Istituto Nazionale di Fisica Nucleare
Sezione di Padova

How large can the light quark Yukawa couplings be?

Higgs 2024, Uppsala, 6 Nov 2024

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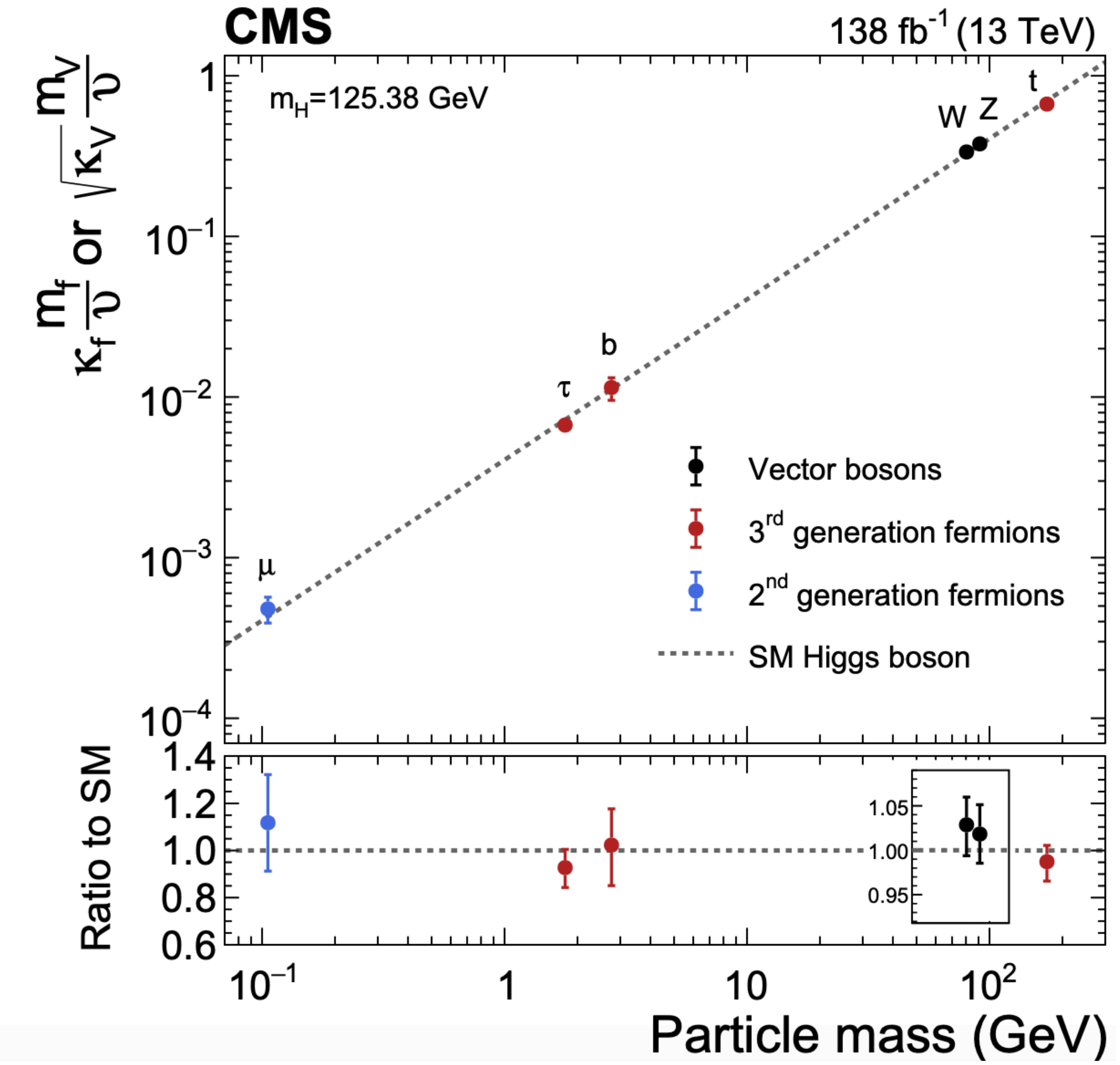
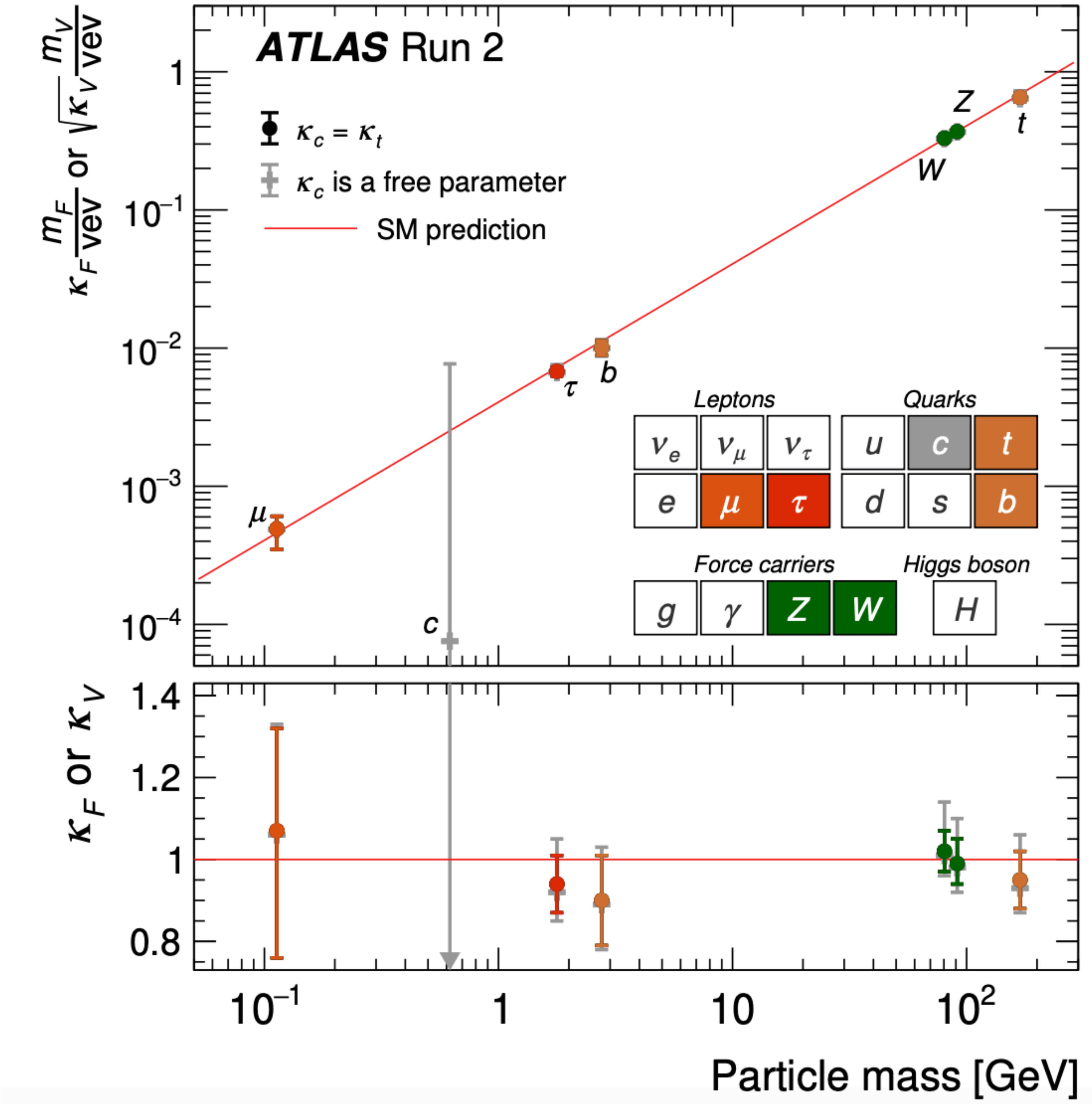
Based on work with:

Barbara Anna Erdelyi, Ramona Gröber

arXiv:2410.08272

A portrait of the Higgs





It is responsible for (most of) electroweak symmetry breaking and the generation of the third-family fermion masses.

What about light families?

Light-quark Yukawas

$$\kappa_q = \frac{y_{hqq} v}{\sqrt{2} m_q}$$

Direct constraints on the **Higgs-charm** coupling in $pp \to V(h \to c\bar{c})$:

- ATLAS **arXiv:2410.19611**: $|\kappa_c| < 4.2$ @ 95% CL
- CMS **arXiv:2205.05550**: $|\kappa_c| < 5.5$ @ 95% CL

$$|\kappa_c| < 1.2$$
$$|\kappa_s| < 13$$
$$|\kappa_u| < 260$$
$$|\kappa_d| < 156$$

HL-LHC @ 95% CL

Many proposals to further constrain the **light-quark** couplings to Higgs:

- The Higgs p_T distribution: F. Bishara, U. Haisch, P. F. Monni, and E. Re; **arXiv:1606.09253**
- $W^{\pm}h$ charge asymmetry: F. Yu; **arXiv:1609.06592**
- Global fits to Higgs data: J. de Blas et al.; **arXiv:1905.03764**
- Higgs pair production: L. Alasfar, R. Corral Lopez, and R. Gröber; **arXiv:1909.05279**
- $h + \gamma$ production: J. A. Aguilar-Saavedra, J. M. Cano, and J. M. No; **arXiv:2008.12538**
- Triboson final states: A. Falkowski, S. Ganguly, P. Gras, J. M. No, K. Tobioka, N. Vignaroli, and T. You; **arXiv:2011.09551**
- Off-shell Higgs measurements: Y. Zhou; E. Balzani, R. Gröber, and M. Vitti; **arXiv:1505.06369**; **arXiv:2304.09772**

$|\kappa_c| < 1.2$

$|\kappa_s| < 13$

$|\kappa_u| < 260$

$|\kappa_d| < 156$

HL-LHC @ 95% CL

Are there models/particles which can give rise to these without having been excluded already?

Exploration of the BSM space

We assume heavy new physics -- and use SMEFT. *See talk by Konstantin for a nice introduction.*

Anything that matches to:

$$\mathcal{O}_{u\phi} = \bar{q}_L \tilde{\phi} u_R \phi^\dagger \phi \quad \text{and/or} \quad \mathcal{O}_{d\phi} = \bar{q}_L \phi d_R \phi^\dagger \phi$$

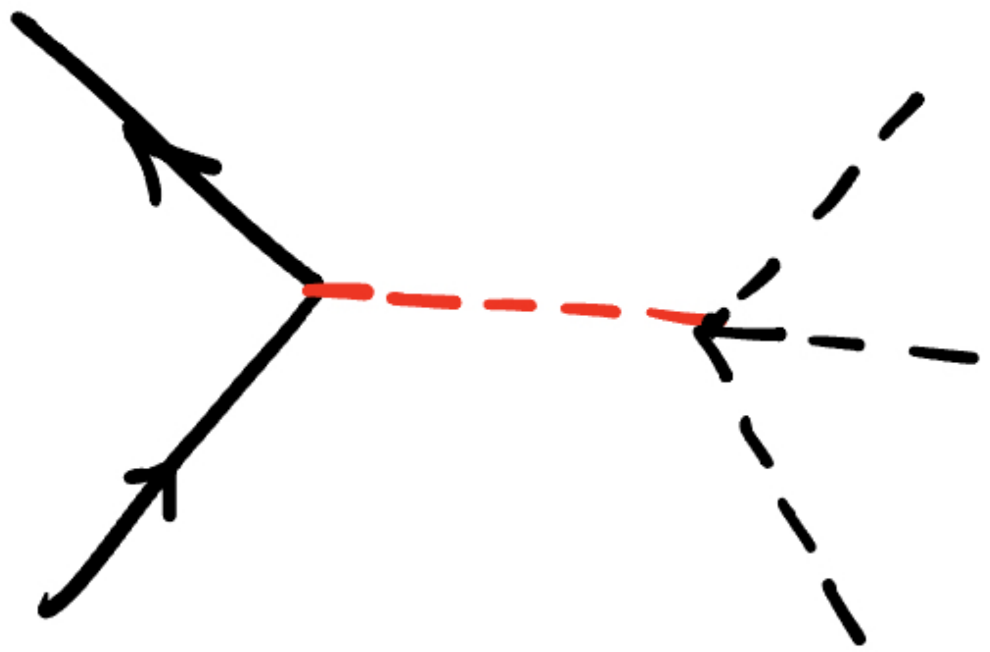
modify the effective Higgs-quark coupling

$$-\mathcal{L} \supset g_{hq_i\bar{q}_j} \bar{q}_j q_i h \quad \text{with} \quad g_{hq_i\bar{q}_j} = \frac{m_q}{v}\delta_{ij}\left[1 + v^2 \mathcal{C}_{\phi,\mathrm{kin}}\right] - \frac{v^2}{\sqrt{2}}(\tilde{\mathcal{C}}_{q\phi})_{ij}$$

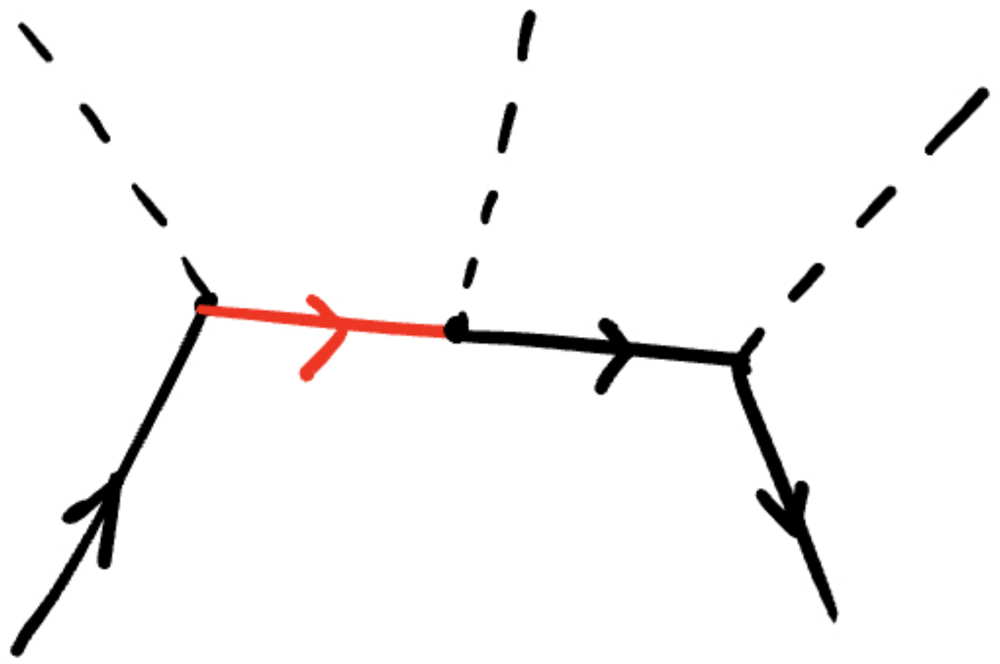
1. Single mediators.

Two options:

New scalars:



New fermions:



Higgs bosons with large couplings to light quarks: D. Egana-Ugrinovic, S. Homiller, P. Meade; **arXiv:1908.11376**

How charming can the Higgs be? A.S. Giannakopoulou, P. Meade, M. Valli; **arXiv:2410.05236**

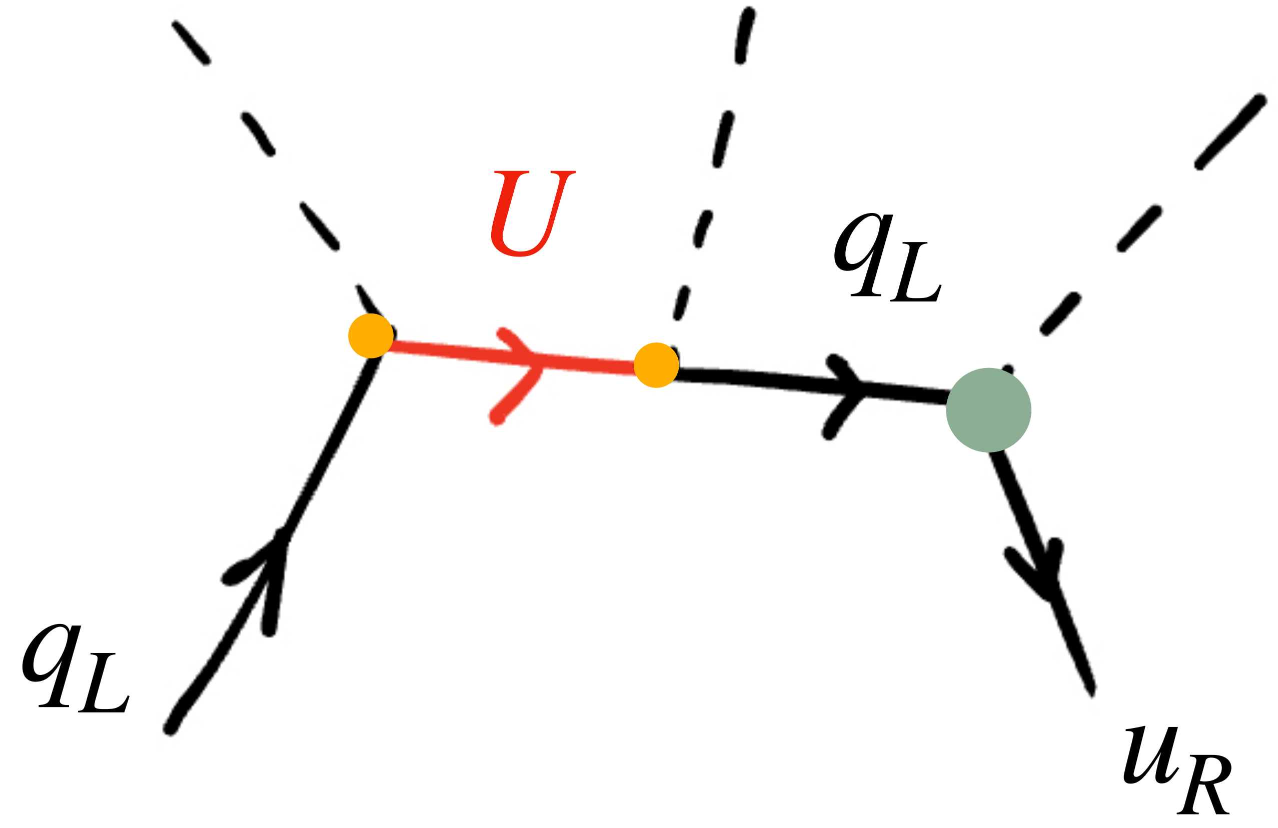
Exploration of the BSM space

$\boxed{\mathcal{O}_{u\phi} = \bar{q}_L\tilde{\phi}u_R\phi^\dagger\phi}$ and $\boxed{\mathcal{O}_{d\phi} = \bar{q}_L\phi d_R\phi^\dagger\phi}$

1. Single mediators.

Difficult to produce sizeable modifications as:

$C_{q\phi} \simeq y_q \times \lambda_{\mathrm{NP}}^2$ such that $\kappa_q = \frac{g_{hqq}}{g_{hqq}^{\mathrm{SM}}} \simeq 1 \pm \frac{v^2}{\Lambda_{\mathrm{NP}}^2}\lambda_{\mathrm{NP}}^2$



Concrete example: $U \sim (3,1)_{2/3}$

$$-\mathscr{L} \supset \lambda_U \bar{U}_R \tilde{\phi}^\dagger q_L + M_U \bar{U}U$$

$$[C_{u\phi}]_{ij} = \frac{[y_u^*]_{jk}[\lambda_U]_k[\lambda_U^*]_i}{2M_U^2} \longrightarrow \kappa_u \simeq 1 + \frac{v^2|[\lambda_U]_1|^2}{2M_U^2} = 1 - \sqrt{2}\delta g_{Zu}$$

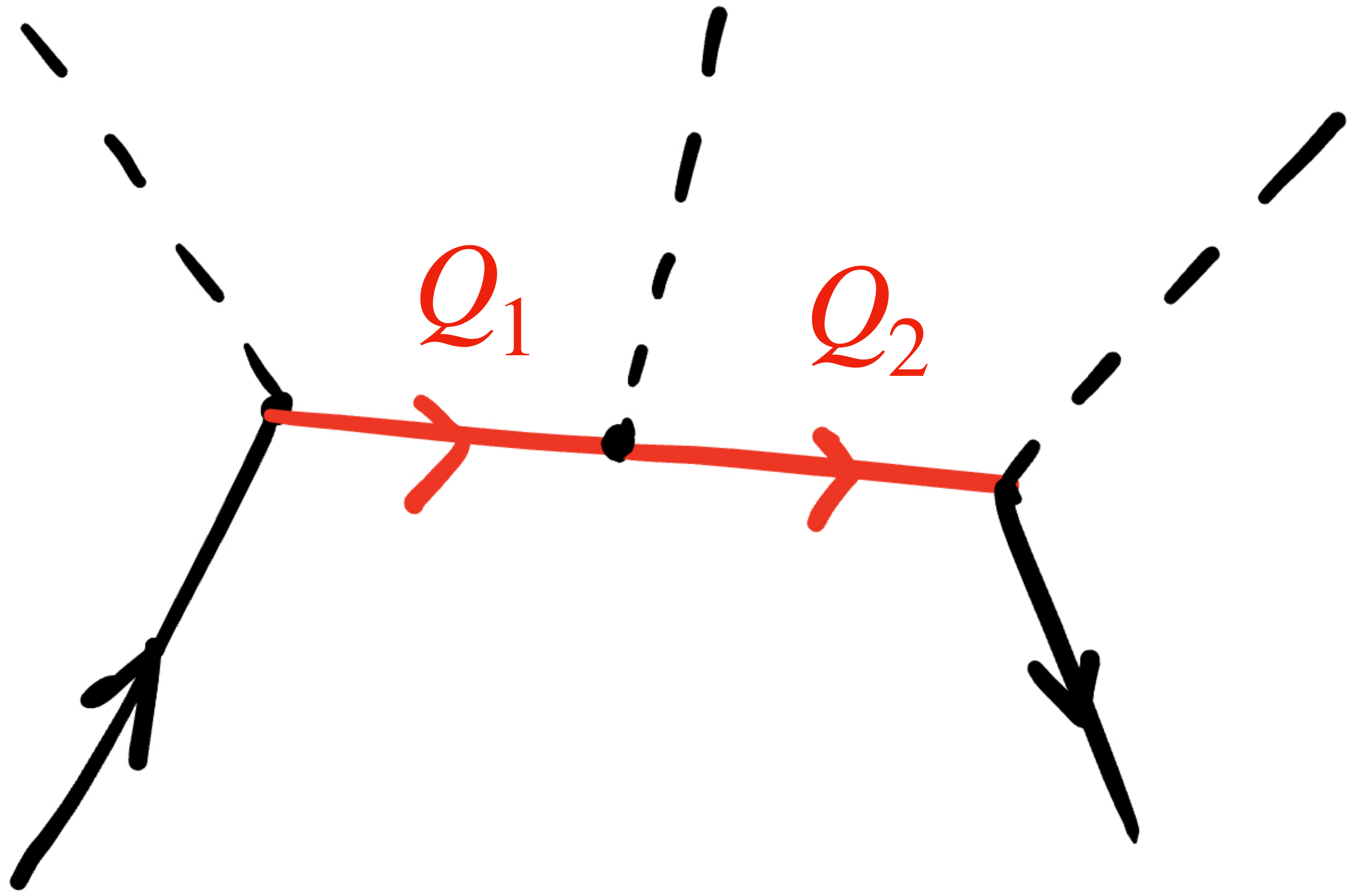
Already very constrained by electroweak processes

Exploration of the BSM space

$\boxed{\mathcal{O}_{u\phi} = \bar{q}_L\tilde{\phi}u_R\phi^\dagger\,\phi}$ and $\boxed{\mathcal{O}_{d\phi} = \bar{q}_L\phi d_R\,\phi^\dagger\phi}$

$\mathscr{C}_{q\phi} \neq y_q(1 \pm \mathcal{O}(1)\,v^2/\Lambda^2)$ can be achieved with **a pair** of new particles

2. New pairs:



There is no dim-4 Yukawa y_q insertion.

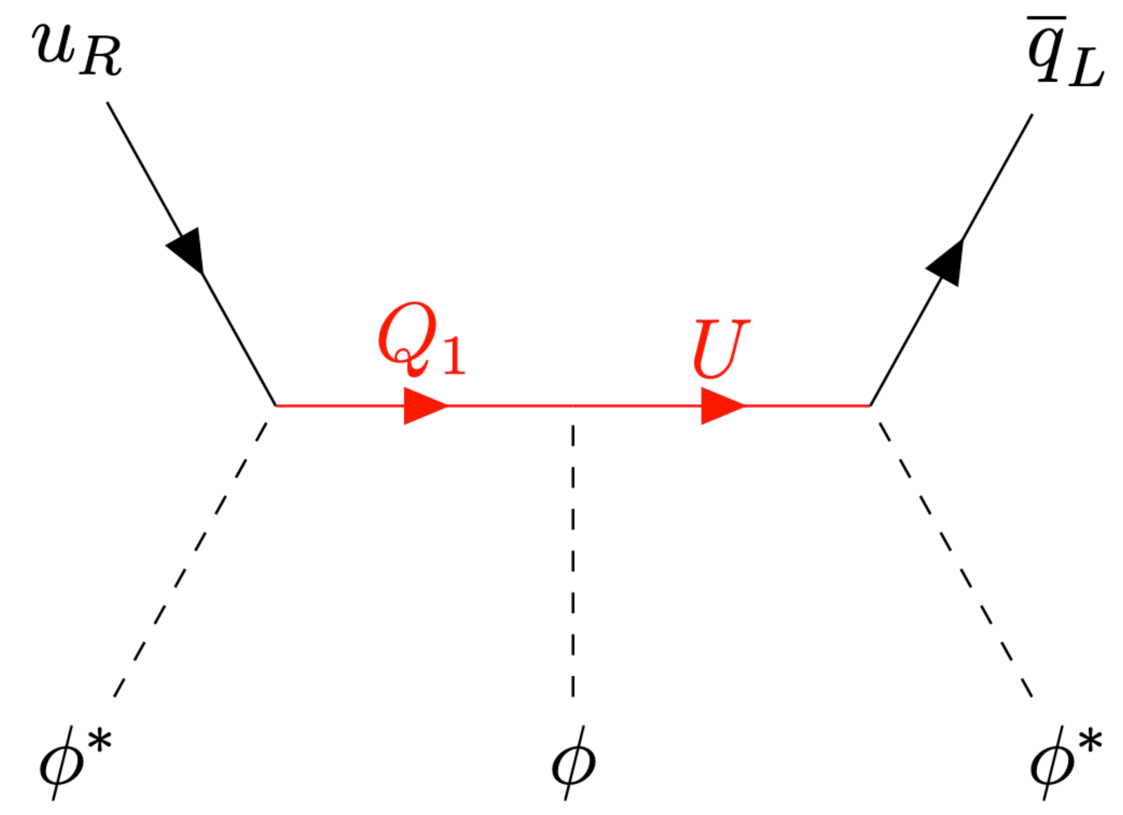
Exploration of the BSM space

Seven vector-like quarks that allow for the couplings to the Higgs doublet and the SM fermions:

Name	U	D	Q_1	Q_5	Q_7	T_1	T_2
Irrep under G_{SM}	$(\mathbf{3},\mathbf{1})_{\frac{2}{3}}$	$(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$	$(\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	$(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$	$(\mathbf{3},\mathbf{2})_{\frac{7}{6}}$	$(\mathbf{3},\mathbf{3})_{-\frac{1}{3}}$	$(\mathbf{3},\mathbf{3})_{\frac{2}{3}}$

Eight possible simplified models:

Singlet + Doublet		Doublet + Triplet	
Model 1	$U + Q_1$	Model 5	$T_1 + Q_1$
Model 2	$D + Q_1$	Model 6	$T_1 + Q_5$
Model 3	$U + Q_7$	Model 7	$T_2 + Q_1$
Model 4	$D + Q_5$	Model 8	$T_2 + Q_7$



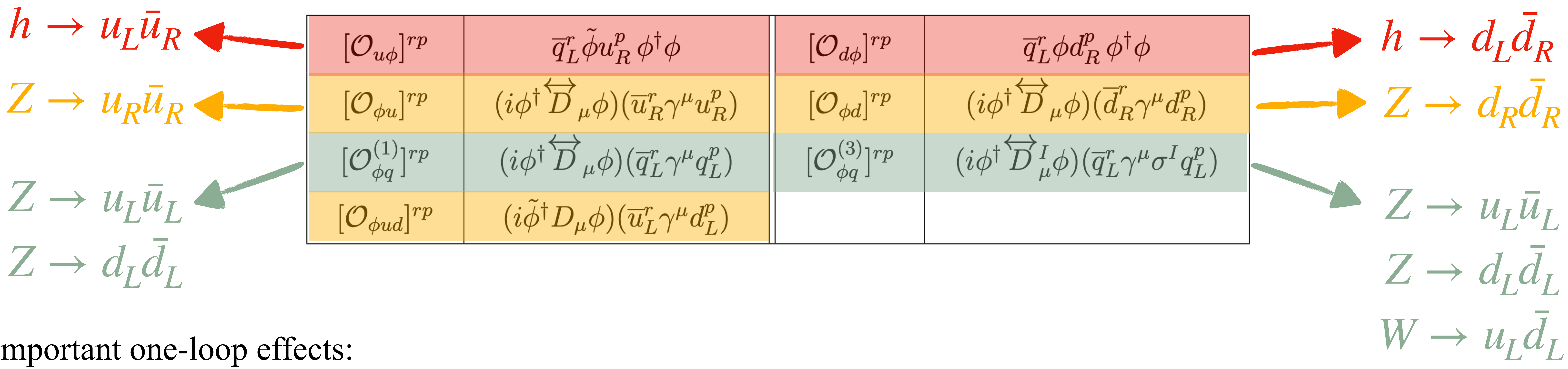
e.g. Model 1

All characterised by (schematically):

$$-\mathscr{L} \supset \boxed{\lambda_{q_L}}\, Q_1\, \phi\, q_L + \boxed{\lambda_{q_R}}\, Q_2\, \phi\, q_R + \boxed{\lambda_{Q_1Q_2}}\, Q_1\, \phi\, Q_2 \longrightarrow \kappa_q - 1 \sim \frac{v^2 \lambda_{q_L} \lambda_{q_R} \lambda_{Q_1Q_2}}{M_{Q_1} M_{Q_2}}$$

Constraints

The following operators are generated at tree-level:



$h \to u_L\bar{u}_R$

$Z \to u_R\bar{u}_R$

$Z \to u_L\bar{u}_L$

$Z \to d_L\bar{d}_L$

$[\mathcal{O}_{u\phi}]^{rp}$	$\bar{q}_L^r\tilde{\phi}u_R^p\,\phi^\dagger\phi$	$[\mathcal{O}_{d\phi}]^{rp}$	$\bar{q}_L^r\phi d_R^p\,\phi^\dagger\phi$
$[\mathcal{O}_{\phi u}]^{rp}$	$(i\phi^\dagger\overleftrightarrow{D}_\mu\phi)(\bar{u}_R^r\gamma^\mu u_R^p)$	$[\mathcal{O}_{\phi d}]^{rp}$	$(i\phi^\dagger\overleftrightarrow{D}_\mu\phi)(\bar{d}_R^r\gamma^\mu d_R^p)$
$[\mathcal{O}_{\phi q}^{(1)}]^{rp}$	$(i\phi^\dagger\overleftrightarrow{D}_\mu\phi)(\bar{q}_L^r\gamma^\mu q_L^p)$	$[\mathcal{O}_{\phi q}^{(3)}]^{rp}$	$(i\phi^\dagger\overleftrightarrow{D}^I_\mu\phi)(\bar{q}_L^r\gamma^\mu\sigma^I q_L^p)$
$[\mathcal{O}_{\phi ud}]^{rp}$	$(i\tilde{\phi}^\dagger D_\mu\phi)(\bar{u}_L^r\gamma^\mu d_L^p)$		

$h \to d_L\bar{d}_R$

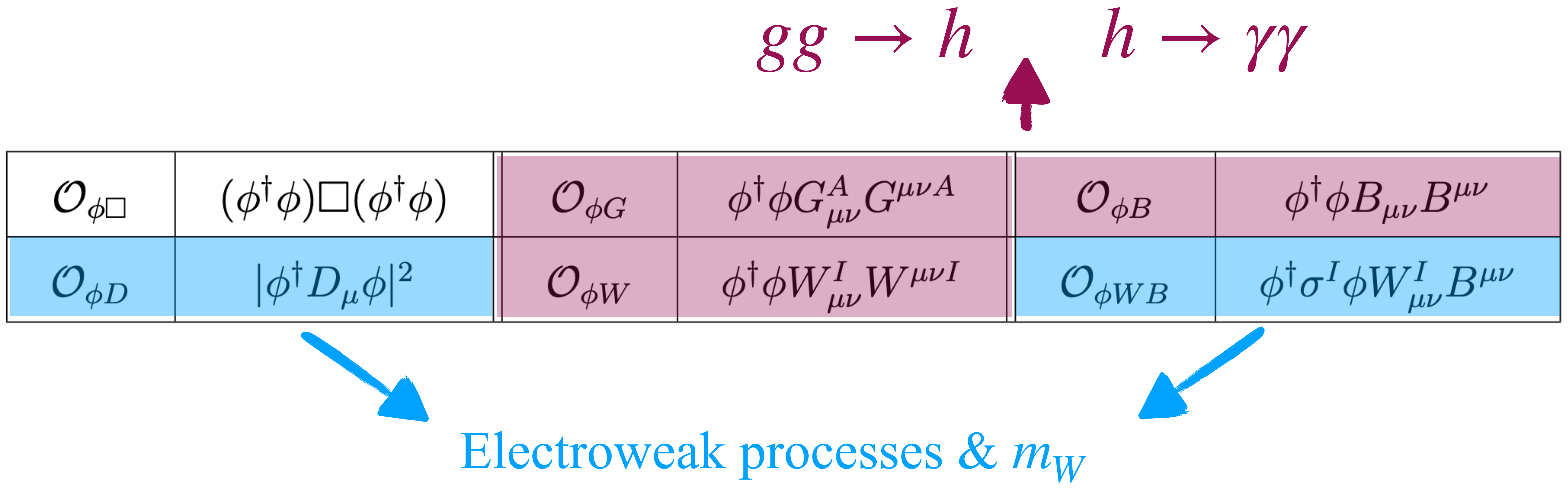
$Z \to d_R\bar{d}_R$

$Z \to u_L\bar{u}_L$

$Z \to d_L\bar{d}_L$

$W \to u_L\bar{d}_L$

Important one-loop effects:



$gg \to h$ $\quad h \to \gamma\gamma$

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

Electroweak processes & m_W

Constraints

Direct searches:
ATLAS **arXiv:2405.19862**

VLQ pair production
+
$Q \to Wq$

Flavor transitions:
New physics
couplings are flavored

$\lambda^{i}_{q_L}\,,\lambda^{i}_{q_R}$

↓

$\Delta F = 1\,,\Delta F = 2$

Electroweak
processes:

$\delta g^{Zu}_{L,R} \quad \delta g^{Zd}_{L,R} \quad \delta g^{W}_{L}$

↓

EWPOs:
$\Gamma_Z\,,A_e\,,\sigma_{\text{had}}\,,A^b_{\text{FB}}\ldots$

Higgs physics:
$\delta g^{u,d}_{h}$

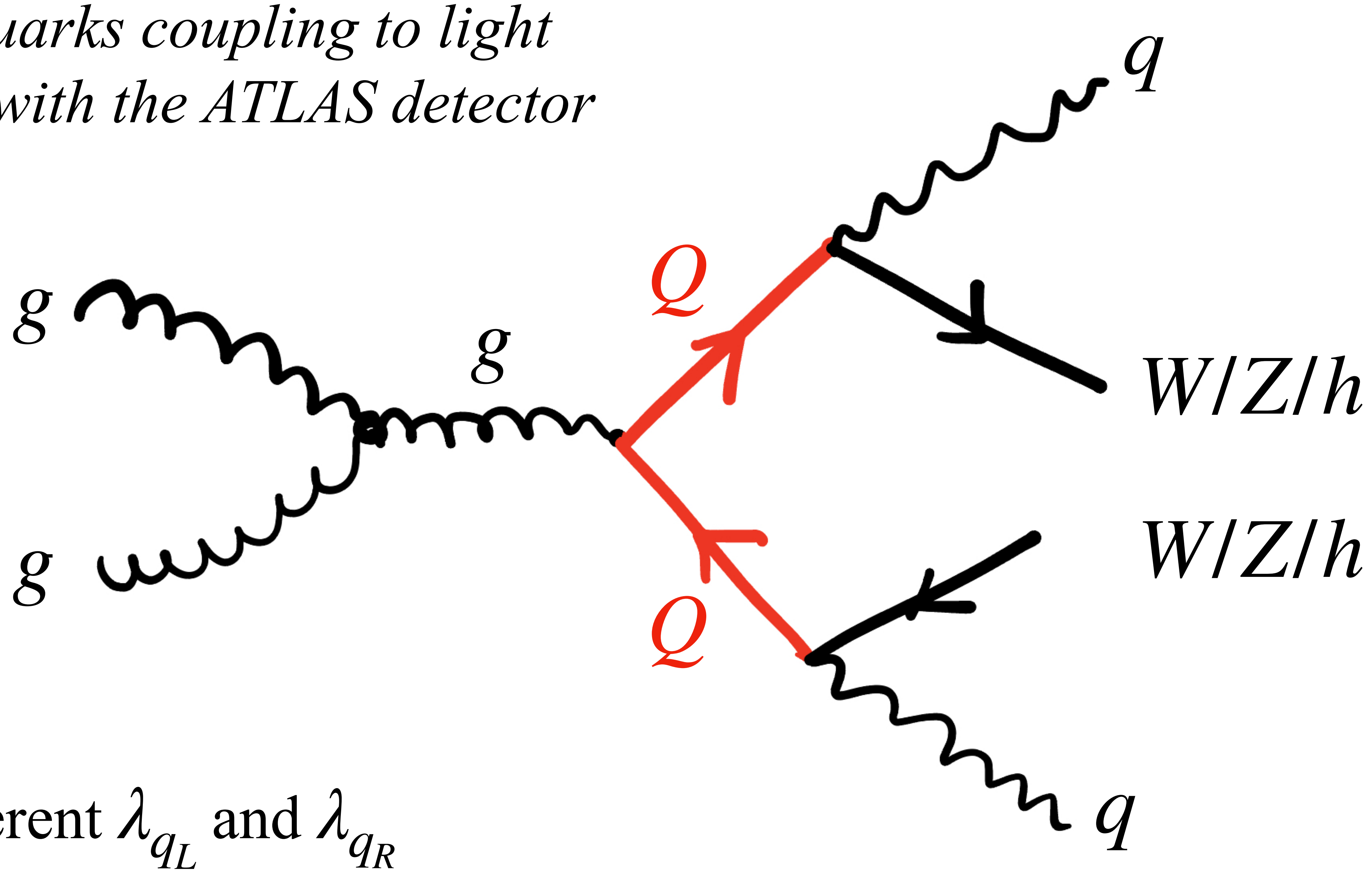
↓

New production channels
+
enhanced $BR(h \to qq)$

Direct searches

Run II 140 fb^{-1}:

ATLAS **arXiv:2405.19862**: *Search for pair-produced vector-like quarks coupling to light quarks in the lepton plus jets final state using 13 TeV pp collisions with the ATLAS detector*



$\text{BR}(Q \to Wq) = 1$

$M_Q > 1530$ GeV @ 95% CL

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

$M_Q > 1150$ GeV @ 95% CL

Different branching ratios can be obtained in Models $1-8$ for different λ_{q_L} and λ_{q_R}

We set $M_{Q_1} = M_{Q_2} = \Lambda > 1.6$ TeV.

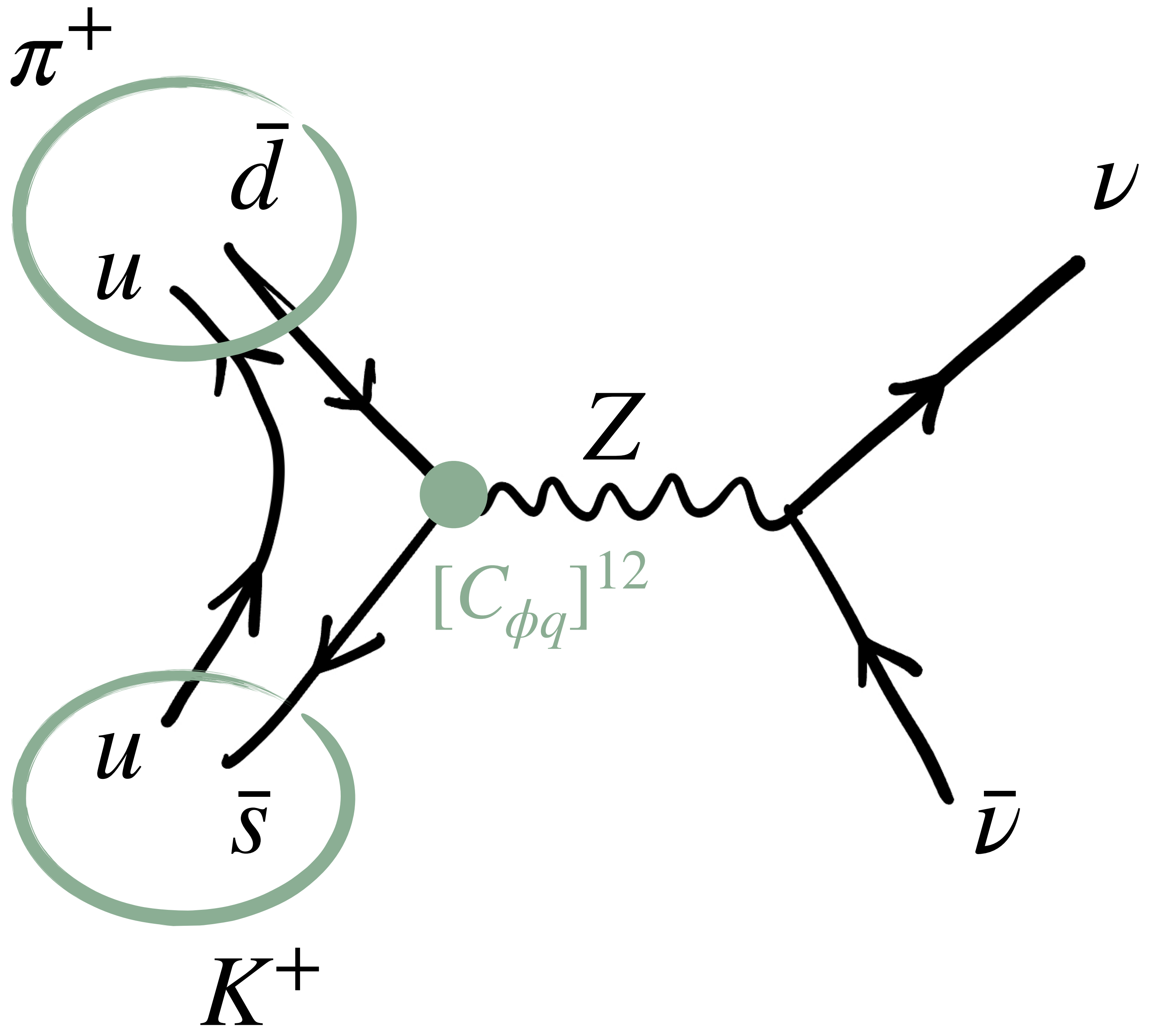
Flavor transitions

$$-\mathscr{L} \supset \lambda_{q_L}^{i}\, Q_1\, \phi\, q_L^{i} + \lambda_{q_R}^{i}\, Q_2\, \phi\, q_R^{i} + \lambda_{Q_1 Q_2}\, Q_1\, \phi\, Q_2 \quad \longrightarrow \quad [C_{q\phi}]^{ij} \sim \frac{v^2 \lambda_{q_L}^{i}\, \lambda_{q_R}^{j}\, \lambda_{Q_1 Q_2}}{M_{Q_1} M_{Q_2}}$$

but also

$$\longrightarrow \quad [C_{\phi q_L}]^{ij} \sim \frac{v^2 \lambda_{q_L}^{i}\, \lambda_{q_L}^{j}}{M_{Q_1}^2} \quad \text{and} \quad \longrightarrow \quad [C_{\phi q_R}]^{ij} \sim \frac{v^2 \lambda_{q_R}^{i}\, \lambda_{q_R}^{j}}{M_{Q_2}^2}$$

$[\mathcal{O}_{\phi u}]^{rp}$	$(i\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\overline{u}_R^r \gamma^\mu u_R^p)$	$[\mathcal{O}_{\phi d}]^{rp}$	$(i\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\overline{d}_R^r \gamma^\mu d_R^p)$
$[\mathcal{O}_{\phi q}^{(1)}]^{rp}$	$(i\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\overline{q}_L^r \gamma^\mu q_L^p)$	$[\mathcal{O}_{\phi q}^{(3)}]^{rp}$	$(i\phi^\dagger \overleftrightarrow{D}^I_\mu \phi)(\overline{q}_L^r \gamma^\mu \sigma^I q_L^p)$



Example: $Q_1 \sim (3,2)_{1/6}$ with $-\mathscr{L} \supset [\lambda_{q_1}^{d}]_i\, \bar{Q}_1\, \phi\, d_R^i$

$K^+ \to \pi^+ \nu\bar{\nu}$: constrains $M_{Q_1} > 128 \times \sqrt{|[\lambda_{Q_1}^{d}]_1|\, |[\lambda_{Q_d}^{2}]_2|}$ TeV

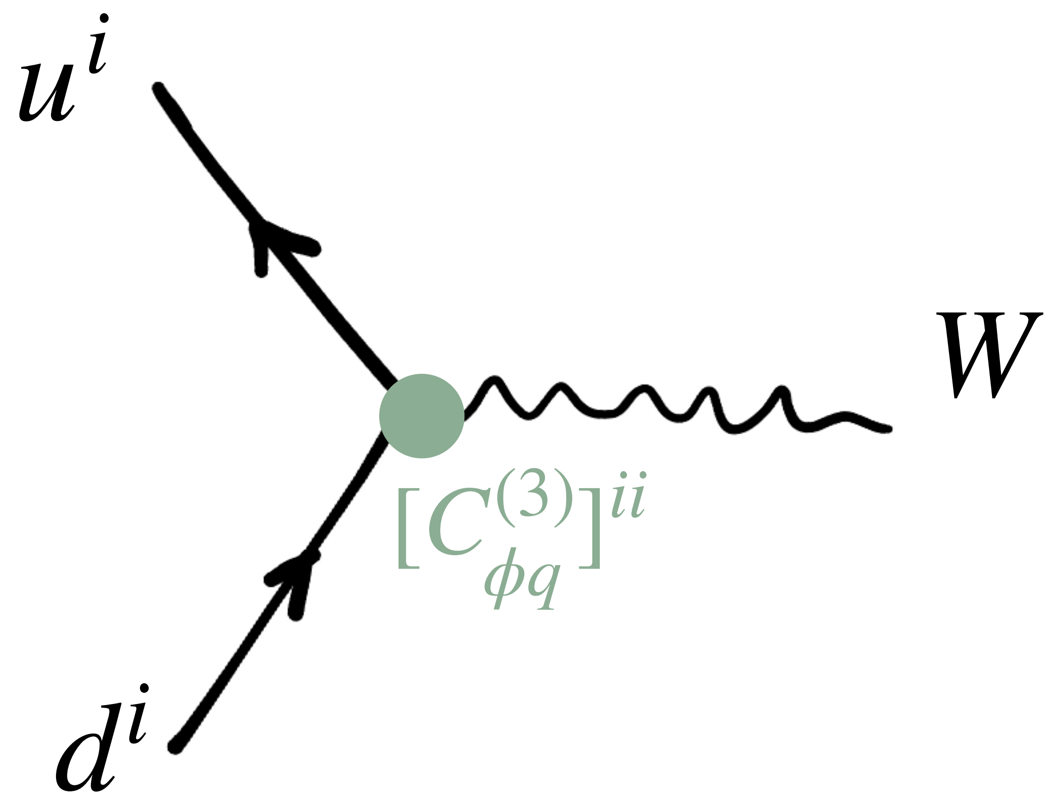
(no chance to observe contributions to light Yukawas)

New states have to couple to **only one** family!

Flavor transitions

Even then, states which match to $\mathcal{O}_{\phi q}^{(3)}$ modify W interactions:

$$\delta g_W^{ii} \sim v^2 [C_{\phi q}^{(3)}]^{ii} \sim \frac{v^2 |\lambda_Q|_i^2}{M_{Q_1}^2}$$



which manifest as unitarity violation of the CKM matrix

$$S_{ii} = |V_{i1}|^2 + |V_{i2}|^2 + |V_{i3}|^2 = \begin{cases} 1\,, & \text{SM} \\ 1 \pm \dfrac{v^2 |\lambda_Q|_i^2}{M_{Q_1}^2}\,, & \text{NP} \end{cases}$$

Exp: $S_{11} = 0.9984 \pm 0.0007$, first row unitarity (PDG: **Phys. Rev. D 110 no. 3, (2024) 030001**)

$$M_\Psi > 3.2 \times |[\lambda_\Psi]_1| \ \text{TeV}\,, \qquad \Psi = U, D\,,$$
$$M_\Psi > 1.6 \times |[\lambda_\Psi]_1| \ \text{TeV}\,, \qquad \Psi = T_1, T_2$$

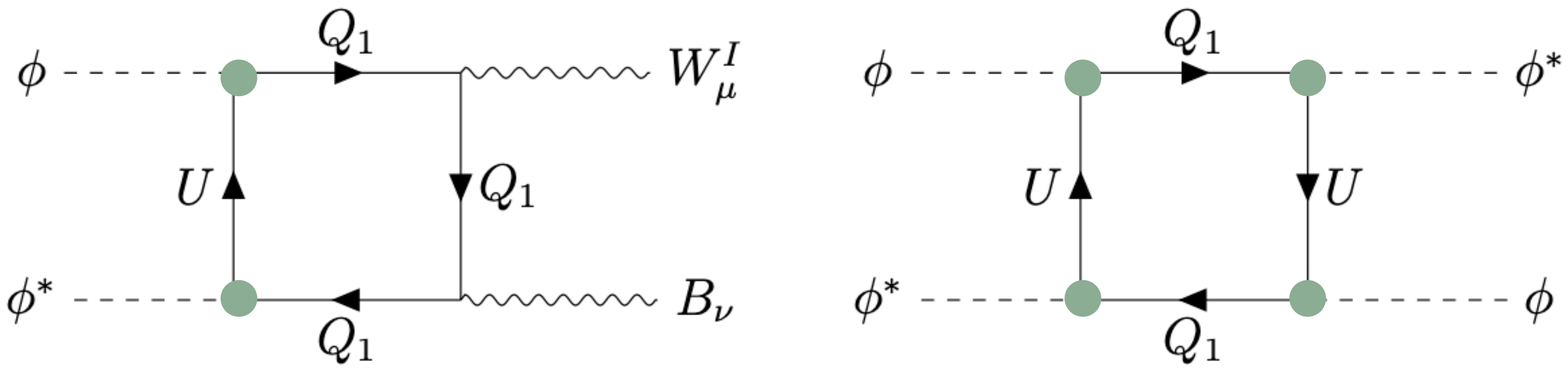
Electroweak processes

Observable	Definition	Observable	Definition
Γ_Z	$\sum_f \Gamma(Z \to f\bar{f})$	R_{uc}	$\frac{\Gamma(Z\to u\bar{u})+\Gamma(Z\to c\bar{c})}{2\sum_q \Gamma(Z\to q\bar{q})}$
σ_{had}	$\frac{12\pi}{m_Z}\frac{\Gamma(Z\to e^+e^-)\Gamma(Z\to q\bar{q})}{\Gamma_Z^2}$	m_W	m_W
R_f	$\frac{\Gamma(Z\to f\bar{f})}{\sum_q \Gamma(Z\to q\bar{q})}$	Γ_W	$\sum_{f_1,f_2} \Gamma(W \to f_1 f_2)$
A_f	$\frac{\Gamma(Z\to f_L\bar{f}_L)-\Gamma(Z\to f_R\bar{f}_R)}{\Gamma(Z\to f\bar{f})}$	$\text{BR}(W \to \ell\nu)$	$\frac{\Gamma(W\to \ell\nu)}{\Gamma_W}$
$A_{\text{FB}}^{0,\ell}$	$\frac{3}{4}A_e A_\ell$	R_{W_c}	$\frac{\Gamma(W\to cs)}{\Gamma(W\to ud)+\Gamma(W\to cs)}$
A_c^{FB}	$\frac{3}{4}A_e A_c$	A_b^{FB}	$\frac{3}{4}A_e A_b$

$$\delta m_W = -\frac{v^2 g_2^2}{4(g_2^2 - g_1^2)}\mathcal{C}_{\phi D} - \frac{v^2 g_1 g_2}{g_2^2 - g_1^2}\mathcal{C}_{\phi WB}$$

$$\vdots$$

$$\chi^2_{\text{EWPO}} = \sum_{ij}[O_{i,\exp} - O_{i,\text{th}}](\sigma^{-2})_{ij}[O_{j,\exp} - O_{j,\text{th}}]$$



Crucial as sensitive to
VLQ-VLQ-Higgs coupling

$$-\mathscr{L} \supset \lambda_{q_L} Q_1 \phi\, q_L + \lambda_{q_R} Q_2 \phi\, q_R + \boxed{\lambda_{Q_1 Q_2}} Q_1 \phi\, Q_2 \longrightarrow C_{q\phi} \sim \frac{v^2 \lambda_{q_L} \lambda_{q_R} \boxed{\lambda_{Q_1 Q_2}}}{M_{Q_1} M_{Q_2}}$$

Higgs physics

Enhanced light Yukawa couplings affect the Higgs production ($pp \to h$):

$$\sigma = \left[48.68 + 2.83 \cdot 10^4 \, v^2 \mathcal{C}_{\phi G} + (8.52 \, \kappa_u^2 + 2.71 \, \kappa_d^2) \cdot 10^{-6} + 2.53 \cdot 10^{-3} \kappa_s^2 + 0.25 \, \kappa_c^2\right] \text{pb}$$

and decays:

$$\Gamma_h^{\text{SMEFT}} \supset \sum_q \kappa_q^2 \Gamma_q^{\text{SM}}$$

We perform the fit using the signal strengths:

$$\mu_i = \frac{\sigma \cdot \text{BR}_i}{\sigma^{\text{SM}} \cdot \text{BR}_i^{\text{SM}}}$$

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

Decay Channel i	BR_i^{SM}	μ_i^{exp}
$h \to WW$	22.00%	0.97 ± 0.09
$h \to ZZ$	2.71%	0.97 ± 0.12
$h \to b\bar{b}$	57.63%	1.05 ± 0.22
$h \to \tau^+\tau^-$	6.21%	0.85 ± 0.10
$h \to \mu^+\mu^-$	0.0216%	1.21 ± 0.44
$h \to \gamma\gamma$	0.227%	1.13 ± 0.09

Constructing the fit

$$\chi^2_{\mathrm{TOT}} = \chi^2_{\mathrm{EWPO}} + \chi^2_{\mathrm{Higgs}} + \boxed{\chi^2_{\mathrm{Flav}}} \longrightarrow$$

and $\Lambda = 1.6$ TeV

E.g. Model 1 with the first family couplings:

$$\chi^2_{\mathrm{Flav}} = 3.84 \left(\frac{3.2\,|[\lambda_U]_1|}{1.6} \right)^2$$

implements the CKM unitarity violation constraint.

$$-\mathscr{L} \supset \boxed{\lambda_{q_L}}\, Q_1\, \phi\, q_L + \boxed{\lambda_{q_R}}\, Q_2\, \phi\, q_R + \boxed{\lambda_{Q_1 Q_2}}\, Q_1\, \phi\, Q_2 \longrightarrow C_{q\phi} \sim \frac{v^2}{\Lambda^2} \times \lambda_{q_L}\, \lambda_{q_R}\, \lambda_{Q_1 Q_2}$$

We present the results for the allowed regions in the $\lambda_{q_L} - \lambda_{q_R}$ plane:

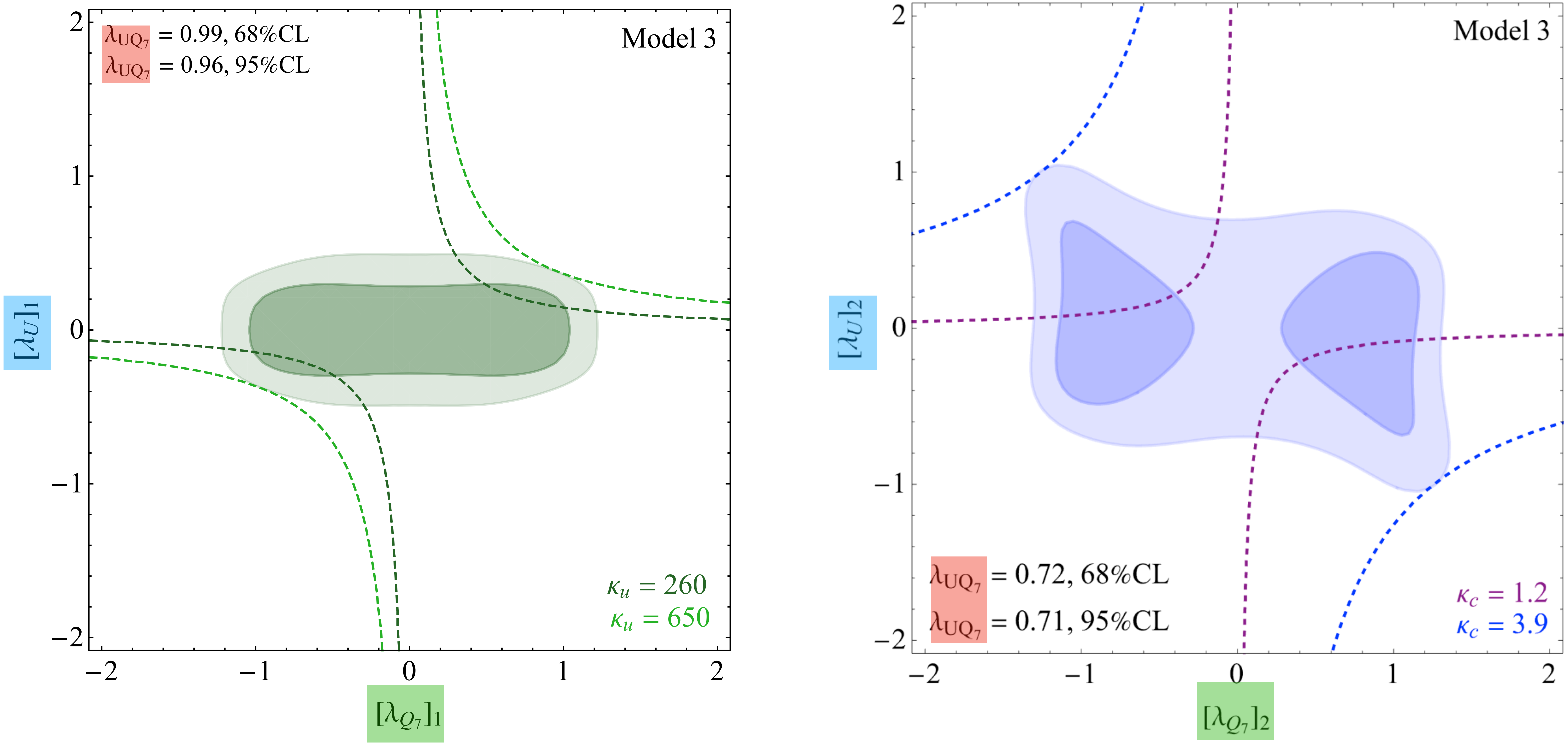
$$\boxed{\chi^2_{\mathrm{TOT}}(\lambda_{q_L}, \lambda_{q_R}) < \chi^2_{\mathrm{TOT}}(\lambda_{q_L}, \lambda_{q_R})\,|_{\mathrm{min}} + \chi^2(95\,\%\,\mathrm{CL})}$$

While the coupling $\lambda_{Q_1 Q_2}$ is chosen to maximise κ_q under the condition:

$$\chi^2_{\mathrm{TOT}}(\lambda_{q_L}, \lambda_{q_R}, \lambda_{Q_1 Q_2}) < \chi^2_{\mathrm{TOT}}(\lambda_{q_L}, \lambda_{q_R}, \lambda_{Q_1 Q_2})\,|_{\mathrm{min}} + \chi^2(95\,\%\,\mathrm{CL})$$

Results

Example Model 3: $-\mathcal{L}_3^{\text{int}} = \lambda_U \overline{U}_R \tilde{\phi}^\dagger q_L + \lambda_{Q_7} \overline{Q}_{7L} \phi\, u_R + \lambda_{UQ_7} \overline{U} \phi^\dagger Q_7 + \text{h.c.}$



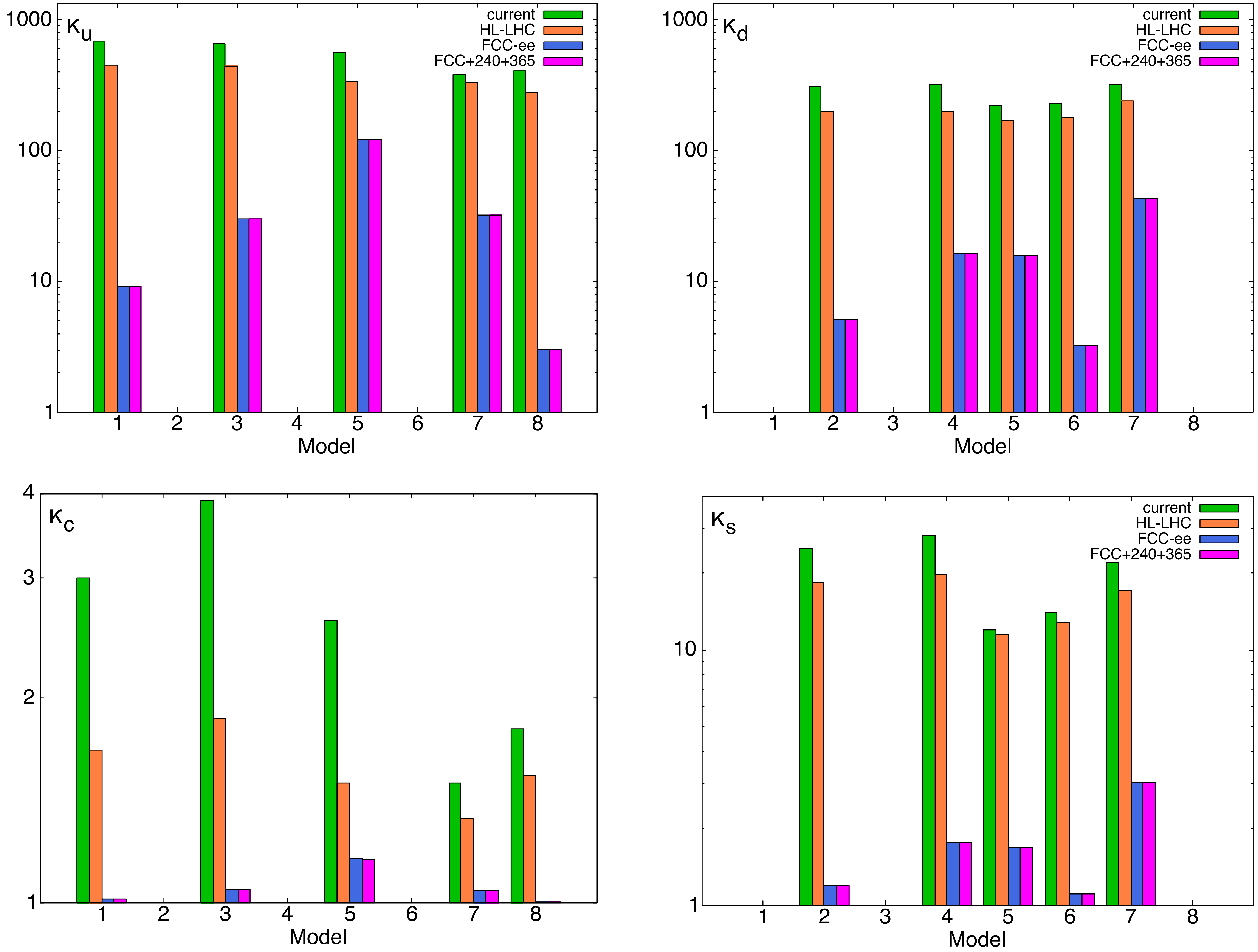
Results

Allowed coupling modifiers for other models:

	Mod.1	Mod.2	Mod.3	Mod.4	Mod.5	Mod.6	Mod.7	Mod.8
κ_u								
Current	680	-	650	-	940	-	380	410
κ_d								
Current	-	310	-	320	220	230	360	-
κ_c								
Current	3.0	-	3.9	-	2.6	-	1.5	1.8
κ_s								
Current	-	25	-	28	12	14	14	-

cf. $|\kappa_u| < 260$, $|\kappa_d| < 156$, $|\kappa_c| < 1.2$, $|\kappa_s| < 13$ at HL-LHC @ 95%CL

Projections



G. Bernardi et al., “The Future Circular Collider: a Summary for the US 2021 Snowmass Process”: **arXiv:2203.06520**

J. De Blas, G. Durieux, C. Grojean, J. Gu, and A. Paul, “On the future of Higgs, electroweak and diboson measurements at lepton colliders”: **arXiv:1907.04311**

$$|\kappa_c| < \mathcal{O}(1.04)$$

$$|\kappa_s| < \mathcal{O}(1.8)$$

$$|\kappa_u| < \mathcal{O}(10)$$

$$|\kappa_d| < \mathcal{O}(20)$$

FCC-ee

current 🟩
HL-LHC 🟧
FCC-ee 🟦
FCC+240+365 🟪

Conclusions

1. Enhanced light Yukawa couplings are possible.
   $\kappa_u \sim \mathcal{O}(600)\,, \kappa_d \sim \mathcal{O}(300)\,, \kappa_s \sim \mathcal{O}(20)\,, \kappa_c \sim \mathcal{O}(3)$
   (Vector-like fermions are everywhere in BSM - not so difficult to imagine these scenarios)

2. Continue with experimental effort.
   (Models exist such that the light Yukawa measurements are their best probe)

3. Non-trivial interplay between the light quark Yukawa enhancements and limits on other operators in an EFT.
   (The possibility of largely enhanced light quark Yukawa couplings should be taken into account when performing fits to data)