Probing light Yukawa couplings in Higgs pair production

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One of the puzzles of the SM is the large hierarchy between the Yukawa couplings of different flavours. Yukawa couplings of the first and the second generation are constrained only very weakly so far. However, one can obtain large deviations in the Yukawa couplings in several New Physics (NP) models, such as e.g. models with new vector-like quarks, or new Higgs bosons that couple naturally to individual fermion families.

In this work, we investigate the potential bounds on the NP Higgs Yukawa couplings modification κ_f for light quarks from double-Higgs at the LHC, starting from a model independent formalism. We have looked at the two Higgs boson final state $b\bar{b}\gamma\gamma$, and the relevant experimental cuts to reduce backgrounds and estimated the potential exclusion bounds for κ_f. We have considered both linear and non-linear effective field theory for the Higgs light quark coupling modifications.

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1. Effective field theory of light Yukawa couplings

In the Standard Model (SM), the Higgs doublet ϕ couples to the quarks via a Yukawa interaction term

$$\mathscr{L}_y = -y^u_{ij}\bar{Q}^i_L\tilde{\phi}u^j_R - y^d_{ij}\bar{Q}^i_L\phi d^j_R + h.c., \tag{1.1}$$

with $\tilde{\phi} = i\sigma_2\phi^*$, σ_2 is the second Pauli matrix, Q^i_L the left-handed $SU(2)$ quark doublet of the i-th generation and u^j_R and d^j_R the right-handed up- and down-type fields of the j-th generation, respectively.

It is possible to modify this coupling via a dimension 6 operator in the SM effective field theory formalism (SMEFT) with a UV cutoff scale Λ

$$\Delta\mathscr{L}_y = \frac{\phi^\dagger\phi}{\Lambda^2}\left(c^u_{ij}\bar{Q}^i_L\tilde{\phi}u^j_R + c^d_{ij}\bar{Q}^i_L\phi d^j_R + h.c.\right). \tag{1.2}$$

The resulting mass matrices can be diagonalised by means of a bi-unitary transformation $V^q_{L/R}$ in order to recover the measured quark masses. The Yukawa couplings ($h\bar{q}q$) will be modified by this new operator. Moreover, a new coupling between quark anti-quark pair and two Higgs bosons $hh\bar{q}q$ appears with coupling constant

$$g_{h\bar{q}_iq_j}: \quad \frac{m_{q_i}}{v}\delta_{ij} - \frac{v^2}{\Lambda^2}\frac{\tilde{c}^q_{ij}}{\sqrt{2}}, \qquad\qquad g_{hh\bar{q}_iq_j}: \quad -\frac{3}{2\sqrt{2}}\frac{v}{\Lambda^2}\tilde{c}^q_{ij}, \tag{1.3}$$

where

$$\tilde{c}^q_{ij} = \left(V^q_L\right)^*_{ni}c^q_{nm}\left(V^q_R\right)_{mj}, \quad\text{with}\quad q = u,d, \tag{1.4}$$

and $V^q_{L/R}$ denote the transformation matrices from current to mass eigenstates.

It has been shown in [1, 2, 3] that it is possible to introduce large modifications to the Yukawa couplings without flavour-changing neutral currents (FCNCs) at tree-level, which strongly constrain off-diagonal couplings [4], and without assuming minimal flavour violation (MFV) [5]. Very little is known though about the flavour-diagonal Higgs coupling to light quarks, as seen from the weak bounds on these coupling modifications, *cf.* ref. [6]. Therefore, we only restrict ourselves to varying the diagonal light quark Higgs couplings, writing

$$g_{h\bar{q}_iq_i} = \kappa_q g^{\text{SM}}_{h\bar{q}_iq_i}, \qquad\qquad g_{hh\bar{q}_iq_i} = -\frac{3}{2}\frac{1-\kappa_q}{v}g^{\text{SM}}_{h\bar{q}_iq_i}. \tag{1.5}$$

Here, we have abused the κ-formalism notation that is used heavily in experimental searches. Another way to modify the Yukawa couplings in a model-independent way is via the electroweak chiral Lagrangian [7]. Using the chiral Lagrangian by taking the 0th chiral mode and restricting ourselves to the flavour diagonal couplings we get

$$-\mathscr{L} = \bar{q}_L\frac{m_q}{v}\left(v + c_q h + \frac{c_{qq}}{v}h^2 + \dots\right)q_R + h.c. \tag{1.6}$$

Thus, in this formalism, the Yukawa and $hh\bar{q}q$ couplings are uncorrelated, making the Higgs pair production the most accessible process to test the potential correlation between the Higgs-light quark couplings.
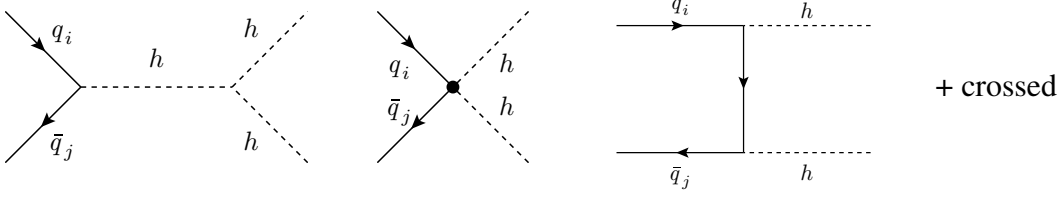
Figure 1: Feynman diagrams for the qqA Higgs pair production.

2. Higgs pair production with modified Yukawa couplings

In the SM, the production of Higgs pairs in hadron colliders (such as the LHC) is dominated by gluon-gluon fusion (ggF) which at leading order (LO) is ~ 21fb.

Higher order QCD corrections to this process have been computed up to order α_s^4 [8]. For the inclusive cross section the LO calculation can be corrected by a K-factor,

$$K = \frac{\sigma_{NNLO}}{\sigma_{LO}}, \quad K_{14\,\text{TeV}} = 1.72. \tag{2.1}$$

In our analysis, we use the state-of-the-art calculation of the ggF inclusive cross section at 14 TeV [9] $\sigma_{NNLO}^{\text{SM}} = 36.69_{-2.57}^{+1.99}$ fb.,

However, if the light quark Yukawa couplings are significantly increased, the ggF process will become subdominant compared to the quark anti-quark annihilation (qqA), due to the abundance of light quarks in the proton. This happens if the coupling modifiers are of order $\kappa_c^{qqA=ggF} \sim 5$, $\kappa_s^{qqA=ggF} \sim 10$ and $\kappa_u^{qqA=ggF} \sim \kappa_d^{qqA=ggF} \sim 10^3$. Those values are not yet excluded by current measurements. The qqA Higgs pair production is calculated from the diagrams shown in fig. 1. up to NLO QCD, see [3]. The shape difference between the normalized ggF and qqA dominant distributions is used in the analysis to extract sensitivity limits on modifications of light quark Yukawa couplings.

3. Phenomenological analysis

In order to estimate the sensitivity of the high-luminosity LHC (HL-LHC) for the light quark scalings, we have used the profile likelihood method to estimate the signal strength μ, defined as (for general resonance R production)

$$\mu = \frac{N_{expec}}{N_{expec}^{SM}}, \quad \text{with} \quad N_{expec} = \sigma(pp \to R)\,\mathscr{B}(R \to X)\,L\,\varepsilon_{\text{SEL}}, \tag{3.1}$$

where $\sigma(pp \to R)\,\mathscr{B}(R \to X)$ is the production cross section of R times the branching fraction for the final state X, $L = 3\text{ab}^{-1}$ the integrated luminosity of the HL-LHC, and ε_{SEL} is the experimental selection.

In our analysis we have chosen the two Higgs final state $hh \to b\bar{b}\gamma\gamma$ due to its high potential of reconstruction at the HL-LHC [10, 11]. We have modified the FORTRAN programme `HDECAY` [12] to obtain the Higgs boson branching ratios, including state-of-the art QCD corrections and the light fermion loops and decay channels.

The Higgs pair production and decays were implemented into Pythia 6.4 for parton showering. Then the events were analysed according to [13] in order to estimate the selection efficiency. In addition to *b*-tagging, we have used charm mistagging probability of *b*-jets combined with *c*-tagging working points for CMS [14] and ATLAS [15], as developed in [16, 17] in order to constrain κ_c and κ_s. This will allow us to put bounds on the second generation quark Yukawa couplings, while otherwise no sensitivity can be obtained, due to the fact that the lowering of the branching fraction of the final state $hh \to b\bar{b}\gamma\gamma$ is larger than the cross-section enhancement. This method will allow us to probe the final state $hh \to c\bar{c}\gamma\gamma$ using the current *c*-tagging techniques [18, 19] or the improved ones after the ATLAS HL-LHC upgrade [20, 21], thus in total improving the expected sensitivity for the second generation couplings.

4. Results

Using a likelihood fit for estimating μ, assuming that SM Higgs pair production is the null hypothesis, then preforming a scan over κ_u and κ_d, we obtain the 68% and 95% CL sensitivity likelihood contours for the HL-LHC shown in fig. 2.
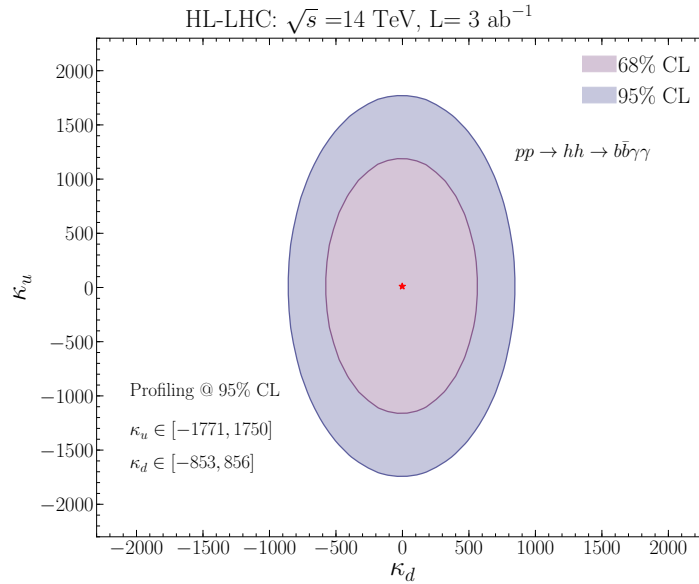

Figure 2: The expected sensitivity likelihood contours at 68% and 95% CL of the HL-LHC for the first generation Yukawa coupling scalings.

We show now results for non-linear EFT Wilson coefficients c_q and c_{qq} of the chiral Lagrangian of eq. (1.6) by scanning over them separately in order to obtain the sensitivity bounds on the non-linear EFT illustrated in fig. 3.

For the linear EFT hypothesis, it was not possible to construct sensitivity bounds using only the final state with *b*-quarks for the second generation quarks as discussed before. We hence directly include into fig. 4 final states with *c*-quarks, which depends on the *c*-tagging working points as discussed also in [3, 16, 22]. The expected sensitivity limits for the charm quark Yukawa modifications are an improvement compared to the current direct bounds and prospects for the HL-LHC, see [16, 22].
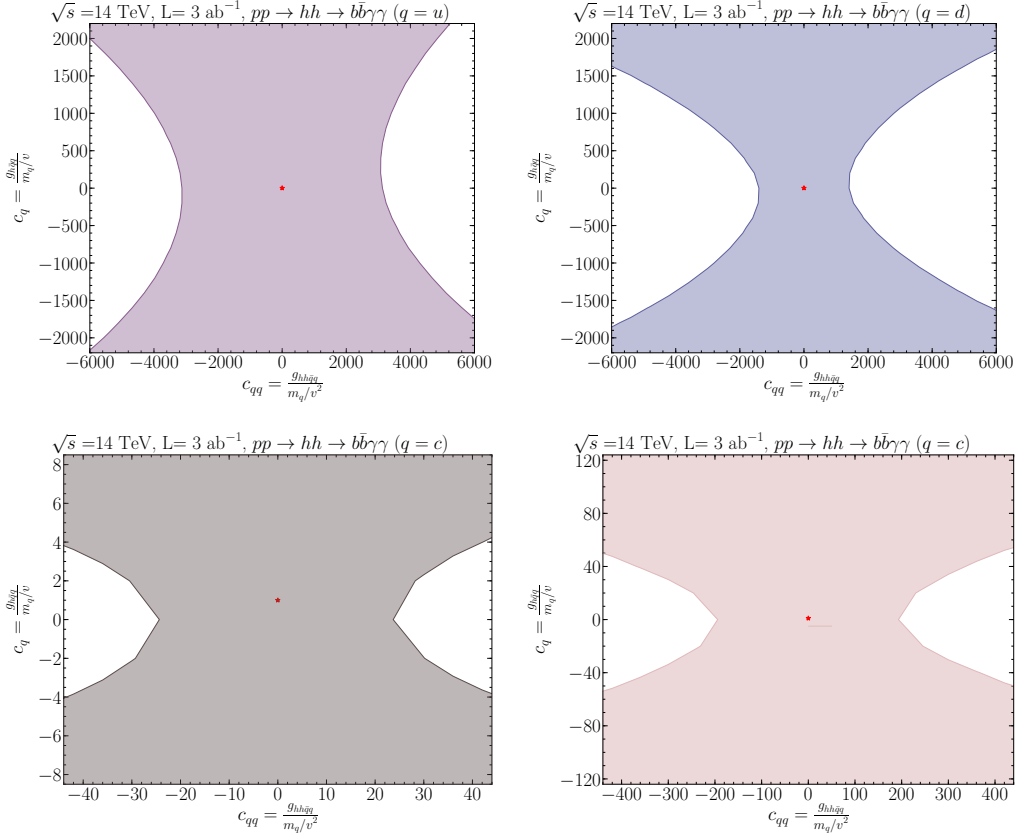
Figure 3: 95% CL likelihood contours for the non-linear EFT coefficients c_{qq} and c_q for up (*upper left*), down (*upper right*), charm (*lower left*) and strange quarks (*lower right*).

5. Conclusion

Searching for the production of Higgs pairs (*hh*) provides a great insight into the least understood Higgs couplings, the trilinear Higgs self-coupling and the light quark Yukawa couplings. As we showed, it is possible to set prospective model-independent bounds on the light quark Yukawa couplings which are comparable to the prospects from a global fit making use of the Higgs pair production process. The expected sensitivity is $|\kappa_u| \lesssim 1170$ and $|\kappa_d| \lesssim 850$, *cf.* fig. 2.

Moreover, with mixed *b*- and *c*-tagging working points, the Higgs pair production provides competitive sensitivity for constraining modifications of the charm Yukawa coupling i.e. $|\kappa_c| \lesssim 5$ and $|\kappa_s| \lesssim 100$, *cf.* fig. 4, where the first prospective limit is comparable to the prospects from charm tagging in the *Vh* channel [16]. Furthermore, it turns out that the process is in particularly sensitive to the non-linearities in the light quark-Higgs couplings, so providing a possible insight into the linear or non-linear nature of the Higgs boson.
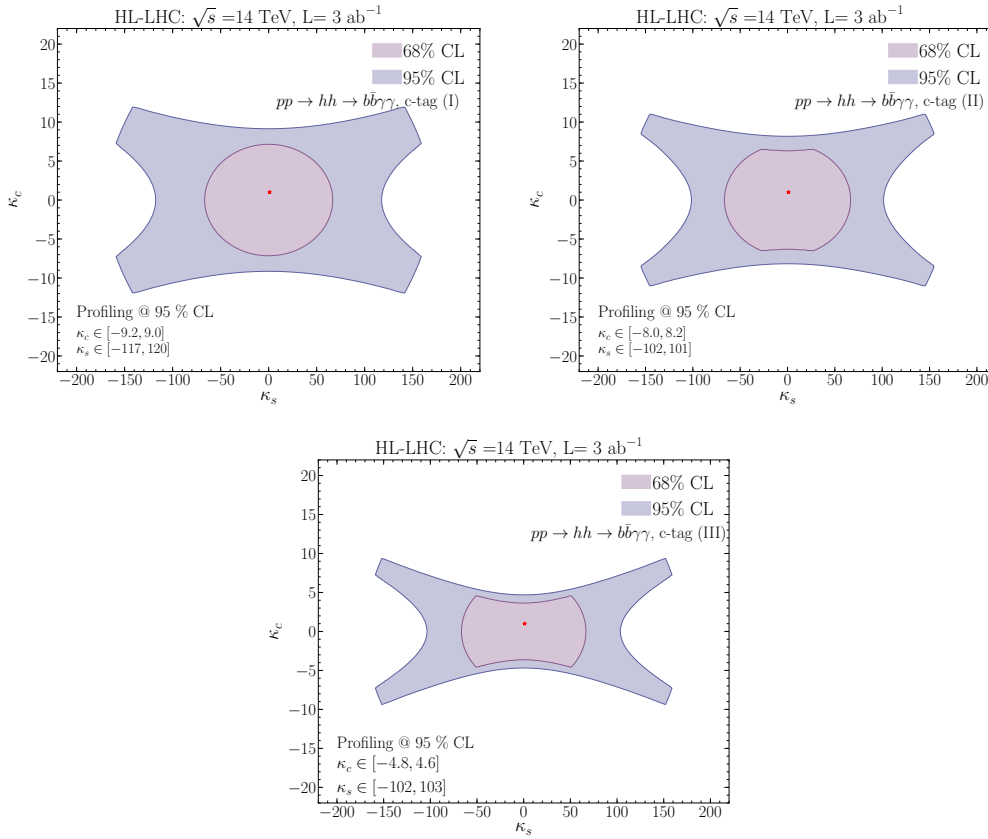
6. Acknowledgements

Figure 4: The expected sensitivity likelihood contours at 68% CL and 95% CL for an integrated luminosity $L = 3\text{ab}^{-1}$ for modified second generation quark Yukawa couplings, using the c-tagging I (*upper pannel, left*), II (*upper pannel, right*) and III (*lower pannel*) working points, see [3].

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