How large can the light Yukawa couplings be?

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arXiv: 2410.08272 and arXiv: 2501.07628

[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?

(*κ*f) and heavy gauge bosons (*κ*V), in different datasets: discovery (red), the full

bosons, the square root of the coupling modifier is plotted, to keep a linear

LHC and HL-LHC projections

Charm quark: can be tagged

 $pp \to V(h \to c\bar{c})$: <code>ATLAS: $|\kappa_c| < 4.2$ @95 % <code>CL</code> [arXiv:2410.19611]</code> **CMS:** $|\kappa_c|$ < 5.5 @ 95 % **CL** [arXiv: 2205.05550]

Light quark Yukawa couplings in flavour space encoding the interactions between fermions and the *SU*(2) Higgs doublet (˜ ⁼ *ⁱ*2⇤) which develops a vacuum expectation value (vev), *^v* ⁼ *[|]µ|/* **P** $Lizant quark Yukawa coupling$ The part of \mathcal{L} matrix \mathcal{L} and the leading contribution to the e \mathcal{L} \int \int \ln α c \int The part of the leading contribution to the earthquarter of th *^Ou* ⁼ *^qL*˜*uR†* and *^Od* ⁼ *^qLd^R † .* (5) Together with the operators

Light fermion Yukawa couplings in Standard Model Effective Field Theory modified by fermion interactions after the electroweak symmetry-breaking is encoded in *d* = 6 terms. In t and the latticity \int denotive completely state schronard tribute σ _{\int} couple to the e σ Líght fermíon Yukawa couplíngs ín Standard Model Effectíve Fíeld Theory modífied by *O*⇤ = (*†*)⇤(*†*) and *O^D* = (*† Dµ*) (*† D^µ*)*,* (6)

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

rescales all Huggs
ence constrained by Higgs cou ✓ 0 mgs *r* $\frac{1}{2}$
(hence constrained by Higgs c rescales all Higgs d rescales all Higgs couplings
(hence constrained by Higgs couplings to vector bosons) **rescales all Higgs couplings (hence constrained by Higgs couplings to vector bosons)**

which modify the kinetic term of the Higgs field requiring a field requiring a field redefinition for a canonical redefinition for a field redefinition for a canonical redefinition for a canonical redefinition for a canon

C^D wi
 ass éLaenbasis) *C^D ,* (7) **(mass eigenbasis)** ◆ the mass basis, noting that the definition of the up- and down-type masses in terms of the **dominant modification**

Single mediator

Single mediator - extra scalar

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

$$
y_q^\varphi
$$
 probed also in direct production of φ

very constrained by electroweak precision measurements

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

suppressed by small SM Yukawa

Two mediators

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Vector-like quark Models

- **• Eight models**
- The Yukawa couplings of the first and second-generation quarks are notoriously difficult to measure due to **the light quarks • they generate further operators for instance operators that modify the Z couplings to**
- are constrained by Higgs physics, flavour physics, direct searches and electroweak ω bservables the SM value and to ω (1) for the SM value and to ω **observables**

Constraints

The models generate at tree-level

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

stroweak precision: modifies couplings of Z and W bosons to quarks $t_{\rm{recon}}$ states construction μ and σ the first-generation σ or **electroweak precision: modifies couplings of Z and W bosons to quarks**

PHYSICAL UP-quark mass, the physical up-quark mass, the physical up-quark mass, there is no exist some amount o tuning between the marginal Yukawa coupling in *L*SM and the NP contribution encoded in Table 4: Relevant dimension-6 \mathcal{A} , \mathcal **electroweak precision: "S" and "T" parameters**

 Ramona Gröber — Università di Padova and INFN, Sezione di Padova / 15 e↵ectively act as *v*⁴*/*⇤⁴, where ⇤ is the placeholder for vector-like quark masses *M^U* and *M^Q*¹ . *Cu*. For that reason, we expect [*yu*]¹¹ ' *v*²[*Cu*]11*/*2, such that the first two terms in Eq. (24) a ana infn, Sezione ai Pado

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: Γ*Z*, *Af*, *σhad*, . . . **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*3 Results*

 $F_{\rm eff}$, and the coupling enhancements at a 95% CL for the constant at a 95% CL for the constant models at a 95

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?

*^L*¹¹ represents the modifcation of the *Z*-coupling to electrons induced by this state

study all models that generate $C_{e\Phi}$ at tree-level A pair of vector-like leptons ¹ and ². **(d)** A new scalar and a vector-like lepton .

where *gZe*

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

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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 $\frac{1}{2}$, and the moment $\frac{1}{2}$ and $\frac{1}{2}$. Interaction vertices in $\frac{1}{2}$ insertion wherever possible and *X^µ* denotes either *B^µ* or *W^I µ* .

The leading new physics contribution, and in the leading new physics contribution, and in the leading new physics

Electroweak precision tests

lous magnetic moment of the electron *a^e* = (*ge*2)*/*2 can be encoded in terms of the following efective operators of the SMEFT Lagrangian **Higgs physics:**

a^e '

ments in the coupling on real new physics coupling on real new physics couplings,2 the contribution to the anoma-

for models with only scalars also λ_{hhh}

Re (*Ce*) *,* (50)

Vector-like lepton models Vector-like lepton + scalar models

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Electron Yukawa coupling Model [*Ce*] Y uk*Rawa cou*pling for models with pairs of scalars to the *O*

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

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

Scalar models 11

in scalar models huge values possible, κ_e probes scalar potential *couplings* The tree-level matching to *Oe* is presented in Tab. 2. We point out that these results ge values possible, κ_e probes scalar potential ϵ

 i n models with vLLs $(g-2)_e$ projections might probe κ_e better **than FCC-ee** There are for simplified models containing pairs of the vector-like leptons like leptons li

Table 3: The vector-like leptons studied in the context of enhanced electron Yukawa coupling.

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

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Thanks for your attention!

Electroweak precision tests

*L*int

² = *DDR†*

² = *DDR†*

q^L + *^u*

q^L + *^u*

*^Q*1*Q*1*L*˜*u^R* ⁺ *^d*

*^Q*1*Q*1*L*˜*u^R* ⁺ *^d*

*^Q*1*Q*1*L d^R* + *DQ*1*D†*

relevant e α ective Lagrangian describing dynamics of the electroweak gauge bosons reads reads reads reads re

*L*int

*^Q*1*Q*1*L d^R* + *DQ*1*D†*

*Q*¹ + h.c. *,* (17)

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

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

$$
[Englet, (Soreq), Spannowsky '14]
$$

\n
$$
ZZ(m_h) = K_{hZZ}(m_{4\ell})
$$

\nATLAS: 4.6^{2.6}_{-2.6} MeV
\n
$$
IATLAS-CONF-2022-068
$$

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]

Off-shell Higgs:Kinematic discriminants sensitive to similar order of magnitude modifications of light quark Yukawa coupling than $G/G \subseteq K$ ling in analysis G lementing analysis In order to set limits on the light quark Yukawa couplings we perform a shape analysis

^s distributions. While we could in principle also include the *mZZ* distribution in

the analysis we found no di↵erence doing so. The significance in the *i*th bin is computed as

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

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

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

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on the *D^d*

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HL-LHC Light Yukawa couplings

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

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for this *hγ* **could be helpful [Augilar-Saavedra, Cano, No '20]**

Combination of all the proposals might be good