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Phenomenology of enhanced light quark Yukawa couplings and the $W^{\pm}h$ charge asymmetry

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Abstract: I propose the measurement of the $W^{\pm}h$ charge asymmetry as a consistency test for the Standard Model (SM) Higgs, which is sensitive to enhanced Yukawa couplings of the first and second generation quarks. I present a collider analysis for the charge asymmetry in the same-sign lepton final state, $pp \to W^{\pm}h \to (\ell^{\pm}\nu)(\ell^{\pm}\nu jj)$, aimed at discovery significance for the SM $W^{\pm}h$ production mode in each charge channel with $300\,\text{fb}^{-1}$ of 14 TeV LHC data. Using this decay mode, I estimate the statistical precision on the charge asymmetry should reach 0.4% with $3\,\text{ab}^{-1}$ luminosity, enabling a strong consistency test of the SM Higgs hypothesis. I also discuss direct and indirect constraints on light quark Yukawa couplings from direct and indirect probes of the Higgs width as well as Tevatron and Large Hadron Collider Higgs data. While the main effect from enhanced light quark Yukawa couplings is a rapid increase in the total Higgs width, such effects could be mitigated in a global fit to Higgs couplings, leaving the $W^{\pm}h$ charge asymmetry as a novel signature to test directly the Higgs couplings to light quarks.

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Contents

1 Introduction

After the discovery of the Higgs boson in 2012 by the ATLAS and CMS experiments [1, 2], the experimental Higgs effort has transitioned to a full-fledged program of Higgs characterization and precision measurements of its couplings to Standard Model (SM) particles. The direct observation of the Higgs to vector bosons has been established at high significance [3–5], while decays to taus and bottom quarks have yet to reach discovery significance and direct knowledge about the couplings of the Higgs to first and second generation fermions is utterly lacking.

The most straightforward information about light generation Yukawas would come from direct decays of the Higgs. While these are certainly viable possibilities for the charged leptons [6, 7], the inability to distinguish light quark-initiated jets from each other renders this avenue a practical impossibility, with the notable exception of charm tagging. A few studies [8–10] have investigated the prospects for identifying direct decays of Higgs to charm jets, where bottom- and charm-jet tagging work in tandem to disentangle enhanced bottom and charm Yukawa couplings.

Aside from direct decays of the Higgs to light quark jets, the other possibilities for measuring light quark Yukawa couplings come from charm-Higgs associated production [11], which also requires a careful calibration of charm jet tagging efficiencies and a precise determination of Higgs and associated jet backgrounds. The practical applicability of this technique is not well established, however, since a systematic treatment of Higgs and non-Higgs backgrounds is still absent.

An enhanced light quark Yukawa can also lead to significant effects in rare Higgs decays to quark-anti-quark mesons and vector bosons [12–15]. The impressive control

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of theoretical uncertainty in these calculations and the corresponding proof of principle searches for such rare decays from Z and Higgs bosons [16–18] make it an interesting channel to pursue. In these channels, though, interpreting a deviation from the SM expectation would require knowledge of the Higgs vertices in the so-called indirect contributions. A deviation in the rate for $h \to J/\Psi\gamma$, for example, could be attributed to a nonstandard effective coupling of the Higgs to two photons as well as the charm Yukawa coupling. Hence, the realistic sensitivity of these rare Higgs decays to nonstandard light quark Yukawas suffers not only from the small expected SM rates, but also because the indirectness of the probe necessitates a combination with other Higgs measurements.

Nevertheless, the power of combined fits to Higgs signal strengths cannot be discounted as an important tool in constraining nonstandard Yukawa couplings [9, 14, 19]. Such combined fits, however, are handicapped by the inability to determine the total width of the Higgs and thus require model-dependent assumptions in order to extract Higgs couplings [20]. For example, the possibility of exotic production modes of the Higgs boson contaminating the Higgs dataset [21] would introduce new physics parameters outside of the coupling deviation framework, spoiling the entire applicability of the κ-framework.

We see that many of the proposed tests of non-standard Yukawa couplings have varied difficulties in experimental applicability or theoretical interpretation. While direct decay tests are best and subject to the least theoretical bias, the only potentially viable channel is the $h \to c\bar{c}$ decay. Production tests, like measuring $hc + h\bar{c}$ production, are fraught with many backgrounds and experimental challenges such as charm tagging. Indirect tests, whether via Higgs rare decays to quantum chromodynamics (QCD) mesons and vectors or combined coupling fits to Higgs data, are most robust when conducted as consistency tests of the SM.

In the spirit of offering new channels for probing the Standard Model Yukawa couplings, we motivate the charge asymmetry in vector boson associated Higgs production at the LHC. As a proton-proton machine, the LHC handily favors W^+h production over W^-h production, mainly through the Higgsstrahlung process $qq' \to W^{\pm *} \to W^{\pm}h$. At the 14 TeV LHC, for example, with $m_H = 125.09\,\text{GeV}$, $\sigma(W^+h)/\sigma(W^-h) = 1.56$ [22, 23]. We point out, however, that this inclusive charge asymmetry is dramatically changed if the light SM quarks have large Yukawa couplings. Concomitant effects from large light quark Yukawa couplings, such as $q\bar{q}$ s-channel Higgs production and a rapid increase in the total Higgs width, provide additional channels for indirectly constraining enhanced quark Yukawas.

In section 2, we provide a theory motivation and background on Yukawa coupling deviations. In section 3, we discuss the charge asymmetry of $pp \to W^{\pm}h$ production in the SM and the modifications induced by anomalous light quark Yukawa couplings. We then present a collider analysis for same-sign leptons targetting the $W^{\pm}h$ charge asymmetry measurement in section 4, demonstrating that the charge asymmetry can be measured at the LHC to subpercent accuracy. We proceed to discuss other phenomenological consequences of enhanced light quark Yukawa couplings and their constraints in section 5. We conclude in section 6.

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2 Yukawa deviations

The question of fermion mass generation is a central aspect of the structure of the Standard Model. A nonstandard Yukawa coupling in the SM Lagrangian leads to unitarity violation for $f\bar{f} \to VV$ scattering amplitudes. In the Higgs post-discovery phase, and in the absence of direct knowledge of the Yukawa coupling for a given SM fermion f, we can calculate a unitarity bound from $f\bar{f} \to W^+W^-$ scattering [24] by requiring the partial amplitude satisfies unitarity, $|a_0| \leq 1/2$. The scale of unitarity violation is then given by

$$E_f \simeq \frac{8\pi v^2 \xi}{|m_f - y_f v|}\,, \tag{2.1}$$

where $v = 246\,\text{GeV}$ is the Higgs vev, $\xi = 1/\sqrt{3}$ for quarks and $\xi = 1$ for charged leptons. This unitarity violation is a general feature in theories with chiral fermion masses arising from spontaneous symmetry breaking if the fermion mass is mismatched with its Yukawa coupling. A stronger bound on E_f can be found by studying $f\bar{f}$ scattering to arbitrary numbers of longitudinal modes of electroweak bosons [25].

Resolving the mass-Yukawa coupling mismatch necessarily requires either new sources of $\text{SU}(2)_L$ breaking beyond the Higgs vacuum expectation value (vev) or new matter fermions which mix with the SM fermions. Such completions would add new diagrams to the partial wave amplitude calculated above in precisely the necessary manner to remove the $\sqrt{s}$ growth in the amplitude.

We note that regardless of the source of the new sources of Yukawa deviations, the unitarity bound can be far beyond the reach of the LHC. For example, light quarks with $\mathcal{O}(1)$ Yukawa couplings (which requires fine-tuning of SM and new physics Lagrangian parameters to reproduce the physical light quark masses) motivate $E_f \sim 3.6\,\text{TeV}$ as the scale of unitarity breakdown. Although such a fine-tuned light quark mass is aethestically unappealing, such a mismatch between the quark mass and the Higgs Yukawa coupling cannot be discounted from collider searches for heavy fermions, seeing that limits on vector-like top parters reach only the 1 TeV scale [26, 27].

The unitarity bound and inadequacy of the ad-hoc renormalizable Lagrangian can be simultaneously cast into more familiar language by appealing to dimension-6 effective operators for Higgs physics. Here, the SM provides the usual dimension-4 couplings that preserve the mass-coupling relation expected in SM physics, but the fermion masses and their Yukawa couplings get additional contributions from dimension-6 operators. We have

$$\mathcal{L} \supset y_u \bar{Q}_L \tilde{H} u_R + y'_u \frac{H^\dagger H}{\Lambda^2} \bar{Q} \tilde{H} u_R + y_d \bar{Q}_L H d_R + y'_d \frac{H^\dagger H}{\Lambda^2} \bar{Q} H d_R + \text{h.c.}\,, \tag{2.2}$$

where y_u, y'_u, y_d and y'_d are 3×3 matrices in the flavor space of Q_L, u_R, and d_R. The flavor rotations of $Q_L = (u_L\ d_L)^T$, u_R, and d_R are then used to ensure the mass matrices,

$$m_f = \frac{y_f v}{\sqrt{2}} + \frac{y'_f v^3}{2\sqrt{2}\Lambda^2}\,, \tag{2.3}$$

are diagonal, with f denoting up-type or down-type quarks, and we have expanded $H = \frac{1}{\sqrt{2}}(h + v)$ about its vev. Importantly, these flavor rotations does not guarantee in general that the Yukawa matrices

$$\frac{y_{f,\,\text{eff}}}{\sqrt{2}} = \frac{y_f}{\sqrt{2}} + \frac{3y'_f v^2}{2\sqrt{2}\Lambda^2} = \frac{m_f}{v} + \frac{2y'_f v^2}{2\sqrt{2}\Lambda^2}\,, \tag{2.4}$$

are diagonal. Simultaneous diagonalization of m_f and y'_f is not guaranteed unless they are aligned, and hence without additional assumptions, the Yukawa terms in dimension-6 Higgs effective theory are expected to introduce flavor-changing Higgs couplings. Moreover, phases in y'_f are not guaranteed to vanish, so we also expect CP violation in Higgs couplings (the overall phase in each Yukawa matrix is not observable). Bounds on both flavor-changing Higgs couplings and CP-violating couplings can be obtained from studying meson mixing [28, 29] and electron and neutron dipole moment constraints [30].

Nevertheless, a large, enhanced diagonal coupling for fermions is readily achieved from eq. (2.4). Note that for y'_u, $y'_d \sim \text{diag}(\mathcal{O}(1))$ and $v/\Lambda \sim \mathcal{O}(1\,\text{TeV})$, we obtain Yukawa enhancements κ of $\mathcal{O}(10^3–10^4)$ for first generation quarks, $\mathcal{O}(10^2)$ for second generation quarks, and $\mathcal{O}(10^2–10^0)$ for third generation quarks, precisely reflecting the universality of the dimension-6 Higgs $H^\dagger H/\Lambda^2$ operator compared to the hierarchical structure of the SM Yukawa matrix.

3 W^+h vs. W^-h charge asymmetry

In the Standard Model, inclusive $W^\pm h$ production exhibits a charge asymmetry of 21.8% at the $\sqrt{s} = 14\,\text{TeV}$ LHC [22, 23]. This charge asymmetry directly results from the inequality of the LHC pp parton distribution functions (PDFs) under charge conjugation. The tree level diagrams for $W^\pm h$ production are shown in figure 1, and in the SM, the Higgsstrahlung diagrams are completely dominant compared to the Yukawa-mediated diagrams. As a result, the mismatch between $u\bar{d}$ vs. $\bar{u}d$ PDFs at the LHC drives the bulk of the charge asymmetry, which is ameliorated by the more symmetric $c\bar{s}$ vs. $\bar{c}s$ PDFs. The Cabibbo-suppressed contributions from $u\bar{s}$ vs. $\bar{u}s$ and $c\bar{d}$ vs. $\bar{c}d$ PDFs also enhance and dilute, respectively, the charge asymmetry.

Enhanced light quark Yukawa couplings cause the inclusive $W^\pm h$ charge asymmetry to deviate significantly from the SM expectation. For very large Yukawa enhancements, we can neglect the Higgsstrahlung diagrams in figure 1 and focus on the Yukawa-mediated diagrams. If the charm Yukawa dominates the other couplings, then the $c\bar{s}$ vs. $\bar{c}s$ PDFs symmetrize $W^\pm h$ production, and the overall charge asymmetry even turns negative from the residual $c\bar{d}$ vs. $\bar{c}d$ PDFs. Similarly, an enhanced strange Yukawa drives the balanced $c\bar{s}$ vs. $\bar{c}s$ PDFs to dominate $W^\pm h$ production, while the Cabibbo-suppressed $u\bar{s}$ vs. $\bar{u}s$ initial states still retains a positive asymmetry. Finally, large down and up quark Yukawas actually enhance the positive charge asymmetry beyond the SM expectation, since the ameliorating effects from second generation quarks in the proton PDFs are weakened.

We adopt the usual κ notation to describe rescalings of the Higgs Yukawa couplings to the first and second generation quarks, $y_{f,\,\text{eff}} = \kappa_f y_{f,\,\text{SM}}$ for $f = d$, u, s, or c. Throughout this work, we will only consider one Yukawa deviation at a time and will comment briefly

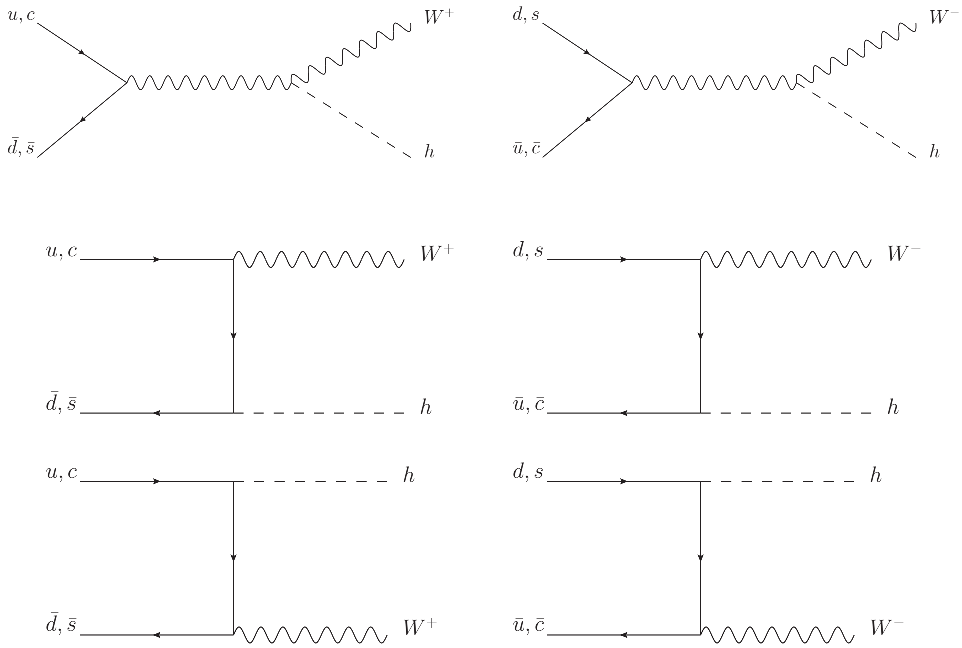

Figure 1. Leading order W^+h (left column) and W^-h (right column) production diagrams, showing the Higgsstrahlung process (top row) and Yukawa-mediated contributions (bottom two rows).

in the conclusions about simultaneous deviations in multiple Yukawa couplings. For convenience, we also use the $\bar{\kappa}_f$ normalization, which rescales κ_f into units of $y_b^{\rm SM}$ evaluated at $\mu = 125\,\text{GeV}$:

$$\bar{\kappa}_f \equiv \frac{m_f(\mu = 125\ \text{GeV})}{m_b(\mu = 125\ \text{GeV})}\kappa_f\ . \tag{3.1}$$

In figure 2, we show the inclusive charge asymmetry

$$A = \frac{\sigma(W^+h) - \sigma(W^-h)}{\sigma(W^+h) + \sigma(W^-h)}\,, \tag{3.2}$$

for the 14 TeV LHC as a function of $\bar{\kappa}_f$ for individually enhanced Yukawa couplings, $f = d,\ u,\ s$, and c. These results were generated using MadGraph v2.4.3 [31] where the Yukawa couplings were implemented via a FeynRules [32] model implementing automatic next-to-leading order (NLO) quantum chromodynamics (QCD) corrections at 1-loop from NLOCT v1.0 [33] interfaced with the NNPDF2.3 NLO [34] PDF set. Yukawa couplings were renormalized using the boundary values from the Particle Data Group [35] and run to the Higgs mass with RunDec [36]. The boundary values are $m_d = 4.8\,\text{MeV}$, $m_u = 2.3\,\text{MeV}$, $m_s = 0.95\,\text{GeV}$ at $\mu = 2\,\text{GeV}$, and $m_c = 1.275\,\text{GeV}$ at $\mu = m_c$. We used a two-step procedure in the renormalization group running to account for the change in the α_s behavior at b-mass scale, $m_b = 4.18\,\text{GeV}$ at $\mu = m_b$. The extracted SM quark masses at $\mu = 125\,\text{GeV}$ are $m_d = 2.73\,\text{MeV}$, $m_u = 1.31\,\text{MeV}$, $m_s = 54\,\text{MeV}$, $m_c = 634\,\text{MeV}$, and $m_b = 2.79\,\text{GeV}$, which are used in eq. (3.1) to rescale κ_f to $\bar{\kappa}_f$. The Higgs coupling to W bosons was fixed to the SM value for this scan.

While QCD theory uncertainties are formally expected to cancel out in a charge asymmetry, since QCD interactions respect charge conservation, the factorization of the $W^{\pm}h$

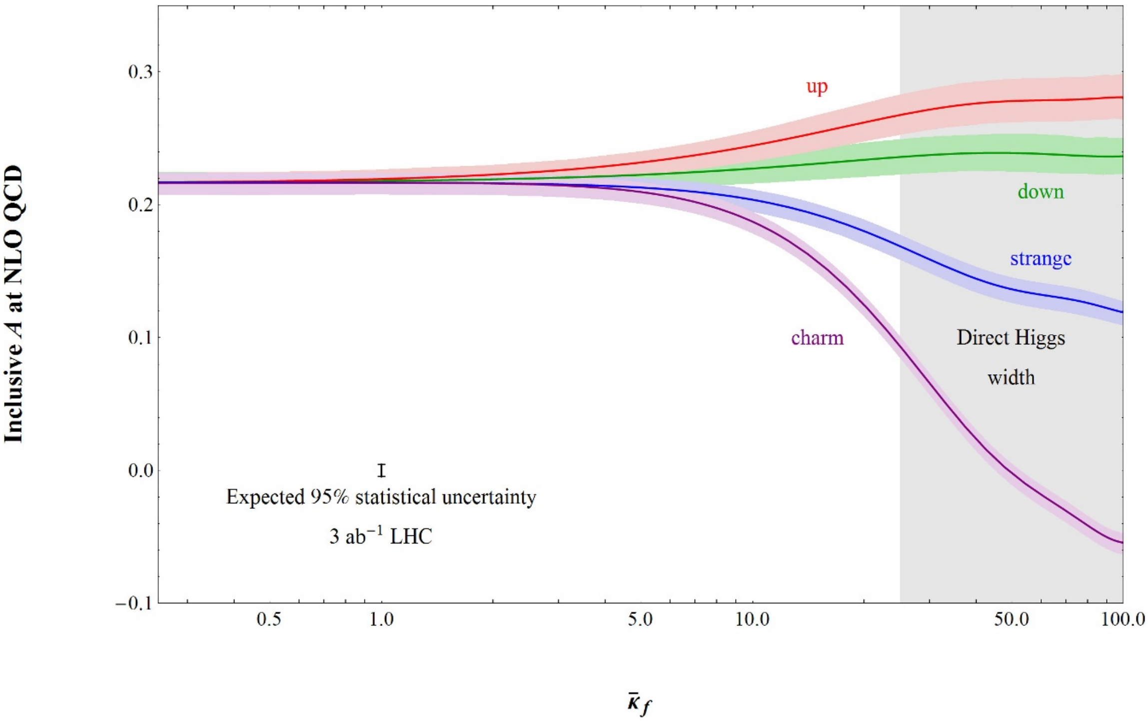

Figure 2. Inclusive charge asymmetry $A = (\sigma(W^+h) - \sigma(W^-h))/(\sigma(W^+h) + \sigma(W^-h))$ at NLO QCD for the $\sqrt{s} = 14\,\text{TeV}$ LHC as a function of individual Yukawa rescaling factors $\bar{\kappa}_f$ for $f = u$ (red), d (green), s (blue), and c (purple). Shaded bands correspond to scale uncertainties at 1σ from individual $\sigma(W^+h)$ and $\sigma(W^-h)$ production, which are conservatively taken to be fully uncorrelated. The gray region shows the bound from the direct Higgs width measurement, $\Gamma_H < 1.7\,\text{GeV}$ [4], which excludes $\bar{\kappa}_f > 25$ for each light quark flavor and is discussed in section 5. The expected statistical error from this measurement using $3\,\text{ab}^{-1}$ of LHC data is also shown.

partonic hard process from the parent protons spoils this expectation and hence scale and PDF uncertainties will not generally cancel. We show the 1σ scale uncertainty for the whole range of $\bar{\kappa}_f$ in figure 2 as a shaded band. We also evaluated the PDF uncertainty using a leading order calculation interfaced with the leading order NNPDF2.3 and CTEQ6L [37] PDF sets. The two PDF sets leads to a $\approx 1\%$ disagreement in the asymptotic values of the charge asymmetry for very large individual κ_f.

We remark that the statistical precision on the exclusive charge asymmetry, which we propose to measure in section 4, is expected to be at the subpercent level, which we expect will improve the overall status of PDF determinations at the LHC [38], regardless of the sensitivity to light quark Yukawa couplings. Moreover, $W^\pm h$ measurements complement $W^\pm Z$ and $W^\pm +$ jets measurements, and improved measurements of the charge asymmetry in these separate channels will confirm or refute whether $W^\pm h$ production is dominated by the light quarks as expected in the SM.

Measuring the asymmetry at the collider requires tagging the leptonic decay of the W boson and using a Higgs decay final state that simultaneously tempers the background and retains sufficient statistics to enable subpercent level accuracy. In this vein, very clean Higgs decays, such as $h \to ZZ^* \to 4\ell$ or $h \to \gamma\gamma$ are inadequate for this purpose because

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the expected SM rates for $\sigma(W^\pm h)\times$ Br$(W^\pm \to \ell^\pm \nu)\times$ Br$(h \to 4\ell)$ or Br$(h \to \gamma\gamma)$ are not statistically large. On the other hand, the largest SM Higgs decay channel, $h \to b\bar{b}$, must contend with both the charge-symmetric semi-leptonic $t\bar{t}$ background and the charge-asymmetric $W^\pm$+ jets background: therefore, extracting the $W^\pm h$ charge asymmetry from this Higgs final state will be challenging. An interesting decay is $h \to \tau^+\tau^-$, where improvements in hadronic and leptonic τ decays have led to important evidence for the Higgs decays to taus [5]. The efficacy of these Higgs resonance reconstruction methods in the presence an additional lepton and neutrino, however, has not been demonstrated.

We instead explore a new Higgs process, $W^\pm h \to (\ell^\pm \nu)(\ell^\pm \nu jj)$, taking advantage of the semi-leptonic decay of the Higgs via WW^*. This process has a number of features that make it attractive for measuring the $W^\pm h$ charge asymmetry. First, this same-sign lepton final state inherits the same charge asymmetry as the inclusive $W^\pm h$ process. Second, the leading non-Higgs background processes for same-sign leptons are all electroweak processes, in contrast to the $h \to b\bar{b}$ decay discussed before. Finally, although the Higgs resonance is not immediately reconstructible in this decay channel, we have a number of kinematic handles to isolate the Higgs contribution to this final state, which make it eminently suitable to extract the charge asymmetry.

4 Collider analysis: same-sign leptons from associated $W^\pm h$ production

Having motivated the possibility and importance of direct tests for light quark Yukawa couplings via their effects in the charge asymmetry of $W^\pm h$ production, we now present a search for $W^\pm h \to \ell^\pm \ell^\pm \not{E}_T$ + 1 or 2 jets, with $\ell = e$ or μ, which can be a benchmark process for measuring the charge asymmetry. We emphasize that the charge asymmetry measured in an exclusive Higgs decya mode is at best considered a consistency test of the Standard Model, since large Yukawa deviations in light quark couplings will dilute the SM Higgs branching fractions, which we address in section 5. Nevertheless, the charge asymmetry of $W^\pm h$ production is a prediction of the Standard Model that can be affected by deviations in light quark Yukawa couplings.

The primary backgrounds for the $\ell^\pm \ell^\pm \not{E}_T$ + 1 or 2 jets signature are $W^\pm W^\pm jj$, $W^\pm Z$, with $Z \to \ell^+\ell^-$ and a lost lepton, and W^+W^- with charge mis-identification. Note that all of these diboson backgrounds are electroweak processes, giving the benefit that $W^\pm h$ signal rates are roughly comparable to the background rates. On the other hand, these backgrounds also have their own charge asymmetries, but these can be probed via complementary hadronic channels, inverting selection cuts, or data-driven techniques.

Other backgrounds we do not consider are fully leptonic $t\bar{t}$, which we discard because it requires charge mis-identification and would be killed by b-jet vetoes. The single vector boson backgrounds, W+ jets and Z+ jets, are neglected because they need a jet faking a lepton or in the case of the Z with charge mis-identification, would still reconstruct the Z peak. We do not consider hard brehmstrahlung with subsequent photon conversion, and we ignore jet faking lepton rates, which eliminates QCD backgrounds.

Signal and background samples are generated for $\sqrt{s}$ = 14 TeV LHC using MadGraph 5 v2.2.1 [31] at leading order in QCD. Signal bosons are decayed on-shell via

Cross section, cut, survival efficiency	**SM $W^{\pm}h$** 6.5 fb + 4.2 fb	$W^{\pm}W^{\pm}jj$ 113 fb	$W^{+}Z$ 630 fb	$W^{-}Z$ 440 fb	$W^{+}W^{-}$ 8.80 pb
Exactly two leptons, $p_T > 10\,\text{GeV}$	53.4%	32.6%	32.2%	31.9%	46.3%
Same-charge leptons	53.1%	31.7%	6.6%	6.6%	0.087%
Either one or two jets, $p_T > 25\,\text{GeV}$	34.2%	22.5%	3.3%	3.4%	0.044%
$60\,\text{GeV} < m_{jj} < 100\,\text{GeV}$	28.1%	11.7%	2.6%	2.6%	0.029%
$m_{T,\,\text{subleading}\,\ell jj} < 200\,\text{GeV}$	25.1%	4.9%	2.1%	2.2%	0.022%
Number of events	496 + 312	1070 + 604	3960 + 11	10 + 2860	270 + 303
Statistical significance, $300\,\text{fb}^{-1}$, $S/\sqrt{S+B}$	6.5σ, $4.9\sigma \Rightarrow 8.1\sigma$				

Table 1. Cut flow for same-sign leptons from $W^{\pm}h$ production, where we denote the $++$ and $--$ contributions to the total number of events separately.

$W^{\pm} \to \ell^{\pm}\nu$ and $h \to \ell^{\pm}\nu jj$, where the lepton charges are chosen to be the same, and $\ell = e$ or μ. Backgrounds must pass the preselection requirements of jet $p_T > 30\,\text{GeV}$, lepton $p_T > 10\,\text{GeV}$, and $\Delta R_{jj} > 0.2$. In the background samples, τ leptons are included in the boson decays, since softer leptonic decays from τs can contaminate the signal region. We perform MLM matching [39, 40] for the $W^{\pm}Z$ and $W^{+}W^{-}$ backgrounds up to 1 jet, with the matching scale set to 30 GeV. Events are passed to Pythia v6.4 [47] for showering and hadronization and then simulated using a mock detector simulation based on ATLAS and CMS performance measurements using electrons [48], muons [49], jets [50], and $\not{E}_T$ [51]. We adopt an electron charge mis-identification rate of 0.16% for $0 < |\eta_e| < 1.479$ and 0.3% for $1.479 < |\eta_e| < 3$ and neglect muon charge mis-identification [52].

We calculate and apply flat NLO QCD K-factors using MCFM v7.0 [41–43] and find $K = 1.71$ for $W^{+}Z$, $K = 1.74$ for $W^{-}Z$, and $K = 1.55$ for $W^{+}W^{-}$. The NLO QCD corrections to the $W^{\pm}W^{\pm}jj$ background have been calculated in refs. [44–46], from which we adopt a flat $K = 1.5$ factor. After preselection, K-factors, and specified leptonic branching fractions, our background rates are 113 fb for $W^{\pm}W^{\pm}jj$, 630 fb for $W^{+}Z$, 440 fb for $W^{-}Z$, and 8.80 pb for $W^{+}W^{-}$.

To enhance the $W^{\pm}h$ contribution to the final state, we select exactly two same-sign leptons with $p_T > 10\,\text{GeV}$, $|\eta| < 2.5$. We then select either one or two jets with $p_T > 20\,\text{GeV}$, $|\eta| < 2.5$, where jets are clustered using the anti-k_T algorithm [53] with $R = 0.4$ from FastJet v3.1 [54]. We allow events with only one jet because the second jet from the Higgs decay is too soft or merges with the first jet a significant fraction of the time. Two-jet events are required to be consistent with a hadronic W candidate, $60\,\text{GeV} < m_{jj} < 100\,\text{GeV}$. Since the subleading lepton typically arises from the Higgs semileptonic decay, we require $m_{T,\,\text{subleading}\,\ell,jj} < 200\,\text{GeV}$ for two jet events. These cuts are summarized in table 1.

Normalizing the signal to the SM expectation [22, 23], $\sigma(W^{+}h)\times$ Br$(W^{+} \to \ell^{+}\nu)\times$ Br$(h \to \ell^{+}\nu jj) = 6.5\,\text{fb}$, $\sigma(W^{-}h)\times$ Br$(W^{-} \to \ell^{-}\bar{\nu})\times$ Br$(h \to \ell^{-}\nu jj) = 4.2\,\text{fb}$, where $\ell = e$ or μ only, we have a combined statistical significance of $S/\sqrt{S+B} = 8.12\sigma$ from $300\,\text{fb}^{-1}$ of 14 TeV LHC luminosity, and the individual $++$ and $--$ sign combinations are expected to reach 6.5σ and 4.9σ, respectively. Hence, this mode should provide practical discovery sensitivity to $W^{\pm}h$ production compared to the null hypothesis. Although this mode does

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not admit a resonant reconstruction of the Higgs candidate, the presence of the two same-charge leptons with manageable background rates makes it a uniquely robust analysis for studying the $W^{\pm}h$ charge asymmetry.

After our cuts, the $W^{\pm}h$ signal asymmetry is 22.8%, while the total charge asymmetry from background contamination is 16.8%. A more careful study of systematic effects, subleading backgrounds, and further reduction of the diboson backgrounds in this channel is certainly warranted but beyond the scope of this work. Optimized cuts on the hadronic $W^{(*)}$ candidate from the Higgs signal would help minimize the dominant charge-asymmetric $W^{\pm}Z$ background and improve the signal to background discrimination. Moreover, binning the charge asymmetry according to the leading lepton pseudorapidity can help test enhanced Yukawa couplings via different admixtures of underlying PDF contributions. We note, however, that this is a relatively mild effect because the leading lepton does not always originate from the associated parent W and, in the case that one Yukawa coupling is enhanced at a time, the signal $W^{\pm}h$ process is still produced from combinations of valence and sea quark PDFs because of the non-negligible Cabibbo angle.

We expect future studies from additional reconstructable decay modes of the Higgs, such as $h \to b\bar{b}$, $h \to \ell^+\ell^-\nu\nu$ (via ZZ^* or WW^*), $h \to \tau^+\tau^-$, and $h \to \gamma\gamma$ will also contribute to the overall sensitivity of measuring the $W^{\pm}h$ charge asymmetry. Each of these modes requires, however, a dedicated discussion of the charge asymmetries in their dominant backgrounds, which is the scope of future work. We expect that decay channels giving comparable discovery significance of the $W^{\pm}h$ associated production mode will add further improvements to an overall global fit of PDFs, if $W^{\pm}h$ production is assumed to be SM-like, and simultaneously, be instrumental in testing for nonstandard light quark Yukawa couplings.

Extrapolating to $3\,\text{ab}^{-1}$, we find that the charge asymmetry of the $W^{\pm}h$ process can be tested with a statistical precision of $\approx 0.4\%$, which would be sensitive to higher order theory uncertainties, including PDF errors, and experimental systematic uncertainties, which we have neglected in this treatment. We note that the statistical precision will be comparable to the QCD scale uncertainty in the theory calculation and the expected $\mathcal{O}(few)\%$ PDF uncertainty already with $300\,\text{fb}^{-1}$ of LHC luminosity using the current cuts. Rigorous optimization of this analysis focusing on improving the signal to background ratio, however, will avoid this sensitivity saturation to larger luminosities. Moreover, improved measurements of charge asymmetries in $W+$ jets and $W^{\pm}Z$ processes [38] will further reduce the light quark PDF uncertainties, while measurements of $W^{\pm}c$ rates with charm-tagging will significantly improve the determination of s, $\bar{s}$ PDFs. Overall, the charge asymmetry in the $W^{\pm}h$ channel complements the charge asymmetry measurements in other $W^{\pm}$ production modes, and in the event of a discrepancy, provides a direct, diagonstic tool to test for enhanced Higgs couplings to light quarks.

We remark that for non-standard Yukawa couplings, the kinematic distributions for $W^{\pm}h$ production are expected to change, resulting in small differences in the quoted efficiencies. For example, with $\kappa_d = 1000$ ($\kappa_u = 1000$) the final $W^{\pm}h$ signal efficiency decreases to 24.8% (24.5%) compared to the SM benchmark efficiency of 25.1%.

5 Phenomenology of quark Yukawa couplings and current constraints

The set of Higgs measurements from the LHC and the Tevatron provide a broad but patchwork picture of Higgs couplings constraints. We emphasize that a direct measurement of Higgs couplings at the LHC is not currently feasible since the total width of the Higgs is unknown, and thus interpretation of Higgs measurements requires model assumptions about the underlying Lagrangian dictating the Higgs couplings and possible new light degrees of freedom. For example, the κ-framework for studying Higgs coupling deviations is invalid when new exotic modes for Higgs production are accessible [21], which cause changes in signal efficiency that are not captured by simple coupling rescalings.

5.1 Total width constraints

The only direct test for enhanced light quark Yukawa couplings from the LHC is the constraint from the direct measurement of the total Higgs width. From the 7+8 TeV combined analyses using the $\gamma\gamma$ and 4ℓ channels, ATLAS reported a Higgs total width Γ_H constraint of 2.6 GeV at 95% CL [55] and CMS reported a tighter bound of 1.7 GeV [4]. With the latest 13 TeV data, CMS observed a bound of 3.9 GeV (expected 2.7 GeV) in the 4ℓ channel [57] compared to a bound of 3.4 GeV (expected 2.8 GeV) with the Run I dataset [56], indicating that lineshape measurements of the Higgs have already saturated the resolution expected from the LHC. We remark that the next-generation e^+e^- Higgs factory machines [58–60] will inaugurate the true precision era of Higgs measurements by virtue of being able to tag Higgs-candidate events via the recoil mass method, which can determine the SM Higgs width with 2–5% precision [20]. Since light quarks are kinematically accessible decay modes of the 125 GeV Higgs, however, the on-shell decay of the Higgs to light quarks via enhanced Yukawa couplings is untamed for large $\bar{\kappa}$.

We can thus use the $\Gamma_H < 1.7\,\text{GeV}$ constraint from CMS [4] to bound the individual light quark Yukawa couplings:

$$\kappa_d < 27500, \qquad \kappa_u < 57400, \qquad \kappa_s < 1300, \qquad \kappa_c < 120\,, \tag{5.1}$$

using the renormalized quark masses calculated from RunDec [36]. These translate to

$$\bar{\kappa}_f \lesssim 25\,, \tag{5.2}$$

for each of the first or second generation light quarks, $f = d$, u, s, or c. These bounds are indicated in the gray region of figure 2.

If we recast the latest indirect measurements of the Higgs width $\Gamma_H < 41\,\text{MeV}$ [57], obtained from ratios of Higgs-mediated events in $gg \to ZZ \to 4\ell$ production in off-shell vs. on-shell Higgs regions [61–63], we find $\bar{\kappa}_f \lesssim 4$. This bound depends, however, on model assumptions about the behavior of Higgs couplings in the off- and on-shell regions, controlled theory uncertainties in the NLO QCD corrections to the interference between the $gg \to ZZ$ box diagram and the Higgs amplitude, and fixing all other Higgs partial widths to their SM values. Referring to figure 2, this current bound still permits a percent-level deviation in the inclusive charge asymmetry, which we expect is measureable with

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the full dataset of the LHC. In our view, the indirect width measurement of the Higgs and the charge asymmetry measurement are equally valid as consistency tests of the Standard Model Higgs, and we strongly advocate for the charge asymmetry test in future LHC Higgs analyses.

5.2 Inclusive charge asymmetry

At the fully inclusive level, the Higgs Yukawa couplings can be tested via the proposed charge asymmetry measurement. While more stringent constraints on the light quark Yukawa couplings can be obtained from global fits combining all Higgs data, these global fits suffer from the requirement of a theoretical model dependence, most commonly the κ framework.

We point out, however, that absent deviations in light quark Yukawa couplings the fully inclusive charge asymmetry also provides a model-independent measurement of the Higgs coupling to W bosons. Fully inclusive Higgs production processes are not normally considered at hadronic colliders because of the inability to ascertain the Higgs contribution independent of the Higgs decay mode. This is analogous to the recoil mass method advocated for e^+e^- Higgs factories, which allows a fully inclusive rate measurement sensitive to the hZZ coupling. At the moment, though, there is no practical proposal for measuring such an inclusive variable in any Higgs process and all Higgs data stems from analyses for specific Higgs decays, and so the intriguing possibility of a fully inclusive Higgs measurement to extract a Higgs production coupling remains remote.

5.3 Exclusive Higgs measurements and current constraints

In eq. (2.2), we only introduced new physics operators that modified the mass generation and Yukawa couplings of the SM quarks, leaving the Higgs-vector couplings untouched. As a result, enhanced Yukawa couplings lead to increased rates for $\sigma(qq' \to W^\pm h)$ and $\sigma(q\bar{q} \to h)$ production, but the effective signal strengths μ_{Wh} and μ_{gg} of exclusive Higgs decays to a particular X final state are depleted according to

$$\mu_{Wh}(h \to X) = \frac{(\sigma_{Wh}^{\rm NP})}{(\sigma_{Wh}^{\rm SM})} \times \frac{\Gamma(h \to X)^{\rm NP}/\Gamma_H^{\rm NP}}{\Gamma(h \to X)^{\rm SM}/\Gamma_H^{\rm SM}}\,, \tag{5.3}$$

$$\mu_{gg}(h \to X) = \frac{(\sigma_{gg}^{\rm NP} + \sigma_{q\bar{q}}^{\rm NP})}{(\sigma_{gg}^{\rm SM})} \times \frac{\Gamma(h \to X)^{\rm NP}/\Gamma_H^{\rm NP}}{\Gamma(h \to X)^{\rm SM}/\Gamma_H^{\rm SM}}\,, \tag{5.4}$$

where we have included s-channel $q\bar{q}$ Higgs production in the overall gluon fusion rate. We remark that the gluon fusion and $q\bar{q}$ annihilation production modes can be possibly disentangled at the LHC by studying Higgs candidate kinematics [64–66], while the $q\bar{q}$ decay can also possibly be probed at e^+e^- Higgs factories [67].

Solely turning on large Yukawa couplings for light quarks is hence strongly constrained by combined coupling fits using current Higgs data, since the increased production rates from the Yukawa-mediated processes is not enough to counterbalance the rate loss in measured Higgs modes such as $h \to 4\ell$ and $h \to \gamma\gamma$. For example, if we require that $\mu_{gg}(h \to 4\ell)$

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is within 40% of the SM signal strength, consistent with the latest 13 TeV Higgs measurement results [57] and only allow one light quark Yukawa coupling to deviate at a time, then we derive the following constraints:

$$\kappa_d < 1270, \qquad \kappa_u < 2860, \qquad \kappa_s < 53, \qquad \kappa_c < 5\,, \tag{5.5}$$

which can be converted to

$$\bar{\kappa}_d < 1.24, \qquad \bar{\kappa}_u < 1.34, \qquad \bar{\kappa}_s < 1.03, \qquad \bar{\kappa}_c < 1.14\,, \tag{5.6}$$

where we have fixed $\sigma_{gg} = 48.58\,\text{pb}$ [68, 69] using $m_H = 125\,\text{GeV}$ for both the SM and NP rates and only considered the additional contribution from $q\bar{q}$ annihilation. These ad-hoc constraints are only presented to demonstrate the naive sensitivity to light quark Yukawa couplings from a 1-parameter test, where all other SM couplings are held fixed. We note that the intrinsic contribution from light quarks affecting gluon fusion is suppressed by the loop function dependent on the quark masses. Moreover, new colored particles in the gluon fusion loop (see, e.g., ref. [70] and references therein) can add to the s-channel $q\bar{q}$ Higgs production channel to compensate for the drop in the $h \to 4\ell$ branching fraction. In principle, an enhanced coupling of the Higgs bosons to electroweak vectors can also relieve the bounds above, although concrete possibilities are limited [71]. A global analysis performed in ref. [14], allowing all Higgs couplings to vary, has derived the constraints $\bar{\kappa}_d < 1.4$, $\bar{\kappa}_u < 1.3$, $\bar{\kappa}_s < 1.4$, and $\bar{\kappa}_c < 1.4$.

We note that the Tevatron also provides constraints on enhanced light quark Yukawa couplings given the nature of the machine as a proton-anti-proton collider. The primary search channel at the Tevatron sensitive to s-channel Higgs production was the WW^* decay mode [72], which constrained $\sigma(gg \to H)\times$ Br$(H \to WW^*)$ at $m_H = 125\,\text{GeV}$ to be less than 0.77 pb. If $\sigma(gg \to H)$ and Br$(H \to WW^*)$ are held fixed, then this constrains the extra production from $\sigma(q\bar{q} \to H)$ at a level roughly a factor of 2–10 weaker than the naive estimate in eq. (5.5), with the strongest constraints for κ_d and κ_u; again, this is an inconsistent treatment of the bounds unless new physics is introduced to keep Br$(H \to W^+W^-)$ fixed. In a similar manner, double Higgs production rates are also increased, but their impact at the LHC is already excluded in a model independent fashion from the total Higgs width measurement discussed earlier.

Finally, probing enhanced quark Yukawa couplings using the exclusive charge asymmetry measurement discussed in section 4 requires also requires an increased $h \to WW^*$ partial width in order to maintain the signal rate comparable to the SM expectation. Nevertheless, the measurement of the charge asymmetry provides an important consistency test of the SM Higgs boson. Moreover, the 0.4% statistical precision afforded by the proposed $W^\pm h \to \ell^\pm \ell^\pm jj + \not{E}_T$ measurement establishes a new channel to constrain and evaluate parton distribution functions and their uncertainties if light quark Yukawa deviations are absent.

6 Conclusions

In this work, we have explored the prospects for measuring light quark Yukawa couplings at the LHC via the charge asymmetry of $W^\pm h$ production. From the limited set of new physics operators considered, the net effect of enhanced light quark Yukawa couplings was to rapidly increase the total Higgs width, which can be tested in a model-independent fashion at the LHC in the high resolution $\gamma\gamma$ and 4ℓ final states. Enhanced light quark Yukawa couplings consistent with the direct Higgs width constraint predict inclusive charge asymmetries that deviate significantly from the SM expectation.

We hence motivated the possible measurement of the $W^\pm h$ charge asymmetry in the exclusive mode $W^\pm h \to \ell^\pm \ell^\pm \not{E}_T + 1$ or 2 jets, which is a clean same-sign dilepton final state that inherits the same charge asymmetry as the original Higgs production process. After accounting for the main backgrounds from electroweak diboson production, we estimate that the individual $++$ and $--$ final states reach a statistical $\approx 5\sigma$ significance each with $300\,\text{fb}^{-1}$ of 14 TeV LHC data. Even though the Higgs boson is not fully reconstructed in this decay, the clean same-sign dilepton signature can be readily extrapolated to the expected $3\,\text{ab}^{-1}$ high luminosity run, enabling a statistical precision on the exclusive charge asymmetry of 0.4%. If the measured asymmetry deviates from the SM expectation, then a likely interpretation would be an enhanced SM light quark Yukawa counterbalanced by additional new physics effects that preserve rough current consistency of the Higgs data with SM expectation. A future deviation can favor enhanced down and up quark Yukawas if the observed charge asymmetry exceeds the SM expectation, while strange and charm quark Yukawas would be responsible if the charge asymmetry were smaller.

The $W^\pm h$ charge asymmetry hence provides an interesting and new consistency test for Higgs measurements. We conclude by remarking that although we focused on the prospects for testing light quark Yukawa coupling deviations using the charge asymmetry, this measurement also probes the Higgs coupling to $W^\pm$ bosons directly, which adds a new ingredient in combined coupling fits for testing custodial symmetry.

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