Higgs Decays in the Standard Model EFT at NLO

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October 26th
NBIA, Copenhagen
HEFT 2016

Outline

Motivation

Higgs properties subject of intense study, especially as a link to new physics

- Many decay channels available for study within the SM
- Links to new physics?
    - Portal to Dark Matter?
    - Part of an extended Higgs sector?
- Can use a bottom up EFT to parametrise new physics effects

Motivation

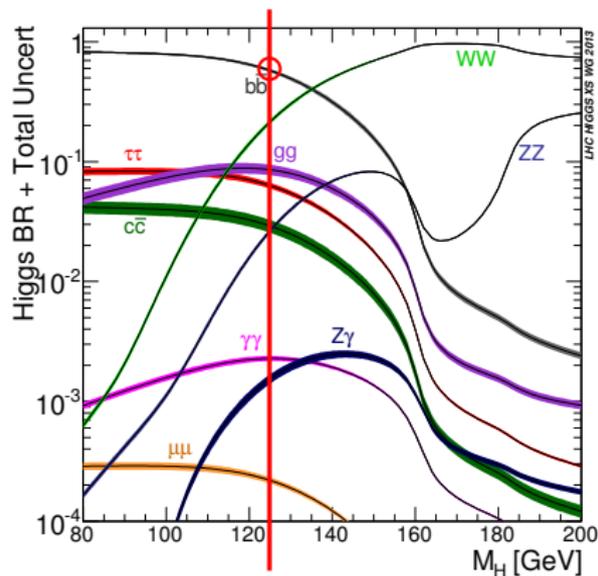Higgs properties subject of intense study, especially as a link to new physics

- Many decay channels available for study within the SM

- Links to new physics?
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    - Part of an extended Higgs sector?

- Can use a bottom up EFT to parametrise new physics effects

$$\mathrm{BR}(\mathrm{h} \to \mathrm{b}\bar{\mathrm{b}}) \sim 0.6$$

Investigating $h \to b\bar{b}$

We can begin to apply this framework in the context of Higgs decays to b-quarks.
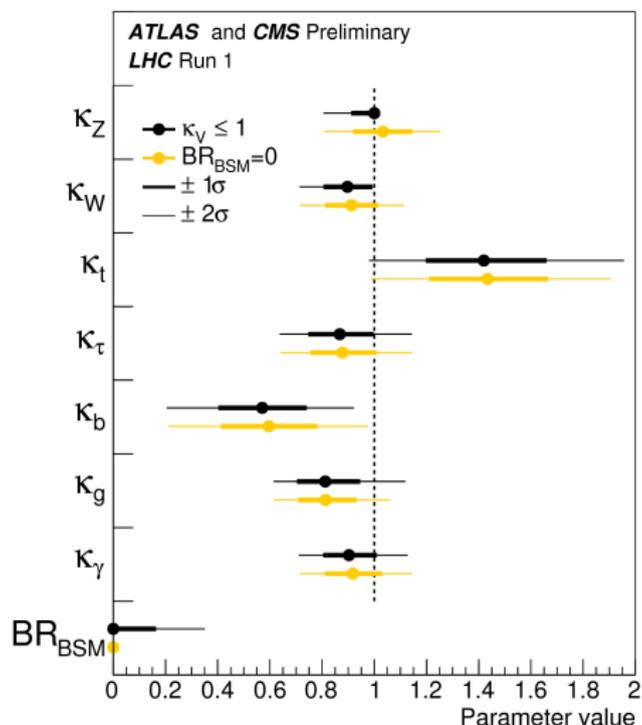
Recent results within the kappa formalism.

Combined ATLAS+CMS results:

$\kappa_b = 0.6 \pm 0.18$
(Assuming $\mathrm{Br_{BSM}} = 0$)
[ATLAS-CONF-2015-044]

Standard Model EFT

- The addition of higher dimension operators allows a bottom up approach to encoding the effects of new physics into the SM

- "Model Independent" framework

- Considering only baryon number conserving operators

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + ...$$

$$\mathcal{L}^{(5)} = \tilde{C} \frac{(\overline{L^c}\tilde{H}^*)(\tilde{H}^\dagger L)}{\Lambda_{\mathrm{NP}}} + \mathrm{h.c.} \qquad \mathcal{L}^{(6)} = \sum_{i=1}^{59} \frac{\tilde{C}_i}{\Lambda_{\mathrm{NP}}^2} \mathcal{O}_i$$

Need to pick a basis for these operators, though the results should be independent of this choice. Here we employ the Warsaw basis.
[Grzadkowski, Iskrzynski, Misiak, Rosiek; [1008.4884]]

Standard Model EFT

At dimension-6 there are 59 independent operators which conserve baryon number.

1 : X^3		2 : H^6		3 : H^4D^2		5 : ψ^2H^3 + h.c.	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar l_p e_r H)$
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$			Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$	Q_{uH}	$(H^\dagger H)(\bar q_p u_r \widetilde{H})$
Q_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$
$Q_{\widetilde{W}}$	$\epsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$						

4 : X^2H^2		6 : ψ^2XH + h.c.		7 : ψ^2H^2D	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$	$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar l_p \tau^I \gamma^\mu l_r)$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p \gamma^\mu e_r)$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$	$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p \gamma^\mu u_r)$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p \gamma^\mu d_r)$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$

as well as Class 8 four-fermion operators

Tree-level effect of Dim-6 operators on Higgs Couplings

Inclusion of dimension-6 operators alters SM parameters at tree level. For example:

- Q_H: $(H^\dagger H)^3 \to$ Alters Higgs VEV (denoted v_T)
- Q_{HG}: $(H^\dagger H)\, G_{\mu\nu}^A G^{A\,\mu\nu} \to$ Introduces coupling with gluons.
- Q_{dH}: $(H^\dagger H)\, (\bar{q}_p d_r H) \to$ Modifies Yukawa couplings

In particular, this last operator can introduce flavour violating effects!
We do not consider any flavour violation beyond that already present in the Yukawa couplings:

Minimal Flavour Violation (MFV)

Exploring the Yukawa sector in more detail

New Yukawa and Mass matrix terms in broken phase.
MASS MATRIX:

$$[\mathcal{M}]_{rs} = -\frac{v_T}{\sqrt{2}} \left[\left(Y^d\right)_{rs} - (C_{dH}^*)_{sr} \, \frac{v_T}{2} \right] + \text{h.c.}$$
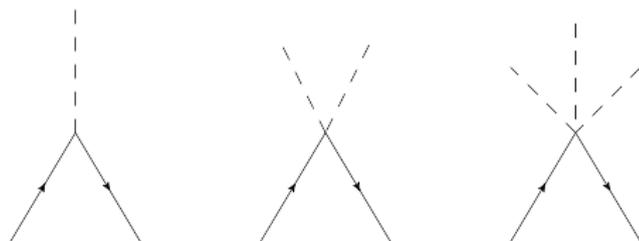
YUKAWA:

$$[\mathcal{Y}]_{rs} = -\frac{1}{\sqrt{2}} \left[\left(Y^d\right)_{rs} - \frac{3}{2} \, (C_{dH}^*)_{sr} \, v_T^2 \right] + \text{h.c.}$$

From now on, flavour indices will be suppressed

Operators for Tree-level calculation

The following operators appear in Higgs decays at tree level

- $Q_{bH} = (H^\dagger H)(\overline{Q}^L H b^R)$
  - Modifies Yukawa couplings (as well as introducing new 4/5-point vertices which play a role at NLO)

- $Q_{H\square} = (H^\dagger H)\square(H^\dagger H)$ ⎫ Modify the Higgs
- $Q_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D^\mu H)$ ⎬ kinetic term
- We'll write $C_{H,\text{kin}} = \left(C_{H\square} - \frac{1}{4}C_{HD}\right)v^2$
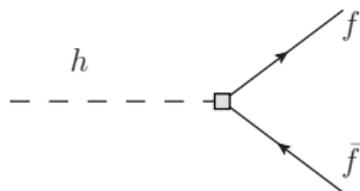
The Leading Order result for Higgs decay to fermions is now straightforward

$$i\mathcal{M}^{(0)}(h \to f\bar{f}) = -i\bar{u}(p_f)\left(\mathcal{M}^{(0)}_{f,L}P_L + \mathcal{M}^{(0)*}_{f,L}P_R\right)v(p_{\bar{f}})$$

where

$$\mathcal{M}^{(0)}_{f,L} = \frac{m_f}{v_T}\left[1 + C_{H,\text{kin}}\right] - \frac{v_T^2}{\sqrt{2}}C^*_{fH}$$

Input Parameters

- Choose to work with the following independent, physical parameters

  - $\bar{e}, m_H, M_W, M_Z, m_f, C_i$

- In particular, the VEV can be expressed as,

$$\frac{1}{v_T} = \frac{\bar{e}}{2M_W \bar{s}_w} \left(1 + \frac{\hat{c}_w}{2\hat{s}_w} C_{HWB} \hat{v}_T^2 \right)$$

Barred quantities ($\bar{e}$, $\bar{s}_w$) appear in the covariant derivative in the broken phase of the theory while hatted quantities have their usual definition as in the SM; $\hat{v}_T$ is the usual Standard Model VEV

$$\hat{v}_T \equiv \frac{2M_W \hat{s}_w}{\bar{e}}$$

- In practise, we'll choose to eliminate M_W in terms of the Fermi-constant G_F.

Going beyond Leading Order

- In principle, we could stop at this point and perform a global fit. However...
- There may be operators which are introduced at loop level which are poorly constrained at tree level in other processes
- Not all such terms can be anticipated from a straightforward RG analysis
- It is important to correctly account for such operators
- Higher orders reduce uncertainty in the result

At most one dimension-6 operator per diagram.
Only interfere such diagrams with SM ones.

$\Rightarrow$ Do not generate terms $\mathcal{O}(\Lambda_{\mathrm{NP}}^{-4})$ $\Leftarrow$

Renormalisation

Amplitude requires bare diagrams & counterterms

$$\mathcal{M}^{(1-\text{loop})}(h \to f\bar{f}(g)) = \mathcal{M}^{(1),\text{bare}} + \mathcal{M}^{\text{C.T.}}$$

- Necessary to specify the renormalisation scheme
- We choose to renormalise the electric charge, masses and wavefunctions in the **on-shell scheme**
- The Wilson coefficients are renormalised using the $\overline{\textbf{MS}}$ **scheme**
- Using such a scheme for the Wilson coefficients allows the use of previously calculated anomalous dimension matrices
  [Manohar, Jenkins & Trott; [1308.2627], [1310.4838]]
  [Alonso, Manohar, Jenkins & Trott; [1312.2014]].
- This will provide an additional check on the calculation

Renormalisation

- The on-shell scheme gives our renormalisation condition for $\bar{e}, m_H, M_W, M_Z$ and m_f (see [Denner; [0709.1075]])

- The renormalisation constants can be obtained from 2-point functions

$$Z_h \qquad\qquad Z_b,\ \delta m_b \qquad\qquad \delta M_Z,\ \delta M_W \qquad\qquad \delta\bar{e}$$
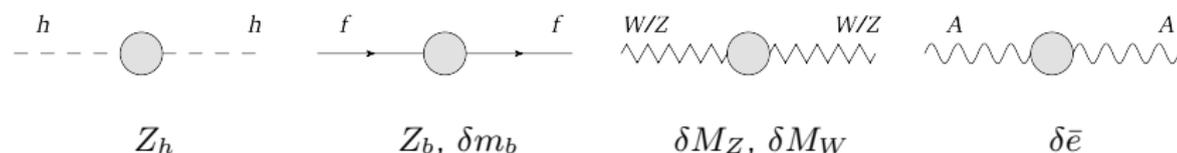
- In general, the renormalisation constants will receive both SM and dimension-6 contributions

$$\delta Z = \frac{1}{16\pi^2}\bigg(\overbrace{\delta Z^{(4)}}^{\text{SM contributions}} + \overbrace{\delta Z^{(6)}}^{\substack{\text{Dimension-6} \\ \text{contributions}}} \bigg)$$
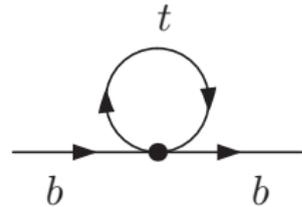
- The renormalisation constants for C_i are constructed using the anomalous dimensions. ([Trott et. al], previous slide)

Example: Four Quark Operator

Example contributions to mass (and wavefunction) renormalisation.

$$\delta m_b = \delta m_b^{(4)} + \delta m_b^{(6)}$$

$$\delta m_b^{(6)} = \frac{1}{\epsilon}\left[\frac{m_t^3}{2}\left((2N_c+1)\left(C_{qtqb}^{(1)} + C_{qtqb}^{(1)*}\right) + \right.\right.$$

$$c_{F,3}\left(C_{qtqb}^{(8)} + C_{qtqb}^{(8)*}\right)\right) - 4m_b^3\left(C_{qb}^{(1)} + c_{F,3}C_{qb}^{(8)}\right)$$

$$\left. + m_\tau^3\left(C_{l\tau bq} + C_{l\tau bq}^*\right)\right] + \delta m_b^{\text{fin}}(\mu)$$

$$\hat{A}_0(s) = s - s\ln\left(\frac{s-i0}{\mu}\right)$$

$$\delta m_b^{\text{fin}}(\mu) = \frac{m_t}{2}\hat{A}_0(m_t^2)\left((2N_c+1)\left(C_{qtqb}^{(1)} + C_{qtqb}^{(1)*}\right) + c_{F,3}\left(C_{qtqb}^{(8)} + C_{qtqb}^{(8)*}\right)\right)$$

$$+ 2m_b\left(m_b^2 - 2\hat{A}_0(m_b^2)\right)\left(C_{qb}^{(1)} + c_{F,3}C_{qb}^{(8)}\right) + m_\tau\hat{A}_0(m_\tau^2)\left(C_{l\tau bq} + C_{l\tau bq}^*\right)$$

We can choose to convert this to the $\overline{\text{MS}}$-scheme. (Will do this later explicitly for the QCD results)

The counterterm for the $h \to f\bar{f}$ decay amplitude can now be written as

$$i\mathcal{M}^{\text{C.T.}}(h \to f\bar{f}) = -i\bar{u}(p_f)\left(\delta\mathcal{M}_L P_L + \delta\mathcal{M}_L^* P_R\right)v(p_{\bar{f}})$$

The calculation of the two-point functions is straightforward and will not be addressed.

Counterterm Construction

Explicit form of the counterterm. Many of these terms are zero for QCD corrections

$$
\delta\mathcal{M}_L^{(6)} = \left(\frac{m_f}{v_T} C_{H,\mathrm{kin}} \right) \left(\frac{\delta m_f^{(4)}}{m_f} - \frac{\delta v_T^{(4)}}{v_T} + \frac{1}{2}\delta Z_h^{(4)} + \frac{1}{2}\delta Z_f^{(4),L} + \frac{1}{2}\delta Z_f^{(4),R*} \right)
$$

$$
- \frac{v_T^2}{\sqrt{2}} C_{bH}^* \left(2\frac{\delta v_T^{(4)}}{v_T} + \frac{1}{2}\delta Z_h^{(4)} + \frac{1}{2}\delta Z_f^{(4),L} + \frac{1}{2}\delta Z_f^{(4),R*} \right)
$$

$$
+ \frac{m_f}{v_T} \left(\frac{\delta m_f^{(6)}}{m_f} - \frac{\delta v_T^{(6)}}{v_T} + \frac{1}{2}\delta Z_h^{(6)} + \frac{1}{2}\delta Z_f^{(6),L} + \frac{1}{2}\delta Z_f^{(6),R*} \right)
$$

$$
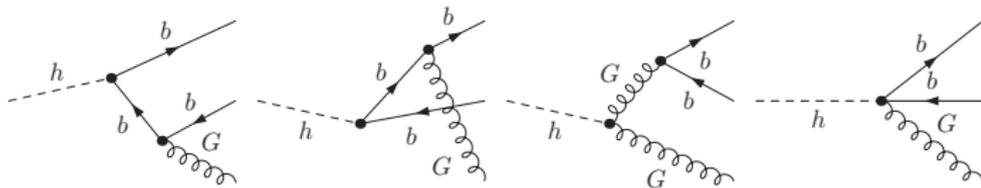+ \frac{m_f}{v_T}\delta C_{H,\mathrm{kin}} - \frac{v_T^2}{\sqrt{2}}\delta C_{fH}^*
$$

We now turn our attention to the NLO diagrams from QCD in the Standard Model EFT.

$$
\mathcal{M}^{(1-\mathrm{loop}),\mathrm{bare}} = \mathcal{M}_{h\to b\bar{b}} + \mathcal{M}_{h\to b\bar{b}g}
$$

Going beyond Leading Order: QCD

We can compute the 1-loop corrections to the decay width. Here
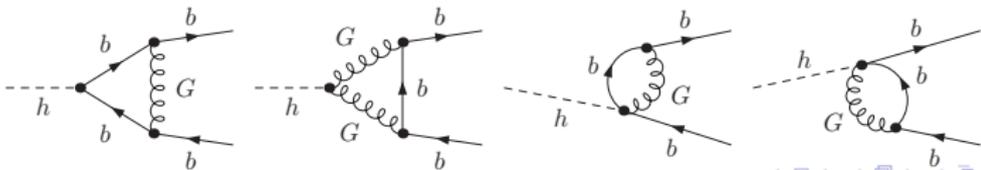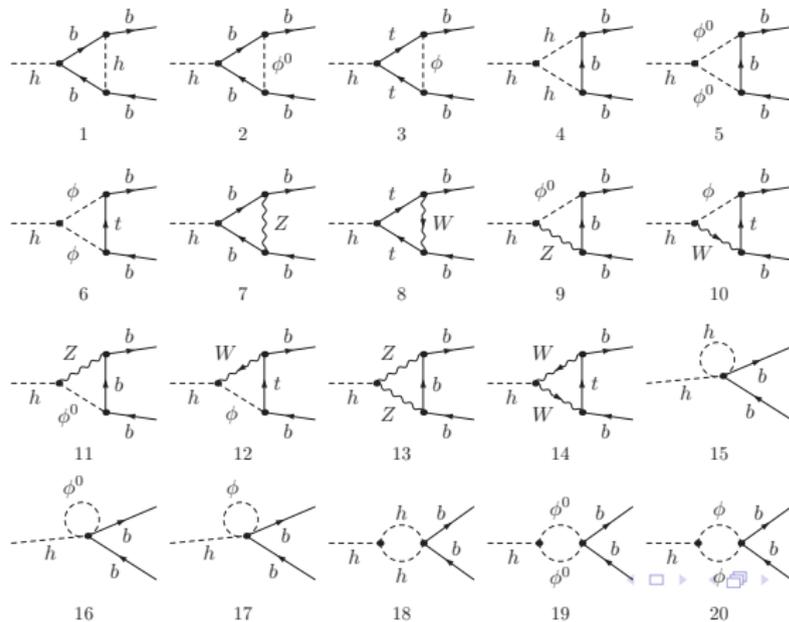we focus on the QCD corrections.

Real Emission:

C_{bH}

C_{bG}, C_{HG}

Virtual:

Going beyond Leading Order: $\mathcal{O}(\alpha/M_W^2)$ Corrections

- Had previously calculated the 1-loop corrections $\mathcal{O}(\alpha/M_W^2)$.
  Specifically includes non-logarithmic terms
  $\mathcal{O}(m_t^2\alpha/M_W^2) \sim \mathcal{O}(G_F m_t^2)$
  [Gauld, Pecjak, DJS; [1512.02508]]

- Much more involved calculation. Subset of diagrams:

Resulting amplitudes:

$$A_b^{(4,0)} = \left(\sqrt{2}G_F\right)^{\frac{1}{2}} m_b$$

$$A_b^{(6,0)} = A_b^{(4,0)}C_{H,\text{kin}} - \frac{C_{bH}}{2G_F} + A_b^{(4,0)}\frac{\Delta R^{(6,0)}}{2G_F}$$

The one-loop results are

$$A_b^{(4,1)} = A_b^{(4,0)}G_F m_t^2 \left(\frac{-18 + 7N_c}{3\sqrt{2}}\right) \qquad \begin{array}{l} \Delta R \text{ related to expressing} \\ M_W \text{ in terms of } G_F. \end{array}$$

$$A_b^{(6,1)} = A_b^{(4,0)}m_t^2 \left(\frac{3G_F}{\sqrt{2}}(-2 + N_c)C_{H,\text{kin}} + (-1 + N_c)\,C_{Hq}^{(3)}\right)$$

$$+ \frac{(-15 + 4N_c)m_t^2}{12}\frac{C_{bH}}{\sqrt{2}} + \frac{1}{2}\left[A_b^{(4,0)}\dot{C}_{H,\text{kin}} - \frac{1}{2G_F}\dot{C}_{bH}\right]\ln\left(\frac{m_t^2}{\mu^2}\right)$$

$$+ \frac{1}{2G_F}\left(A_b^{(4,0)}\Delta R^{(6,1)} + 3A_b^{(4,1)}\Delta R^{(6,0)}\right)$$

Final Answer: QCD

$$dΓ = \frac{d\phi_2}{2m_h} \sum |\mathcal{M}_{h\to b\bar{b}}|^2 + \frac{d\phi_3}{2m_h} \sum |\mathcal{M}_{h\to b\bar{b}g}|^2$$

The leading order dim-6 results are proportional to the SM ones.

$$Γ^{(4,0)} = \frac{N_c m_h m_b^2 \beta^3}{8\pi v_T^2}$$

$$Γ^{(6,0)} = \left(2C_{H,\text{kin}} - \frac{\sqrt{2}v_T^3}{m_b}C_{bH}\right)Γ^{(4,0)}$$

$$\beta = \sqrt{1 - \frac{4m_b^2}{m_h^2}}$$

For the NLO results, the presence of a large scale separation $(m_b^2 << m_h^2)$ can lead to large logarithms.
We convert the renormalised mass to the $\overline{\text{MS}}$-scheme where such logarithms can be resummed in RG evolution factors.

Final Answer: QCD

The full answer is rather lengthy. However, we find good agreement numerically between it and the result in the $m_b \to 0$ limit. Equivalently $\beta \to 1$. [Gauld, Pecjak, DJS; [1607.06354]]

$$\overline{\Gamma}_{\beta \to 1}^{(4,1)} = \frac{\alpha_s C_F}{\pi} \frac{1}{4} \left(17 + 6 \ln \left[\frac{\mu^2}{m_h^2} \right] \right) \overline{\Gamma}_{\beta \to 1}^{(4,0)}$$

$$\overline{\Gamma}_{\beta \to 1}^{(6,1)} = \left(2 C_{H,\text{kin}} - \frac{\sqrt{2} v_T^3}{\overline{m}_b} C_{bH} \right) \overline{\Gamma}_{\beta \to 1}^{(4,1)}$$

$$+ \frac{\alpha_s C_F}{\pi} \frac{N_c m_h^3 \overline{m}_b}{8 \sqrt{2} \pi v_T} C_{bG} + \frac{\alpha_s C_F}{\pi} \frac{N_c m_h \overline{m}_b^2}{8 \pi} C_{HG}$$

$$\times \left(19 - \pi^2 + \ln^2 \left[\frac{\overline{m}_b^2}{m_h^2} \right] + 6 \ln \left[\frac{\mu^2}{m_h^2} \right] \right)$$

Final Answer

- The cancellation of UV divergences from more than 20 dim-6 operators in the full result gives a highly non-trivial check on the calculation

- The logarithmic corrections could have been deduced from a Leading Log analysis

$$C_i(\mu_t) = C_i(\Lambda_{\mathrm{NP}}) + \frac{1}{2}\frac{1}{16\pi^2}\dot{C}_i(\Lambda_{\mathrm{NP}})\ln\left(\frac{\mu_t^2}{\Lambda_{\mathrm{NP}}^2}\right)$$

- However, calculation of the full NLO calculation illuminates terms which would be missed in an RG analysis

$$\overline{\Gamma}_{\beta\to 1}^{(6,1)} = \left(2C_{H,\mathrm{kin}} - \frac{\sqrt{2}v_T^3}{\overline{m}_b}C_{bH}\right)\overline{\Gamma}_{\beta\to 1}^{(4,1)}$$

$$+ \frac{\alpha_s C_F}{\pi}\frac{N_c m_h^3 \overline{m}_b}{8\sqrt{2}\pi v_T}C_{bG} + \frac{\alpha_s C_F}{\pi}\frac{N_c m_h \overline{m}_b^2}{8\pi}C_{HG}$$

$$\times\left(19 - \pi^2 + \ln^2\left[\frac{\overline{m}_b^2}{m_h^2}\right] + 6\ln\left[\frac{\mu^2}{m_h^2}\right]\right)$$

Impacts on Phenomenology: QCD

Scenario where 5% deviation from SM value is observed.

$$\frac{\Gamma^{h \to b\bar{b}}_{\text{SM}}}{\Gamma^{h \to b\bar{b}}_{\text{Exp}}} = 1.00 \pm 0.05$$

Such an effect would be measurable at the ILC!

– ILC Technical Design Report 2: Physics

Considering for a moment only the QCD corrections.

Inputs

$$\overline{\Gamma}_{\beta \to 1} = 2.67 \text{ MeV}$$
$$+ \left(\frac{v_T}{\Lambda_{\text{NP}}}\right)^2 \left(5.34 \tilde{C}_{H,\text{kin}} + 1.57 \tilde{C}_{bG}\right) \text{ MeV}$$
$$- \left(\frac{v_T}{\Lambda_{\text{NP}}}\right)^2 \left(310 \tilde{C}_{bH} + 6.91 \tilde{C}_{HG}\right) \text{ MeV}$$

$$m_Z = 91.1876 \text{ GeV}$$
$$\alpha_s(m_Z) = 0.1184$$
$$\bar{m}_b(\bar{m}_b) = 4.18 \text{ GeV}$$
$$m_t = 173.0 \text{ GeV}$$
$$m_h = 125.0 \text{ GeV}$$

Impacts on Phenomenology: QCD

$$\frac{\overline{\Gamma}_{\beta \to 1}^{h \to b\bar{b}}}{\mathrm{MeV}} = 2.67 + \left(\frac{v_T}{\Lambda_{\mathrm{NP}}}\right)^2 \left(5.34\tilde{C}_{H,\mathrm{kin}} + 1.57\tilde{C}_{bG}\right) - \left(\frac{v_T}{\Lambda_{\mathrm{NP}}}\right)^2 \left(310\tilde{C}_{bH} + 6.91\tilde{C}_{HG}\right)$$

Attributing the 5% difference to the dimension-6 contributions:
$\overline{\Gamma}^{(6)} \sim 0.13$ MeV.

1) $\tilde{C}_i \sim \mathcal{O}(1)$**:**
Only $\tilde{C}_{bH}$ is relevant.
$\frac{\overline{\Gamma}^{(6)}}{\mathrm{MeV}} \sim -310 \left(\frac{v_T}{\Lambda_{\mathrm{NP}}}\right)^2 \implies \Lambda_{\mathrm{NP}} \sim 10$ TeV

2) $\tilde{C}_{bH} \sim y_b \bar{C}_{bH}$**:**
Many BSM models scale modified Higgs couplings (chirality
flipped couplings) by Yukawa terms, as done in related work.
[Elias-Miro, Espinosa, Masso, Pomarol; [1308.1879]]
Here, all coefficients same order of magnitude.
$\frac{\overline{\Gamma}^{(6)}}{\mathrm{MeV}} \sim 8.54 \left(\frac{v_T}{\Lambda_{\mathrm{NP}}}\right)^2 \implies \Lambda_{\mathrm{NP}} \sim 2$ TeV
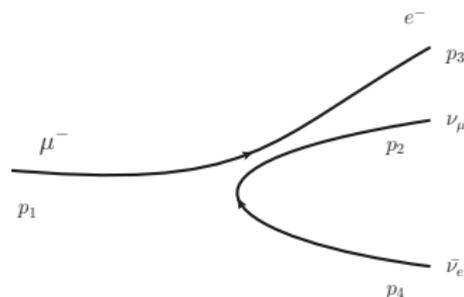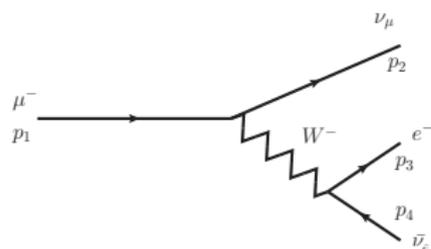
Summary & Conclusion

- We have computed two different contributions to Higgs decays to b-quarks from dimension-6 operators within the context of Standard Model EFT:
    - A) NLO QCD corrections
    - B) 1-loop contributions enhanced by $\mathcal{O}(\alpha/M_W^2)$ & four-fermion operators
- Involved a non-trivial renormalisation scheme checked by the cancellation of divergences from more than 20 different operators
- Compared to LO, NLO corrections
    - Reduce theory errors associated with higher order corrections
    - Induce corrections proportional to coefficients which do not appear at tree level (and are not necessarily well constrained) and aren't always accessible from an RG analysis
- It is important to remember that the phenomenological study belongs in the context of a global analysis (at NLO where available), possibly with partially model dependent assumptions included

ADDITIONAL SLIDES

Fermi Constant: G_F

- We said before we'd like to replace M_W with the Fermi constant G_F as one of our input parameters
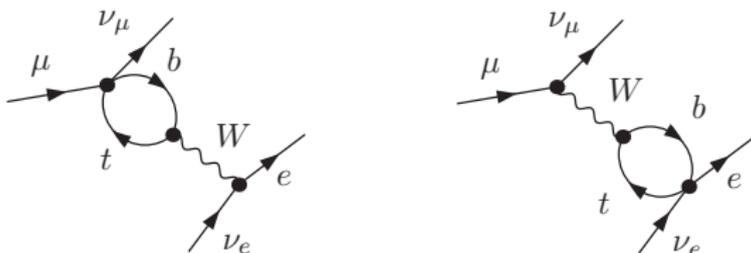
- Defined and extracted from muon decay

$$\frac{1}{\sqrt{2}}\frac{1}{v_T^2} = G_F - \frac{1}{\sqrt{2}}\left(C_{Hl\;ee}^{(3)} + C_{Hl\;\mu\mu}^{(3)}\right) + \frac{1}{2\sqrt{2}}\left(C_{ll\;\mu ee\mu} + C_{ll\;e\mu\mu e}\right)$$

Fermi constant at one-loop

- Necessary to work out G_F to one-loop also

$$\frac{1}{\sqrt{2}}\frac{1}{v_T^2}(1+\underbrace{\Delta r}_{\substack{\text{1-loop}\\\text{non-QED}\\\text{corrections}}}) = G_F + \overbrace{\underbrace{\Delta R^{(6,0)}}_{\substack{\text{Obtained by matching}\\\text{with tree-level}\\\text{from before}}} + \Delta R^{(6,1)}}^{\substack{\text{Finite}\\\text{SMEFT}\\\text{contribution}}}$$

- $\Delta R^{(6,1)}$ Obtained from the following diagrams

- It is noteworthy that the counterterms take on a much simpler form with this replacement

Renormalisation: The VEV

- An interesting point is the renormalisation of the VEV, v_T

$$\frac{1}{v_T} = \frac{\bar{e}}{2M_W \bar{s}_w} \left(1 + \frac{v^2 \hat{c}_w}{2\hat{s}_w} C_{HWB}\right)$$

- Bare VEV, in terms of renormalised VEV

$$\frac{1}{v_T^{(0)}} = \frac{1}{v_T}\left(1 - \frac{\delta v_T}{v_T}\right)$$

$$\begin{aligned}
\frac{\delta v_T}{v_T} = &\frac{\delta M_W}{M_W} + \frac{\delta \bar{s}_w}{\bar{s}_w} - \frac{\delta \bar{e}}{\bar{e}} - \frac{\hat{v}_T^2 \hat{c}_w}{2\hat{s}_w}\delta C_{HWB} \\
&- \frac{\hat{c}_w}{2\hat{s}_w}\hat{v}_T^2\left(\frac{\delta \hat{c}_w}{\hat{c}_w} - \frac{\delta \hat{s}_w}{\hat{s}_w} + 2\frac{\delta \hat{v}_T}{\hat{v}_T}\right)C_{HWB}
\end{aligned}$$

Wilson Coefficient renormalisation

We use the $\overline{\text{MS}}$ scheme for the renormalisation of the Wilson coefficients. To one-loop order, we can write

$$C_i^{(0)} = C_i(\mu) + \frac{\delta C_i(\mu)}{16\pi^2} = C_i(\mu) + \frac{1}{2\hat{\epsilon}} \frac{1}{16\pi^2} \dot{C}_i(\mu)$$

$$\dot{C}_i(\mu) \equiv 16\pi^2 \left(\mu \frac{d}{d\mu} C_i(\mu) \right) = 16\pi^2 \left(\Gamma_{ij} C_j(\mu) \right)$$

$\hat{\epsilon}$ simply indicates we subtract the universal γ_E and $\ln(4\pi)$: $\overline{\text{MS}}$-scheme

Full 1-loop calculation of these anomalous dimension matrices recently completed.
[Manohar, Jenkins & Trott; [1308.2627], [1310.4838]]
[Alonso, Manohar, Jenkins & Trott; [1312.2014]].