LIGHT QUARK YUKAWAS FROM THE $W^\pm h$ CHARGE ASYMMETRY

Felix Yu
JGU Mainz

[1609.06592]
Motivation: SM mass-coupling degeneracy

- Test one-to-one prediction between mass and Higgs coupling in SM
- Any deviation will signal profound new physics
- Prospects for light quark Yukawas?

ATLAS, CMS JHEP 1608, 045 (2016) [1606.02266]
Motivating non-standard Yukawas

- Chiral SM fermions imply unitarity violation in $f \bar{f} \rightarrow V_L V_L$ scattering if $y_f$ and $m_f$ mismatched

  \[ y_f \bar{Q}_L \tilde{H} u_R + y_u \frac{H^\dagger H}{\Lambda^2} \bar{Q} \tilde{H} u_R \]

  \[ + y_d \bar{Q}_L H d_R + y_d' \frac{H^\dagger H}{\Lambda^2} \bar{Q} H d_R + \text{h.c.} \]

  - Diagonalize the mass combination $m_f = \frac{y_f v}{\sqrt{2}} + \frac{y_f' v^3}{2 \sqrt{2} \Lambda^2}$

  - Yukawas are not necessarily diagonal or CP-conserving

  \[ \frac{y_f, \text{ eff}}{\sqrt{2}} = \frac{y_f}{\sqrt{2}} + \frac{3 y_f' v^2}{2 \sqrt{2} \Lambda^2} = \frac{m_f}{v} + \frac{2 y_f' v^2}{2 \sqrt{2} \Lambda^2} \]

  - Effective diagonal Yukawas can strongly deviate from SM

Appelquist, Chanowitz, PRL 59, 2405 (1987)
Direct NP searches vs. Yukawa probes

• Since BSM Yukawa couplings must involve new states beyond the SM, can eschew Yukawa probes and search directly for NP sources
  – Necessary UV ingredient is new source of $SU(2)_L$ breaking or new fermions with vector-like masses
    • cf. 2HDM, VLQ searches

• From unitarity arguments, however, NP scales can be beyond direct reach of LHC
  – Yukawa probes are hence strongly motivated
  – Must distinguish between direct and indirect tests
Importance of direct probes

• Literature survey\(^1\) of proposed collider probes of \(y_q\)
  • Direct decays: \(h \rightarrow b\bar{b}\) in tandem with \(h \rightarrow c\bar{c}\), probes \(y_c\)
  • Direct production: \(h + c(\bar{c})\), probes \(y_c\)
  • Total Higgs width lineshape: probes \(y_d, y_u, y_s, y_c\) combination
  • Higgs kinematics: probes \(y_d, y_u, y_s, y_c\) combination
  • Indirect Higgs width: many caveats to NP interpretation
  • Rare decays, \textit{e.g.} \(h \rightarrow J/\psi \gamma\): SM expected rates very small
  • Searches for fermion partners, heavy Higgses
  • Global fit for Higgs couplings: best sensitivity, requires assumptions

\(^1\)Isidori, et. al. [1305.0663]; Kagan, et. al. [1406.1722]; Bodwin, et. al. [1407.6695]; Perez, et. al. [1503.00290, 1505.06689]; König, et. al. [1505.03870]; Zhou [1505.06369]; Brivio, et. al. [1507.02916]; Bishara, et. al. [1606.09253]; Soreq, et. al. [1606.09621]; Bonner, et. al. [1608.04376]; Alte, et. al. [1609.06310]
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  - Direct production: \(h + c(\bar{c})\), probes \(y_c\)
  - Total Higgs width lineshape: probes \(y_d, y_u, y_s, y_c\) combination

**New direct probes still needed – can test assumptions used in the global fit**
- Rare decays, e.g. \(h \rightarrow J/\psi \gamma\). SM expected rates very small
- Searches for fermion partners, heavy Higgses
- Global fit for Higgs couplings: best sensitivity, requires assumptions

\(^1\)Isidori, et. al. [1305.0663]; Kagan, et. al. [1406.1722]; Bodwin, et. al. [1407.6695]; Perez, et. al. [1503.00290, 1505.06689]; König, et. al. [1505.03870]; Zhou [1505.06369]; Brivio, et. al. [1507.02916]; Bishara, et. al. [1606.09253]; Soreq, et. al. [1606.09621]; Bonner, et. al. [1608.04376]; Alte, et. al. [1609.06310]
A new proposal: $W^\pm h$ charge asymmetry

- $W^\pm h$ production asymmetric at LHC
  - Asymmetry driven by proton PDFs
  - Consider $W^+ h$:
    - Unitarity violation requires NP completion

\[
\begin{array}{c}
\text{u, c} \\
\text{d, s}
\end{array}
\quad \text{W}^+ \quad \text{u, c} \\
\text{d, s} \\
\text{h} \quad \text{u, c} \\
\text{d, s} \\
\text{h}
\]

Insensitive to Yukawas

\[
\begin{array}{c}
\text{u, c} \\
\text{d, s} \\
\text{Y}_u, Y_c \\
\text{W}^+
\end{array}
\quad \text{h} \\
\text{d, s} \\
\text{Y}_d, Y_s \\
\text{W}^+
\]

14 TeV:
<table>
<thead>
<tr>
<th>$W^+ H$ (pb)</th>
<th>$W^- H$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.922</td>
<td>0.591</td>
</tr>
</tbody>
</table>

Higgs XSWG
A new proposal: \( W^{\pm}h \) charge asymmetry

- \( W^{\pm}h \) production asymmetric at LHC
  - Asymmetry driven by proton PDFs
  - Consider \( W^{-}h \):
    - Unitarity violation requires NP completion

\[
\begin{array}{cccc}
d, s & d, s & d, s & d, s \\
\bar{u}, \bar{c} & \bar{u}, \bar{c} & \bar{u}, \bar{c} & \bar{u}, \bar{c} \\
\end{array}
\]

Insensitive to Yukawas

\[
\begin{array}{c}
\begin{array}{c}
W^{-} \\
\hline
W^{-}\ H \ (pb)
\end{array}
\end{array}
\]

\[
\begin{array}{c}
\begin{array}{c}
W^{+}H \ (pb)
\end{array}
\end{array}
\]

14 TeV:

\[
\begin{array}{cc}
0.922 & 0.591 \\
\end{array}
\]

Higgs XSWG
Inclusive charge asymmetry

\[ A = \frac{\sigma (W^+ h) - \sigma (W^- h)}{\sigma (W^+ h) + \sigma (W^- h)} \]

\[ \bar{\kappa}_f \equiv \frac{m_f(\mu = 125 \text{ GeV})}{m_b(\mu = 125 \text{ GeV})} \kappa_f \]

RG effects calculated using RunDec [hep-ph/0004189]
PDF behavior

• In SM, net positive asymmetry driven by $u\bar{d}$, mitigated by $c\bar{s}$ (neglect Cabibbo angle)
  – For enhanced $y_d$ or $y_u$, charge-asymmetric PDFs take over
  – For enhanced $y_s$ or $y_c$, charge-symmetric PDFs dominate

• Important, subleading corrections from Cabibbo angle

  e.g. Asymptotically, for $y_u$ or $y_c$, compare these proton-proton PDFs:
Measuring SM $W^+h$ vs. $W^-h$ asymmetry

• Survey all possible final states that can give clean lepton asymmetry measurement

Using Standard Model BRs, include e, $\mu$ decays of W, # events for 14 TeV LHC

<table>
<thead>
<tr>
<th>Mode</th>
<th>Luminosity</th>
<th>$H\to b\bar{b}$</th>
<th>$H\to \tau^+\tau^-$</th>
<th>$H\to \gamma\gamma$</th>
<th>$H\to l^+l^-l^+l^-$ (l=e,(\mu))</th>
<th>$H\to l^+l^-\nu\nu$ (l=e or $\mu$, (v=\text{any}))</th>
<th>$H \to l^+l^- qq$ (l=e or $\mu$, q=udcsb)</th>
<th>$H \to l^+\nu qq$ (l=e or $\mu$, q=udcsb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+h$</td>
<td>300 fb$^{-1}$</td>
<td>36177</td>
<td>3897</td>
<td>141</td>
<td>8</td>
<td>659</td>
<td>152</td>
<td>1946</td>
</tr>
<tr>
<td>$W^-h$</td>
<td>300 fb$^{-1}$</td>
<td>23218</td>
<td>2501</td>
<td>91</td>
<td>5</td>
<td>423</td>
<td>98</td>
<td>1249</td>
</tr>
</tbody>
</table>

• Focus on same-sign dilepton signature
  – Inherits charge asymmetry from production
  – (Follow-up study: $b\bar{b}$ and $\tau^+\tau^-$ channels with S. Alte)
Same-sign lepton collider study

• Signal
  – $W^\pm h \rightarrow (l^\pm \nu) (l^\pm vjj)$: Final state is two same-sign leptons, one or two resolved jets, some missing transverse energy

• Backgrounds
  – $W^\pm W^\pm jj$
  – $W^\pm Z$, $Z$ decays leptonically (and OS lepton lost)
  – $W^+W^-$ with charge mis-identification rates:
    • electrons: 0.16% for $0 < |\eta| < 1.479$, 0.3% for $1.479 < |\eta| < 3$
    • muons: negligible
Same-sign lepton collider study

- Initial efficiencies already account for leptonic BRs
- Reduce $W^+W^-$ by same charge requirement
- Reduce $W^\pm W^\pm jj$ by $60 < m_{jj} < 100$ GeV cut
  – Also cut on transverse mass with subleading lepton

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

- Discovery sensitivity for each $W^+h$ and $W^-h$ production with 300 fb$^{-1}$ luminosity
- Scaling to 3 ab$^{-1}$, statistical sensitivity is $\approx0.4$
  - Expected statistical precision will challenge theoretical uncertainties, mainly PDFs
  - Measurement well-motivated as consistency test of the SM prediction
    - Viability for NP Yukawa scenarios challenging – effective BR for $h \to l^\pm vjj$ decreases as Higgs width increases from large $y_q$
    - Nonetheless, Charge asymmetry provides a unique window to light quark Yukawa couplings
Current direct constraint on large Yukawas

• Total Higgs width increases rapidly once Yukawa exceeds $y_b$
  – Open possibility that $y_b$ is non-SM, mitigate width effects

• Direct measurements of Higgs lineshape:
  – CMS 7+8 TeV analysis ($\gamma\gamma + 4l$): $\Gamma_H < 1.7$ GeV
  – ATLAS 7+8 TeV analysis ($\gamma\gamma + 4l$): $\Gamma_H < 2.6$ GeV
  – CMS 13 TeV analysis (4l): $\Gamma_H < 3.9$ GeV
  – Results have largely saturated expected the $O$(GeV) resolution sensitivity, but is irreducible direct effect for large Yukawa couplings

[1412.8662] [1406.3827] [HIG-16-033]
Current direct constraint on large Yukawas

- Total Higgs width increases rapidly once Yukawa exceeds $y_b$
  - Open possibility that $y_b$ is non-SM, mitigate width effects

- Direct measurements of Higgs lineshape:
  - Using $\Gamma_H < 1.7$ GeV [CMS], obtain

\[
\kappa_d < 27500, \quad \kappa_u < 57400, \quad \kappa_s < 1300, \quad \kappa_c < 120
\]

\[
\Rightarrow \bar{\kappa}_f < 25
\]

- Still allows for large inclusive charge asymmetry deviations

[1412.8662]
Inclusive charge asymmetry

\[ A = \frac{\sigma(W^+ h) - \sigma(W^- h)}{\sigma(W^+ h) + \sigma(W^- h)} \]

\[ \bar{\kappa}_f \equiv \frac{m_f(\mu = 125 \text{ GeV})}{m_b(\mu = 125 \text{ GeV})} \kappa_f \]

RG effects calculated using RunDec [hep-ph/0004189]
Indirect constraints on large Yukawas

• Use observed Higgs rates to constrain enhanced Yukawas
  – Increase in total Higgs width partially mitigated by new production modes

• Overall signal strengths
  – $W^{\pm}h$ associated production
    \[
    \mu_{Wh}(h \rightarrow X) = \frac{\sigma_{Wh}^{NP}}{\sigma_{Wh}^{SM}} \times \frac{\Gamma(h \rightarrow X)^{NP}/\Gamma_H^{NP}}{\Gamma(h \rightarrow X)^{SM}/\Gamma_H^{SM}}
    \]
  – Gluon fusion and quark-initiated s-channel production
    \[
    \mu_{gg}(h \rightarrow X) = \frac{\sigma_{gg}^{NP} + \sigma_{qq}^{NP}}{\sigma_{gg}^{SM}} \times \frac{\Gamma(h \rightarrow X)^{NP}/\Gamma_H^{NP}}{\Gamma(h \rightarrow X)^{SM}/\Gamma_H^{SM}}
    \]
Indirect constraints on large Yukawas

• Naïve one-parameter fit to signal strength \((gg \to h \to ZZ)\) within 40%:
  \[
  \bar{\kappa}_d < 1.24, \quad \bar{\kappa}_u < 1.34, \\
  \bar{\kappa}_s < 1.03, \quad \bar{\kappa}_c < 1.14
  \]

• Compare to global fit:
  \[
  \bar{\kappa}_d < 1.4, \quad \bar{\kappa}_u < 1.3, \\
  \bar{\kappa}_s < 1.4, \quad \bar{\kappa}_c < 1.4
  \]

  Kagan, Perez, Petriello, Soreq, Stoynev, Zupan [1406.1722]

• Still allows \(O(0.1\text{-}1\%)\) deviations in charge asymmetry, can probe with HL-LHC
Future outlook

• Measuring the charge asymmetry in the same-sign lepton final state gives an useful self-consistency test of Higgs
  – Can test assumptions exercised in global coupling fits

• Ultimate sensitivity requires controlled theory errors (PDF uncertainties) and better optimization from experiment
  – Looking to add information from $b\bar{b}$, $\tau^+\tau^-$ final states

• Can also diagnose new neutral scalars (2HDM)

work in progress (Alte, FY)

work in progress (Kagan, FY, Zupan)
Conclusions

• New same-sign dilepton channel for testing Higgs properties
  – Different systematics and experimental challenges than charm tagging or rare decays – easily extrapolated to HL-LHC
  – Theoretical uncertainty on charge asymmetry mainly from PDFs; QCD corrections cancel
  – Same-sign lepton channel also useful probe for Higgs coupling to vectors
    • No immediate test to disentangle many simultaneous Yukawa deviations

• Important (and straightforward) consistency test that is yet to be performed using LHC data
  – Charge asymmetry measurement is a viable direct test of up, down, strange Yukawa couplings, and can compete with charm proposals
Atomic force probes

• Analogous to DM direct detection scattering, consider short-range Higgs force in isotope shifts of atomic physics enhanced by Yukawas
  
  • Delaunay, Ozeri, Perez, Soreq [1601.05087]
  • Frugiuele, Fuchs, Perez, Schlaffer [1602.04822]
  • Delaunay, Soreq [1602.04838]

  – Needs electron Yukawa, strong bounds possible?

\[
V_{\text{Higgs}}(r) = -\frac{y_e y_A}{4\pi} \frac{e^{-r m_n}}{r}
\]

\[
Y_n \approx 7.7 y_u + 9.4 y_d + 0.75 y_s + 2.6 \times 10^{-4} c_g ,
\]

\[
Y_p \approx 11 y_u + 6.5 y_d + 0.75 y_s + 2.6 \times 10^{-4} c_g ,
\]
Motivating non-standard Yukawas

• SM fermions are chiral $\rightarrow$ mismatch between Yukawa coupling and mass leads to unitarity violation in $f\bar{f} \rightarrow VV$ scattering

  Appelquist, Chanowitz, PRL 59, 2405 (1987)

  – For example, $W^+W^-$ scattering breaks unitarity at

  \[ E_f \sim \frac{8\pi v^2}{\zeta |m_f - y_f v|}, \quad \zeta = \sqrt{3} \text{ quarks} \]
  \[ \zeta = 1 \text{ leptons} \]

• UV completion needed to satisfy perturbative unitarity

  – e.g. 2HDM, vector-like fermion partners
Motivating non-standard Yukawas

• Scale of unitarity violation can be subsumed by adopting dimension-6 effective operators

\[ \mathcal{L} \supset y_u \bar{Q}_L \tilde{H} u_R + y_u' \frac{H^\dagger H}{\Lambda^2} \bar{Q} \tilde{H} u_R \]

\[ + \quad y_d \bar{Q}_L H d_R + y_d' \frac{H^\dagger H}{\Lambda^2} \bar{Q} H d_R + \text{h.c.} \]

– Diagonalize the mass combination

\[ m_f = \frac{y_f v}{\sqrt{2}} + \frac{y'_f v^3}{2\sqrt{2}\Lambda^2} \]

• Resulting Yukawa interactions are not necessarily diagonal, or CP-conserving

\[ \frac{y_f, \text{ eff}}{\sqrt{2}} = \frac{y_f}{\sqrt{2}} + \frac{3y'_f v^2}{2\sqrt{2}\Lambda^2} = \frac{m_f}{v} + \frac{2y'_f v^2}{2\sqrt{2}\Lambda^2} \]
Motivating non-standard Yukawas

• Effective Yukawa interactions can strongly deviate from SM expectations

\[ \frac{y_f, \text{ eff}}{\sqrt{2}} = \frac{y_f}{\sqrt{2}} + \frac{3y'_f v^2}{2\sqrt{2}\Lambda^2} = \frac{m_f}{v} + \frac{2y'_f v^2}{2\sqrt{2}\Lambda^2} \]

– Will only focus on diagonal, \( CP \)-conserving Yukawas

Quark CPV phases studied in Chien, Cirigliano, Dekens, de Vries, Mereghetti [1510.00725]
Collider study of \( \tau \) Yukawa CPV phase in Harnik, Martin, Okui, Primulando, FY [1308.1094]

• For light quarks, dominant Yukawa contribution can come from higher dimensional operator

– Admittedly requires fine-tuning mass generation term
Suite of measurement possibilities

• SM fermions are chiral, hence Yukawa deviations require new sources of $SU(2)_L$ breaking or new fermions with vector-like masses
  – Motivates direct searches for new vector-like fermion partners – top partners are a prime example

[Diagram showing a triangle with axes labeled $T(tZ)$, $T(bW)$, and $T(tH)$, with a color scale indicating observed 95% CL quark mass limit (GeV) ranging from 700 to 950.]

CMS [1509.04177]
Suite of measurement possibilities

- SM fermions are chiral, hence Yukawa deviations require new sources of SU(2)_L breaking or new fermions with vector-like masses
  - Also, search for heavy Higgses: H^0, A, H^±
  - New Yukawa structures
    - Generally induce FCNCs
Suite of measurement possibilities

• Directly measure in $q\bar{q}$ decays
  – Use bottom and charm tagging in tandem to profile over enhanced $c$ content in Higgs decays

<table>
<thead>
<tr>
<th>$M_H = 125$ GeV</th>
<th>BR</th>
<th>Rel. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H\rightarrow bb$</td>
<td>5.77E-1</td>
<td>+/- 3%</td>
</tr>
<tr>
<td>$H\rightarrow cc$</td>
<td>2.91E-2</td>
<td>+/- 12%</td>
</tr>
<tr>
<td>$H\rightarrow ss$</td>
<td>2.46E-4</td>
<td>+/- 5%</td>
</tr>
<tr>
<td>$H\rightarrow \mu\mu$</td>
<td>2.19E-4</td>
<td>+/- 6%</td>
</tr>
</tbody>
</table>

$\mu_b \equiv \frac{\sigma_h \text{BR}_{b\bar{b}}}{\sigma_{h}^{SM} \text{BR}_{b\bar{b}}^{SM}} \rightarrow \frac{\sigma_h \text{BR}_{c\bar{c}} \epsilon_b \epsilon_c}{\sigma_{h}^{SM} \text{BR}_{c\bar{c}}^{SM} \epsilon_b \epsilon_c} + \frac{\sigma_h \text{BR}_{b\bar{b}} \epsilon_b \epsilon_c}{\sigma_{h}^{SM} \text{BR}_{b\bar{b}}^{SM} \epsilon_b \epsilon_c} + \frac{\sigma_h \text{BR}_{c\bar{c}} \epsilon_b \epsilon_c}{\sigma_{h}^{SM} \text{BR}_{c\bar{c}}^{SM} \epsilon_b \epsilon_c}$

Higgs XSWG [1307.1347]

Perez, et. al. [1505.06689]
Suite of measurement possibilities

- Directly measure in $q\bar{q}$ decays
  - Use bottom and charm tagging in tandem, profile over enhanced $c$ content in Higgs decays

<table>
<thead>
<tr>
<th></th>
<th>$\epsilon_b$</th>
<th>$\epsilon_c$</th>
<th>$\epsilon_l$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$-tagging</td>
<td>70%</td>
<td>20%</td>
<td>1.25%</td>
</tr>
<tr>
<td>$c$-tagging I</td>
<td>13%</td>
<td>19%</td>
<td>0.5%</td>
</tr>
<tr>
<td>$c$-tagging II</td>
<td>20%</td>
<td>30%</td>
<td>0.5%</td>
</tr>
<tr>
<td>$c$-tagging III</td>
<td>20%</td>
<td>50%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

Perez, et. al. [1505.06689]
Suite of measurement possibilities

• For charm Yukawa, measure in $h+c(\bar{c})$ production, use $h \to \gamma\gamma$ decay (fixed to SM BR)
  – $p_T(j) > 20$ GeV
  – $\varepsilon_c = 40\%$, $\varepsilon_b = 30\%$, $\varepsilon_g = 1\%$
  – Only considered $h+g$, $h+b$ backgrounds (notably absent, $q\bar{q} \to \gamma\gamma +$ jets)

\[
\begin{array}{c|cccccccccc}
\kappa_c & 0 & 0.25 & 0.5 & 0.75 & 1 & 1.25 & 1.5 & 1.75 & 2 \\
\hline
S & 874 & 877 & 885 & 899 & 917 & 941 & 973 & 1008 & 1052 \\
\end{array}
\]

\[
\begin{array}{c|cccccccccc}
\kappa_c & 2.25 & 2.5 & 2.75 & 3 & 3.25 & 3.5 & 3.75 & 4 & 4.25 & 4.5 \\
\hline
S & 1097 & 1148 & 1206 & 1276 & 1350 & 1424 & 1504 & 1590 & 1683 & 1786 \\
\end{array}
\]

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

• Direct Higgs width measurements
  – Generally expect large Yukawas to rapidly increase Higgs width
Suite of measurement possibilities

- Indirect Higgs width bounds

1503.01060 [also ATLAS-CONF-2016-079]

1507.06656 [also CMS-HIG-16-033]
Suite of measurement possibilities

• Indirectly measure in rare decays: e.g. $h \rightarrow J/\psi \gamma$
  
  – Yukawa contribution interferes with loop-induced vertex with virtual $\gamma/Z$

Isidori, Manohar, Trott [1305.0663]
Kagan, Perez, Petriello, Soreq, Stoynev, Zupan [1406.1722]
Bodwin, Chung, Ee, Lee, Petriello [1407.6695]
Perez, Soreq, Stamou, Tobioka [1503.00290, 1505.06689]
König, Neubert [1505.03870]
Small SM rates

\[
\begin{align*}
\text{Br}(h \to \phi \gamma) &= (2.31 \pm 0.03_{f \phi} \pm 0.11_{h \to \gamma \gamma}) \cdot 10^{-6} \\
\text{Br}(h \to J/\psi \gamma) &= (2.95 \pm 0.07_{J/\psi} \pm 0.06_{\text{direct}} \pm 0.14_{h \to \gamma \gamma}) \cdot 10^{-6} \\
\text{Br}(h \to \Upsilon(1S) \gamma) &= (4.61 \pm 0.06_{\Upsilon(1S)}^{+1.75}_{-1.21_{\text{direct}}} \pm 0.22_{h \to \gamma \gamma}) \cdot 10^{-9}
\end{align*}
\]

König, Neubert [1505.03870]

\[
\mathcal{B}(H \to (J/\psi)\gamma) < 1.5 \times 10^{-3}
\]

CMS [1507.03031]

ATLAS [1501.03276]; [1607.03400]
Direct tests vs. global Higgs coupling fits

• Global fit for Higgs couplings can and does give the best sensitivity to nonstandard Yukawas
  – Important caveat: need model-dependent assumptions to over-determine system of constraints

• At LHC, total Higgs width is not (expected to be) directly measurable
  \[ N_{\text{events}} = L\sigma B \times \epsilon \times A \propto \frac{g_p^2 g_d^2}{\sum_i \Gamma_i, \text{vis} + \Gamma_{\text{unobs}}} \]
  – Cannot go beyond self-consistency test without assumptions about nature of NP

  Exotic production modes of the Higgs not captured by κ-framework or Higgs EFT, see FY [1404.2924]

• Direct tests still needed – can reveal faulty assumptions used in the global coupling fit
Same-sign lepton collider study

- Each contribution is unit-normalized

![Histogram of M_{jj} for two-jet events](image)

- Blue: Wh
- Red: WWjj
- Green: WZ
- Magenta: WW
Same-sign lepton collider study

- Each contribution is unit-normalized

$M_{T, l_2jj}$ for two-jet events

Blue: Wh
Red: WWjj
Green: WZ