How large can the light Yukawa couplings be?

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arXiv: 2410.08272 and arXiv: 2501.07628

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[ChatGPT on proposal of my daughter]

Higgs couplings

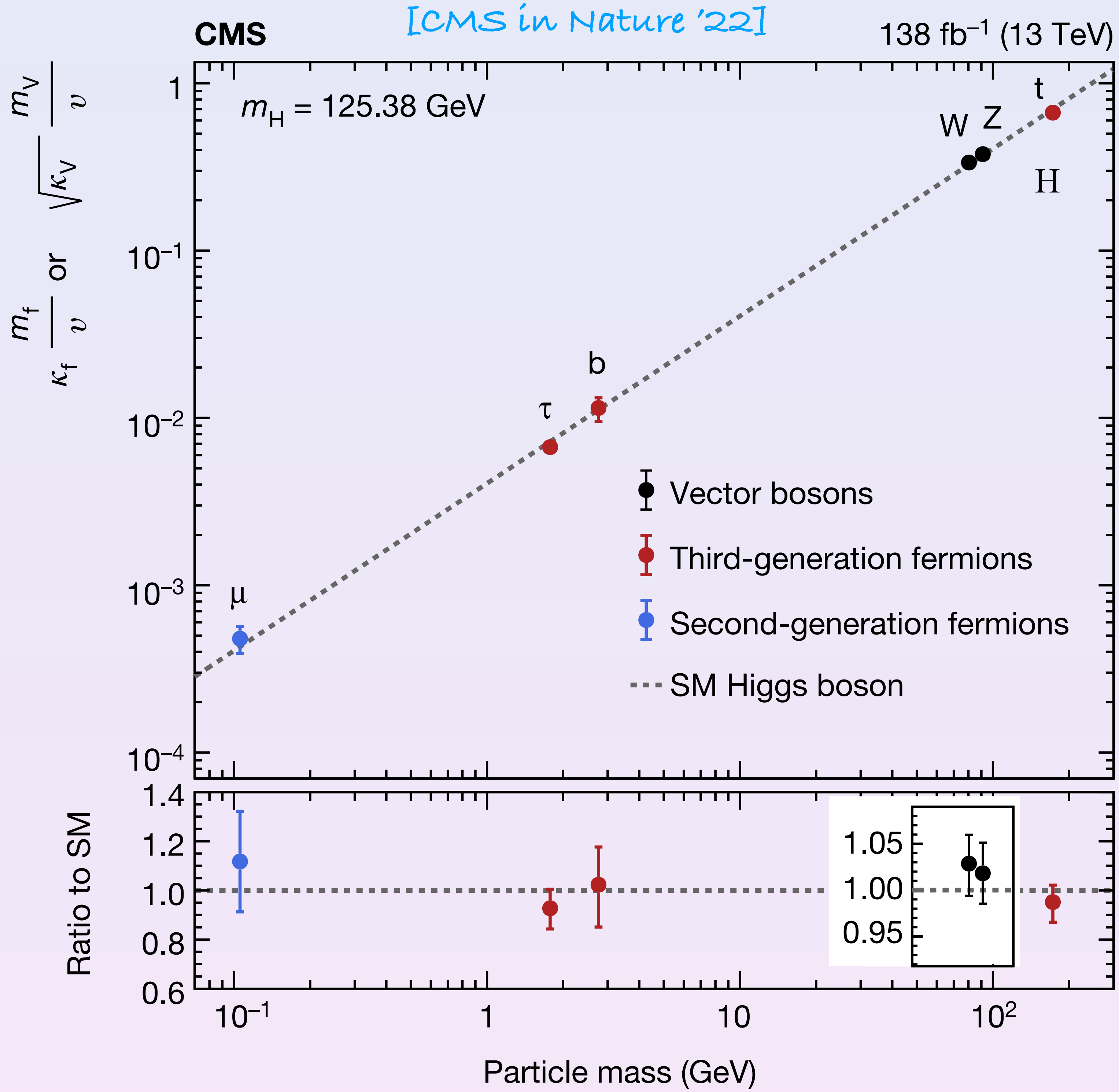
3rd generation fermion and gauge boson couplings to Higgs boson fairly good measured

2nd generation fermion couplings first results available

First and second generation quark Yukawa couplings?

Electron Yukawa coupling?

[CMS in Nature '22]



LHC and HL-LHC projections

Charm quark: $pp \to V(h \to c\bar{c})$: ATLAS: $|\kappa_c| < 4.2\,@\,95\,\%$ CL [arXiv: 2410.19611]

can be tagged CMS: $|\kappa_c| < 5.5\,@\,95\,\%$ CL [arXiv: 2205.05550]

Further proposals for light quark Yukawa couplings: $\kappa_f = g_{hff}/g_{hff}^{SM}$

- Higgs p_T spectrum [Bishara, Haisch, Monni, Re '16, Soreq, Zhu, Zupan '16]
- $W^{\pm}h$ charge asymmetry [Yu '16]
- Global fits to Higgs data [De Blas et al '19]
- Higgs pair production [Alasfar, Corral Lopez, RG '19, Alasfar, RG, Grojean, Paul, Qian '22]
- Higgs + photon [Aquilar-Saavedra, Cano, No '20]
- Tri-boson production [Falkowski et al '20]
- Higgs off-shell production [Balzani, RG, Vitti '23]

$|\kappa_c| < 1.2$

$|\kappa_s| < 13$

$|\kappa_d| < 156$

$|\kappa_u| < 260$

@ HL-LHC

Electron Yukawa coupling:

- Higgs decays to electrons ATLAS: $|\kappa_e| < 260$

[PLB 801 (2020) 135148]

$|\kappa_e| < 120$

@ HL-LHC

[Cepeda et al. '19]

Light quark Yukawa couplings

Light fermion Yukawa couplings in Standard Model Effective Field Theory modified by

$$\mathcal{O}_{u\phi} = \bar{q}_L \tilde{\phi} u_R \phi^\dagger \phi \qquad \mathcal{O}_{d\phi} = \bar{q}_L \phi d_R \phi^\dagger \phi \qquad \mathcal{O}_{e\phi} = \bar{\ell}_L \phi e_R \phi^\dagger \phi$$

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

rescales all Higgs couplings
(hence constrained by Higgs couplings to vector bosons)

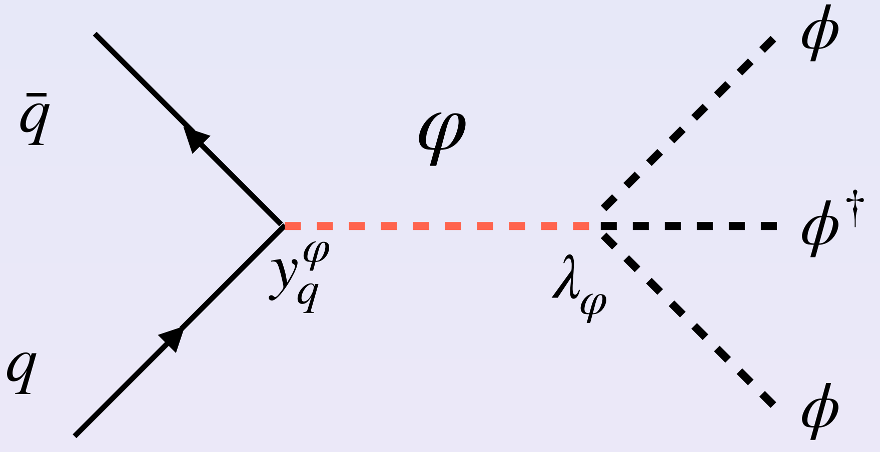
dominant modification
(mass eigenbasis)

Single mediator

Single mediator - extra scalar

$$C_{q\phi} \propto \frac{y_q^{\varphi}\lambda_{\varphi}}{M_{\varphi}^2}$$

y_q^{φ} probed also in direct production of φ



[studied in Egana-Ugrinovic, Homiller, Meade '19, Giannakopoulou, Meade, Valli '24]

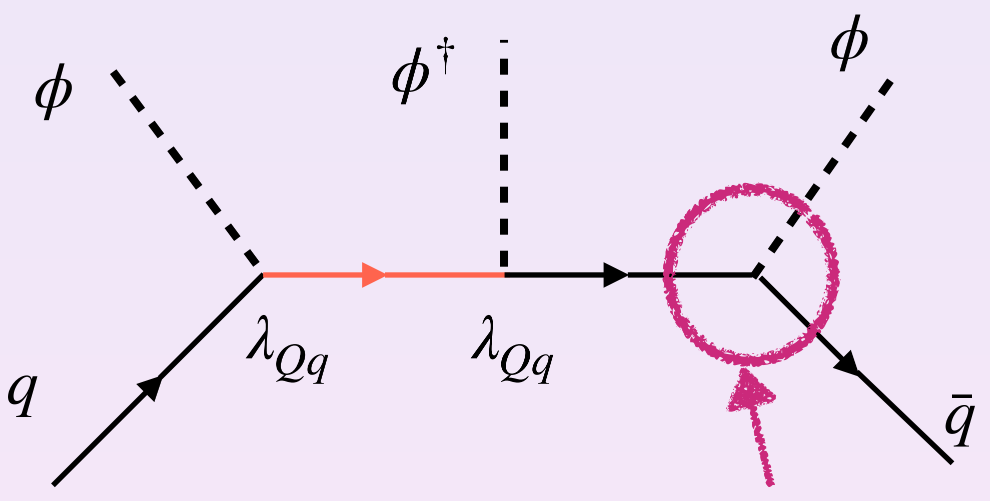
Single mediator - extra vector-like quark

$$C_{q\phi} \propto \frac{y_q |\lambda_{Qq}|^2}{M_Q^2} \longrightarrow \kappa_q = \frac{g_{hqq}}{g_{hqq}^{SM}} = 1 + \frac{v^2|\lambda_{Qq}|^2}{M_Q^2}$$

$$= 1 - \sqrt{2}\delta g_{Zq}$$

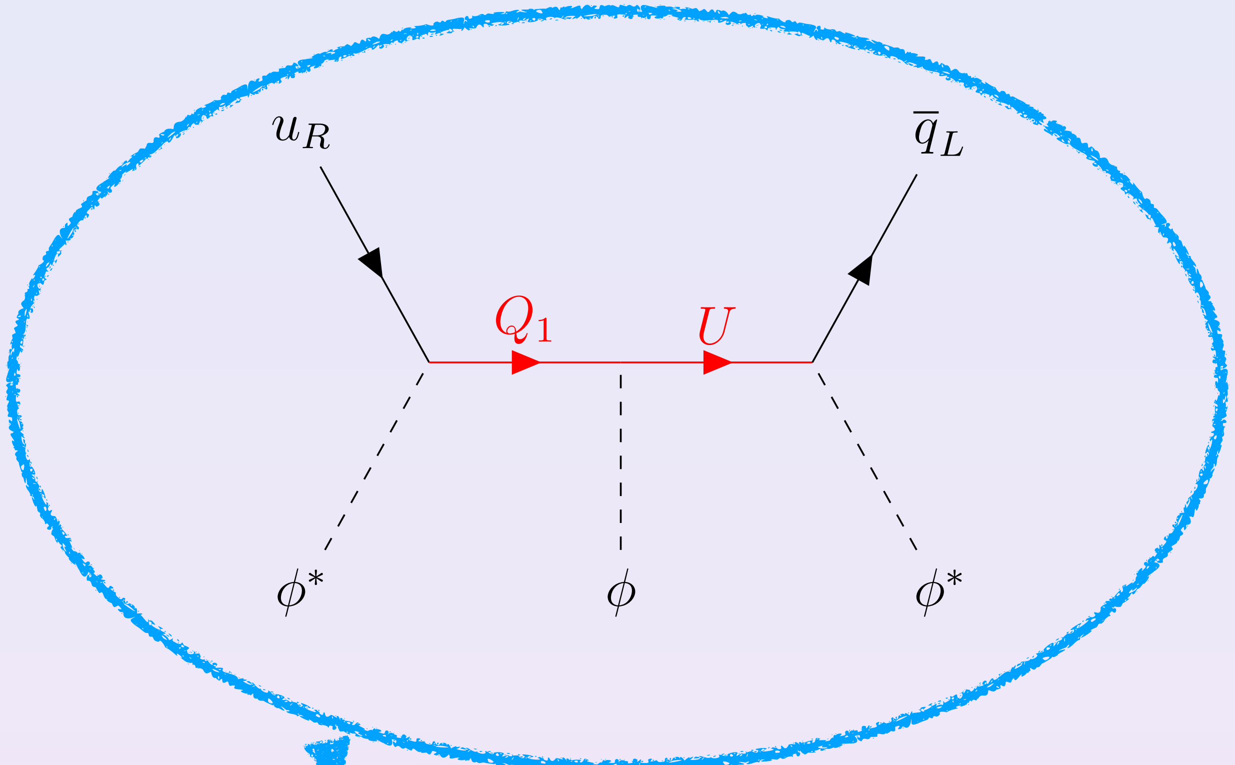
generates also $C_{\phi q}$

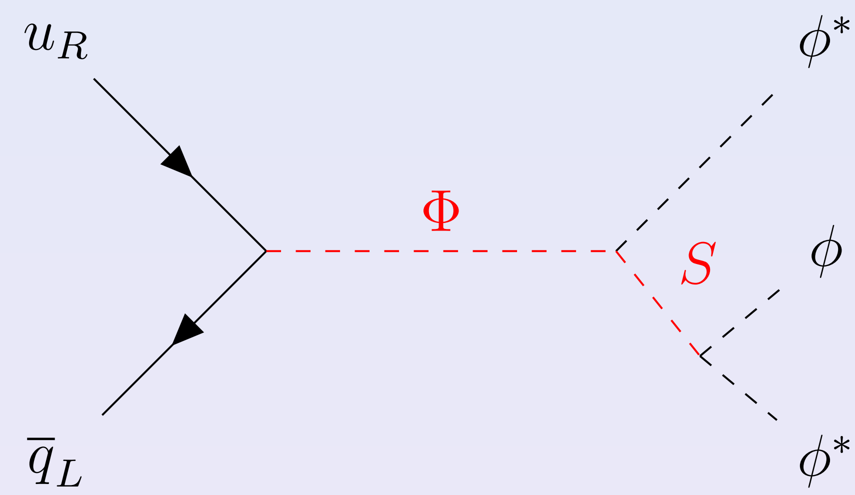
very constrained by electroweak precision measurements

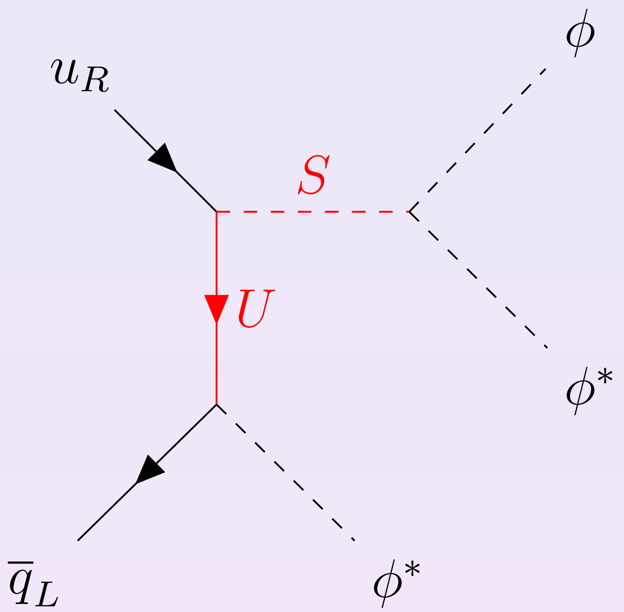


suppressed by small SM Yukawa

Two mediators







two VLQ representations
no s channel resonance
decaying to dijets

$$-\mathcal{L}_1^{\rm int} = \lambda_U \overline{U}_R \tilde{\phi}^\dagger q_L + \lambda^u_{Q_1} \overline{Q}_{1L} \tilde{\phi}\, u_R + \lambda_{UQ_1} \overline{U} \tilde{\phi}^\dagger\, Q_1 + \text{h.c.}$$

study case of two VLQs

schematically $\kappa_q = 1 + \dfrac{v^2 \lambda^u_{Q_1} \lambda_U \lambda_{UQ_1}}{M_Q M_U}$

Vector-like quark Models

Model	VLQs	Model	VLQs	Model	VLQs
1	$(3,1)_{2/3}+(3,2)_{1/6}$	4	$(3,1)_{-1/3}+(3,2)_{-5/6}$	7	$(3,2)_{1/6}+(3,3)_{2/3}$
2	$(3,1)_{-1/3}+(3,2)_{1/6}$	5	$(3,2)_{1/6}+(3,3)_{-1/3}$	8	$(3,2)_{7/6}+(3,3)_{2/3}$
3	$(3,1)_{2/3}+(3,2)_{7/6}$	6	$(3,2)_{-5/6}+(3,3)_{-1/3}$		

- Eight models
- they generate further operators for instance operators that modify the Z couplings to the light quarks
- are constrained by Higgs physics, flavour physics, direct searches and electroweak observables

The models generate at tree-level

$[\mathcal{O}_{u\phi}]^{rp}$	$\overline{q}^r_L\tilde{\phi}u^p_R\,\phi^\dagger\phi$	$[\mathcal{O}_{d\phi}]^{rp}$	$\overline{q}^r_L\phi d^p_R\,\phi^\dagger\phi$
$[\mathcal{O}_{\phi u}]^{rp}$	$(i\phi^\dagger\overleftrightarrow{D}_\mu\phi)(\overline{u}^r_R\gamma^\mu u^p_R)$	$[\mathcal{O}_{\phi d}]^{rp}$	$(i\phi^\dagger\overleftrightarrow{D}_\mu\phi)(\overline{d}^r_R\gamma^\mu d^p_R)$
$[\mathcal{O}^{(1)}_{\phi q}]^{rp}$	$(i\phi^\dagger\overleftrightarrow{D}_\mu\phi)(\overline{q}^r_L\gamma^\mu q^p_L)$	$[\mathcal{O}^{(3)}_{\phi q}]^{rp}$	$(i\phi^\dagger\overleftrightarrow{D}^I_\mu\phi)(\overline{q}^r_L\gamma^\mu\sigma^I q^p_L)$
$[\mathcal{O}_{\phi ud}]^{rp}$	$(i\tilde{\phi}^\dagger D_\mu\phi)(\overline{u}^r_L\gamma^\mu d^p_L)$		

Higgs physics: additional production channels, enhanced $BR(h\to q\bar{q})$

electroweak precision: modifies couplings of Z and W bosons to quarks

and at one-loop level

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

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

electroweak precision: "S" and "T" parameters

Constraints

Flavour: flavour transitions constrain models up to very high scales

solution: couple new physics to one generation at a time

nevertheless bounds from CKM unitarity

Direct searches: pair production with subsequent decays to W/Z/h and q

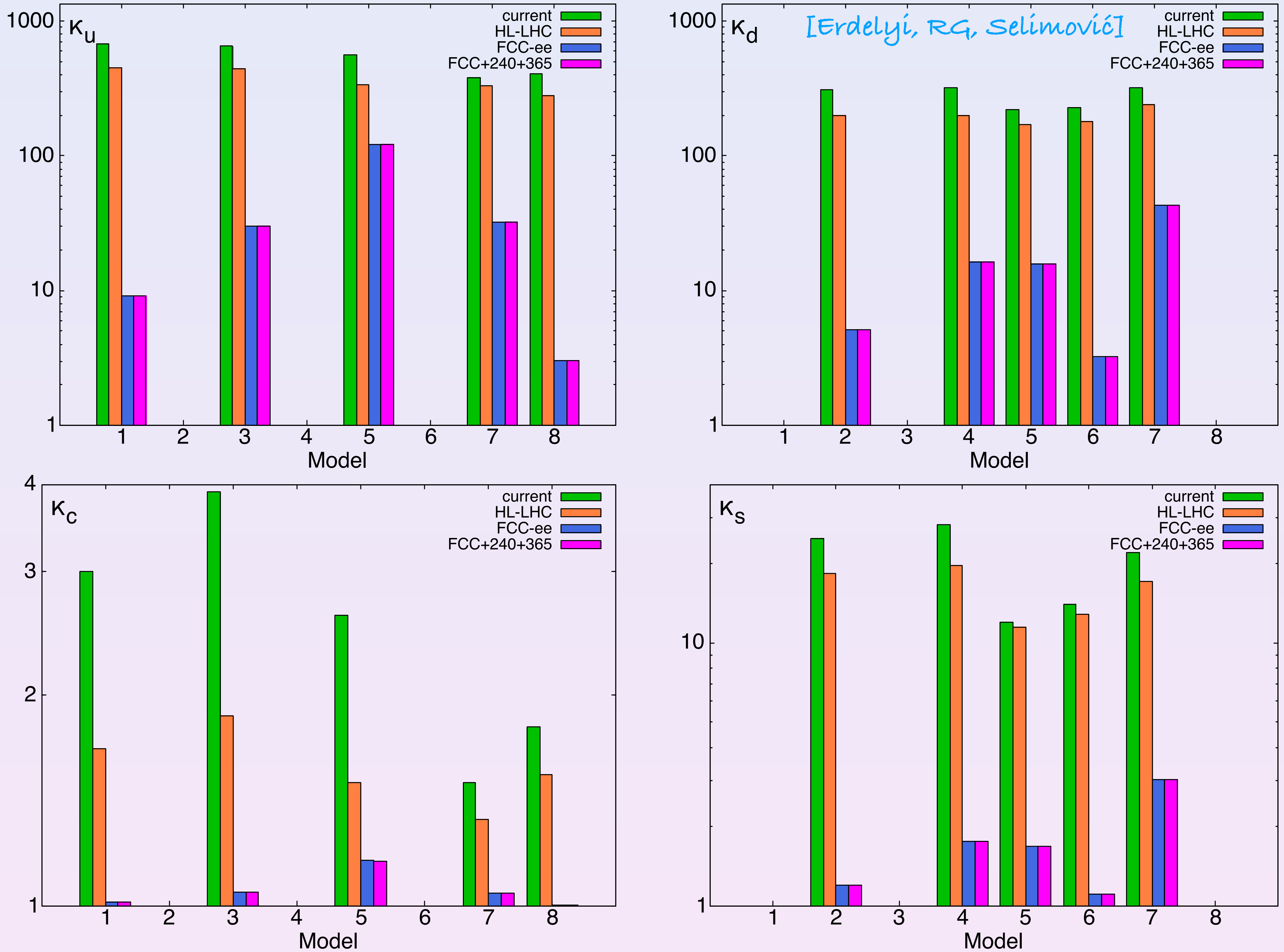
ATLAS: [2405.19862] $M > 1.6$ TeV HL-LHC: $M > 2.4$ TeV [Freitas et al. '20]

Electroweak precision observables: $\Gamma_Z, A_f, \sigma_{had}, \ldots$

including one-loop matching, sensitivity to all couplings

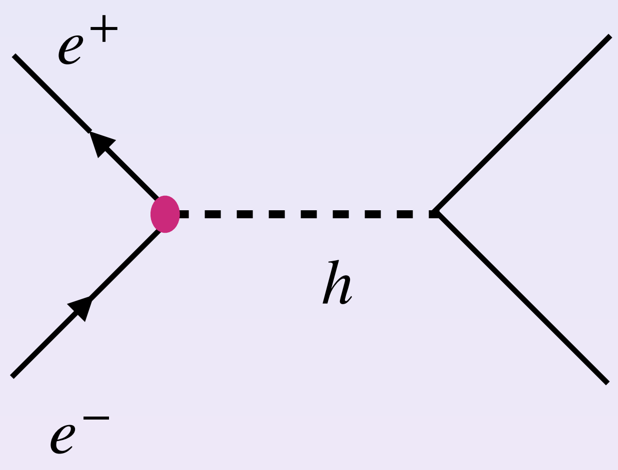
Higgs physics: new production channels at the HL-LHC, enhanced decays to light quarks, ...

Light quark Yukawa couplings



Electron Yukawa coupling

FCC-ee can directly measure the electron Yukawa coupling by dedicated run at Higgs pole mass



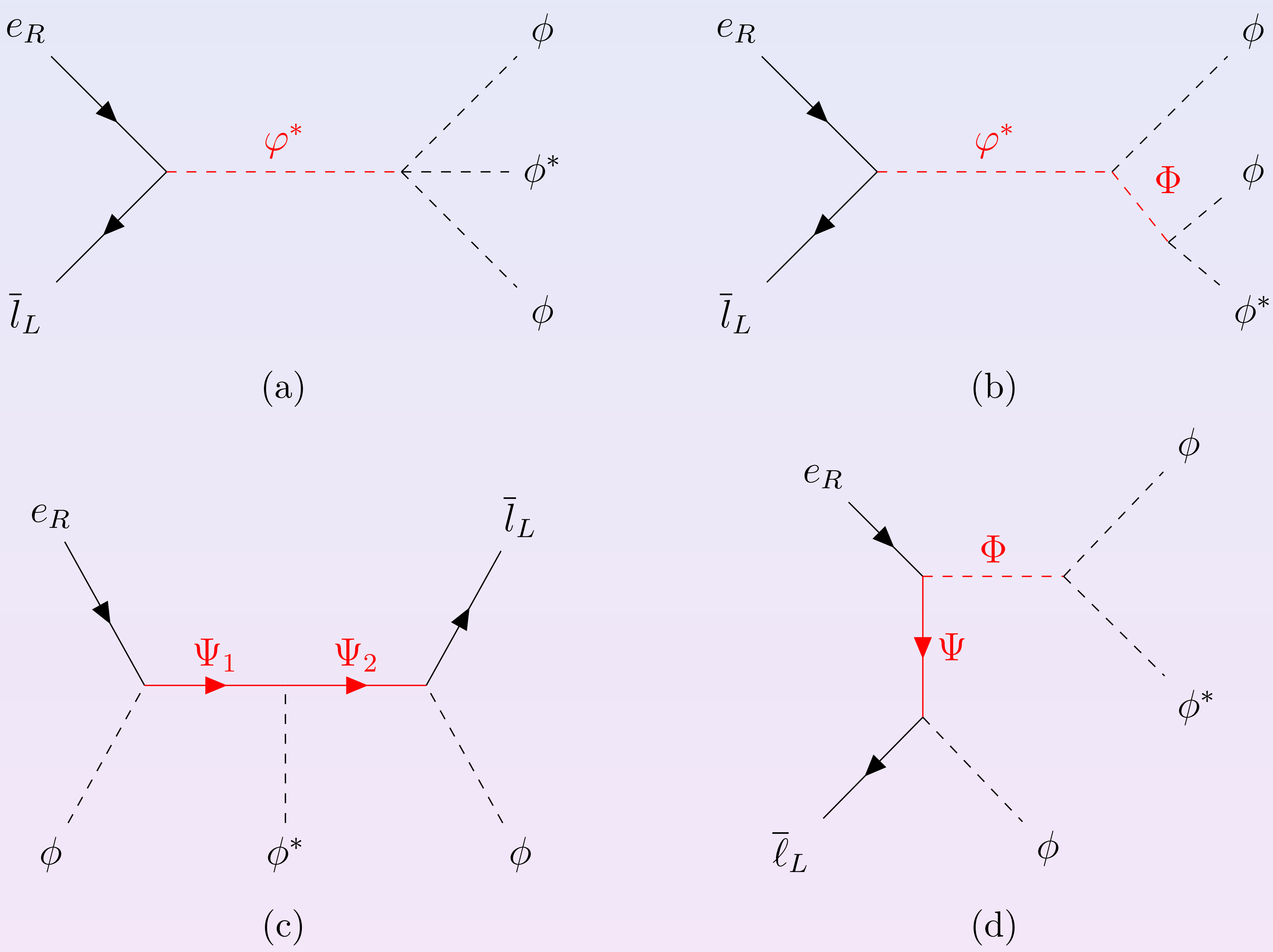
probes $\kappa_e < 1.6$

[d'Enterria, Poldaru, Wojcik '21]

requires monocromatised e^+e^- beam,
precise knowledge of Higgs boson mass,
extended timeline

And which models are probed?

Electron Yukawa coupling



study all models that generate $C_{e\Phi}$ at tree-level

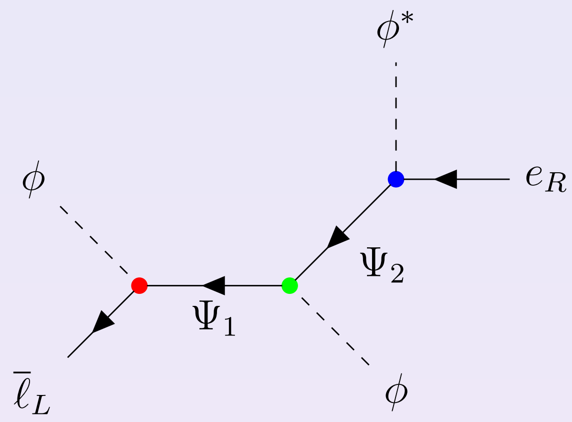
difference with quark case: new states not easily produced at LHC

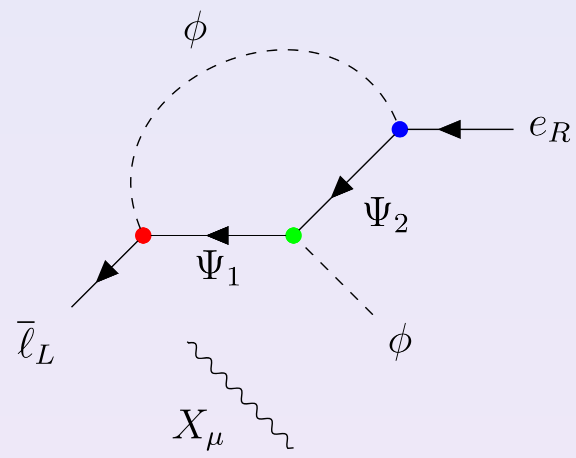
Electron Yukawa coupling

Flavour: flavour transitions constrain models up to very high scales

solution: couple new physics to one generation at a time

direct correlation with $(g-2)_e$ for models with VLLs





Direct searches: pair production with subsequent decays to W/Z/h and ν/e

HL-LHC: depending on model between 600 GeV and 2.1 TeV

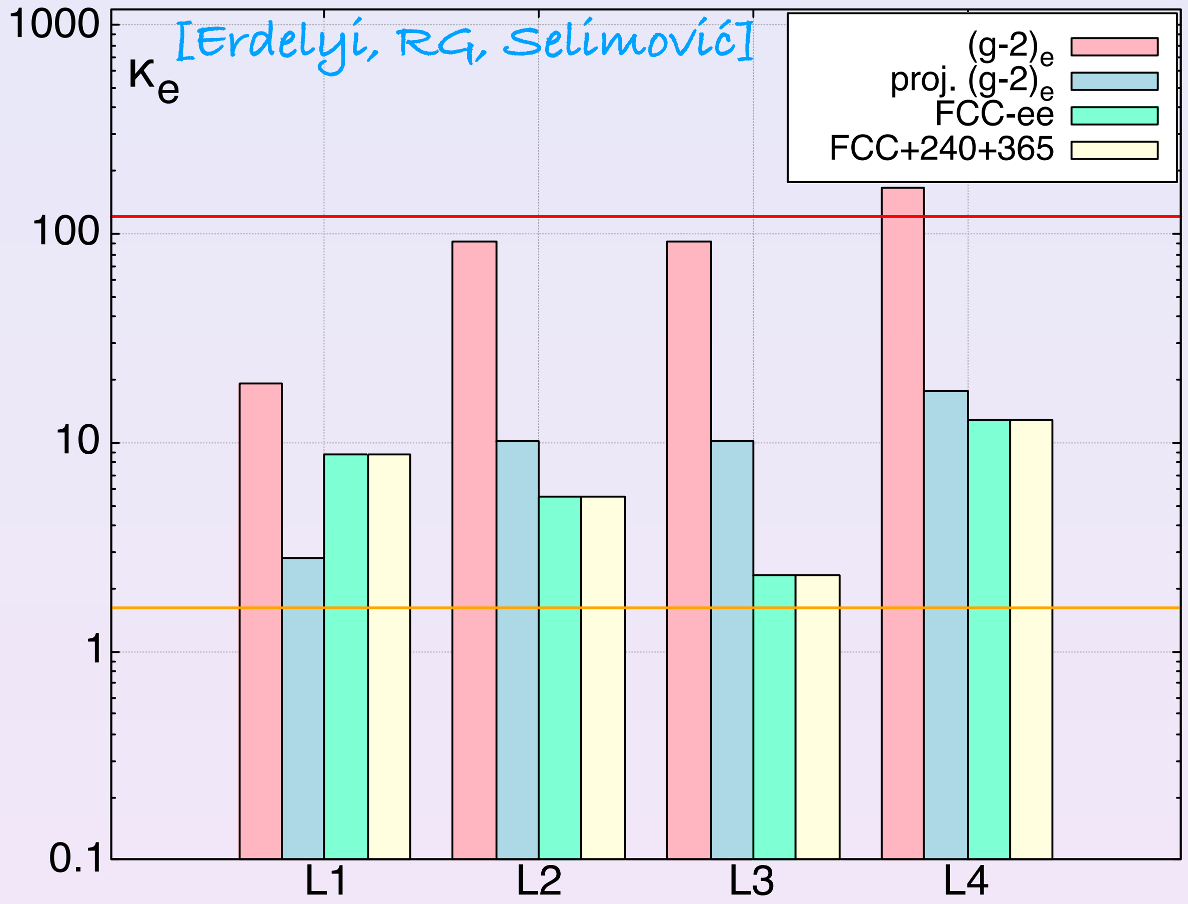
Electroweak precision tests

Higgs physics:

for models with only scalars also λ_{hhh}

Electron Yukawa coupling

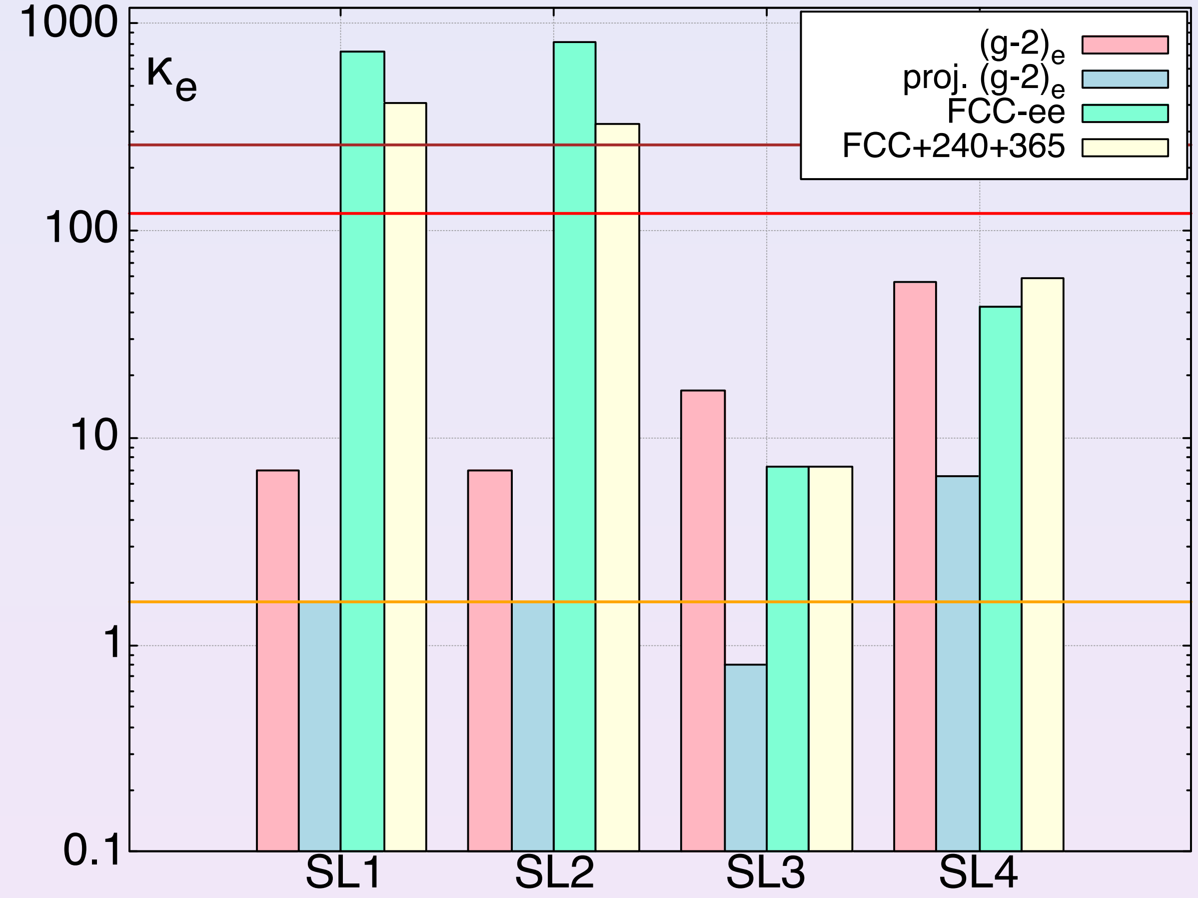
Vector-like lepton models



$E+\Delta_1$ $E+\Delta_3$ $\Sigma_1+\Delta_3$ $\Sigma_1+\Delta_1$

VLL	E	Δ_1	Δ_3	Σ	Σ_1
Irrep.	$(\mathbf{1},\mathbf{1})_{-1}$	$(\mathbf{1},\mathbf{2})_{-\frac{1}{2}}$	$(\mathbf{1},\mathbf{2})_{-\frac{3}{2}}$	$(\mathbf{1},\mathbf{3})_{0}$	$(\mathbf{1},\mathbf{3})_{-1}$

Vector-like lepton + scalar models



$S+E$ $S+\Delta_1$ $\Xi+\Delta_1$ $\Xi+\Sigma_1$

Scalars	S	φ	Ξ	Ξ_1
Irrep.	$(\mathbf{1},\mathbf{1})_{0}$	$(\mathbf{1},\mathbf{2})_{\frac{1}{2}}$	$(\mathbf{1},\mathbf{3})_{0}$	$(\mathbf{1},\mathbf{3})_{1}$

Electron Yukawa coupling

$$C_{e\phi} = \frac{1}{M_\varphi^2}\left(\lambda_\varphi - \frac{1}{M_S^2}\kappa_{S\varphi}\kappa_S\right)\left[y_\varphi^e\right]^*_{11}$$

$$-\mathcal{L}_{S1} = -\mathcal{L}_\varphi - \mathcal{L}_S + \left(\kappa_{S\varphi} S \varphi^\dagger \phi + \text{h.c.}\right) ,$$

Scalar models

Particle content	φ	$\varphi + S$	$\varphi + \Xi$
κ_e	780	1460	585

→ in scalar models huge values possible, κ_e probes scalar potential couplings

→ in models with VLLs $(g-2)_e$ projections might probe κ_e better than FCC-ee

VLL	E	Δ_1	Δ_3	Σ	Σ_1
Irrep.	$(\mathbf{1},\mathbf{1})_{-1}$	$(\mathbf{1},\mathbf{2})_{-\frac{1}{2}}$	$(\mathbf{1},\mathbf{2})_{-\frac{3}{2}}$	$(\mathbf{1},\mathbf{3})_0$	$(\mathbf{1},\mathbf{3})_{-1}$

Scalars	S	φ	Ξ	Ξ_1
Irrep.	$(\mathbf{1},\mathbf{1})_0$	$(\mathbf{1},\mathbf{2})_{\frac{1}{2}}$	$(\mathbf{1},\mathbf{3})_0$	$(\mathbf{1},\mathbf{3})_1$

Conclusion

- Light fermion couplings little constrained from current measurements

- we showed how simple models can be constructed that allow for large enhancements

- quark Yukawa couplings: the FCC-ee can improve on the HL-LHC by around 1-2 orders of magnitude

- electron Yukawa coupling: in models where the enhanced electron Yukawa coupling is achieved by scalars large enhancements can only be constrained in a dedicated Higgs pole run

- electron Yukawa coupling: for models with VLLs $(g-2)_e$ and the other FCC-ee runs might already constrain below the Higgs pole run sensitivity

Conclusion

- Light fermion couplings little constrained from current measurements
- we showed how simple models can be constructed that allow for large enhancements
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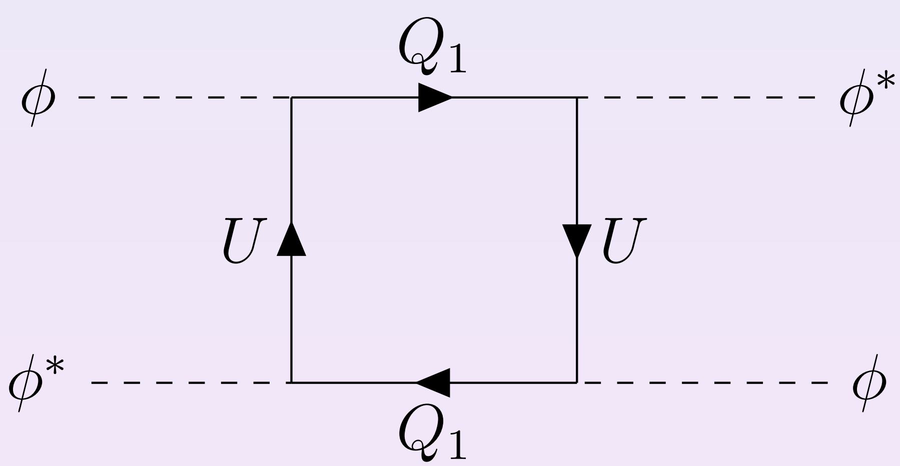
Thanks for your attention!

Electroweak precision tests

[Snowmass '22] [De Blas et al. '19]

(10^{-3})	LEP/SLD	FCC-ee [101]	(10^{-3})	LEP/SLD	FCC-ee [102]
Γ_Z (GeV)	2.3	0.03	R_e	50	6
Γ_W^* (GeV)	20.1	1	R_μ	33	1
m_W^* (GeV)	7.1	0.4	R_τ	45	2
$\sigma_{\rm had}$ (nb)	37.0	4	A_μ	15	0.022
A_e	4.9	0.02	A_τ	15	0.04
A_{FB}^b	1.55	0.1	R_c	3.0	0.26
R_b	0.66	0.06	A_b	20	3
			A_c	27	5

box contribution to $C_{\phi D}$ probes coupling of two heavy states with ϕ



at LO unconstrained

$$\kappa_q = 1 + \frac{v^2 \lambda^u_{Q_1} \lambda_U \lambda_{UQ_1}}{M_Q M_U}$$

$$-\mathcal{L}_1^{\rm int} = \lambda_U \overline{U}_R \tilde{\phi}^\dagger q_L + \lambda^u_{Q_1} \overline{Q}_{1L} \tilde{\phi}\, u_R + \lambda_{UQ_1} \overline{U} \tilde{\phi}^\dagger Q_1 + \text{h.c.}$$

Off-shell Higgs production

Considered as probe of Higgs width

[Kauer, Passarino '12, Carla, Melnikov '13, Campbell, Ellis, Williams '13]

$$\frac{\mu_{on}}{\mu_{off}} \propto \frac{\kappa_{ggh}^2(m_h)\kappa_{hZZ}^2(m_h)}{\Gamma_h/\Gamma_h^{SM}} \frac{1}{\kappa_{ggh}^2(m_{4\ell})\kappa_{hZZ}^2(m_{4\ell})}$$

works for

[Englert, (Soreq), Spannowsky '14]

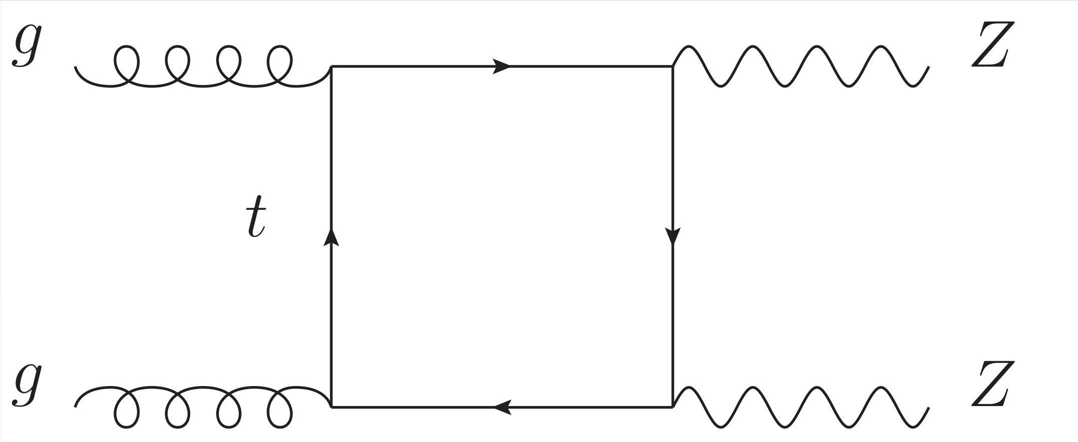
$$\kappa_{ggh}(m_h) = \kappa_{ggh}(m_{4\ell}) \qquad \kappa_{hZZ}(m_h) = \kappa_{hZZ}(m_{4\ell})$$

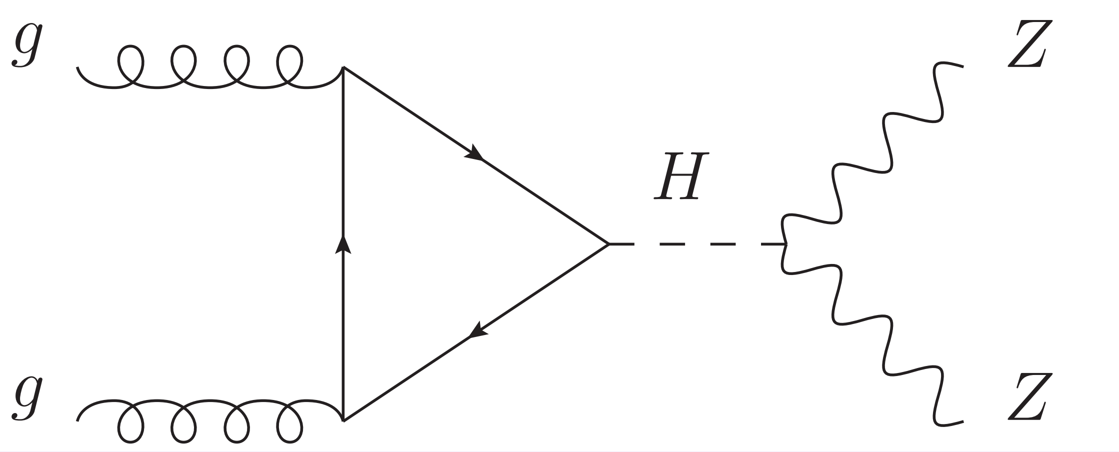
CMS: $3.2^{2.4}_{-1.7}$ MeV

[CMS in Nature 18 (2022) 1392]

ATLAS: $4.6^{2.6}_{-2.6}$ MeV

[ATLAS-CONF-2022-068]





For enhanced light quark Yukawa couplings it does not work:

use instead kinematic properties of off-shell production

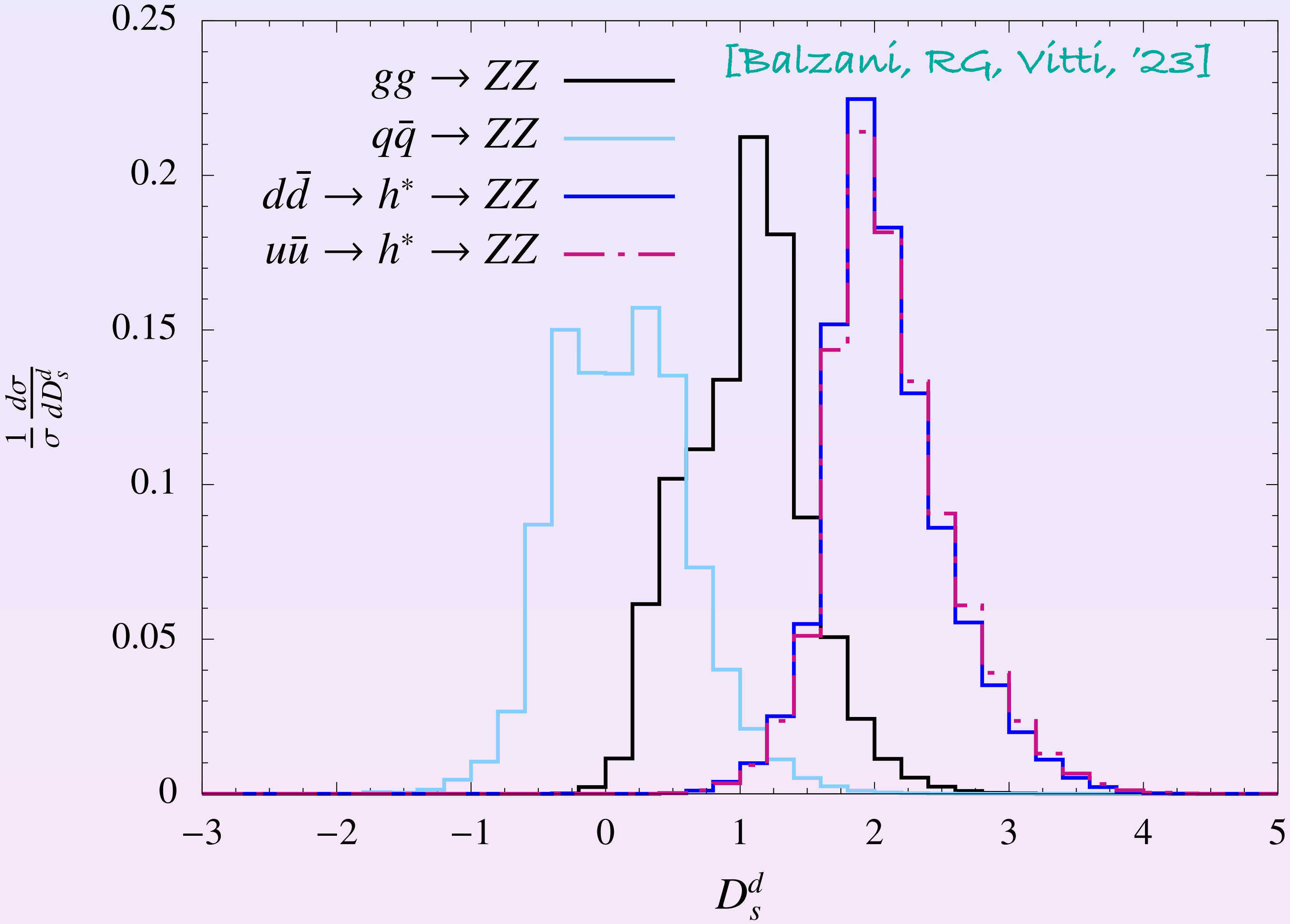
[works nicely also for other BSM scenarios see Haisch, Koole '21 '22, Haisch, Ruhrdorfer, Schmid, Weiler '23]

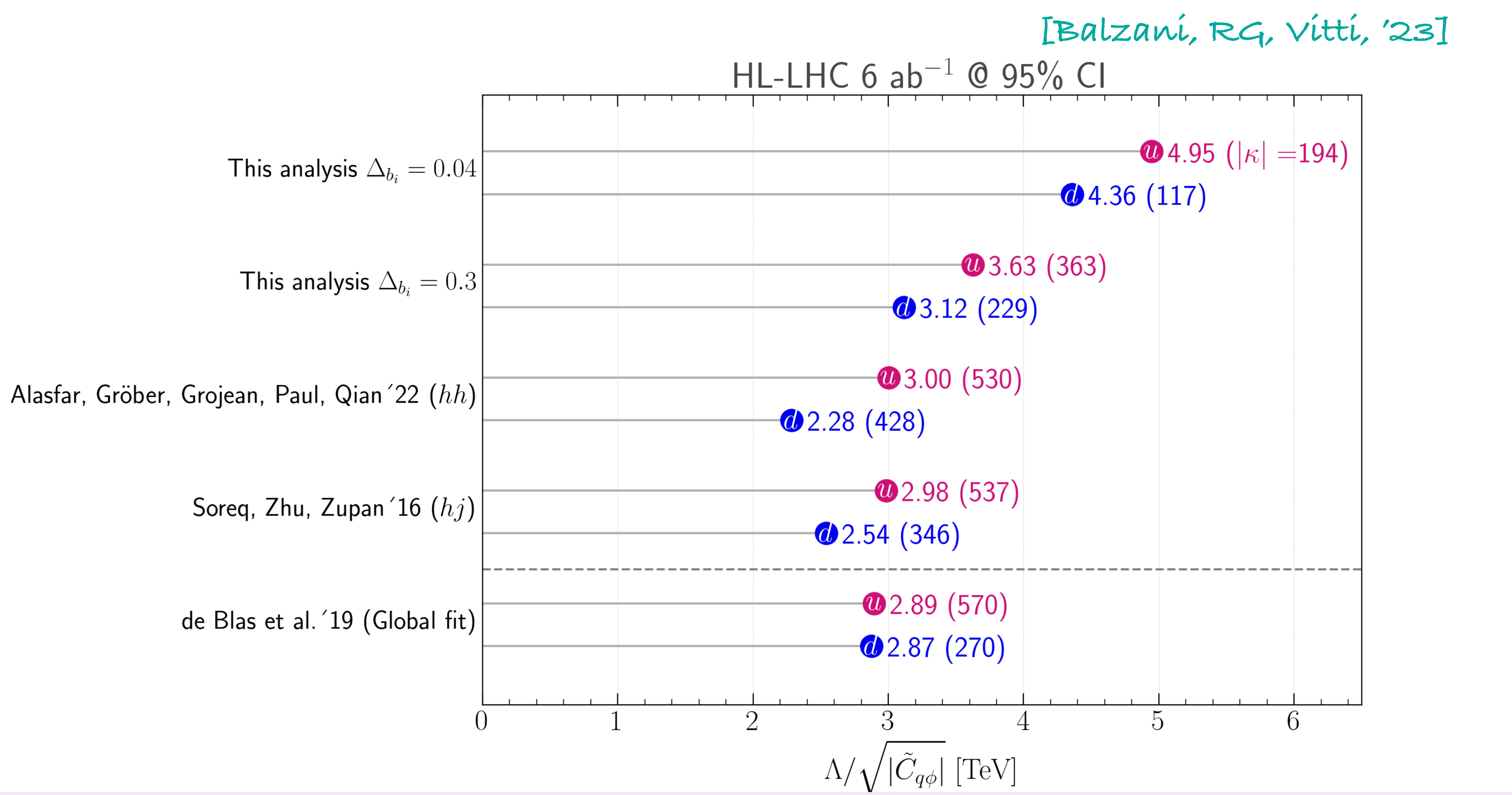
$$D_s^d = \log_{10}\left(\frac{P_{sig}^{d\bar{d}}}{P_{back}^{q\bar{q}} + P_{back}^{gg}}\right)$$

Poisson ratio of likelihoods

$$Z_i = \sqrt{2\left[(s_i+b_i)\ln\frac{(s_i+b_i)(b_i+\sigma_{b_i}^2)}{b_i^2+(s_i+b_i)\sigma_{b_i}^2} - \frac{b_i^2}{\sigma_{b_i}^2}\ln\left(1+\frac{s_i\sigma_{b_i}^2}{b_i(b_i+\sigma_{b_i}^2)}\right)\right]}$$

$$\sigma_{b_i} = \Delta_{b_i} b_i$$





Caveat: these probes do not allow to distinguish well between up and down Yukawa probes

for this $h\gamma$ could be helpful [Augilar-Saavedra, Cano, No '20]

Combination of all the proposals might be good