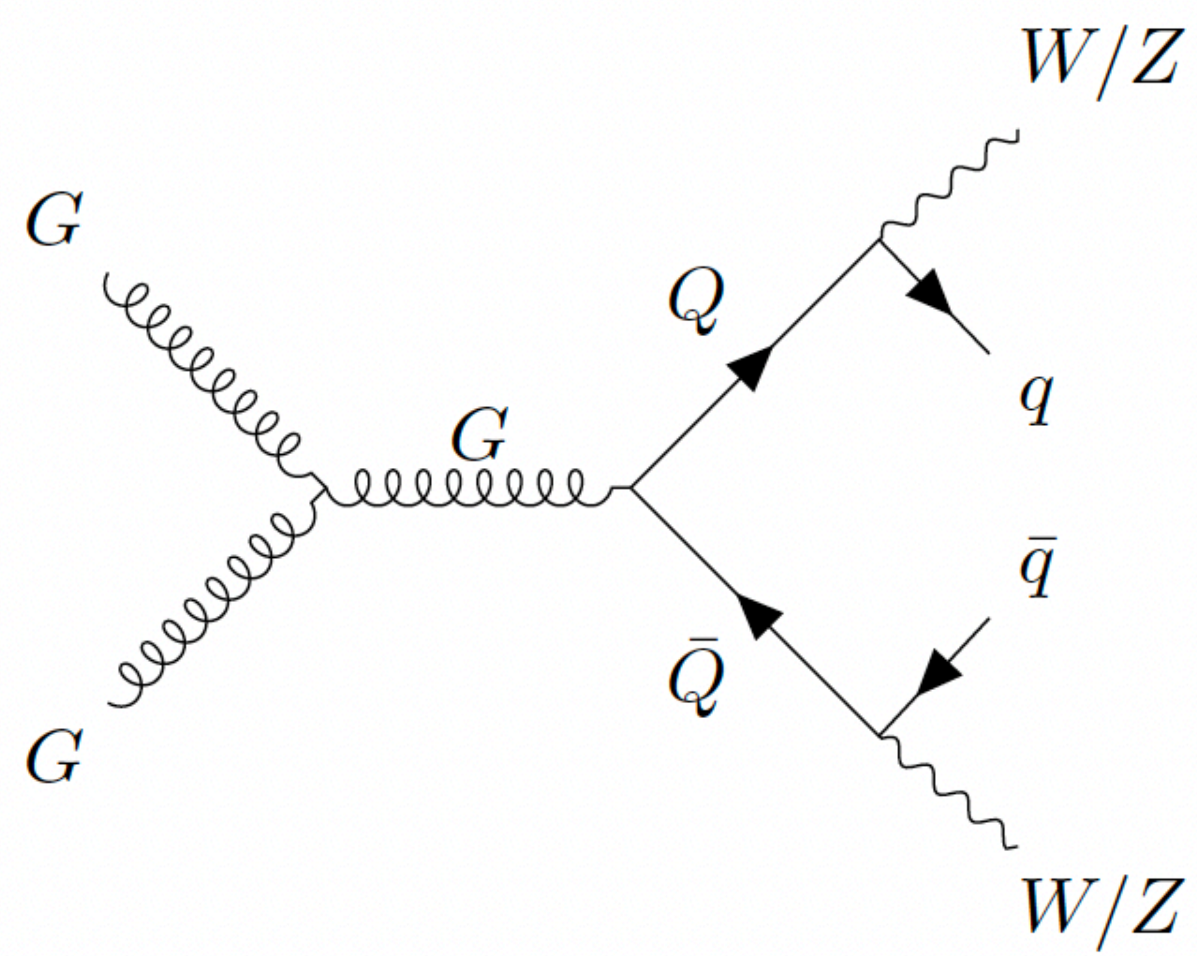
$$S_{11} = |V_{i1}|^2 + |V_{i2}|^2 + |V_{i3}|^2 = 0.9984 \pm 0.0007$$

[Particle Data Group, 2024]

Lower bounds on masses

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

[ATLAS Collaboration, 2024]: Search of VLQs coupled to light quarks.



Focus on charged decay channel, assuming:

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

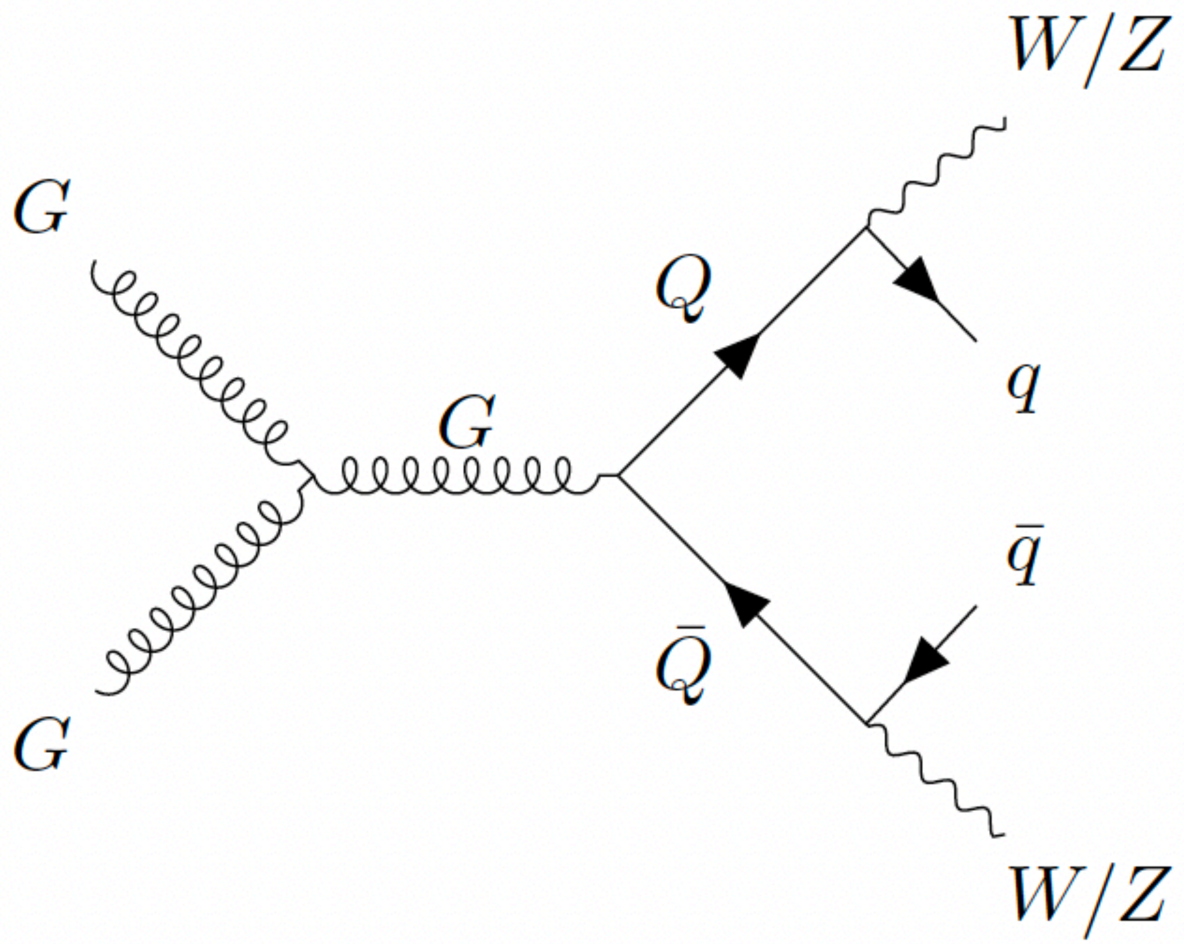
  $\Rightarrow M_Q > 1.15$ TeV at $95\ \%$ C.L.

- BR $\left(Q \to Wq\right) = 1$

  $\Rightarrow M_Q > 1.53$ TeV at $95\ \%$ C.L.

Constraints: Direct searches for Vector-like Quarks

[ATLAS Collaboration, 2024]: Search of VLQs coupled to light quarks.



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- BR $\left(Q \to Wq\right) = 1$

  $\Rightarrow M_Q > 1.53$ TeV at $95\,\%$ C.L.

Electric charge conservation: $\begin{array}{l} Q_{\frac{5}{3}} \to W^+u \\ Q_{-\frac{4}{3}} \to W^-d \end{array} \Rightarrow M_Q = \Lambda = 1.6\,\text{TeV}\,.$

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

[Bresó-Pla, Falkowksi, González-Alonso, 2021] , [Allwicher, Isidori, Lizana, Selimović, Stefanek, 2023]

Constraints: Higgs Physics Observables

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

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

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

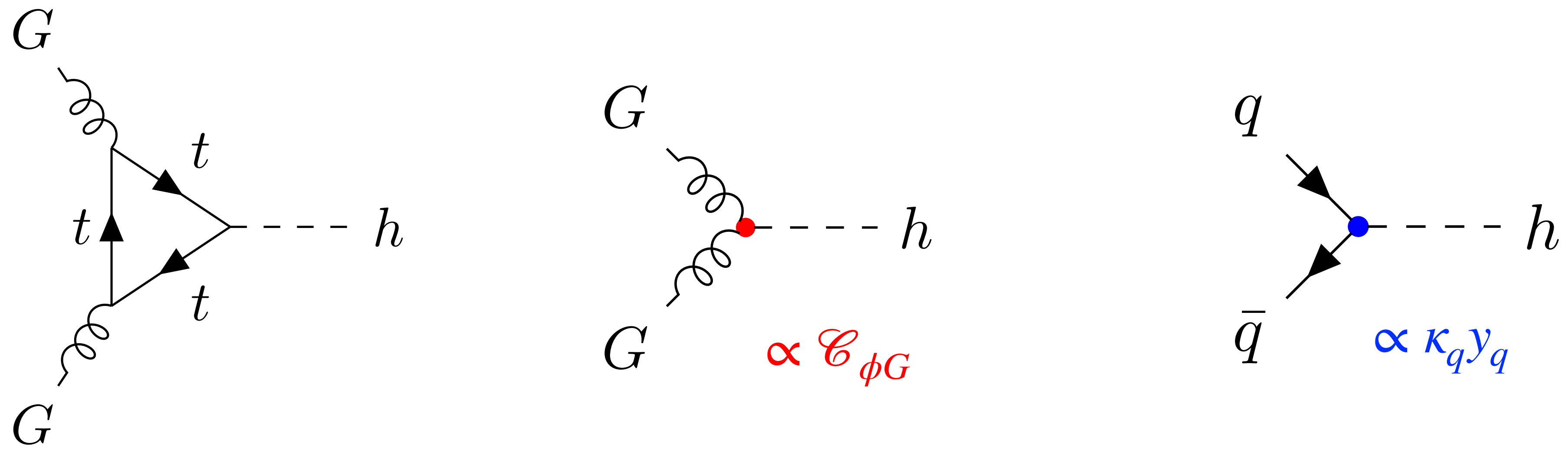
$$\alpha = \gamma\gamma,\ ZZ,\ W^+W^-,\ \mu^+\mu^-,\ \tau^+\tau^-,\ \bar{b}b.$$

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

Constraints: Higgs Physics Observables

Higgs boson production in SMEFT:

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



Constraints: Higgs Physics Observables

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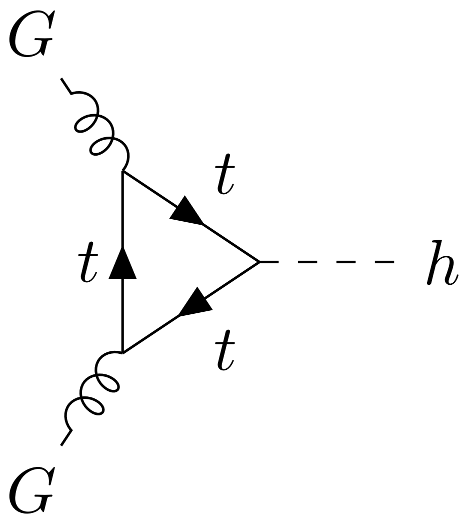
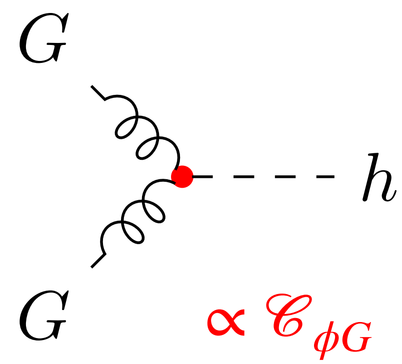
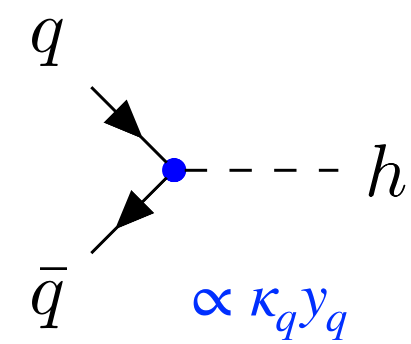
$$\sigma_h^{SMEFT} = \sigma_h^{SM} + \sigma_{GGh}^{SMEFT} + \kappa_u^2\ \sigma_{uuh}^{SM} + \kappa_d^2\ \sigma_{ddh}^{SM}\,.$$



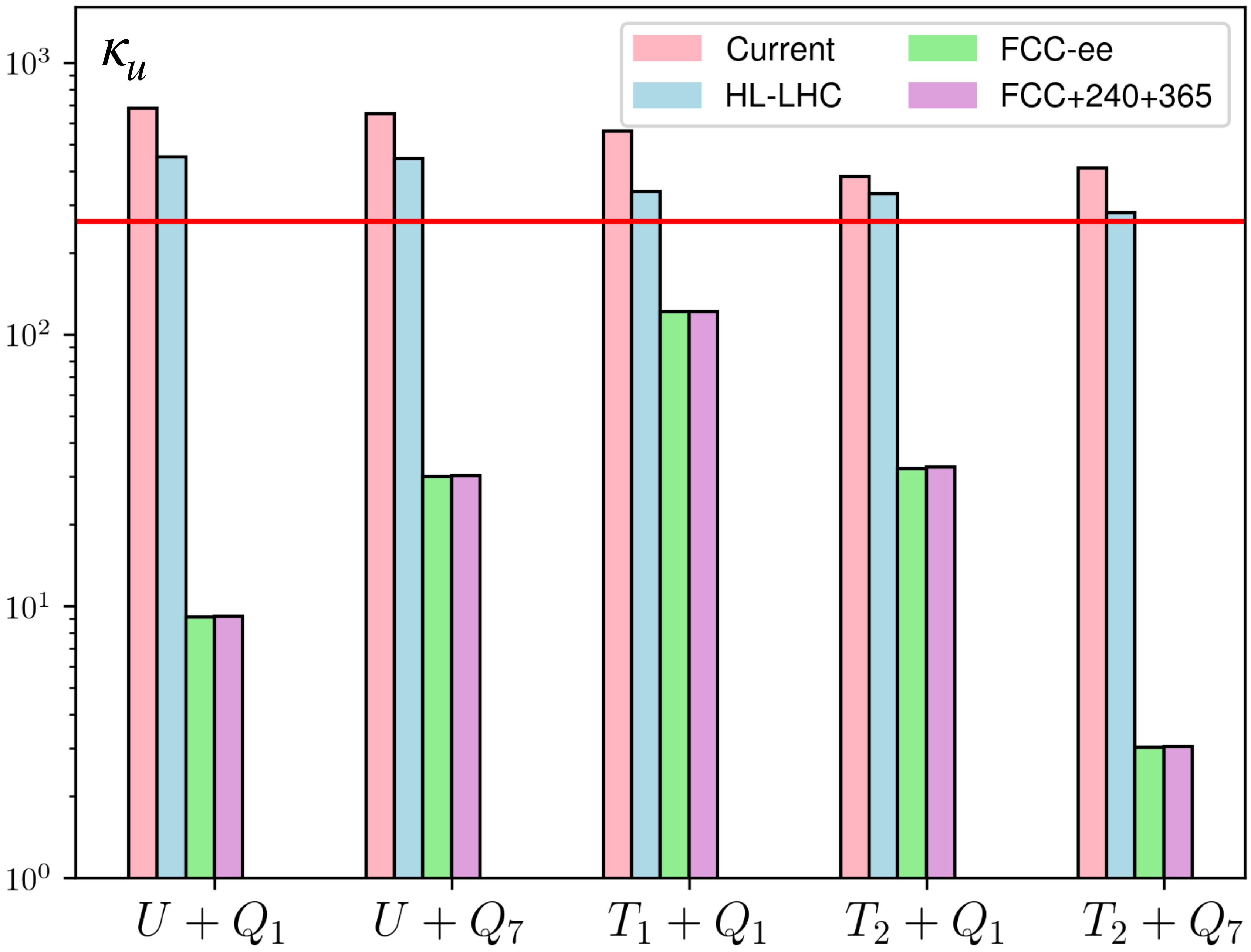




Higgs boson decays in the SMEFT:

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

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



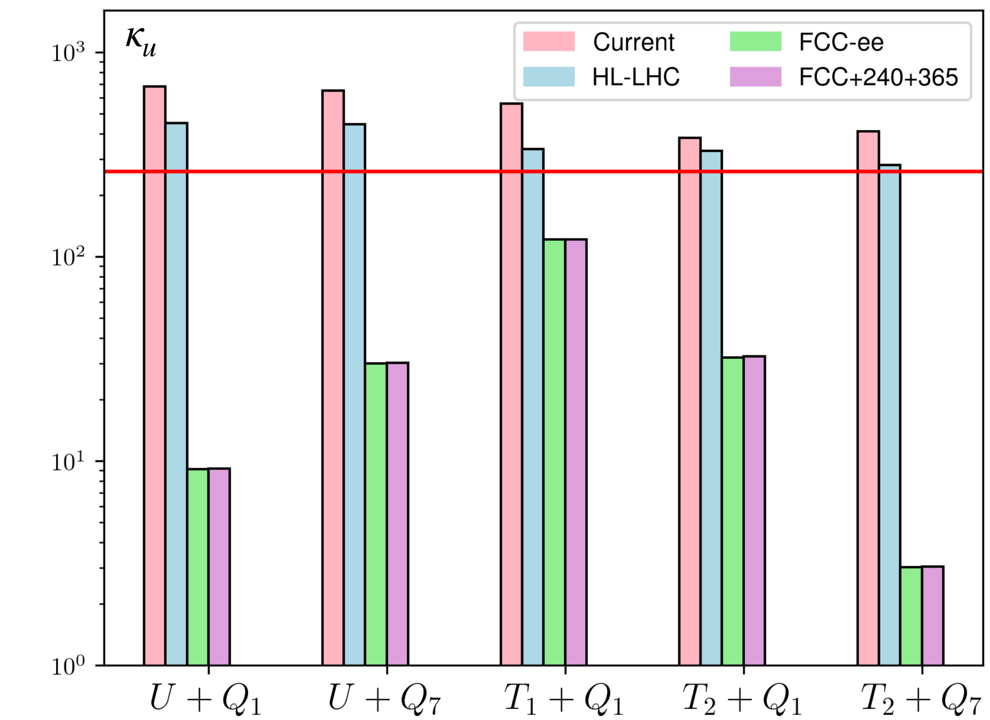
$\kappa_u = 260$ [Balzani, Gröber, Vitti, 2023]

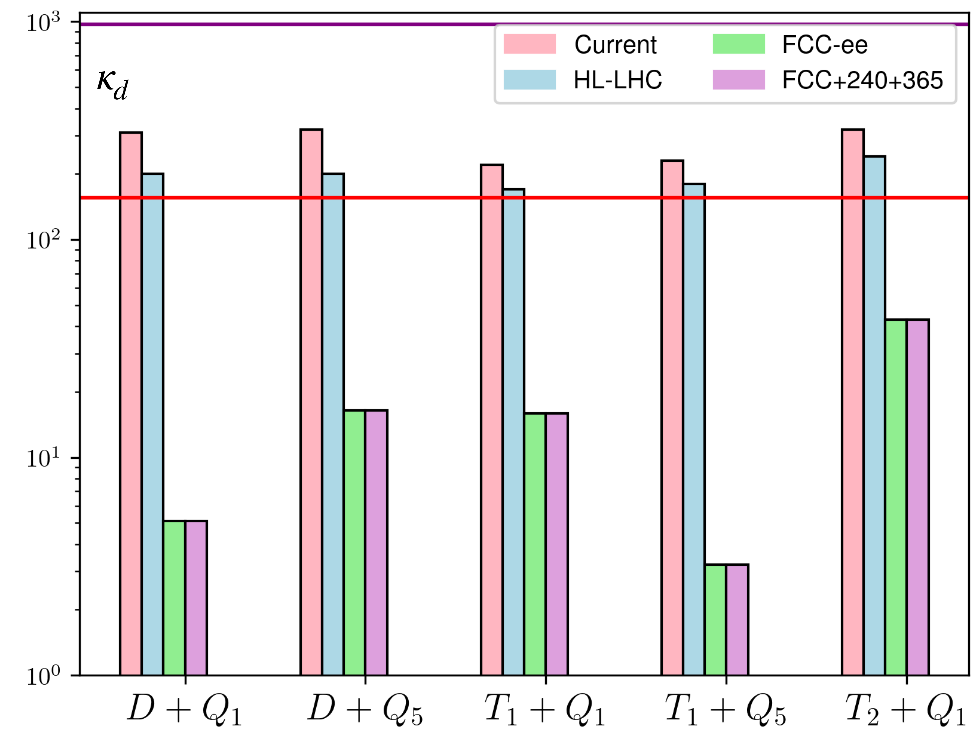
Current:
setup discussed so far

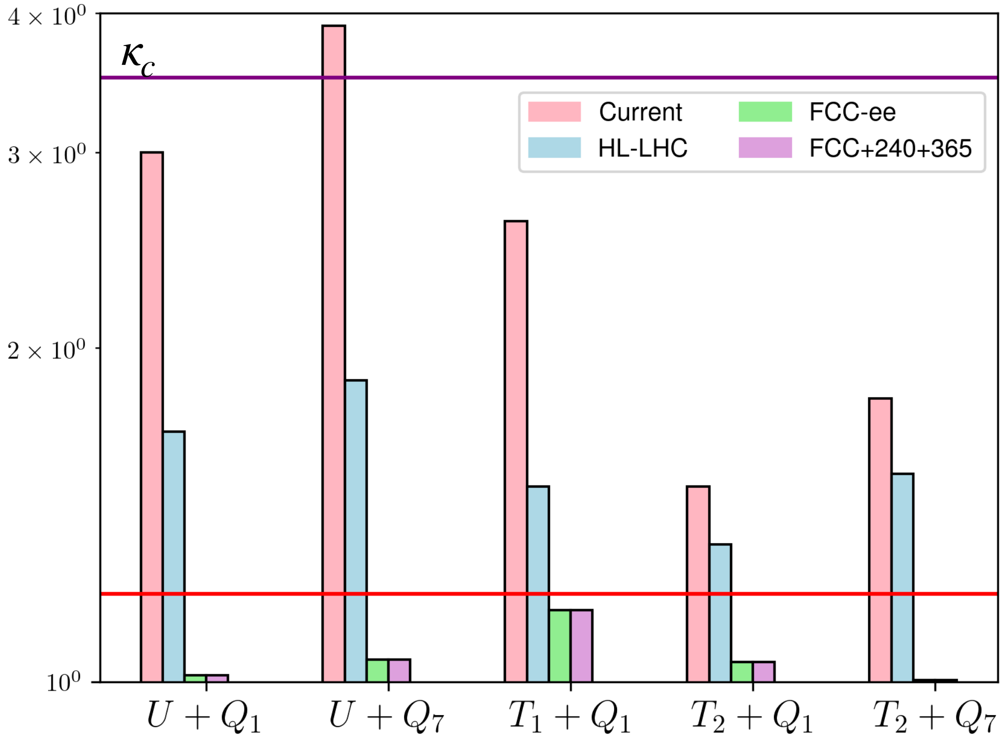
Future projections:
$\Lambda = 2.4$ TeV [Freitas, Gonçalves, Morais, Pasechnik, 2022]

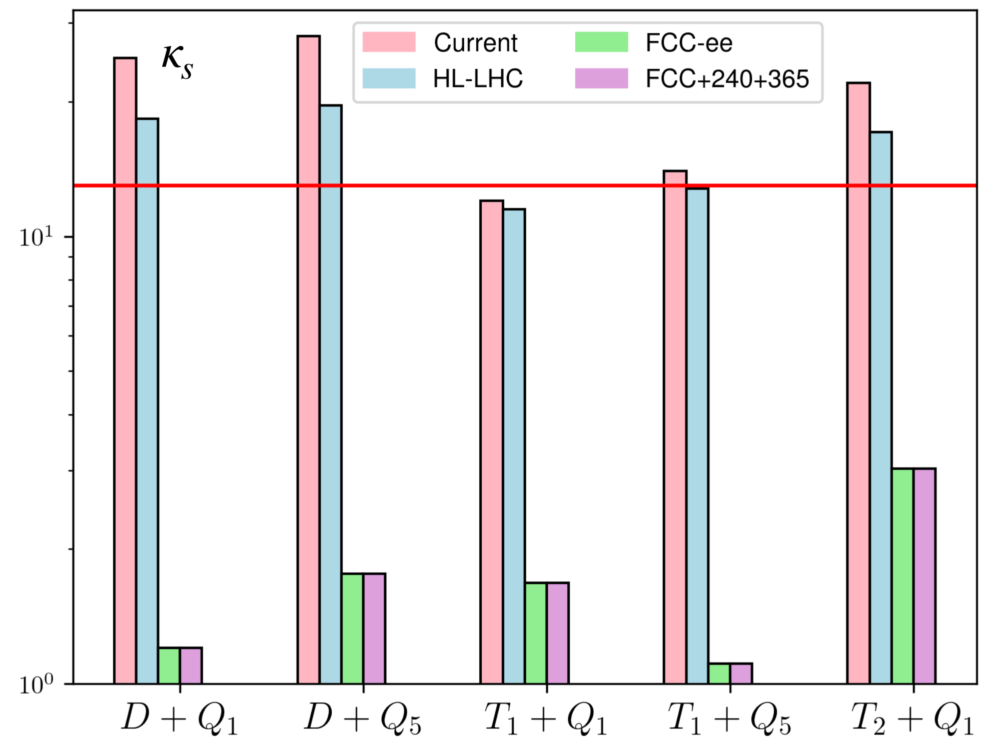
HL-LHC:
Higgs observables projections [Cepeda et al, 2019]

FCC-ee and **FCC+240+365**:
projections for Z-pole and 240 GeV + 365 GeV runs from [de Blas et al, 2019] and [Bernardi et al, 2022]









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

$$|\kappa_u| < 2.3 \cdot 10^3$$
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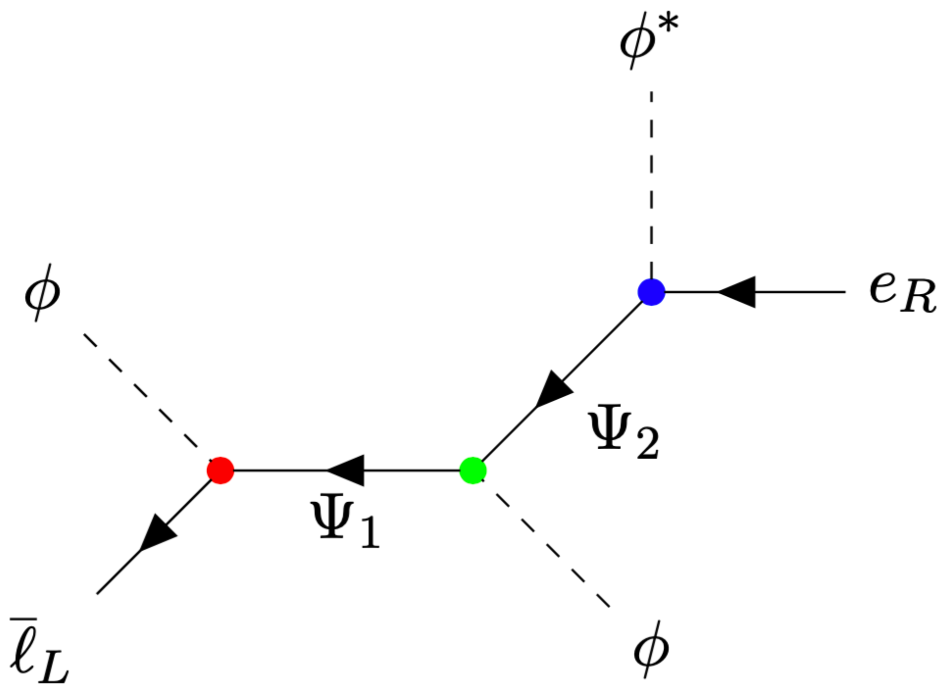
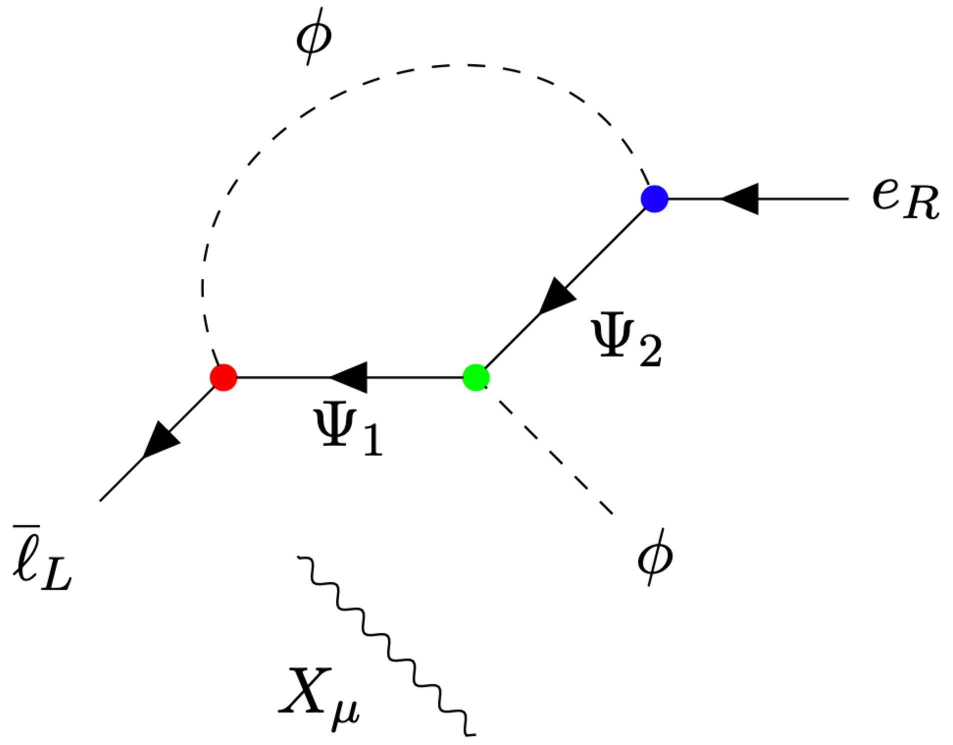
$$-42 < \kappa_s < 44$$
$$-4.0 < \kappa_c < 3.5$$

[CMS Collaboration, 2025]



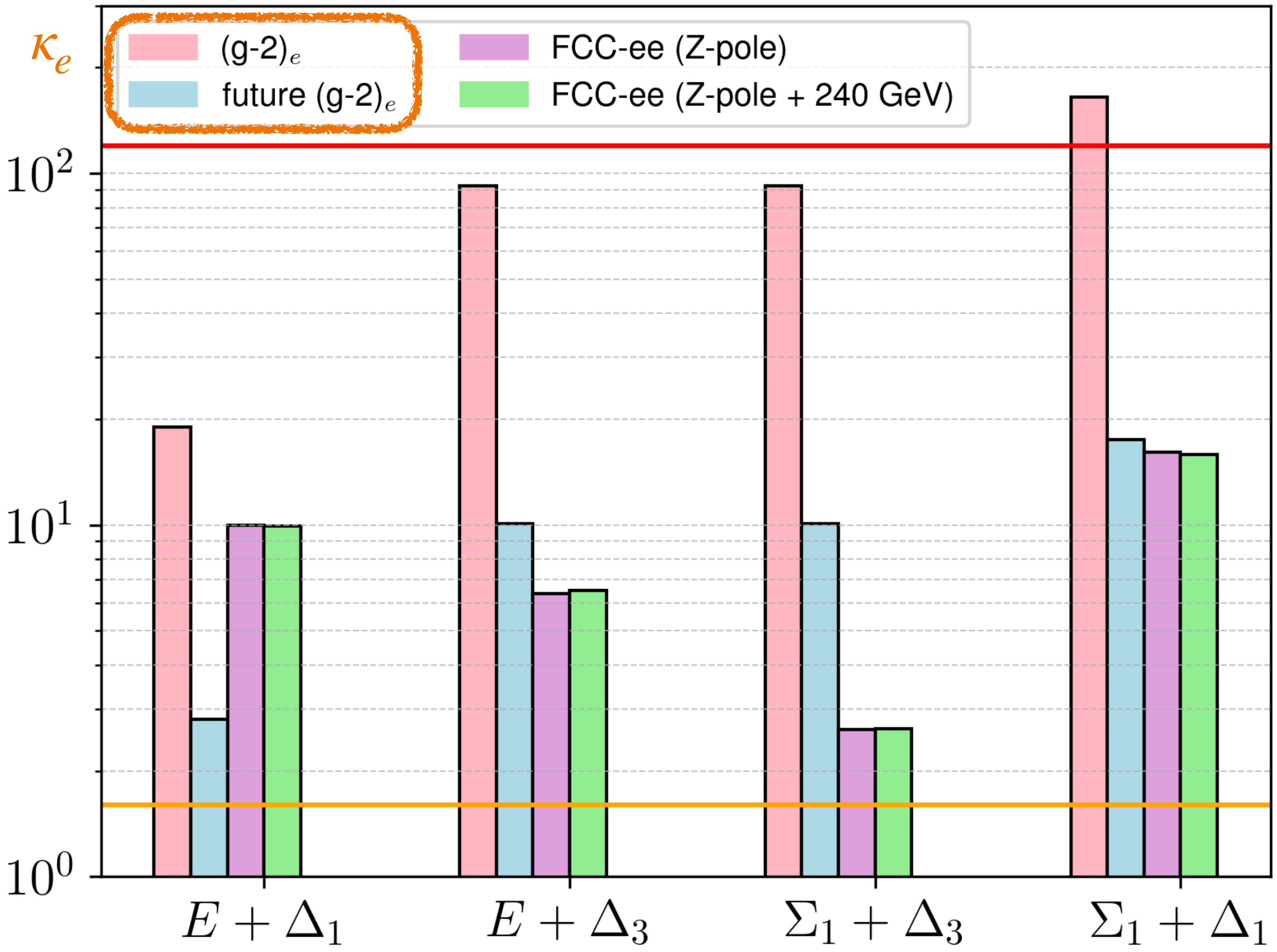


Dipoles: $\mathscr{L}_{SMEFT} \supset \mathscr{C}_{eB}(\bar{l}_L \sigma^{\mu\nu} e_R)\phi B_{\mu\nu} + \mathscr{C}_{eW}(\bar{l}_L \sigma^{\mu\nu} e_R)\sigma^I \phi W^I_{\mu\nu}$ + h.c. .

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

Model	$E + \Delta_1$	$E + \Delta_3$	$\Sigma_1 + \Delta_3$	$\Sigma_1 + \Delta_1$
η	1	1/5	1/5	1/9

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



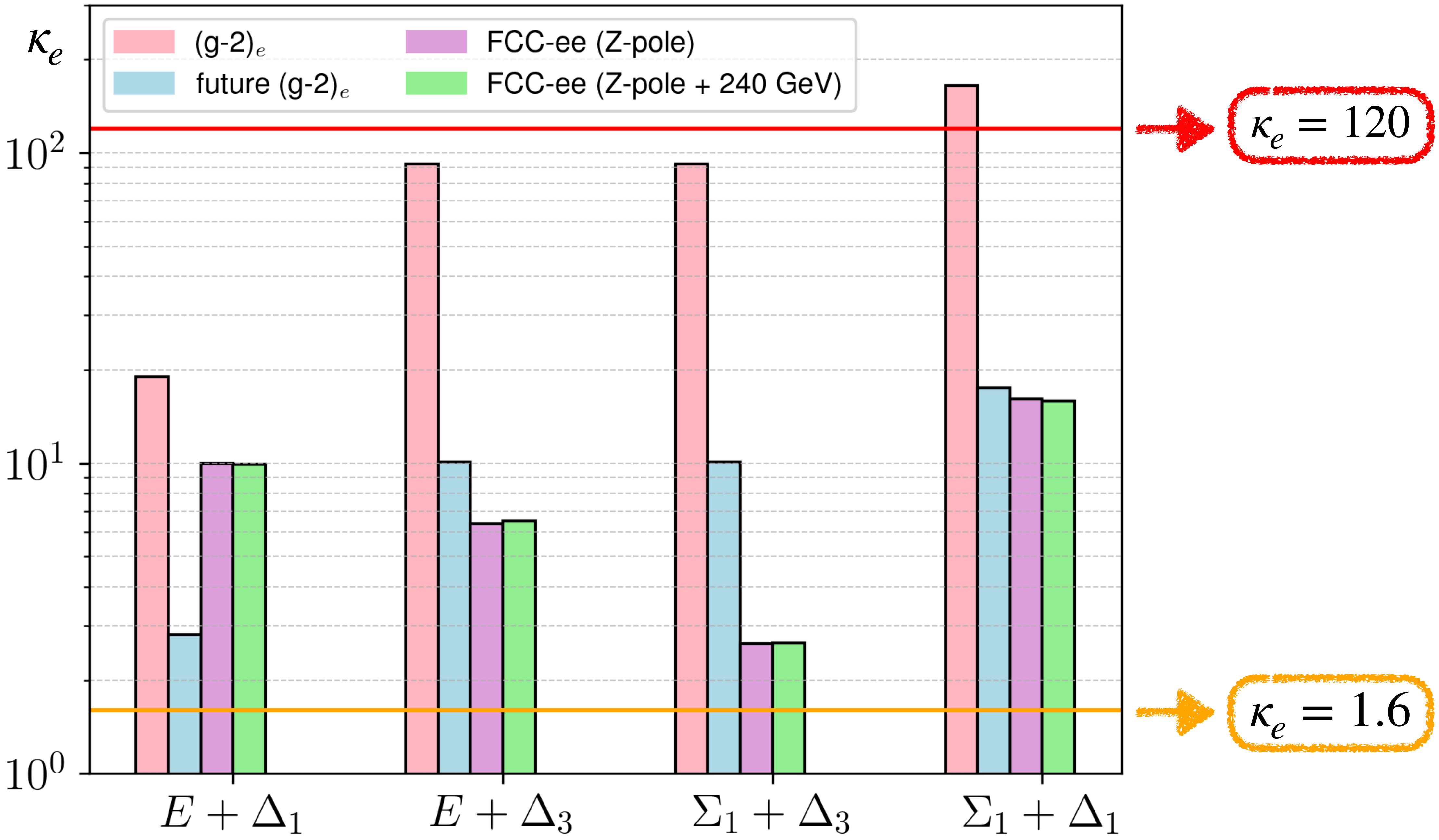
$a_e = (g_e - 2)/2$

SMEFT deviations are correlated to κ_e:

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

- $\Delta a_e < 5 \cdot 10^{-13}$
  [Fan, Myers, Sukra, Gabrielse, 2022]
- $\Delta a_e < 5 \cdot 10^{-14}$
  [Di Luzio, Keshavarzi, Masiero, Paradisi, 2024]

Results: electron



Projections for HL-LHC [Cepeda et al, 2019]

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.

UV models with one vector-like fermion

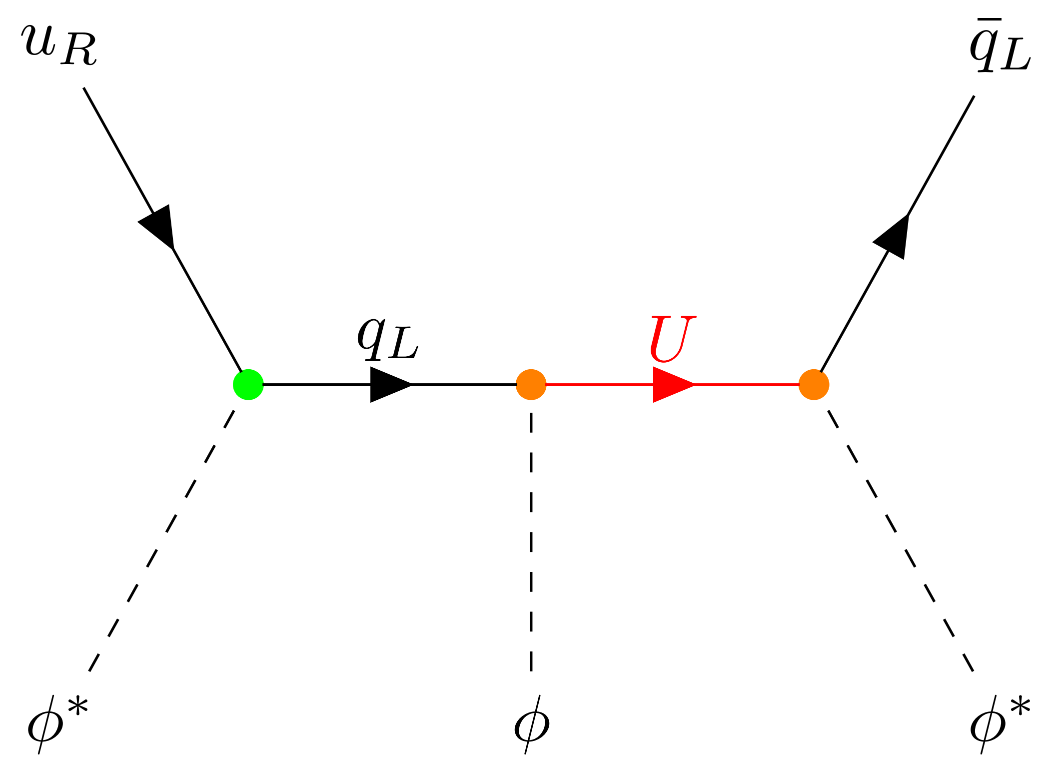
If only one VLF is included, matching results in $\mathscr{C}_{f\phi} \sim y_f \lambda^2_{\rm UV} \Rightarrow \kappa_f - 1 \sim \frac{v^2}{M^2}\lambda^2_{\rm UV}$

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

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

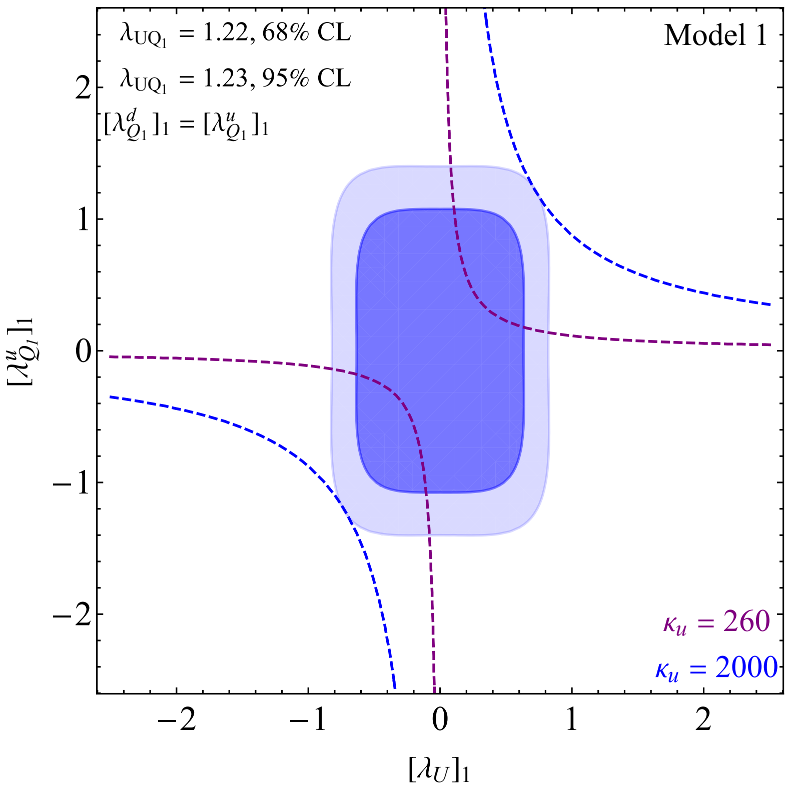
$$[\mathscr{C}_{u\phi}]_{ij} = \frac{[y_u^*]_{jk} [\lambda_U]_k [\lambda_U^*]_i}{2M_U^2}$$

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

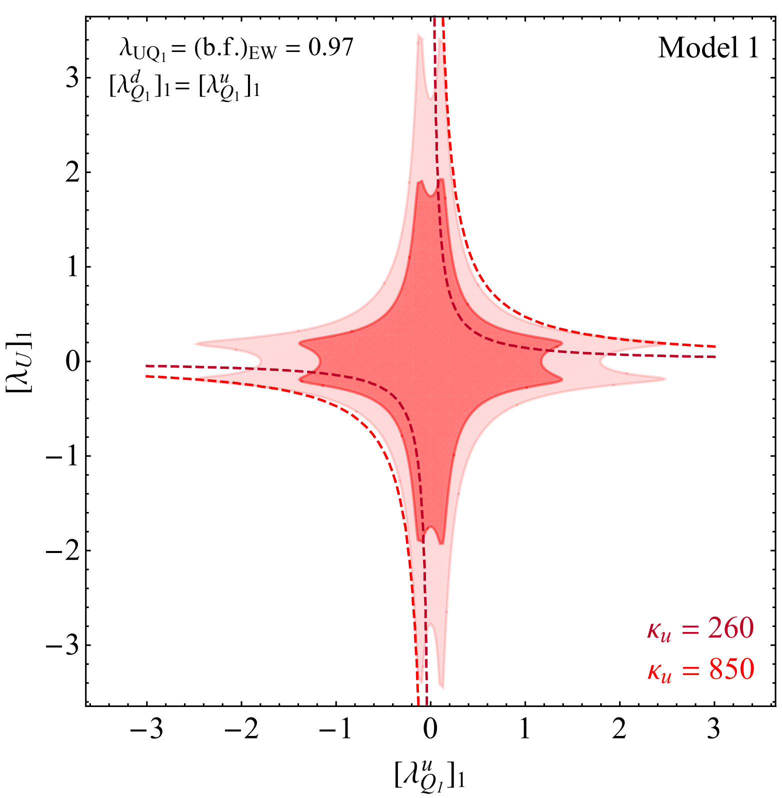


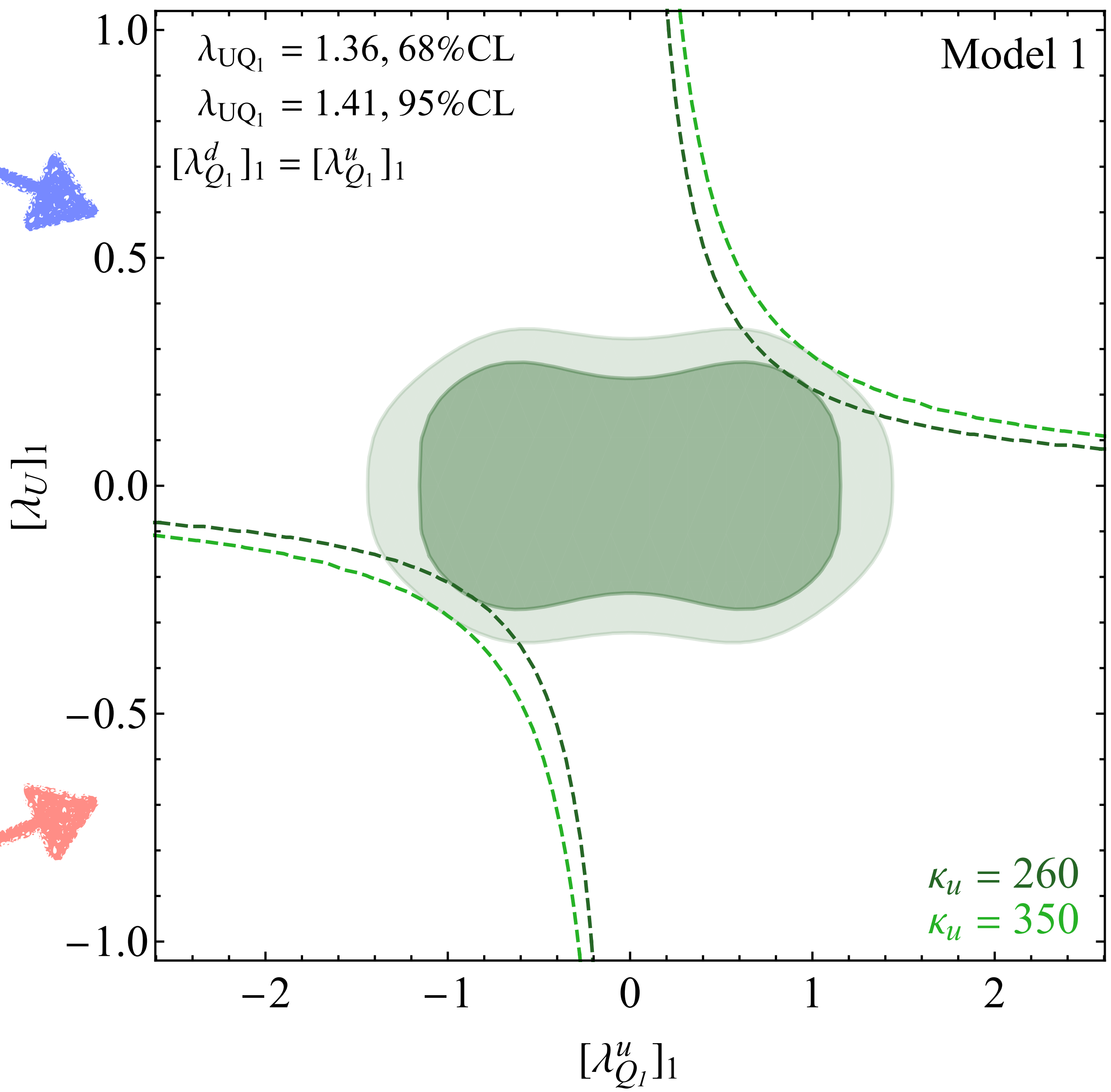
Allowed Parameter Space (Model 1)

EWPOs
+
Flavour



Higgs
Physics
Fit



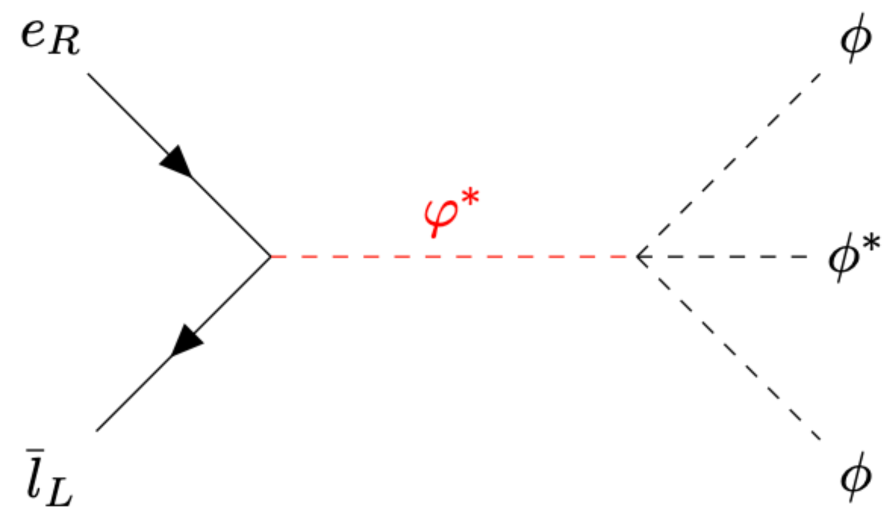


UV models involving only scalars

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]

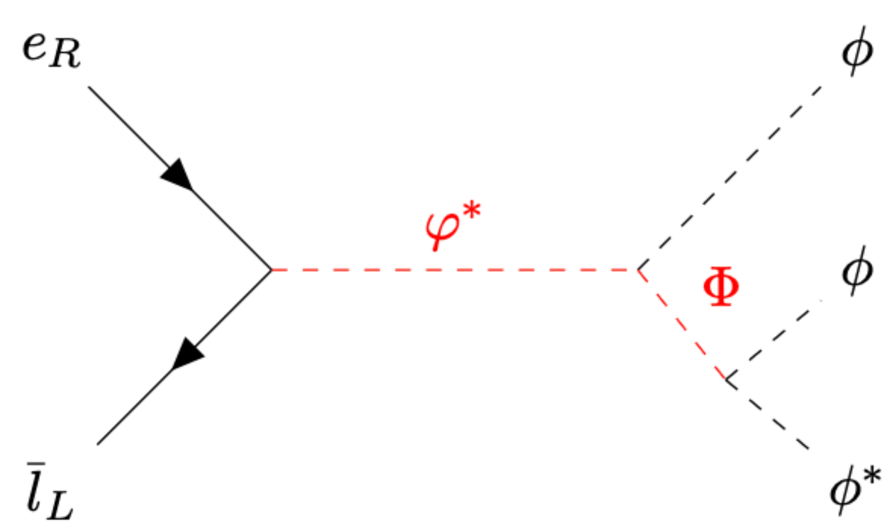
Generates $\mathcal{O}_{\nu\nu} \Rightarrow$ Not considered



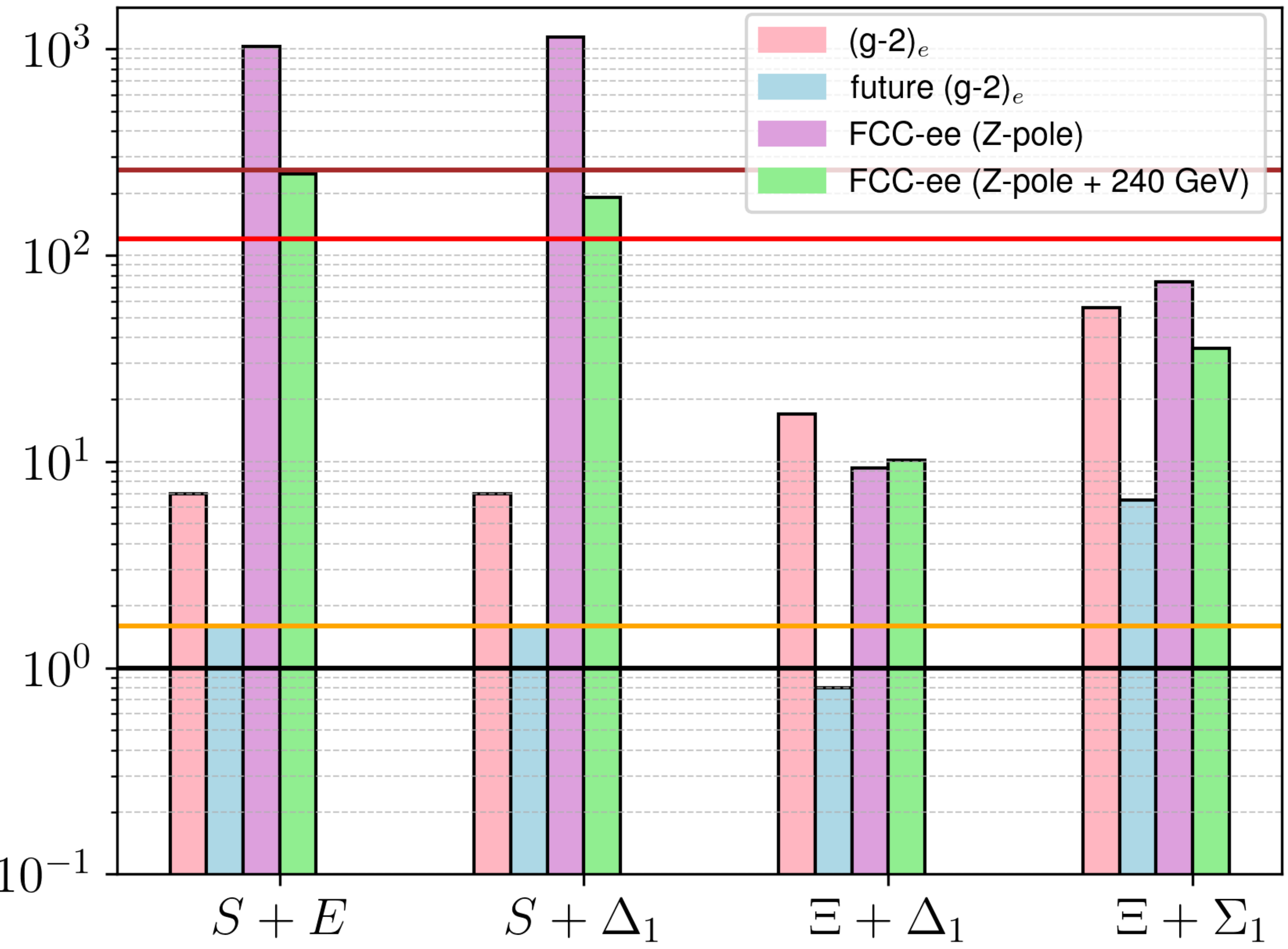
Three available models:

- 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]

Branching Ratios

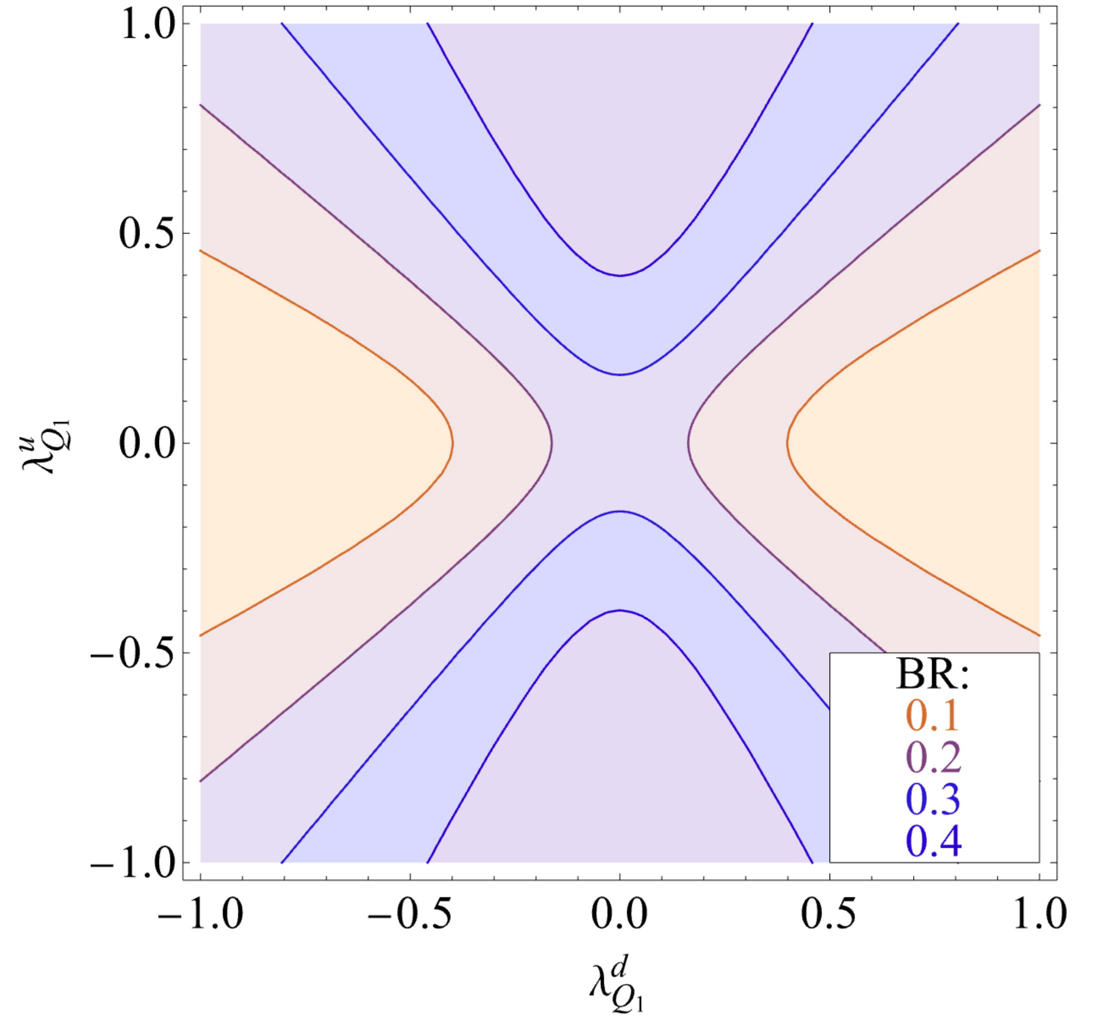
In some models the branching ratios in an appropriate limit can reproduce

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

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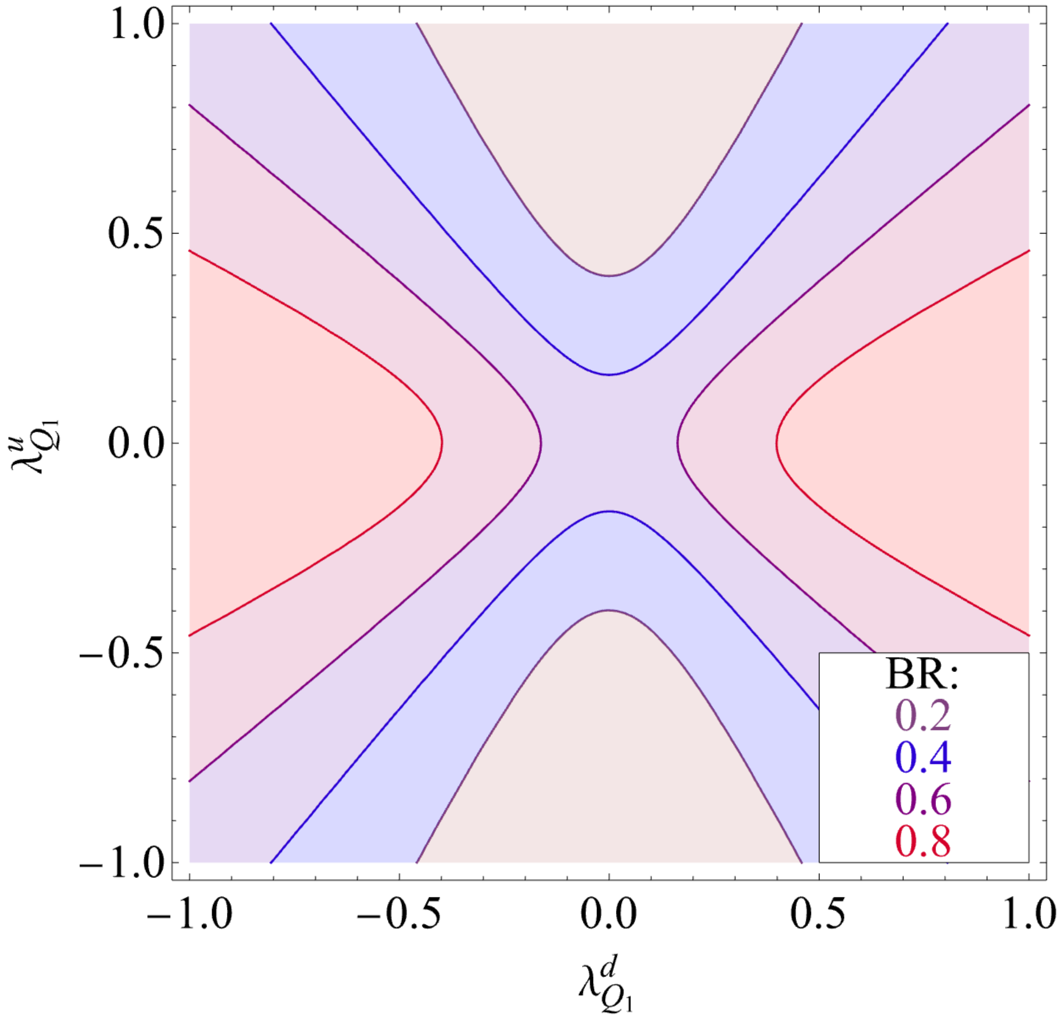
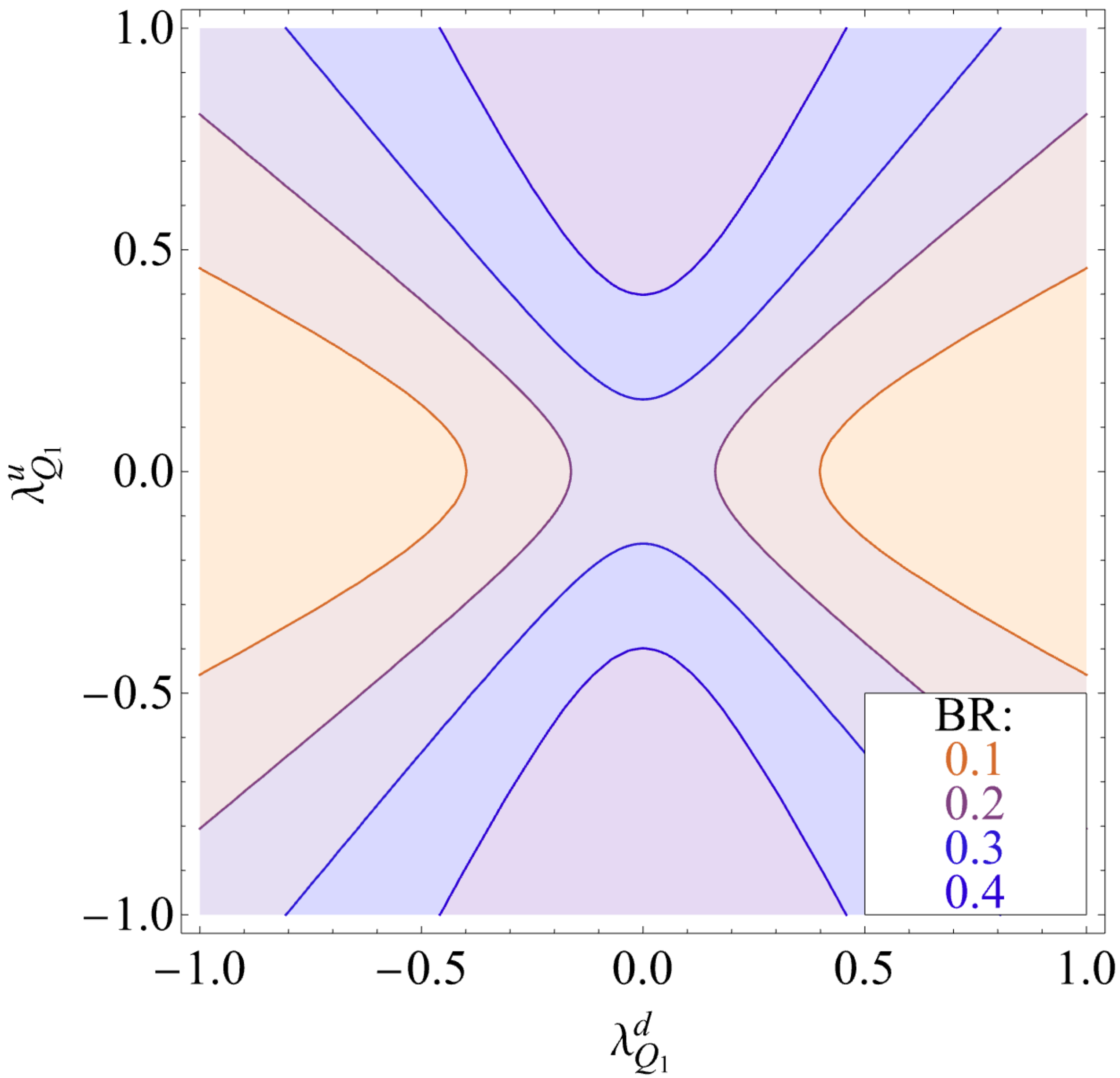
E.g., Model 1 with $Q_1 = \begin{pmatrix} T \\ B \end{pmatrix}$ and U:

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

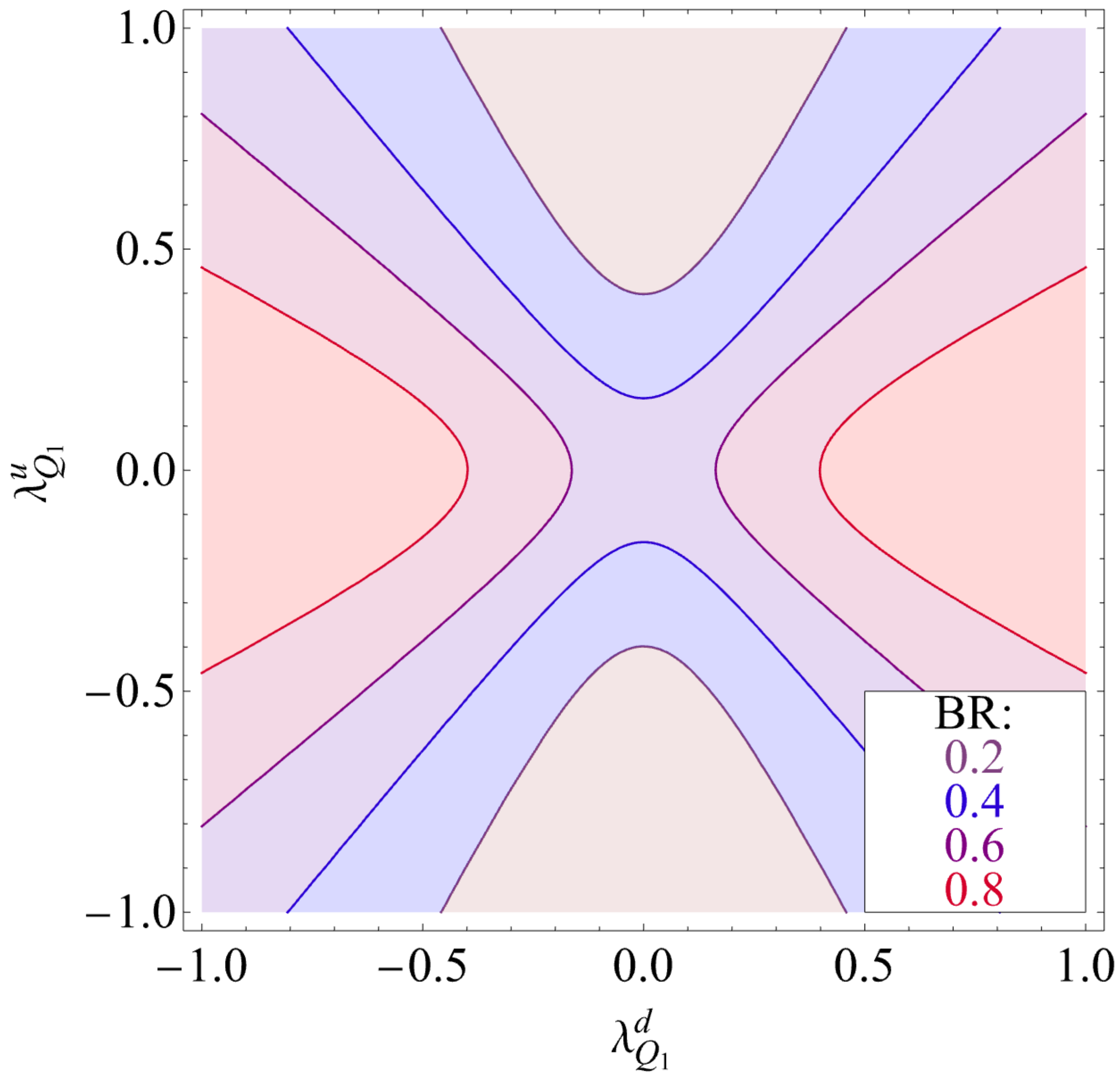


Branching Ratios

Neutral channel



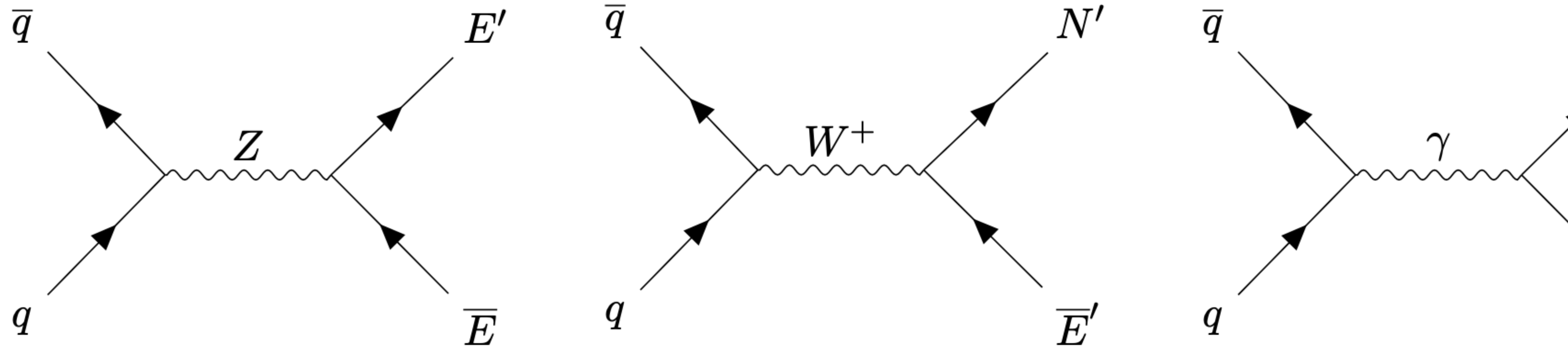
Charged channel



[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



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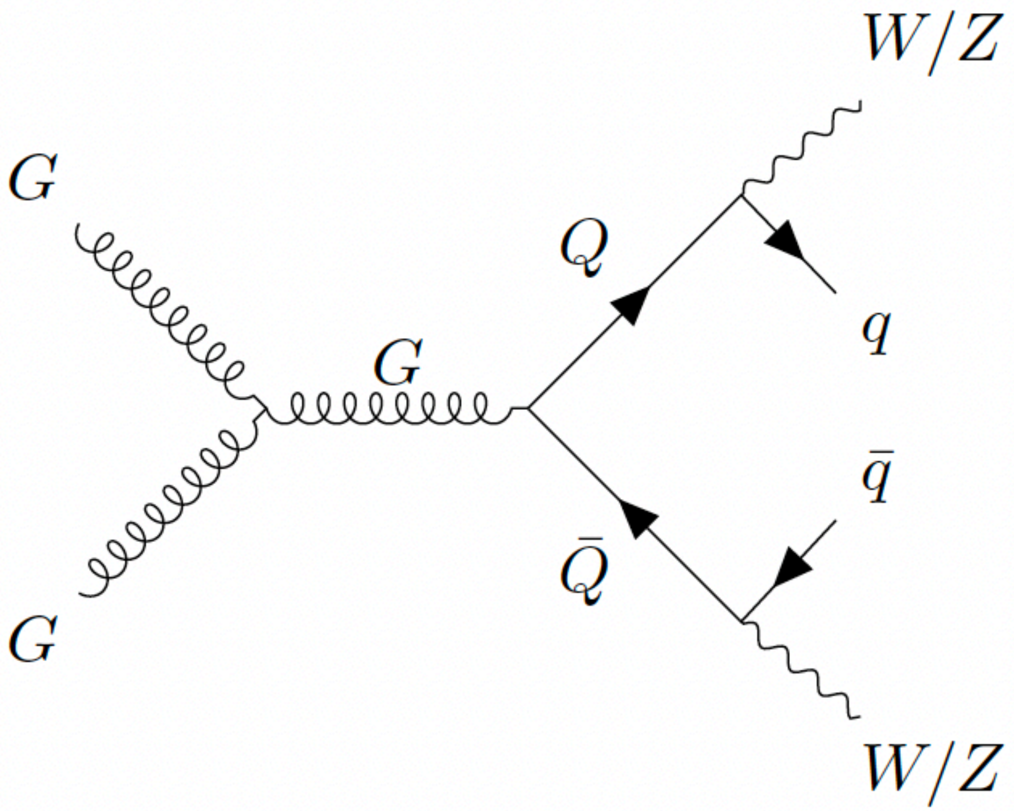
Mass [TeV]	1.8	1.9	2.2	2.1

[Freitas, Gonçalves, Morais, Pasechnik, 2022]: HL-LHC projections for VLQs decaying to light quarks.

Leads to set $M_{Q_1} = M_{Q_2} = \Lambda = 2.4$ TeV.



Models with Vector-like Lepton pairs

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

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

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

Yukawa-like pair interaction

Models

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

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]