Higgs and Flavor: Theory Overview

Fady Bishara

CKM 2018 – Heidelberg
September 17th 2018
Motivation

Is the mechanism responsible for EWSB and fermion mass generation in the SM minimal?

What we know:

• One complex scalar doublet acquires a vev, breaks EW symmetry and gives W/Z and third generation fermions (most) of their masses

What we don’t know:

• Do the first and second generation fermions also get their masses from the same doublet?

• Is this Higgs vev the only source of EWSB?

The SM itself is not minimal with regards to its matter content. And, 20/26 of its free parameters are associated with the flavor sector.
**Parametrization**

\[ \mathcal{L}_{\text{eff},q} = -\kappa_q \frac{m_q}{v_W} \bar{q} q h - i\tilde{\kappa}_q \frac{m_q}{v_W} \bar{q} \gamma_5 q h - \]

\[ \begin{aligned}
\text{Flavor diagonal} & \quad \left( \kappa_{qq'} + i\tilde{\kappa}_{qq'} \right) \bar{q}_L q'_R h + \text{h.c.} \\
\text{CP conserving} & \\
\text{CP violating} & \\
\end{aligned} \]

\[ \mathcal{R} \left( \kappa_{qq'} + i\tilde{\kappa}_{qq'} \right): \text{ CPC} \]

\[ \mathcal{S} \left( \kappa_{qq'} + i\tilde{\kappa}_{qq'} \right): \text{ CPV} \]

In the SM, \( \kappa_q = 1 \) while \( \tilde{\kappa}_q = \kappa_{qq'} = \tilde{\kappa}_{qq'} = 0 \)

**Important def’ns:** \( \kappa_i = \frac{y_i}{y_i^{\text{SM}}} \), \( \bar{\kappa}_i = \frac{y_i}{y_b^{\text{SM}}} \)

For lepton Yukawas, see, e.g.:

**Flavor violation**

- **Neutral current** FV is generically present in any extension of the SM.

- Arises due to misalignment between the mass and Yukawa matrices – e.g., in D6 extension:

  \[
  M_{u,d} = \frac{v_w}{\sqrt{2}} \left( Y_{u,d} + Y'_{u,d} \frac{v_w^2}{2\Lambda^2} \right), \quad y_{u,d} = Y_{u,d} + 3Y'_{u,d} \frac{v_w^2}{2\Lambda^2}
  \]

- Unless additional assumptions are imposed, FV is “naturally” \( O(1) \) → **NP flavor problem**

- In models of flavor discussed earlier, they are typically suppressed by yukawa couplings and CKM matrix elements
Yukawa modifications in flavor models

[FB, Brod, Uttayarat, Zupan: 1504.04022] – see also CERN YR4 Chap. IV.6 [1610.07922]
+ references therein for the specific models

<table>
<thead>
<tr>
<th>Model</th>
<th>$\kappa_t$</th>
<th>$\kappa_{c(u)}/\kappa_t$</th>
<th>$\tilde{\kappa}_t/\kappa_t$</th>
<th>$\tilde{\kappa}_{c(u)}/\kappa_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MFV</td>
<td>$1 + \frac{\text{Re}(a_u v^2 + 2 b_u m_t^2)}{\Lambda^2}$</td>
<td>$1 - \frac{2 \text{Re}(b_u) m_t^2}{\Lambda^2}$</td>
<td>$\frac{\text{Im}(a_u v^2 + 2 b_u m_t^2)}{\Lambda^2}$</td>
<td>$\frac{\text{Im}(a_u v^2)}{\Lambda^2}$</td>
</tr>
<tr>
<td>NFC</td>
<td>$V_{hu} v/\nu_u$</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MSSM</td>
<td>$\cos \alpha/\sin \beta$</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>FN</td>
<td>$1 + \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$</td>
<td>$1 + \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$</td>
<td>$\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$</td>
<td>$\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$</td>
</tr>
<tr>
<td>GL2</td>
<td>$\cos \alpha/\sin \beta$</td>
<td>$\simeq 3(7)$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RS</td>
<td>$1 - \mathcal{O}\left(\frac{v^2}{m_{KK}^2}\right)$</td>
<td>$1 + \mathcal{O}\left(\frac{v^2}{m_{KK}^2}\right)$</td>
<td>$\mathcal{O}\left(\frac{v^2}{m_{KK}^2}\right)$</td>
<td>$\mathcal{O}\left(\frac{v^2}{m_{KK}^2}\right)$</td>
</tr>
<tr>
<td>pNGB</td>
<td>$1 + \mathcal{O}\left(\frac{v^2}{f^2}\right) + \mathcal{O}\left(\frac{y^2 \lambda^2 v^2}{M^2}\right)$</td>
<td>$1 + \mathcal{O}\left(\frac{y^2 \lambda^2 v^2}{M^2}\right)$</td>
<td>$\mathcal{O}\left(\frac{y^2 \lambda^2 v^2}{M^2}\right)$</td>
<td>$\mathcal{O}\left(\frac{y^2 \lambda^2 v^2}{M^2}\right)$</td>
</tr>
</tbody>
</table>

- Generally, modifications $\sim v^2/\Lambda^2 \ll \mathcal{O}(1)$
- Exception: $\square$ GL2 (modified $\square$ GL) where

$$\mathcal{L}_{\text{yuk}} = c_{ij}^{f} \left(\frac{H_{1}^{\dagger} H_{1}}{M^2}\right)^{n_{i,j}} F_{L}^{i} f_{R}^{j} H_{1,2}$$

[Giudice, Lebedev: 0804.1753]
[FB, Brod, Uttayarat, Zupan: 1504.04022]
[Carena, Gemmler, Bauer: 1506.01719, 1512.03458]
Off diagonal Yukawas in flavor models

[FB, Brod, Uttayarat, Zupan: 1504.04022] – see also CERN YR4 Chap. IV.6 [1610.07922] + references therein for the specific models; see also Gori, Grojean, Juste, Paul, [1710.03752]

<table>
<thead>
<tr>
<th>Model</th>
<th>$\kappa_{ct(tc)}/\kappa_t$</th>
<th>$\kappa_{ut(tu)}/\kappa_t$</th>
<th>$\kappa_{uc(cu)}/\kappa_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFV</td>
<td>$\frac{\text{Re} \left( c_w m_b^2 V_{cb}^{(*)} \right) \sqrt{2} m_t(c)}{v \Lambda^2}$</td>
<td>$\frac{\text{Re} \left( c_u m_t^2 V_{ub}^{(*)} \right) \sqrt{2} m_t(u)}{v \Lambda^2}$</td>
<td>$\frac{\text{Re} \left( c_u m_b^2 V_{ub(c)cb}^{(<em>)} V_{ub(ub)}^{(</em>)} \right) \sqrt{2} m_c(u)}{v \Lambda^2}$</td>
</tr>
<tr>
<td>FN</td>
<td>$\mathcal{O} \left( \frac{vm_t(c)}{\Lambda^2}</td>
<td>V_{cb}</td>
<td>^{\pm 1} \right)$</td>
</tr>
<tr>
<td>GL2</td>
<td>$\epsilon(\epsilon^2)$</td>
<td>$\epsilon(\epsilon^2)$</td>
<td>$\epsilon(3)$</td>
</tr>
<tr>
<td>RS</td>
<td>$\sim \lambda(-)^2 \frac{m_t(c)}{v} \tilde{Y}^2 \frac{v^2}{m_{KK}^2}$</td>
<td>$\sim \lambda(-)^3 \frac{m_t(u)}{v} \tilde{Y}^2 \frac{v^2}{m_{KK}^2}$</td>
<td>$\sim \lambda(-)^1 \frac{m_c(u)}{v} \tilde{Y}^2 \frac{v^2}{m_{KK}^2}$</td>
</tr>
<tr>
<td>pNGB</td>
<td>$\mathcal{O} \left( y_\ast^2 \frac{m_t}{v} \lambda_{L(R),2} \frac{\lambda_{L(R),3} m^2_{W}}{M_{s}^2} \right)$</td>
<td>$\mathcal{O} \left( y_\ast^2 \frac{m_t}{v} \lambda_{L(R),1} \frac{\lambda_{L(R),2} m^2_{W}}{M_{s}^2} \right)$</td>
<td>$\mathcal{O} \left( y_\ast^2 \frac{m_c}{v} \lambda_{L(R),1} \frac{\lambda_{L(R),2} m^2_{W}}{M_{s}^2} \right)$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>$\kappa_{ct(tc)}$</th>
<th>Notes/Assumptions</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>$&lt; 4 \times 10^{-8}$</td>
<td>loop-level</td>
<td>[1311.2028]</td>
</tr>
<tr>
<td>MFV</td>
<td>$\sim 10^{-6}(-8)$</td>
<td>$\Lambda = 1$ TeV</td>
<td>[0904.2387], [PLB188(‘87)99], [hep-ph/0207036]</td>
</tr>
<tr>
<td>FN</td>
<td>$\sim 10^{-3}(-2)$</td>
<td>$\Lambda = 1$ TeV</td>
<td>[hep-ph/9310320]</td>
</tr>
<tr>
<td>GL2</td>
<td>$\sim 10^{-2}(-4)$</td>
<td>$\epsilon \sim 1/60$</td>
<td>[0804.1753], [1504.04022]</td>
</tr>
<tr>
<td>RS</td>
<td>$\sim 10^{-2}(-2)$</td>
<td>$\tilde{Y} = 4, m_{KK} = 2.2$ TeV</td>
<td>[09061990], [1505.07018]</td>
</tr>
<tr>
<td>pNGB</td>
<td>$\sim 10^{-3}(-2)$</td>
<td>$g_\ast = 4\pi, M_{\ast} = 3$ TeV</td>
<td>[1303.5701], [1408.4525]</td>
</tr>
</tbody>
</table>
Fermion Yukawas status

ATLAS+CMS [1606.02266]
1\textsuperscript{st} and 2\textsuperscript{nd} generation Yukawas

- Exclusive Higgs decays $h \rightarrow MV$
  - Bodwin et al.: 1306.5770 & 1407.6695; Kagan et al. 1406:1722
  - Koenig & Neubert, 1505.03870

- $Vh$ and associated $hQ$ production
  - Perez et al. 1503.00220 & 1505.06689; Brivio et al. 1505.06689

- Higgs differential distributions
  - Bishara et al.
  - Soreq et al. 1606.09621

- Charge asymmetry in $W^\pm h$
  - Yu [1609.06592]
Exclusive Higgs decays: \( h \rightarrow J/\psi \gamma \)

\[
\text{BR}_{h \rightarrow J/\psi \gamma} = 2.95 \cdot 10^{-6} \left( 1.07 - 0.07 \kappa_C \right)
\]

- ATLAS/CMS search:

\[
\mathcal{B}R(h \rightarrow J/\psi \gamma) < 1.5 \times 10^{-3} \text{ at 95\% CL}
\]

\[
< 3.5 \times 10^{-4} \text{ at 95\% CL}
\]

- Can be extended to strange quark (even \( u \) & \( d \))

Kagan, Perez, Petriello, Soreq, Stoynev, and Zupan [1406.1722]
The interesting case of $\gamma + \gamma$

- Interference $\rightarrow$ sensitive to sign of $y_b$
- Strong (accidental) cancellation between the direct and indirect contributions $\rightarrow$ extremely sensitive to deviations from SM

ATLAS [1807.00802]: $\text{BR}(h \rightarrow \gamma(1S)\gamma)/\text{BR}(h \rightarrow \gamma\gamma) < 0.22$
Fermion Yukawas status

- Same as before, two amplitudes, direct and indirect. Sensitivity from interference
- New bound from ATLAS [ATLAS-CONF-2017-057]

\[
\text{Br}(\phi \rightarrow K^+ K^-) = 48.9\% \quad \text{(PDG)}
\]

\[
\frac{\text{BR}_{h \rightarrow \phi \gamma}}{\text{BR}_{h \rightarrow b\bar{b}}} = \frac{\kappa_{\gamma} [ (2.3 \pm 0.1) \kappa_{\gamma} - 0.43 \kappa_s ] \cdot 10^{-6}}{0.57 \kappa_b^2}
\]


\[
\text{Br}(h \rightarrow \phi(\rho)\gamma < 4.8 \times 10^{-4} \quad (8.8 \times 10^{-4}) \quad \text{at 95\% CL}
\]

- Order of magnitude improvement on previous ATLAS bound on \(\text{Br}(h \rightarrow \phi + \gamma)\) [1607.03400] and first bound on \(\text{Br}(h \rightarrow \rho + \gamma)\)
Light quarks: $u$, $d$, $s$

\[ h \rightarrow \phi \gamma \]

\[ \bar{\kappa}_i = y_i / y_b^{SM} \]

\[ \bar{\kappa}_s \]

\[ \text{ATLAS [1712.02758]} \]

\[ \text{SM} \]

\[ \text{Eby, Petriello, Zupan [unpublished]} \]

\[ B_{r_{h \rightarrow \phi \gamma}} = \frac{10^{-6} \left[ (2.88 \pm 0.12) \kappa_{\gamma}^2 - (0.750 \pm 0.029) \bar{\kappa}_s \kappa_{\gamma} + (4.88 \pm 0.31) 10^{-2} \bar{\kappa}_s^2 \right]}{1 + \bar{\kappa}_s^2 B_{r_{h \rightarrow bb}^{SM}} + (\kappa_{\gamma}^2 - 1) B_{r_{h \rightarrow \gamma \gamma}^{SM}}} \]

\[ B_{r_{h \rightarrow \rho \gamma}} = \frac{10^{-5} \left[ (1.89 \pm 0.11) \kappa_{\gamma}^2 - (0.228 \pm 0.017) \bar{\kappa}_u \kappa_{\gamma} - (0.114 \pm 0.008) \bar{\kappa}_d \kappa_{\gamma} + \ldots \right]}{1 + (\bar{\kappa}_d^2 + \bar{\kappa}_u^2) B_{r_{h \rightarrow bb}^{SM}} + (\kappa_{\gamma}^2 - 1) B_{r_{h \rightarrow \gamma \gamma}^{SM}}} \]
VH production + flavour tagging

They consider $hc$ final state and find (LHC$_{14}$)

$$|\kappa_c| < 3.9 \quad @ \, 95\% \, C.L. \, \text{with} \, 3000 \, fb^{-1}$$

See also: [Brivio, Goertz, Isidori 1507.02916]
Higgs transverse momentum

- Additional emissions probe the structure of the loop in $gg \rightarrow h + jets$
- The loop has a chirality suppression but ...
- The charm is special $\rightarrow$ non-Sudakov double logs dynamically enhance its contribution
- The $p_T$ spectra of the Higgs and the jet have been measured by ATLAS & CMS

See also: [Soreq, Zhu, & Zupan: 1606.09621] for similar work on the u and d yukawas
Measured distributions

ATLAS: 1504.05833

CMS: 1508.07819
Contributions and their scaling

- Many contributions with different scaling in the $m_Q \lesssim p_T \lesssim m_h$ region

- The quark initiated contribution dominates for $\kappa_Q \gg 1$  
  [Soreq, Zhu, & Zupan: 1606.09621]

- Normalized distributions in this regime are sensitive to light d.o.f. but heavy new physics can affect the tail
  
  [Banfi, Martin, Sanz: 1606.09621]  
  [Buschmann, Goncalves, Kuttimalai, Schonherr, Krauss, Plehn: 1410.5806]  
  [Buschmann, Englert, Goncalves, Plehn, Spannowsky: 1405.7651] + others
Contributions and their scaling

\[ \sim \alpha_s^3 y_c m_c \ln^2 \left( \frac{p_T^2}{m_c^2} \right) \]

\[ \sim \alpha_s^2 \alpha_s y_c m_c \quad (= 0 \text{ in 4, 5 flavour scheme}) \]

\[ \sim \alpha_s \alpha_s y_c^2 \quad \text{chirality flip} \]

\[ \sim \alpha_s^2 \alpha_s y_c^2 \quad \text{extra powers of } \alpha_s \text{ from charm PDF} \]

[Sullivan, Nadolsky: hep-ph/0111358]
Results for $p_{T,h}$

95% C.I. after profiling over $\kappa_b$

LHC Run I: $[-16, 18]$

LHC Run II: $[-1.4, 3.8]$

HL-LHC: $[-0.6, 3.0]$

CMS with 35.9 fb$^{-1}$ (13 TeV)

$-8.7 < \kappa_c < 10.6$

PAS HIG-17-028

<table>
<thead>
<tr>
<th></th>
<th>experimental [%]</th>
<th>theoretical [%]</th>
<th>$\kappa_c \in$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$</td>
<td>1.5</td>
<td>2.5</td>
<td>$[-0.6, 3.0]$</td>
</tr>
<tr>
<td>$S_2$</td>
<td>3.0</td>
<td>2.5</td>
<td>$[-0.9, 3.3]$</td>
</tr>
<tr>
<td>$S_3$</td>
<td>1.5</td>
<td>5.0</td>
<td>$[-1.2, 3.6]$</td>
</tr>
<tr>
<td>$S_4$</td>
<td>3.0</td>
<td>5.0</td>
<td>$[-1.3, 3.7]$</td>
</tr>
</tbody>
</table>
First generation Yukawas

[Soreq, Zhu, & Zupan: 1606.09621]

See also Felix Yu [1609.06592] for $W^\pm$ Charge asymmetry sensitive to $O(5)$ deviations in $\bar{\kappa}_{u,d,s}$ at 14 TeV w/3 ab$^{-1}$

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

ATLAS [1707.01404] – 13 TeV, 36.1 fb$^{-1}$, $h\rightarrow\gamma\gamma$

ATLAS [1403.6293, 1509.06047] CMS [1610.04857]
Summary

- Measuring light quark Yukawas crucial to understand mass generation mechanism in SM
- Higgs $p_T$ distribution is sensitive to modified charm Yukawa, constraints at HL-LHC on modification of $y_c$ of $O(\text{few})$ and on $y_s/y_{b_{\text{SM}}} < 0.5$
- LHCb upgrade II projection $|\kappa_c| < 2.2$ and ILC $O(10\%)$
- VH production at LHCb $|\kappa_c| < 2–3$
- Bounds on $\text{BR}(t \rightarrow hc)$ will cut well into parameter space of flavor models
- Other ideas: strange tagging? Proposal for future $e^+e^-$ using charged Kaon reco. – can something similar be done at LHC?

Duarte-Campderros, Perez, Schlaffer, Soffer [Perez talk at 1st FCC physics workshop and Schaffer talk at CLIC physics]
Thank you!
LHCb projections for HL-LHC

LHCb Upgrade II: constraints on $\kappa_c$

- 300 fb$^{-1}$ at 14 TeV: $|\kappa_c| \lesssim 7$
- 30% di-c-tagging efficiency: $|\kappa_c| \lesssim 4$
- Better electron reconstruction: $|\kappa_c| \lesssim 3$
- Further improvements: $|\kappa_c| \lesssim 2.2$

Projections taken from talk by Mike Williams

Slide from Uli Haisch talk at Elba 2017
Based on bounds from M. Williams’ talk
Projections for the ILC

$\sqrt{s} = 250 \text{ GeV, } \mathcal{L} = 250 \text{ fb}^{-1}, \ P(e^-, e^+) = (-0.8, +0.3)$

Uli Haisch based on Ono & Miyamoto [1207.0300]
Normalised distributions @ 8 TeV

$\mathcal{O}(1)$ deviations in $\kappa_c \rightarrow \sim$ few % effect on the shape
Contributions to spectrum @ 8 TeV

\[ gg \rightarrow hj \]

\[ Qg + QQ \rightarrow hj \]

\[ \kappa_c = -10 \]

\[ \kappa_c = -5 \]

\[ \kappa_c = 5 \]
Quark mass effects

- Exact mass dependence only known at L.O.
- L.O. differential distributions include non-factorizing terms $\sim \ln^2(p_\perp^2/m_Q^2)$
  [Mantler, Wiesemann [1210.8263], [Banfi, Monni, and Zanderighi:
  [Grazzini and Sargsyan 1306.4581]
- These $\ln^2$ terms **do not exist** for $p_T < m_Q$
- Recent progress in the direction of NLO, NLL
  → Soft double Logs resummed in the abelian limit
    [Melnikov, Penin: 1602.09020]
  → Two loop virtual corrections in the $m_Q \to 0$ limit
    [Melnikov, Tancredi, Wever: 1610.03747 and 1702.00426]
Varying the systematic errors...

### Experimental error = 1.5%

<table>
<thead>
<tr>
<th>$\kappa_c$</th>
<th>Experimental [%]</th>
<th>Theoretical [%]</th>
<th>$\kappa_c \in$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$</td>
<td>1.5</td>
<td>2.5</td>
<td>[-0.6, 3.0]</td>
</tr>
<tr>
<td>$S_2$</td>
<td>3.0</td>
<td>2.5</td>
<td>[-0.9, 3.3]</td>
</tr>
<tr>
<td>$S_3$</td>
<td>1.5</td>
<td>5.0</td>
<td>[-1.2, 3.6]</td>
</tr>
<tr>
<td>$S_4$</td>
<td>3.0</td>
<td>5.0</td>
<td>[-1.3, 3.7]</td>
</tr>
</tbody>
</table>

$\Delta \chi^2 = 2.3$

$\Delta \chi^2 = 5.99$
Fermion mass generation

See Altmannshofer et al. [1610.02398] for a 2HDM model where 1st and 2nd generation fermions couple predominantly to one doublet whereas the 3rd generation fermions and the weak gauge bosons couple to the other doublet.