Constraining Light-Quark Yukawa Couplings from Higgs Distributions

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We propose a novel strategy to constrain the bottom and charm Yukawa couplings by exploiting Large Hadron Collider (LHC) measurements of transverse momentum distributions in Higgs production. Our method does not rely on the reconstruction of exclusive final states or heavy-flavor tagging. Compared to other proposals, it leads to an enhanced sensitivity to the Yukawa couplings due to distortions of the differential Higgs spectra from emissions which either probe quark loops or are associated with quark-initiated production. We derive constraints using data from LHC run I, and we explore the prospects of our method at future LHC runs. Finally, we comment on the possibility of bounding the strange Yukawa coupling.

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Introduction.—The discovery of a spin-0 resonance and the measurement of its couplings to the standard model (SM) gauge bosons [1,2] have established that the dominant source of electroweak symmetry breaking is the vacuum expectation value (VEV) of a scalar field. In the SM this Higgs VEV is also responsible for giving mass to all charged fermions and the LHC run I measurements support this simple picture in the case of the top and bottom Yukawa couplings y_t and y_b. Direct measurements of the charm Yukawa coupling are, on the other hand, not available at present, and it has been common lore (see, e.g., Refs. [3,4]) that extractions of y_c can only be performed with a few-percent uncertainty at an e^+e^- machine such as the International Linear Collider (ILC) [5].

Only recently it has been realized that gaining direct access to y_c without the ILC is possible as in its high-luminosity run the LHC (HL-LHC) will serve as a Higgs factory producing around 1.7×10^8 Higgs bosons per experiment with 3 ab^{-1} of integrated luminosity [6]. In fact, several different strategies have been proposed to constrain modifications $\kappa_c = y_c/y_c^{\rm SM}$. (Here $y_Q^{\rm SM} = \sqrt{2}m_Q/v$ with $v \simeq 246$ GeV and m_Q is a $\overline{\rm MS}$ mass renormalized at the scale $m_h/2$. In our numerical analysis, we employ $y_b^{\rm SM} = 1.9\times10^{-2}$, $y_c^{\rm SM} = 4.0\times10^{-3}$, and $y_s^{\rm SM} = 3.3\times10^{-4}$.) A first way to probe κ_c consists in searching for the exclusive decay $h\to J/\psi\gamma$ [7–9]. While reconstructing the J/ψ via its dimuon decay leads to a clean experimental signature, the small branching ratio, $\mathrm{Br}(h\to J/\psi\gamma\to\mu^+\mu^-\gamma) = 1.8\times10^{-7}$, implies that only 30 signal events can be expected at each experiment. This makes a detection challenging given the large continuous background due to QCD production of charmonia and a jet faking a photon [10,11]. Search strategies with larger signal cross sections are $pp\to W/Zh(h\to c\bar{c})$ [11–13] and $pp\to hc$ [14]. These strategies, however, rely on charm-tagging (c-tagging) algorithms [15,16] which are currently inefficient.

Given these limitations, it is important to devise another independent procedure that neither suffers from a small signal rate nor depends on the c-tagging performance. In this Letter, we will present a method that relies on the measurements of transverse momentum distributions of Higgs boson plus jets events. This signature receives contributions from gluon fusion ($gg\to hj$) and quark-initiated production ($gQ\to hQ$, $Q\bar{Q}\to hg$). In the $gg\to hj$ channel, the Higgs boson is produced through quark loops that are probed by real emissions in specific kinematic regimes. In particular, when emissions have a transverse momentum $p_\perp$ in the range $m_Q \ll p_\perp \ll m_h$, with m_Q being the internal quark mass, the leading-order (LO) cross section features double logarithms of the form [17]

$$\kappa_Q \frac{m_Q^2}{m_h^2}\ln^2\left(\frac{p_\perp^2}{m_Q^2}\right), \tag{1}$$

due to the interference between the Q- and the top-mediated contributions. These logarithms dynamically enhance the dependence on the Yukawa modification κ_Q. The differential cross section of $gg\to h$ receives radiative corrections which contain up to two powers of the logarithm $\ln(p_\perp^2/m_Q^2)$ for each extra power of the strong coupling constant α_s. If instead the Higgs boson is produced in $gQ\to hQ$, $Q\bar{Q}\to hg$, the resulting LO differential cross section scales as κ_Q^2 (this channel therefore dominates in the large-κ_Q regime that is relevant for first generation quarks [18]), with an additional suppression factor of $\mathcal{O}(\alpha_s/\pi)$ for each initial-state sea-quark parton distribution function (PDF) which is generated perturbatively via gluon splitting. Owing to the different Lorentz structure of the amplitudes in the $m_Q \to 0$ limit, the $gg \to hj$ and $gQ \to hQ$, $Q\bar{Q} \to hg$ processes do not interfere at $\mathcal{O}(\alpha_s^2)$. This ensures that no terms scaling linearly in κ_Q are present in the $gQ \to hQ$, $Q\bar{Q} \to hg$ channels at this order.

The sensitivity to y_Q that arises from the interplay between the different production modes can be studied by means of the differential spectra of the Higgs boson or jet transverse momentum (henceforth generically denoted by p_T) in the moderate-p_T region. In fact, the double logarithms can be numerically large for transverse momenta $p_T \lesssim m_h/2$. This partly compensates for the quadratic mass suppression m_Q^2/m_h^2 appearing in Eq. (1). As a result of the logarithmic sensitivity and of the κ_Q^2 dependence in quark-initiated production, one expects deviations of several percent in the p_T spectra in Higgs production for $\mathcal{O}(1)$ modifications of κ_Q. In the SM, the light-quark effects are small. Specifically, in comparison to the Higgs effective field theory (HEFT) prediction, in $gg \to hj$ the bottom contribution has an effect of around -5% on the differential distributions while the impact of the charm quark is at the level of -1%. Likewise, the combined $gQ \to hQ$, $Q\bar{Q} \to hg$ channels (with $Q = b$, c) lead to a shift of roughly 2%. Precision measurements of the Higgs distributions for moderate p_T values combined with precision calculations of these observables are thus needed to probe $\mathcal{O}(1)$ deviations in y_b and y_c. Achieving such an accuracy is both a theoretical and experimental challenge, but it seems possible in view of foreseen advances in higher-order calculations and the large statistics expected at future LHC runs.

Theoretical framework.—Our goal is to explore the sensitivity of the Higgs-boson ($p_{T,h}$) and leading-jet ($p_{T,j}$) transverse momentum distributions in inclusive Higgs production to simultaneous modifications of the light Yukawa couplings. We consider final states where the Higgs boson decays into a pair of gauge bosons. To avoid sensitivity to the modification of the branching ratios, we normalize the distributions to the inclusive cross section. The effect on branching ratios can be included in the context of a global analysis, jointly with the method proposed here.

The $gg \to hj$ channel was analysed in depth in the HEFT framework where one integrates out the dominant top-quark loops and neglects the contributions from lighter quarks. While in this approximation the two spectra and the total cross section were studied extensively, the effect of lighter quarks is not yet known with the same precision for $p_T \lesssim m_h/2$. Within the SM, the LO distribution for this process was derived long ago [17,19], and the next-to-leading-order (NLO) corrections to the total cross section were calculated in Refs. [20–24]. In the context of analytic resummations of the Sudakov logarithms $\ln(p_T/m_h)$, the inclusion of mass corrections to the HEFT prediction were studied both for the $p_{T,h}$ and $p_{T,j}$ distributions [25–27]. More recently, the first resummations of some of the leading logarithms [Eq. (1)] were accomplished both in the Abelian [28] and in the high-energy [29] limit. The reactions $gQ \to hQ$, $Q\bar{Q} \to hg$ were computed at NLO [30,31] in the five-flavor scheme that we employ here, and the resummation of the logarithms $\ln(p_{T,h}/m_h)$ in $Q\bar{Q} \to h$ was also performed up to next-to-next-to-leading-logarithmic (NNLL) order [32].

In the case of $gg \to hj$, we generate the LO spectra with MG5aMC@NLO [33]. We also include NLO corrections to the spectrum in the HEFT [34–36] using MCFM [37]. The total cross sections for inclusive Higgs production are obtained from HIGLU [38], taking into account the NNLO corrections in the HEFT [39–41]. Sudakov logarithms $\ln(p_T/m_h)$ are resummed up to NNLL order both for $p_{T,h}$ [42–44] and $p_{T,j}$ [45–47], treating mass corrections following Ref. [27]. The latter effects will be significant once the spectra have been precisely measured down to p_T values of $\mathcal{O}(5\ \text{GeV})$. The $gQ \to hQ$, $Q\bar{Q} \to hg$ contributions to the distributions are calculated at NLO with MG5aMC@NLO [48] and cross-checked against MCFM. The obtained events are showered with PYTHIA 8.2 [49] and jets are reconstructed with the anti-k_t algorithm [50] as implemented in FastJet [51] using $R = 0.4$ as a radius parameter.

Our default choice for the renormalization (μ_R), factorization (μ_F), and the resummation (Q_R, for $gg \to hj$) scales is $m_h/2$. Perturbative uncertainties are estimated by varying μ_R, μ_F by a factor of 2 in either direction while keeping $1/2 \leq \mu_R/\mu_F \leq 2$. In addition, for the $gg \to hj$ channel, we vary Q_R by a factor of 2 while keeping $\mu_R = \mu_F = m_h/2$. The final total theoretical errors are then obtained by combining the scale uncertainties in quadrature with a $\pm 2\%$ relative error associated with PDFs and α_s for the normalized distributions. We stress that the normalized distributions used in this study are less sensitive to PDFs and α_s variations; therefore, the above $\pm 2\%$ relative uncertainty is a realistic estimate. We obtain the relative uncertainty in the SM and then assume that it does not depend on κ_Q. While this is correct for the $gQ \to hQ$, $Q\bar{Q} \to hg$ channels, for the $gg \to hj$ production a good assessment of the theory uncertainties in the large-κ_Q regime requires the resummation of the logarithms in Eq. (1). First steps in this direction were taken in Refs. [28,29].

On the other hand, in the small-κ_Q regime that will be probed at future runs of the LHC, the distribution is dominated by the $gg \to hj$ channel. For small values of κ_Q, the $\ln(p_T^2/m_Q^2)$ terms are of moderate size and a good assessment of these effects comes from the NLO calculation of mass corrections in $gg \to hj$ [52,53]. Furthermore, achieving a perturbative uncertainty of a few percent in the considered p_T region would also require improving the accuracy of the resummed $\ln(p_T/m_h)$ terms beyond NNLL. Progress in this direction [46,54] suggests that this will be achieved in the near future. Incorporating higher-order corrections to the full SM process will both reduce the theoretical uncertainties and improve the sensitivity to κ_Q.

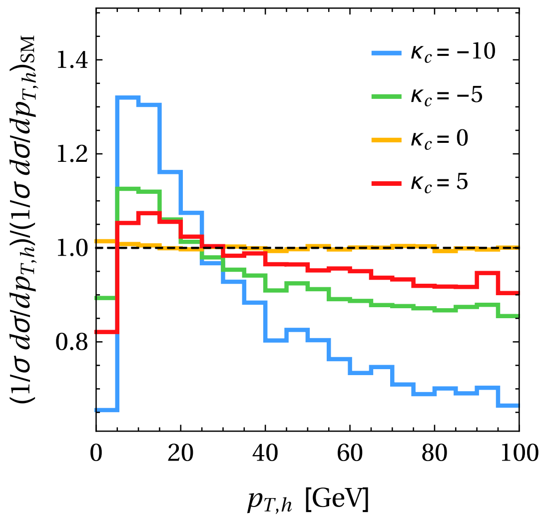

FIG. 1. The normalized $p_{T,h}$ spectrum of inclusive Higgs production at $\sqrt{s} = 8$ TeV divided by the SM prediction for different values of κ_c. Only κ_c is modified, while the remaining Yukawa couplings are kept at their SM values.

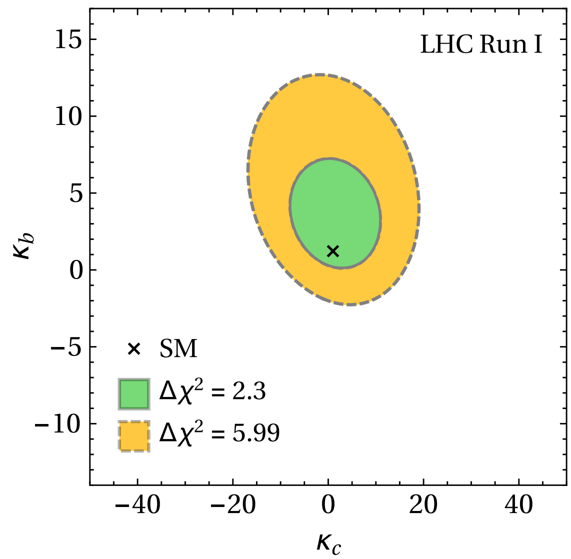

FIG. 2. The $\Delta\chi^2 = 2.3$ and $\Delta\chi^2 = 5.99$ regions in the $\kappa_c - \kappa_b$ plane following from the combination of the ATLAS measurements of the normalized $p_{T,h}$ distribution in the $h \to \gamma\gamma$ and $h \to ZZ^* \to 4\ell$ channels. The SM point is indicated by the black cross.

Figure 1 illustrates the impact of the Yukawa modification κ_c on the normalized $p_{T,h}$ spectrum in inclusive Higgs production. The results are divided by the SM prediction and correspond to pp collisions at a center-of-mass energy ($\sqrt{s}$) of 8 TeV, central choice of scales, and MSTW2008NNLO PDFs [55]. (The ratio of the $p_{T,h}$ spectra to the SM prediction at $\sqrt{s} = 13$ TeV is slightly harder than the $\sqrt{s} = 8$ TeV counterpart, which enhances the sensitivity to κ_b and κ_c at ongoing and upcoming LHC runs as well as possible future hadron colliders at higher energies.) Notice that for $p_{T,h} \gtrsim 50$ GeV, the asymptotic behavior [Eq. (1)] breaks down and consequently the $gQ \to hQ$, $Q\bar{Q} \to hg$ channels control the shape of the $p_{T,h}$ distributions.

We stress that for the $p_{T,h}$ distribution, nonperturbative corrections are small and in the long run, $p_{T,h}$ will be measured to lower values than $p_{T,j}$. While the latter currently gives comparable sensitivity, it is mandatory to study $p_{T,h}$ to maximize the constraints on κ_Q in future LHC runs. Therefore, we use $p_{T,h}$ in the rest of this Letter.

Current constraints.—At $\sqrt{s} = 8$ TeV, the ATLAS and CMS Collaborations have measured the $p_{T,h}$ and $p_{T,j}$ spectra in the $h \to \gamma\gamma$ [56,57], $h \to ZZ^* \to 4\ell$ [58,59] and $h \to WW^* \to e\mu\nu_e\nu_\mu$ [60,61] channels, using around 20 fb^{-1} of data in each case. To derive constraints on κ_b and κ_c, we harness the normalized $p_{T,h}$ distribution in inclusive Higgs production [62]. This spectrum is obtained by ATLAS from a combination of $h \to \gamma\gamma$ and $h \to ZZ^* \to 4\ell$ decays, and represents at present the most precise measurement of the differential inclusive Higgs cross section. In our χ^2 analysis, we include the first seven bins in the range $p_{T,h} \in [0, 100]$ GeV whose experimental uncertainty is dominated by the statistical error. The data are then compared with the theoretical predictions for the inclusive $p_{T,h}$ spectrum described in the previous section. We assume that all the errors are Gaussian in our fit. The bin-to-bin correlations in the theoretical normalized distributions are obtained by assuming that the bins of the unnormalized distributions are uncorrelated and modeled by means of linear error propagation. This accounts for the dominant correlations in normalized spectra. For the data, we used the correlation matrix of Ref. [62].

Figure 2 displays the $\Delta\chi^2 = 2.3$ and $\Delta\chi^2 = 5.99$ contours [corresponding to a 68% and 95% confidence level (C.L.) for a Gaussian distribution] in the $\kappa_c - \kappa_b$ plane. We profile over κ_b by means of the profile likelihood ratio [63] and obtain the following 95% C.L. bounds on κ_c:

$$\kappa_c \in [-16, 18] \qquad \text{(LHC run I)}. \tag{2}$$

Our limit is significantly stronger than the bounds from exclusive $h \to J/\psi\gamma$ decays [10], a recast of $h \to b\bar{b}$ searches, and the measurements of the total Higgs width [2,64], which read $|\kappa_c| \lesssim 429$ [9], $|\kappa_c| \lesssim 234$, and $|\kappa_c| \lesssim 130$ [13], respectively. It is, however, not competitive with the bound $|\kappa_c| \lesssim 6.2$ from a global analysis of Higgs data [13], which introduces additional model dependence.

Turning our attention to the allowed modifications of the bottom Yukawa coupling, one observes that our proposal leads to $\kappa_b \in [-3, 15]$. This limit is thus significantly weaker than the constraints from the LHC run I measurements of $pp \to W/Zh(h \to b\bar{b})$, $pp \to t\bar{t}h(h \to b\bar{b})$, and $h \to b\bar{b}$ in vector boson fusion that already restrict the relative shifts in y_b to around ±50% [1,2].

Future prospects.—As a result of the expected reduction of the statistical uncertainties for the $p_{T,h}$ spectrum at the LHC, the proposed method will be limited by systematic

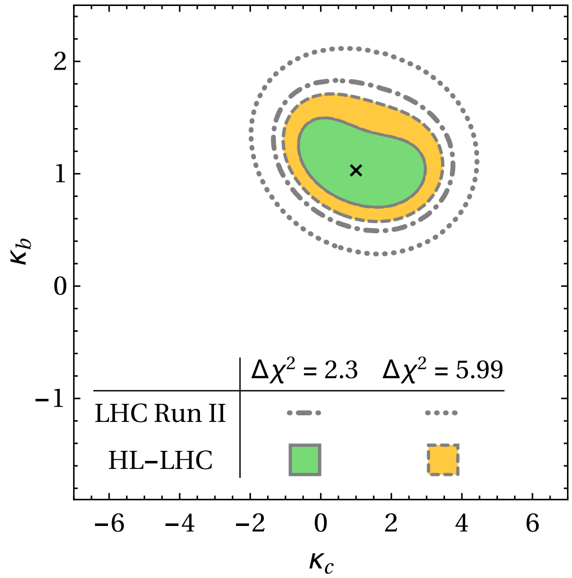

FIG. 3. Projected future constraints in the κ_c-κ_b plane. The SM point is indicated by the black cross. The figure shows our projections for the LHC run II (HL-LHC) with 0.3 ab^{-1} (3 ab^{-1}) of integrated luminosity at $\sqrt{s} = 13$ TeV. The remaining assumptions entering our future predictions are detailed in the main text.

uncertainties in the long run. Recent studies by CMS [65] show that the residual experimental systematic uncertainty will be reduced to the level of a few percent at the HL-LHC. Therefore, it is natural to study the prospects of the method in future scenarios assuming a reduced theory uncertainty given that this error may become the limiting factor.

In order to investigate the future prospects of our method, we need a more precise assessment of the nonperturbative corrections to the $p_{T,h}$ distribution. To estimate these effects, we used MG5aMC@NLO and POWHEG [66] showered with Pythia 8.2 and found that the corrections can reach up to 2% in the relevant $p_{T,h}$ region. This finding agrees with recent analytic studies of nonperturbative corrections to $p_{T,h}$ (see, e.g., Ref. [67]). With improved perturbative calculations, few-percent accuracy in this observable will therefore be reachable.

We study two benchmark cases. Our LHC run II scenario employs 0.3 ab^{-1} of integrated luminosity and assumes a systematic error of $\pm3\%$ on the experimental side and a total theoretical uncertainty of $\pm5\%$. This means that we envision that the nonstatistical uncertainties present at LHC run I can be halved in the coming years, which seems plausible. Our HL-LHC scenario instead uses 3 ab^{-1} of data and foresees a reduction of both systematic and theoretical errors by another factor of 2, leading to uncertainties of $\pm1.5\%$ and $\pm2.5\%$, respectively. The last scenario is illustrative of the reach that can be achieved with improved theory uncertainties. Alternative theory scenarios are discussed in Ref. [68]. In both benchmarks, we employ $\sqrt{s} = 13$ TeV and the PDF4DF4LHCI5_nnlo_mc set [69–72], consider the range $p_T \in [0, 100]$ GeV in bins of 5 GeV, and take into account $h \to \gamma\gamma$, $h \to ZZ^* \to 4\ell$ and $h \to WW^* \to 2\ell 2\nu_\ell$. We assume that future measurements will be centred around the SM predictions. These channels sum to a branching ratio of 1.2%, but given the large amount of data the statistical errors per bin will be at the $\pm2\%$ ($\pm1\%$) level in our LHC run II (HL-LHC) scenario. We model the correlation matrix as in the 8 TeV case.

The results of our χ^2 fits are presented in Fig. 3, showing the constraints in the $\kappa_c - \kappa_b$ plane. The unshaded contours refer to the LHC run-II scenario with the dot-dashed (dotted) lines corresponding to $\Delta\chi^2 = 2.3(5.99)$. Analogously, the shaded contours with the solid (dashed) lines refer to the HL-LHC. By profiling over κ_b, we find in the LHC run II scenario the following 95% C.L. bound on the y_c modifications:

$$\kappa_c \in [-1.4, 3.8] \qquad \text{(LHC run II)}, \tag{3}$$

while the corresponding HL-LHC bound reads

$$\kappa_c \in [-0.6, 3.0] \qquad \text{(HL-LHC)}. \tag{4}$$

These limits compare well not only with the projected reach of other proposed strategies but also have the nice feature that they are controlled by the systematic uncertainties that can be reached in the future. Also, at future LHC runs our method will allow one to set relevant bounds on the modifications of y_b. For instance, in the HL-HLC scenario we obtain $\kappa_b \in [0.7, 1.6]$ at 95% C.L.

Finally, we also explored the possibility of constraining modifications of the strange Yukawa coupling. Under the assumption that y_b is SM-like but profiling over κ_c, we find that at the HL-LHC one should have a sensitivity to y_s values of around 30 times the SM expectation. Measurements of exclusive $h \to \phi\gamma$ decays are expected to have a reach that is weaker than this by a factor of order 100 [11].

Conclusions.—In this Letter, we have demonstrated that the normalized p_T distribution of the Higgs bosons or of jets recoiling against it, provides sensitive probes of the bottom, charm, and strange Yukawa couplings. Our new proposal takes advantage of the fact that the differential Higgs bosons plus jet cross section receives contributions from the channels $gg \to hj$, $gQ \to hQ$, $Q\bar{Q} \to hg$ that feature two different functional dependences on κ_Q. We have shown that in the kinematic region where the transverse momentum $p_\perp$ of emissions is larger than the relevant quark mass m_Q, but smaller than the Higgs mass m_h, both effects can be phenomenologically relevant and thus their interplay results in an enhanced sensitivity to modifications of the Yukawa coupling κ_Q. This feature allows one to obtain unique constraints on y_b, y_c, and y_s at future LHC runs.

We derived constraints in the κ_c-κ_b plane that arise from LHC run I data and provided sensitivity projections of our method in future runs of the LHC. Our results are obtained under the assumption that physics beyond the SM only alters the shape of the distributions via changes of y_c and y_b, while modifications of the effective ggh coupling that are induced by loops of new heavy states are not considered. Since effects of the latter type mainly affect the total Higgs production cross section, they largely cancel in the normalized $p_{T,h}$ spectrum for low and moderate values of the transverse momentum. The remaining model dependence, due to interference of heavy new physics with the light-quark loops, is subleading in the relevant regions of the κ_c-κ_b plane.

Under reasonable assumptions about theoretical progress in the calculation of Higgs bosons plus jet production and the precision of forthcoming experimental measurements we have shown that, at the HL-LHC, it is possible to obtain a limit of $\kappa_c \in [-0.6, 3.0]$ at 95% C.L. using our method alone. Modifications of this order can be realized in some models of flavor (see, e.g., Refs. [73,74]). The fact that our procedure is neither afflicted by a small signal rate nor depends on the performance of heavy-flavor tagging makes it highly complementary to extractions of y_c via $h \to J/\psi\gamma$, $pp \to W/Zh(h \to c\bar{c})$ and $pp \to hc$. In the case of the strange Yukawa coupling, we found that precision measurements of the Higgs p_T distributions have a sensitivity to y_s values of about 30 times the SM expectation, which exceeds the HL-LHC reach in $h \to \phi\gamma$ by about 2 orders of magnitude.

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