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Probing the Charm Quark Yukawa Coupling in Higgs + Charmed Production

Ilaria Brivio,1,† Florian Goertz,2,+ and Gino Isidori3,4,‡

1Departamento de Física Teórica and Instituto de Física Teórica, IFT-UAM/CSIC, Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain
2Theory Division, CERN, 1211 Geneva 23, Switzerland
3Physik-Institut, Universität Zürich, CH-8057 Zürich, Switzerland
4INFN, Laboratori Nazionali di Frascati, I-00044 Frascati, Italy

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We propose a new method for determining the coupling of the Higgs boson to charm quarks, via Higgs production in association with a charm-tagged jet: \( pp \rightarrow h c \). As a first estimate, we find that at the LHC with 3000 fb\(^{-1}\), it should be possible to derive a constraint of order one, relative to the standard model (SM) value of the charm Yukawa coupling. As a by-product of this analysis, we present an estimate of the exclusive \( pp \rightarrow hD(\gamma^{\ast}) \) electroweak cross section. Within the SM, the latter turns out to be not accessible at the LHC even in the high-luminosity phase.

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Introduction.—While the Yukawa couplings of the heavy third generation fermions to the Higgs boson can be measured at the LHC with a \( \mathcal{O}(10\%) \) accuracy (see, e.g., Ref. [1]), constraining the diagonal Yukawa couplings of the second (first) generation quarks at a level close to the standard model (SM) expectations is very challenging. An interesting possibility, especially for the second generation, is trying to indirectly access these couplings via the radiative decays \( h \rightarrow M + \gamma(Z) \) [2–5], where \( M \) is a quarkonium state. (For indirect bounds on first generation Yukawa couplings see Refs. [6,7]). As pointed out in Ref. [8], the exclusive \( h \rightarrow MV \) decays (\( V = \gamma, Z, W \)) may indeed be accessible at the SM level at the LHC and represent a precious source of information on physics beyond the SM. In the specific case of the charm Yukawa coupling (\( Y_c \)), it should be possible to obtain bounds two to three times larger than the SM value in the high-luminosity (HL) phase of the LHC [9]. These constraints are driven mainly by the direct search for \( h \rightarrow cc \) and, to a smaller extent, also by the indirect sensitivity via \( h \rightarrow J/\gamma \).

In this Letter, we propose a new method for measuring \( Y_c \) by means of Higgs production in association with a charm-tagged jet. A particular advantage of this method, compared to the search for \( h \rightarrow cc \), lies in the fact that we probe \( Y_c \) in production—via the interaction with a charm quark from the abundant \( gc \) initial state—allowing us to reconstruct the Higgs boson from its clean decay modes (\( h \rightarrow \gamma \gamma \) or \( h \rightarrow WW \)). This procedure strongly reduces the problem of the non-Higgs background, compared to \( h \rightarrow cc \). Moreover, requiring a single \( c \)-tagged jet in the final state allows us to adopt high-purity (and low-efficiency) \( c \)-tag algorithms in order to reduce background, compared to the case of two \( c \)-tagged jets (as in \( h \rightarrow cc \)).

Compared to the indirect sensitivity to \( Y_c \) in \( h \rightarrow J/\gamma \), our new method has the advantage of being sensitive to \( Y_c \) at the tree level and being based on a process that, after charm- and Higgs-tagging efficiencies, yields \( \mathcal{O}(1000) \) signal events at the HL-LHC. For comparison, we recall that \( \mathcal{B}(h \rightarrow J/\gamma \gamma \rightarrow \mu^{+}\mu^{-}\gamma) \sim 10^{-7} \), corresponding to \( \mathcal{O}(10) \) signal events in \( pp \) collisions at 14 TeV with 3000 fb\(^{-1}\). The main limiting factor of our approach is the theoretical uncertainty on \( \sigma(pp \rightarrow hc) / \sigma(pp \rightarrow hh) \) as a function of \( Y_c \). This error could be reduced in the future by means of higher-order QCD calculations of the ratio \( \sigma(pp \rightarrow hc) / \sigma(pp \rightarrow hh) \) as a function of \( Y_c \) and \( Y_h \).

In principle, the production of the Higgs boson in association with a charm jet (or a charm hadron) can also proceed via electroweak interactions, with the charm being produced by a real or virtual \( W \) boson. To complement this analysis, and previous studies of exclusive hadronic Higgs decays [2,3,5,8], we present here the first estimate of the electroweak production of the Higgs boson in association with a single \( D \) or \( D^{*} \) meson (\( q \bar{q} \rightarrow hD(\gamma^{\ast}) \)). These processes are insensitive to the charm Yukawa coupling and could have represented a potential background for the extraction of \( Y_c \). We have analyzed them in generic extensions of the SM, along the lines of Ref. [8]. We find that, within the SM, the exclusive electroweak production should not be visible at the LHC, even in the high-luminosity phase. Moreover, we find that these process are not competitive with the corresponding exclusive Higgs decays (\( h \rightarrow MV \)) as far as generic new physics (NP) searches are concerned.

Setup.—Within the SM the couplings of the physical Higgs boson to the fermions are completely determined in terms of fermion masses. However, in the presence of NP,
a misalignment between quark-mass and Yukawa matrices is possible. This can be parametrized in a model-independent way by adding the $D = 6$ operators

$$L_b^\gamma = - \frac{1}{v^2} [(\Phi^\dagger \Phi) \bar{q}_L C_u \Phi^c u_R + (\Phi^\dagger \Phi) \bar{q}_L C_d \Phi^c d_R]$$

(1)

to the SM Lagrangian. Here, $\Phi$ denotes the Higgs doublet, parametrized in unitary gauge as $\Phi = 1/\sqrt{2} (0, v)^T$, where $v$ corresponds to the vacuum expectation value $\langle \Phi \rangle = 1/\sqrt{2} (0, v)^T$, $h$ is the physical Higgs field, and $\bar{q}_L, u_R, d_R$ are the chiral SM-quark doublet and singlets (all quark fields being three-vectors in flavor space). Inserting this decomposition of the Higgs doublet into Eq. (1) as well as into the SM-like ($D = 4$) Yukawa terms, we obtain the fermion masses and Higgs couplings in the flavor basis

$$\mathcal{L} \supset - \bar{u}_L \left( \hat{M}^u + \frac{h}{\sqrt{2}} \hat{Y}^u \right) u_R - \bar{d}_L \left( \hat{M}^d + \frac{h}{\sqrt{2}} \hat{Y}^d \right) d_R,$$

(2)

where the Yukawa matrix $\hat{Y}_{u,d} = \hat{Y}_{u,d}^{\text{SM}} + \frac{i}{2} C_{u,d}$ and the mass matrix $\hat{M}^{u,d} = \frac{v}{\sqrt{2}} (\hat{Y}_{SM}^{u,d} + \frac{i}{2} C_{u,d}) = \frac{v}{\sqrt{2}} (\hat{Y}_{u,d}^{\text{SM}} - C_{u,d})$ are independent parameters. After performing a rotation to the mass basis

$$\hat{M}^u = U^{u}_{\text{diag}} M^u_{\text{diag}} U_R^{u\dagger}, \quad M^{u\dagger} = \text{diag}(m_u, m_c, m_t),$$
$$\hat{M}^d = U^{d}_{\text{diag}} M^d_{\text{diag}} U_R^{d\dagger}, \quad M^{d\dagger} = \text{diag}(m_d, m_s, m_b),$$

(3)

with $U^u_R = U^d_R V_{\text{CKM}}$, we finally arrive at the couplings of the physical quarks to the Higgs boson $Y^u = U^u_{\text{diag}} \hat{Y}^u U_R^{u\dagger}, \quad Y^d = U^d_{\text{diag}} \hat{Y}^d U_R^{d\dagger}$, such that

$$\mathcal{L} \supset - \bar{u}_L \left( M^u_{\text{diag}} + \frac{h}{\sqrt{2}} Y^u \right) u_R + (u \to d).$$

(4)

Here, we concentrate on possible experimental constraints on the diagonal entry $Y_c \equiv (Y^c)_{22}$. For convenience, we parametrize the deviations from the SM prediction ($C_u = C_d = 0$) in terms of $\kappa_c \equiv Y_c v / (\sqrt{2} m_q) \neq 1$, which we assume, for simplicity, to be real. (In the following we assume the top and bottom Yukawa couplings to be constrained close to their SM values after the high-luminosity LHC run.)

The QCD-Yukawa $pp \to hc$ process.—We consider the production of a Higgs boson in association with a charm-quark jet. At the LHC, the main partonic process inducing this final state is $gc \to hc$ and the corresponding Feynman diagrams are presented in Fig. 1. The charm Yukawa coupling, depicted as a black dot, enters in the first two graphs, which yield a contribution to the amplitude of $O(q_t Y_c)$. The $t$-channel diagram turns out to be largely dominant. The third diagram is formally of higher order in $\alpha_s$ but is enhanced by the top-quark Yukawa coupling. Here, the crossed vertex corresponds to the effective $ggh$ interaction obtained by integrating out the top quark. This diagram yields the contribution to the amplitude that survives in the limit $\kappa_c \to 0$ (see Table I).

The challenge of the proposed process is to tag the charm-quark jet, as in $h \to cc$. However, as anticipated, it offers some interesting virtues compared to $h \to cc$. In particular, it allows us to fully reconstruct the Higgs boson in a clean decay channel such as $h \to gg$ or $h \to WW$, and it requires only a single charm tag. The main drawback is that the process does not vanish in the limit $Y_c \to 0$ (contrary to $h \to cc$), requiring a good theoretical control on the cross section as a function of $Y_c$. While a full analysis, including the optimization of the event selection, is beyond the scope of this Letter, here we just want to examine the potential of the channel by deriving the expected number of signal and background events, based on reasonable efficiency assumptions.

We have calculated the cross section of $pp \to hc$ at leading order in QCD (including the effective $ggh$, as discussed above) at the LHC with 14 TeV center-of-mass energy for various values of $\kappa_c$, employing MADGRAPH 5 [10], with a tailored model file and CTEQ6L1 parton distribution functions. Using $m_{c}(m_{Z}) = 0.63$ GeV and $m_{h} = 125$ GeV, for $\kappa_c = 1$ (i.e., the SM) we obtain a cross section of $\sigma(pp \to hc) = 166.1$ fb, employing the default cuts of $p_T(j) > 20$ GeV, $\eta(j) < 5$, $\Delta R(j_1, j_2) > 0.4$ for all processes considered here. In the following, we focus on the $h \to gg$ decay channel, with a branching fraction of $B(h \to gg) = 0.0023$. This leads to $S_0 = 2292$ events at the HL-LHC with 3000 fb$^{-1}$, taking into account also the $pp \to h c$ process. Assuming a charm-tagging efficiency of $\epsilon_c = 0.4$ (see, e.g., Ref. [9]), we finally end

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**TABLE I.** Number of signal events $S(\kappa_c)$ in dependence on the charm-quark Yukawa coupling. See the text for details.

| $\kappa_c$ | 0 | 0.25 | 0.5 | 0.75 | 1 | 1.25 | 1.5 | 1.75 | 2 |
|------------|---|------|-----|------|---|------|-----|------|---|
| $S$        | 874 | 877 | 885 | 899 | 917 | 941 | 973 | 1008 | 1052 |

| $\kappa_c$ | 2.25 | 2.5 | 2.75 | 3 | 3.25 | 3.5 | 3.75 | 4 | 4.25 | 4.5 |
|------------|------|-----|------|---|------|-----|------|---|------|-----|
| $S$        | 1097 | 1148 | 1206 | 1276 | 1350 | 1424 | 1504 | 1590 | 1683 | 1786 |
FIG. 2 (color online). The expected $p$ value for a given value of $\kappa_c$ from the process $pp \to hc$ at the 14 TeV LHC with 3000 fb$^{-1}$ and a conservative assumption for the theoretical uncertainty. See the text for details.

The main backgrounds to the process studied here are $pp \to hg$, with the gluon misidentified as a charm quark, as well as $pp \to hb$, with the bottom quark being mistagged. In the first case, we treat separately the case $pp \to hc\bar{c}$, where only one charm-quark jet is reconstructed and the case where the gluon produces a light quark jet. The backgrounds feature $\sigma(pp \to hg) = 12.25$ fb, $\sigma(pp \to hb) = 203$ fb, as well as $\sigma(pp \to hc\bar{c}) = 55$ fb. We employ a conservative assumption for the jet reconstruction efficiency of $1 - e_{\text{miss}}^{\text{jet}} = 95\%$, as well as $g \to c$ and $b \to c$ mistag rates of $e_{g \to c} = 1\%$ and $e_{b \to c} = 30\%$. With these figures we obtain $B = 1705$ background events at 3000 fb$^{-1}$, leading to $N(\kappa_c = 1) = S(\kappa_c = 1) + B = 2622$ total events. We then assume a statistical error on the total number of events ($\sqrt{N}$) and a theoretical (relative) error on the signal events of 20\%. The latter is deduced by the recent next-to-leading order (NLO) analysis of the Higgs production in association with bottom quarks [11]. Finally, statistical and theoretical error are added in quadrature [12].

In the following, we want to examine the expected constraints that can be set on $\kappa_c$ from the process under consideration. To this purpose, we assume the SM to be true and calculate how many standard deviations $\Delta N(\kappa_c)$ away a prediction $N(\kappa_c)$ is from $N(\kappa_c = 1)$, which is the expected outcome of the experiment. The values of $\kappa_c$ that lead to a discrepancy of more than $n$ standard deviations are then expected to be excluded at $na$. We plot the corresponding $p$ value, $p(\kappa_c)$, in Fig. 2, approximating the Poisson distribution of the number of events by a Gaussian. The $1\sigma$ and $2\sigma$ equivalents are depicted by the solid and dashed lines, respectively. A conservative estimate for the expected $1\sigma$ (95\% C.L.) constraint on $\kappa_c$ is thus obtained as

$$|\kappa_c| < 2.5(3.9),$$

which lies in the ballpark of the results quoted in Ref. [9], where the latter combines ATLAS and CMS results to arrive at $2 \times 3000$ fb$^{-1}$ of integrated luminosity.

On the other hand, an improved prediction of the SM cross section $\sigma(pp \to hc)$, leading to $\delta_{\text{th}} = 10\%$, would strengthen our expected $1\sigma$ (95\% C.L.) limit to

$$|\kappa_c| < 1.9(2.6),$$

approaching the SM value of $Y_c$.

We note that optimized cuts can still increase $S/B$ and, in particular, can lead to an enhanced sensitivity on $\kappa_c$. As the statistics at 3000 fb$^{-1}$ is large enough, there are good prospects for still improving the bounds. A corresponding detailed investigation, including detector simulation, is beyond the purpose of this Letter and can be performed best by the experimental community.

We further stress that the dominant source of uncertainty, at present, is the theoretical error on $\sigma(pp \to hc)$. We have indeed verified that the result does not change significantly, worsening the $g \to c$ and $b \to c$ mistag rates to 5\% and 40\%, respectively. As far as the reliability (and possible reduction) of the theoretical error is concerned, a promising possibility would be a dedicated calculation of $\sigma(pp \to hc)/\sigma(pp \to hb)$ at NLO (or next-to-next-to-leading order), as a function of $Y_c/Y_b$, supplemented by measurements of this ratio and $\sigma(pp \to hb)$ with a combination of normal and inverted $b$ vs $c$ tags [13].

*The electroweak $pp \to h\mathcal{M}$ process.*—As anticipated in the Introduction, the production of the Higgs boson in association with the charm quark can proceed also via electroweak interactions, starting from an initial charmless $q\bar{q}$ state ($u\bar{d} \to hW^{(*)} \to hc\bar{c}$). The case of an on-shell $W$ producing a charm jet can be discriminated from the QCD-Yukawa process by means of appropriate cuts on the jet momentum. Less obvious is the discrimination in the case of a virtual $W^*$ producing a low-momentum $c$ jet, or even a single charmed hadron. In the following we estimate in detail the specific case of the single meson production: $pp \to h\mathcal{M}$, with $\mathcal{M}$ being a charmed meson or a charmionum state.

The leading partonic amplitude within the SM is shown in Fig. 3. Following Refs. [8,14], we parametrize the quark currents appearing in the initial and final state with arbitrary vector and axial couplings:

$$j_{q,ij}^\mu = \bar{q}^j \Gamma^{\mu}_{ij} (\gamma^\nu + i g_F \gamma_5 \gamma^\nu) q^i.$$

The matrix element of the current that generates the meson in the final state assumes one of the following structures, depending on the spin of $\mathcal{M}$:
TABLE II. Expected number of $hM$ associated production events at HL-LHC (14 TeV and 3000 fb$^{-1}$) in the energy region $130 \leq \sqrt{s} \leq 1$ TeV for representative charmed-meson final states. The results reported under method (a) are obtained by rescaling bin by bin the cross section distribution of Drell-Yan processes provided by MADGRAPH 5 [10]. The computation of method (b) is performed via numerical convolution of the analytic cross section with the PDF of the MSTW 2008 libraries [15]. Both account only for SM contributions.

| Channel | $m_M$ (MeV) | $f_M$ | Events @ HL-LHC |
|---------|-------------|-------|-----------------|
| $\eta_c$ | 2984 | 200 | 0.10 |
| $J/\psi$ | 3100 | 410 | 0.07 |
| $D^+$ | 1968 | 250 | 0.48 |
| $D^{*+}$ | 2112 | 325 | 0.84 |

The quark current is conserved ($qp^\mu_\nu = 0$) to a good accuracy, and the tensor $T_{\mu\nu}$ can be decomposed in terms of only four Lorentz structures. Using the same notation as in Ref. [8],

\[ T_{\mu\nu} = f_1(q^2)g_{\mu\nu} + f_2(q^2)p_\mu p_\nu + f_3(q^2)(p^\nu q_{\mu\nu} - p_{\mu}q_{\nu}) + \frac{A(q\bar{q}' \to hM)}{M}\langle M|f_{\mu\nu}|0\rangle, \]

where $q_{\mu}$ is the total momentum of the quark pair in the initial state, and $p_{\mu}$ is the meson momentum ($p^2 = m_M^2$).

With these notations the partonic cross section reads

\[ \sigma(q\bar{q}' \to hP)(q^2) = \frac{g_3^2}{8\pi} f_P^2 (g^2_{V} + g^2_{A}) \times \left| f_1(q^2) + m^2_P f_2(q^2)\right|^2 q^2 \lambda(q^2), \]

where, similar to the SM case, $\sigma(q\bar{q}' \to h\nu)$ has the same functional form up to tiny $O(m^2_{\nu}/m^2_{\bar{\nu}})$ corrections. Neglecting the latter terms, we obtain

\[ \frac{\sigma(q\bar{q}' \to hM)_{BSM}(q^2)}{\sigma(q\bar{q}' \to hM)_{SM}(q^2)} = \left| \frac{f_1(q^2)}{f_1(q^2)_{SM}} \right|^2, \]

where $f^\text{BSM}(q^2) \propto 1/[\nu(q^2 - m^2_{\bar{\nu}})]$ and we disregard potential changes to the fermionic currents. Deviation from the SM are thus induced by possible non-pole terms (i.e., contact terms) in the form factor $f_1(q^2)$. Within a generic effective-field theory (EFT) approach to Higgs physics (both linear and nonlinear EFT), contact terms in $f_1(q^2)$ are generated by dimension-six operators. However, their effect would show up exactly in the same functional form either in the on-shell associated production ($pp \to Vh$) or in $h \to VM$ decays that share the same current structure [8,14]. Since the latter processes can be measured (or at least bounded) to a better accuracy, we conclude that $\sigma(pp \to hM)$ is not a very sensitive probe of generic extensions of the SM.

Conclusions.—In this Letter, we proposed a new strategy for the measurement of the Yukawa coupling of the charm quark: the measurement of the production cross section of the Higgs boson in association with a charm jet. A first estimate showed that $Y_c$ could be determined at a level approaching the SM value in this channel, which offers virtues and drawbacks quite different with respect to the $h \to c\bar{c}$ search. A fully realistic analysis was beyond the scope of this Letter. A more realistic evaluation of the efficiencies is likely to decrease the number of signal events $S$ compared to our naive estimate; however, as we have discussed, sensitivity on $Y_c$ could even increase with properly designed $b$- and $c$-tag strategies aimed at measuring the background from data and at reducing the theoretical error on the normalization of the cross section.
This first analysis therefore calls for more detailed studies on both the theoretical and the experimental side.

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ilaria.brivio@uam.es
†florian.goertz@cern.ch
‡isidori@physik.uzh.ch

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[12] The two dominant backgrounds, $pp \rightarrow hb$ and $pp \rightarrow hg$, can both be directly measured at the LHC with specific tags (inverted $b$ vs $c$ tag for the former and light-quark-jet tag for the latter). This is why we do not assign an additional theory error to them. A further source of background comes from non-Higgs signals: this is potentially non-negligible in the $h \rightarrow \gamma\gamma$ case, but less relevant if $h$ is detected via different decay modes (e.g., $h \rightarrow WW^{(*)}$). In the $h \rightarrow \gamma\gamma$ case, this background can be studied and controlled with specific additional cuts on the event: from a naive analysis of its impact (scaling from present $h \rightarrow \gamma\gamma$ data), we find its inclusion does not qualitatively change our conclusions.

[13] In fact, the theoretical reliability (and other systematic uncertainties) can thus be assessed in the bottom sector by comparing $Y_b$ as extracted from $h \rightarrow bb$ with the value that can be obtained from the $pp \rightarrow hb$ process, and the results can be projected to the charm sector.

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