Standard Model EFT at NLO
(focus on $h \to b\bar{b}$)

Rhorry Gauld

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General outline

- Introduction to the Standard Model EFT Framework
    - General set-up
    - Compute $h \to b\bar{b}$ at LO
- Computing $h \to b\bar{b}$ at NLO
    - General approach
    - QCD corrections
    - Vanishing gauge coupling corrections
- Other progress and conclusions

Linear SMEFT

"Generic" theory of physics Beyond-the-SM (BSM)

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \mathcal{L}_8 + \ldots$$

$$\mathcal{L}_i = \frac{1}{\Lambda_{\mathrm{NP}}^{i-4}} \sum_j C_j^{(i)} Q_j^{(i)}$$

Operators effectively describe interactions between SM and NP

	fermions					scalars
field	l_{Lp}^{j}	e_{Rp}	$q_{Lp}^{\alpha j}$	u_{Rp}^{α}	d_{Rp}^{α}	H^j
hypercharge	$-\frac{1}{2}$	-1	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{2}$

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Effective operator constructed from gauge invariant combinations of SM fields (Higgs doublet)

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"Wilson coefficient"

$$\mathcal{L}_i = \frac{1}{\boxed{\Lambda_{\rm NP}^{i-4}}} \sum_j \boxed{C_j^{(i)}}\, \boxed{Q_j^{(i)}}$$

New Physics (NP) scale

Effective operator constructed from gauge invariant combinations of SM fields (Higgs doublet)

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Linear SMEFT

"Generic" theory of physics Beyond-the-SM (BSM)

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \cancel{\mathcal{L}_5} + \boxed{\mathcal{L}_6} + \cancel{\mathcal{L}_7} + \cancel{\mathcal{L}_8} + \ldots$$

$$\boxed{\mathcal{L}_6^{\Delta B=0} = \frac{1}{\Lambda_{\mathrm{NP}}^2} \sum_j C_j^{(6)} Q_j^{(6)}}$$

Ignore operators involving baryon and lepton number violation
Truncate predictions for observables at order $\mathcal{O}(\Lambda_{\mathrm{NP}}^{-2})$

Operators effectively describe interactions between SM and NP

	fermions					scalars
field	l_{Lp}^j	e_{Rp}	$q_{Lp}^{\alpha j}$	u_{Rp}^{α}	d_{Rp}^{α}	H^j
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Basis choice (shouldn't matter)

Warsaw: Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884

Motivation: 1-loop anomalous dimension calculation in Warsaw basis*

[(Alonso) Jenkins, Manohar, Trott : 1308.2627, 1310.4838, (1312.2014)]

$1: X^3$		$2: H^6$		$3: H^4D^2$		$5: \psi^2H^3 + \text{h.c.}$	
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}	$(H^\dagger H)(\bar{q}_p d_r H)$
$Q_{\widetilde{W}}$	$\epsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$						

$4: X^2H^2$		$6: \psi^2XH + \text{h.c.}$		$7: \psi^2H^2D$	
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.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$

$$\tilde{H}^j = \epsilon_{jk}(H^k)^*$$

classes 1-7

59+h.c. operators (classified by field content, 8 classes)

*Important ingredient in renormalisation: see next section

Basis choice (shouldn't matter)

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Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}			
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}			
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}			
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	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}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p\gamma^\mu d_r)$
$Q_{H\widetilde WB}$	$H^\dagger\tau^I H\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p\gamma^\mu d_r)$

Example (class 5):

$$Q_{dH} : (H^\dagger H)(\bar q d H)$$

$$\tilde H^j = \epsilon_{jk}(H^k)^*$$

classes 1-7

59+h.c. operators (classified by field content, 8 classes)

*Important ingredient in renormalisation: see next section

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$8:(\bar{L}L)(\bar{L}L)$		$8:(\bar{R}R)(\bar{R}R)$		$8:(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}R)(\bar{R}L)+\mathrm{h.c.}$		$8:(\bar{L}R)(\bar{L}R)+\mathrm{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$	$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
		$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
		$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
		$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

<u>class 8</u>
(four-fermion)

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$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8:(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$

$8:(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$

Example (class 8):

$$Q_{qtqb}^{(8)} : (\bar{q}^j T^A t)\epsilon_{jk}(\bar{q}^k T^A b)$$

<u>class 8</u>

(four-fermion)

$8:(\bar{L}R)(\bar{R}L)+\mathrm{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8:(\bar{L}R)(\bar{L}R)+\mathrm{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
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59+h.c. operators (classified by field content, 8 classes)

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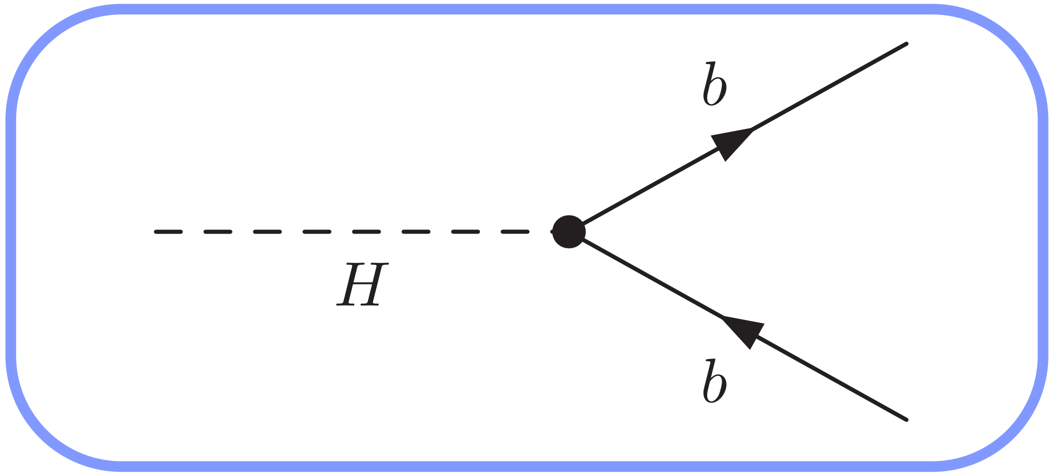
Let's study $h \to b\bar{b}$



$$\Gamma^{\rm SM}_{h\to b\bar{b}} \approx 2.4\ \text{MeV}$$

$$\text{BR}(h \to b\bar{b}) \approx 0.6$$

Experimentally, access through "$\sigma(pp \to h) \cdot \text{BR}(h \to X)$" data

Motivation:

- First and foremost, **easy** theoretically
- Can study QCD and EW corrections
- Largest partial width (in SM)

*Realistically, need a "Higgs-machine" for %-level precision measurements

Interim Kappa-formalism defined in 1307.1347: Section 10

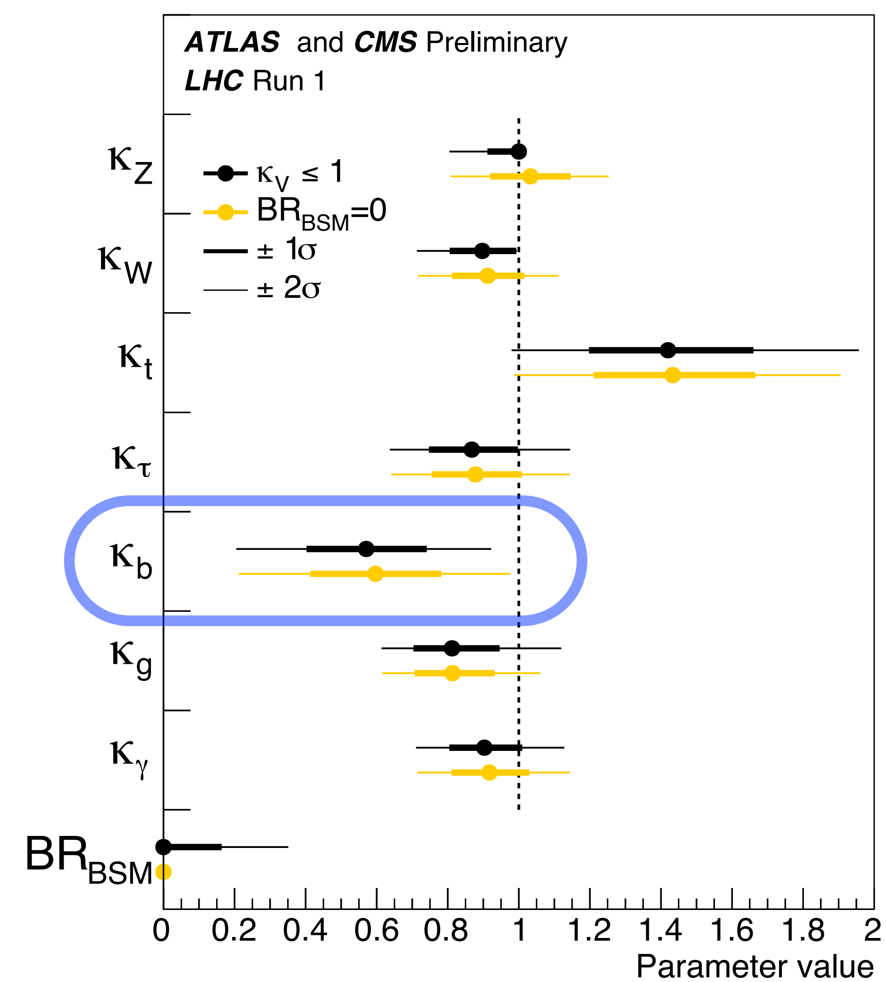


Fig. 14 of ATLAS-CONF-2015-044

Yukawa sector in the SMEFT

Consider the down-type Yukawa interactions in unbroken phase

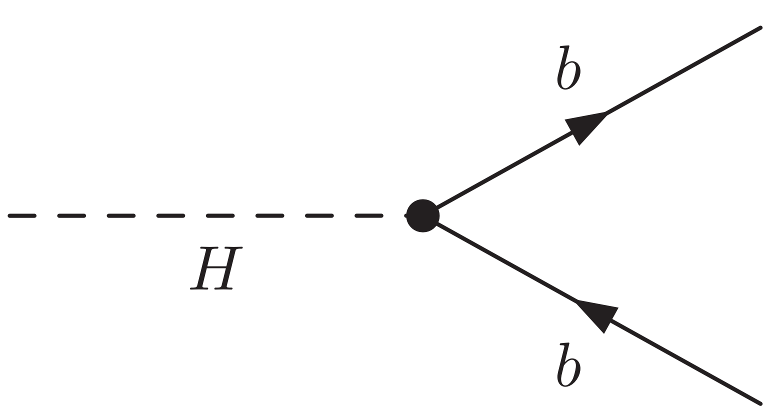
$$\mathcal{L}_d = \left[[Y_d]_{rs} H^{\dagger j} \overline{d}_r \, Q_{sj} + h.c.\right] + \left[C^*_{\substack{dH \\ sr}} (H^\dagger H) H^{\dagger j} \overline{d}_r \, Q_{sj} + h.c.\right]$$

Leads to an effective mass matrix in the broken phase

$$[M_d]_{rs} = \frac{v_T}{\sqrt{2}} \left([Y_d]_{rs} - \frac{v_T^2}{2} C^*_{\substack{dH \\ sr}} \right) \qquad (1)$$

For simplicity, assume SM-like flavour structure

Leads to the following Feynman rule for the $hb\bar{b}$–vertex



$$-\frac{i}{\sqrt{2}} \left(\left[y_b \left[1 + C_{H,\mathrm{kin}}\right] - \frac{3}{2} v_T^2 C^*_{bH} \right] P_L + h.c. \right)$$

From (1), convert into broken phase

$$y_b \to \sqrt{2} \frac{m_b}{v_T} + \frac{v_T^2}{2} C^*_{bH}$$

Compute the partial width

$$d\Gamma = \frac{d\phi_2}{2m_H} \sum |\mathcal{M}_{h\to b\bar{b}}|^2$$

Compute the Born amplitude (use Feynman rule from last slide)

$$\mathcal{M}^{\rm tree}_{h\to b\bar{b}} = -i\bar{u}(p_b)\left(\mathcal{M}^{\rm tree}_L P_L + \mathcal{M}^{\rm tree *}_L P_R\right) v(p_{\bar{b}})$$

where $$\mathcal{M}^{\rm tree}_L = \frac{m_b}{v_T}\left[1 + C_{H,\rm kin}\right] - \frac{v_T^2}{\sqrt{2}} C^*_{bH} + \mathcal{O}(\Lambda^{-4}_{\rm NP})$$

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

EFT $$\boxed{\Gamma^{(6,0)} = \left(2C_{H,\text{kin}} - \frac{\sqrt{2}v_T^3}{m_b} C_{bH}\right)\Gamma^{(4,0)} + \mathcal{O}(\Lambda^{-4}_{\text{NP}})}$$

Compute the partial width

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where $$\mathcal{M}^{\text{tree}}_L = \frac{m_b}{v_T}\left[1 + C_{H,\text{kin}}\right] - \frac{v_T^2}{\sqrt{2}} C^*_{bH} + \mathcal{O}(\Lambda_{\text{NP}}^{-4})$$

(4 = SM, 0 = LO)

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

*More realistic UV completion

$$\tilde{Q}_{bH} = y_b\left(H^\dagger H\right)\left(\bar{q}_L b_R H\right)$$

see: J. Elias-Mero et al. 1308.1879

EFT $$\Gamma^{(6,0)} = \left(2C_{H,\text{kin}} - 2v_T^2 \boxed{\frac{C_{bH}}{y_b}}\right)\Gamma^{(4,0)} + \mathcal{O}(\Lambda_{\text{NP}}^{-4})$$

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$$\mathcal{M}^{\text{tree}}_{h\to b\bar{b}} = -i\bar{u}(p_b)\left(\mathcal{M}^{\text{tree}}_L P_L + \mathcal{M}^{\text{tree}*}_L P_R\right) v(p_{\bar{b}})$$

where $$\mathcal{M}^{\text{tree}}_L = \frac{m_b}{v_T}\left[1 + C_{H,\text{kin}}\right] - \frac{v_T^2}{\sqrt{2}} C^*_{bH} + \mathcal{O}(\Lambda_{\text{NP}}^{-4})$$

Evaluate numerically: $\{m_b = 4.5, m_h = 125, v_T \approx 246\}$ GeV

SM $$\Gamma^{(4,0)} \approx 5 \text{ MeV}$$

*More realistic UV completion

$$\tilde{Q}_{bH} = y_b \left(H^\dagger H\right)\left(\bar{q}_L b_R H\right)$$

see: J. Elias-Mero et al. 1308.1879

EFT $$\Gamma^{(6,0)} \approx \left(\frac{v_T}{\Lambda_{\text{NP}}}\right)^2 \left[2\bar{C}_{H,\text{kin}} - 2\boxed{\frac{\bar{C}_{bH}}{y_b}}\right] \Gamma^{(4,0)} + \ldots$$

$$\bar{C}_{bH} = \Lambda_{\text{NP}}^2 C_{bH}$$

Compute the partial width

$$d\Gamma = \frac{d\phi_2}{2m_H} \sum |\mathcal{M}_{h\to b\bar{b}}|^2$$

Compute the Born amplitude (use Feynman rule from last slide)

$$\mathcal{M}^{\text{tree}}_{h\to b\bar{b}} = -i\bar{u}(p_b)\left(\mathcal{M}^{\text{tree}} P_L + \mathcal{M}^{\text{tree}*} P_R\right) v(p_{\bar{b}})$$

where $\mathcal{M}$ ... $_H + \mathcal{O}(\Lambda_{\text{NP}}^{-4})$

Can think of it as a shift of SM:

$$\Gamma^{\text{LO}} \approx \Gamma^{(4,0)} \left(1 + 2\left[\frac{v_T}{\Lambda_{\text{NP}}}\right]^2 \bar{C}\right)$$

Evaluate numeri ... $246\}$ GeV

SM $\quad \Gamma^{(4,0)} \approx 5\ \text{MeV}$

...ompletion

$$\tilde{Q}_{bH} = y_b \left(H^\dagger H\right)\left(\bar{q}_L b_R H\right)$$

see: J. Elias-Mero et al. 1308.1879

EFT $\quad \Gamma^{(6,0)} \approx \left(\frac{v_T}{\Lambda_{\text{NP}}}\right)^2 \left[2\bar{C}_{H,\text{kin}} - 2\boxed{\frac{\bar{C}_{bH}}{y_b}}\right] \Gamma^{(4,0)} + \ldots$

$$\bar{C}_{bH} = \Lambda^2_{\text{NP}} C_{bH}$$

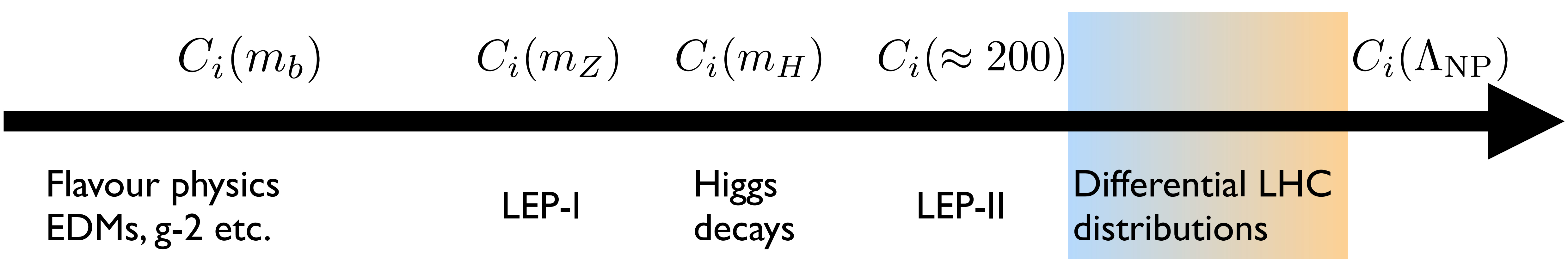
Are we done? Going beyond LO?

It's not difficult to compute observables at LO in the SMEFT
Do a global fit to LHC/LEP/Low energy Observables at LO? NO!

1) E.g. this decay constrains: $C_{bH}(m_H)\,, C_{H,\mathrm{kin}}(m_H)$

- the Wilson coefficients are scale dependent and mix
- must be taken into account when performing a global fit to data (full RGE is known*)

*1-loop anomalous dimension: (Alonso) Jenkins, Manohar, Trott : 1308.627, 1310.4838, (1312.2014)



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2) The SMEFT is like the SM (or other UV completions) where are perturbative expansion is applied

- higher-orders give better precision*
- the Wilson coefficients which appear at one-loop may not be present in tree-level observables (e.g. maybe poorly constrained Wilson coefficients)
- new diagrams appear

*There is a substantial theoretical effort in this direction (QCD/EW) by many groups

Interim

- Computing $h \to b\bar{b}$ at NLO (w/ B.D. Pecjak, D.J.Scott)
    - General approach
    - QCD corrections
    - Vanishing gauge coupling corrections

- Other progress and conclusions

Renormalisation I (field/parameter)

Perform field and parameter renormalisation on-shell*

- Choose a set of independent parameters

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

- Write bare parameters/fields as a combination of renormalised parameters and renormalisation constants:

$$f_L^{(0)} = \sqrt{Z_f^L}\, f_L = \left(1 + \frac{1}{2}\delta Z_f^L\right) f_L$$

- Fix the counterterms with renormalisation conditions (e.g. on-shell)

$$\begin{aligned}\delta Z_f^L = &- \widetilde{\mathrm{Re}}\,\Sigma_f^L(m_f^2) + \Sigma_f^S(m_f^2) - \Sigma_f^{S*}(m_f^2) \\ &- m_f^2 \frac{\partial}{\partial p^2}\widetilde{\mathrm{Re}}\left[\Sigma_f^L(p^2) + \Sigma_f^R(p^2) + \Sigma_f^S(p^2) + \Sigma_f^{S*}(p^2)\right]\Big|_{p^2=m_f^2}\end{aligned}$$

- Express physical quantities in terms of renormalised parameters

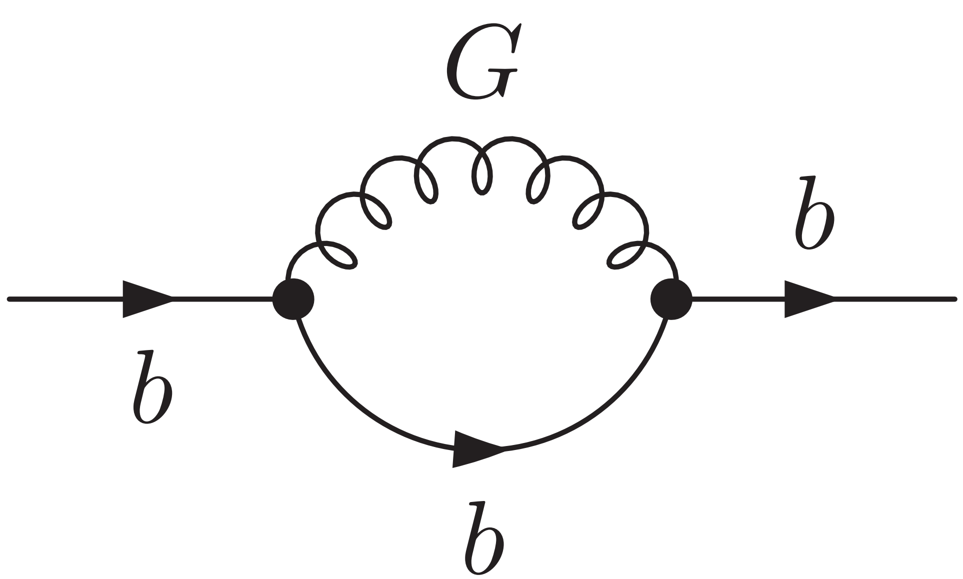
$$\Gamma^{(4,0)} = \frac{N_c m_h m_b^2 \beta^3}{8\pi v_T^2} \to \frac{N_c m_h m_b^2 \bar{e}^2 \beta^3}{32\pi M_W^2 (1 - M_W^2/M_Z^2)}$$

- Fix input values for renormalised parameters with data

*see [Denner - 0709.1075]

Renormalisation I (field/parameter)

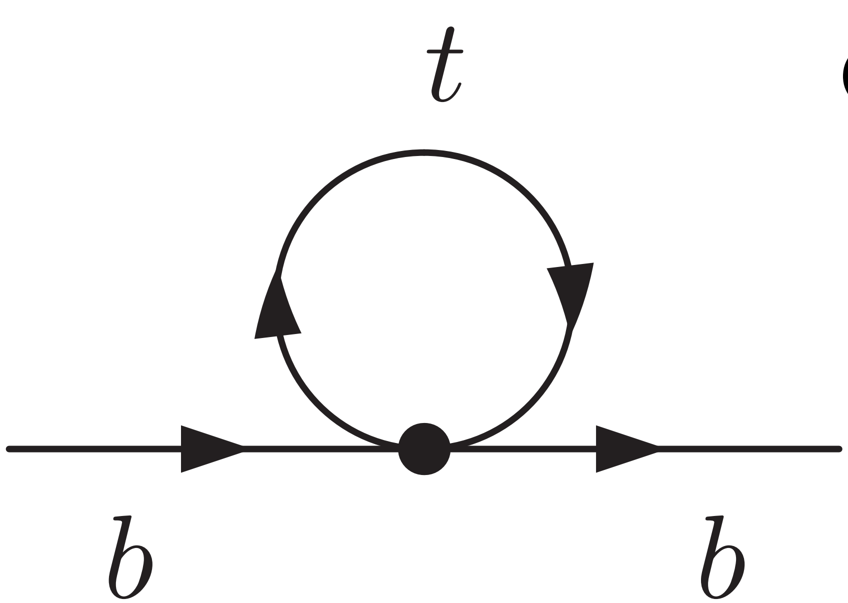
Perform field and parameter renormalisation on-shell*



Usual SM piece

$$\frac{\delta m_b}{m_b} \propto -\frac{\alpha_s C_F C_\epsilon^b}{\pi}\left[\boxed{\frac{m_b v_T}{\sqrt{2}}\left(\frac{3}{\hat{\epsilon}}+1\right) Re\left\{C_{bG}\right\}} + \boxed{\left(\frac{3}{4\hat{\epsilon}}+1\right)}\right]$$

Generated by $Q_{bG} : g_s(\bar{q}\sigma^{\mu\nu}T^A b)HG^A_{\mu\nu}$



Generated by four-fermion operators (bbtt)

$$\frac{\delta m_b}{m_b} \propto \frac{m_t^3 C_\epsilon^t}{m_b}\left(\frac{1}{\hat{\epsilon}}+1\right)\left[(2N_c+1)Re\left\{C^{(1)}_{qtqb}\right\} + C_F Re\left\{C^{(8)}_{qtqb}\right\}\right]$$

$$\frac{1}{\hat{\epsilon}} = \frac{1}{\epsilon} - \gamma_E + ln(4\pi)$$

$$C_\epsilon^f = 1 + \epsilon\, ln\left[\frac{\mu^2}{m_f^2}\right]$$

*see [Denner - 0709.1075]

Renormalisation II (Operators)

Fortunately, can use the results of the full one-loop anomalous dimension calculation performed in the un-broken phase:

[(Alonso) Jenkins, Manohar, Trott : 1308.2627, 1310.4838, (1312.2014)]

$$C_i^{(0)} = C_i(\mu) + \delta C_i(\mu) = C_i(\mu) + \frac{1}{2\hat{\epsilon}} \frac{\dot{C}_i(\mu)}{(4\pi)^2}$$

$$\frac{\dot{C}_i(\mu)}{(4\pi)^2} \equiv \mu \frac{d}{d\mu} C_i(\mu)$$

1. Check which operators appear at tree-level (e.g. C_{bH})
2. Take the relevant Lambda/Yukawa/Gauge dependent terms
3. Convert to broken phase using LO SM relations, e.g.

$$y_f \to \frac{\sqrt{2} m_f}{v_T}, \quad \lambda \to \frac{m_H^2}{2 v_T^2}$$

The combination of field/parameter/wilson coefficient renormalisation allows to construct the necessary 1-loop UV CTs

QCD corrections

See RG, Ben D. Pecjak, D. J. Scott - 1607.06354

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

Relevant operators

$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Appear at tree-level
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$	
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$	New vertices: QHG - hgg QdG - hbbg
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$	
Q_{dG}	$g_s(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$	

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See RG, Ben D. Pecjak, D. J. Scott - 1607.06354

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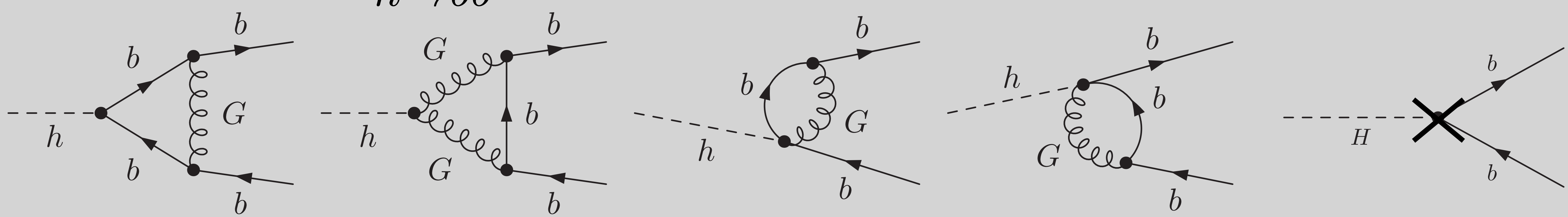
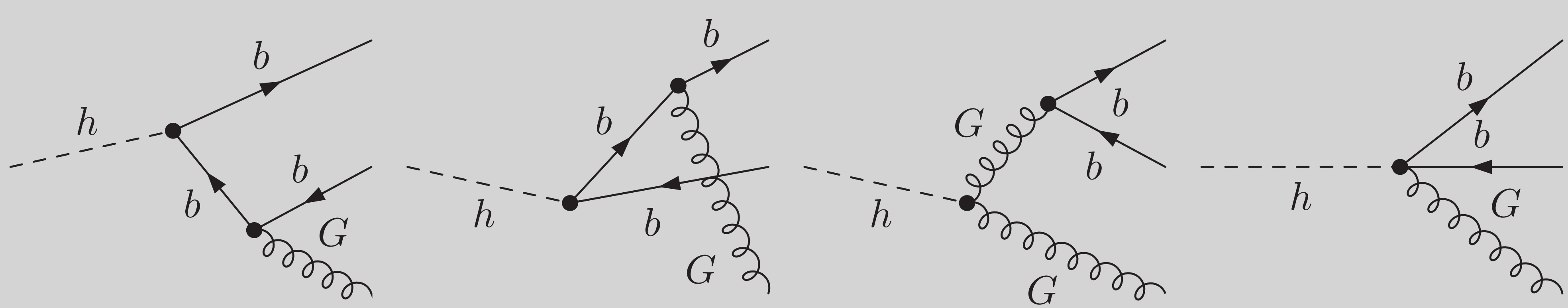
$$\mathcal{M}_{h\to b\bar{b}} = \mathcal{M}^{\mathrm{one-loop}} + \mathcal{M}^{\mathrm{C.T.}} + \mathcal{M}^{\mathrm{tree}}$$



1 2 3 4 5

$$\mathcal{M}_{h\to b\bar{b}g}$$



1 2 3 4

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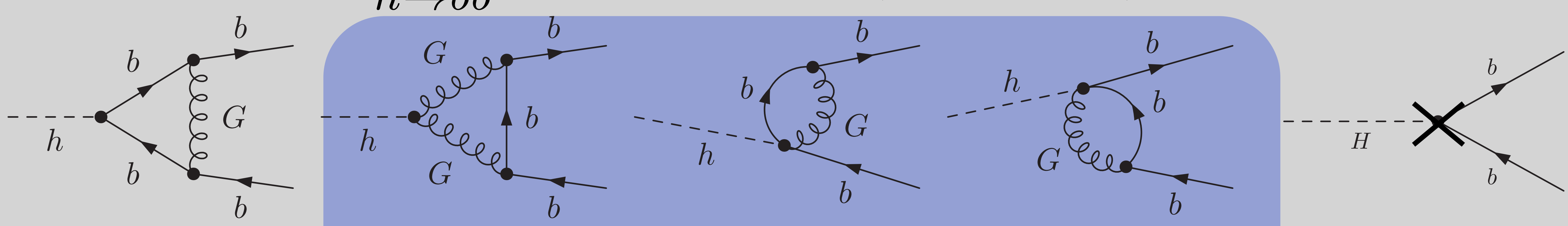

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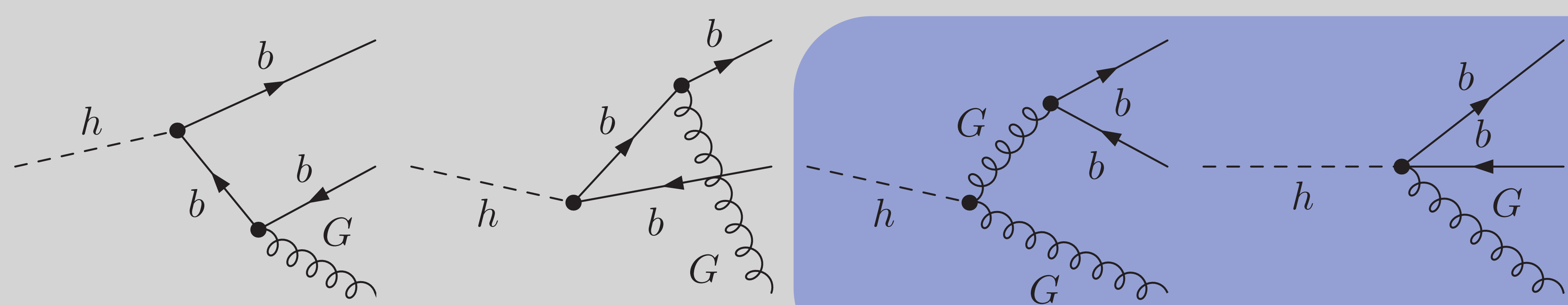
$$\mathcal{M}_{h\to b\bar{b}g}$$



1 2 3 4

QCD corrections

See RG, Ben D. Pecjak, D. J. Scott - 1607.06354

(Answer in MSbar scheme for b-quark mass, and limit $\beta \to 1$)

Proportional to NLO SM result

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

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

$$+ \frac{\alpha_s C_F}{\pi}\frac{N_c m_h \overline{m}_b^2}{8\pi} C_{HG}\left(19 - \pi^2 + \ln^2\left[\frac{\overline{m}_b^2}{m_h^2}\right] + 6\ln\left[\frac{\mu^2}{m_h^2}\right]\right)$$

Contributions from new diagrams

QCD corrections

See RG, Ben D. Pecjak, D. J. Scott arXiv:1607.06354

(Answer in MSbar scheme for b-quark mass, and limit $\beta \to 1$)

*More realistic UV completion

$$\tilde{Q}_{bH} = y_b \left(H^\dagger H\right)\left(\bar{q}_L b_R H\right)$$

see: J. Elias-Mero et al. 1308.1879

$$\overline{\Gamma}^{(6)}_{\beta\to 1} = \left(\frac{v_T}{\Lambda_{\rm NP}}\right)^2 \left(5.33\bar{C}_{H,\rm kin} - 5.33\boxed{\frac{\bar{C}_{bH}}{y_b}}\right)\ \text{MeV} + \left(\frac{v_T}{\Lambda_{\rm NP}}\right)^2 \left(1.57\bar{C}_{bG} + 6.91\bar{C}_{HG}\right)\ \text{MeV}$$

$$@\mu = m_H$$

$$\bar{C}_i = \Lambda^2_{\rm NP} C_i$$

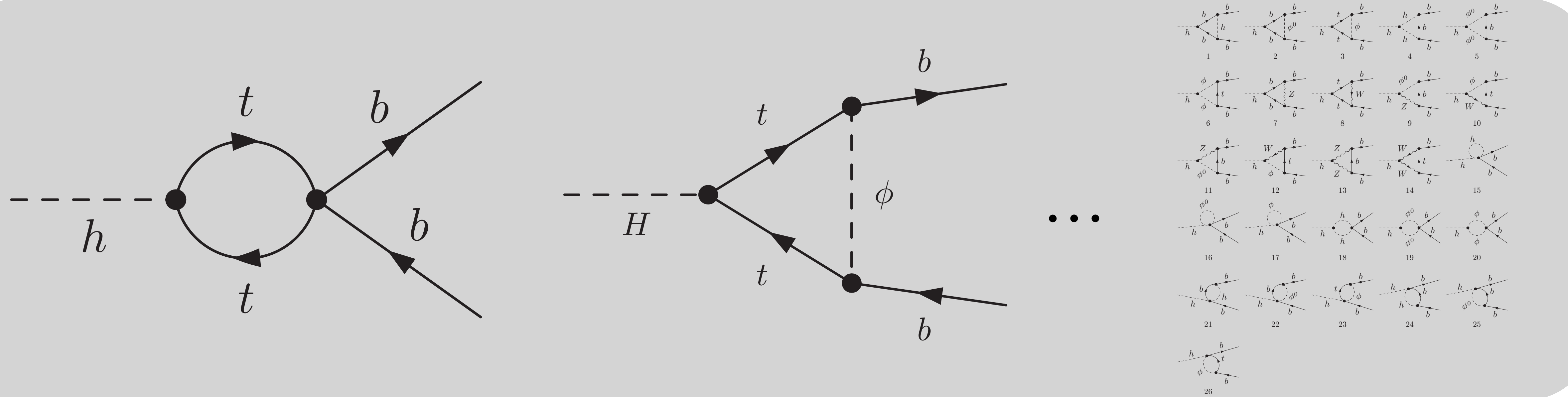
$$\frac{1}{y_b(m_H)} \approx 60$$

- QCD corrections involving C_{HG} and C_{bG} important
- C_{bH}, $C_{H,\rm kin}$ contributions - should scale by N4LO SM QCD
- If C_{bH} $\mathcal{O}(1)$, only sensitive to this effective operator

$$\bar{C}_{H,\rm kin} = \left(C_{H\Box} - \frac{1}{4}C_{HD}\right)\Lambda^2_{\rm NP}$$

Vanishing gauge coupling corrections

See RG, Ben D. Pecjak, D. J. Scott arXiv:1512.02508

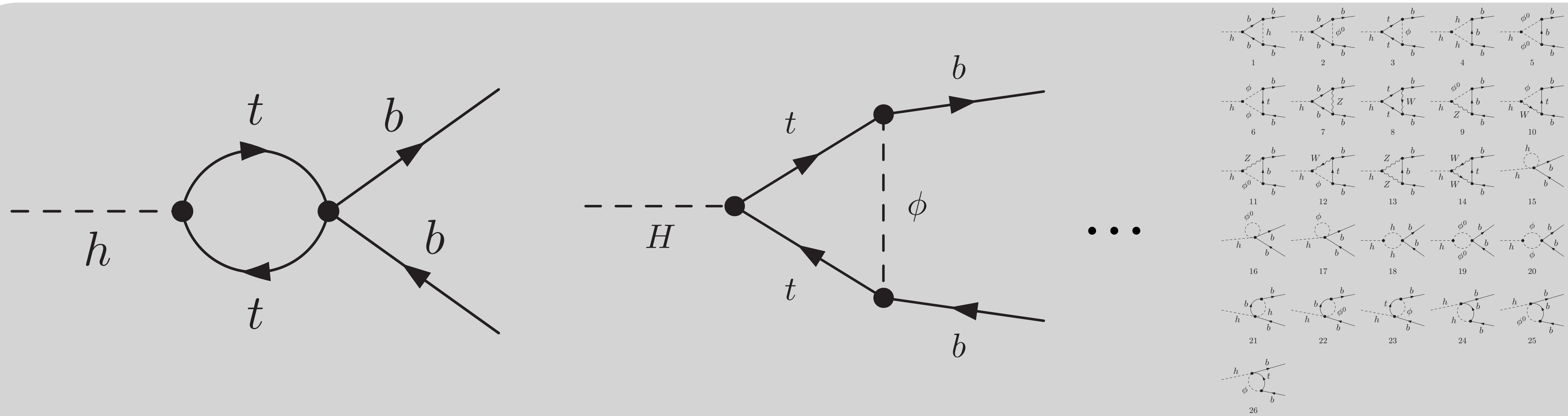


Again, proceeds in a similar way to the SM calculation

unbroken phase	broken phase
$\{y_i\,, g_i, \lambda, C_i\}$	$\{\bar{e},\, g_s\,, m_f,\, M_W,\, M_Z,\, m_H,\, C_i\}$
$\downarrow$ Apply vanishing gauge couplings	$\downarrow$
$\{y_i,\, \lambda,\, C_i\}$	$\{m_f,\, \bar{e}/M_W,\, \bar{e}/M_Z,\, m_H,\, C_i\}$

Vanishing gauge coupling corrections

See RG, Ben D. Pecjak, D. J. Scott arXiv:1512.02508



Much more complicated, over 20 operators contribute

$$\overline{\Gamma}^{(6)QCD}_{\beta\to1} = \left(\frac{v_T}{\Lambda_{\rm NP}}\right)^2\left(-5.33\frac{\bar{C}_{bH}}{y_b}+1.57\bar{C}_{bG}+6.91\bar{C}_{HG}\right)\ \mathrm{MeV} \qquad @\mu = m_H$$

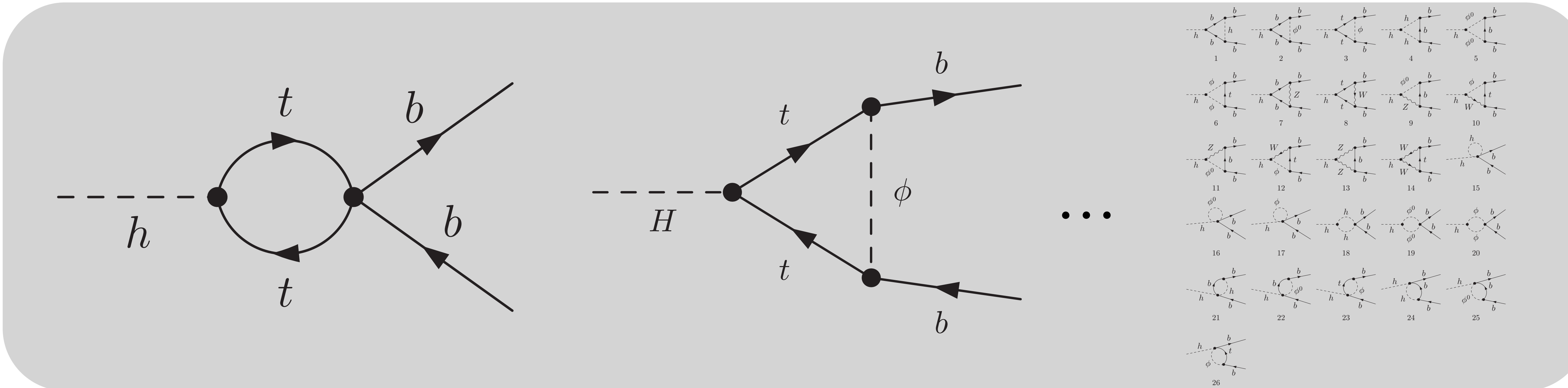
$$\overline{\Gamma}^{(6)QCD+EW}_{\beta\to1} = \left(\frac{v_T}{\Lambda_{\rm NP}}\right)^2\left(\boxed{-5.46}\frac{\bar{C}_{bH}}{y_b}+1.57\bar{C}_{bG}+6.91\bar{C}_{HG}+\boxed{0.02\frac{\bar{C}_{Htb}}{y_by_t}+0.08\frac{\bar{C}^{(1)}_{qtqb}}{y_by_t}+}\ldots\right)\ \mathrm{MeV}$$

assume operators scales as

$$\tilde{Q}^{(1)}_{qtqb} = y_b y_t(\bar{q}^j_3 t)\epsilon_{jk}(\bar{q}^k_3 b)$$

Vanishing gauge coupling corrections

See RG, Ben D. Pecjak, D. J. Scott arXiv:1512.02508



Much more complicated, over 20 operators contribute

$$\bar{\Gamma}^{(6)QCD}_{\beta\to 1} = \left(\frac{v_T}{\Lambda_{\mathrm{NP}}}\right)^2 \left(-5.33\frac{\bar{C}_{bH}}{y_b} + \right.$$

$$\bar{\Gamma}^{(6)QCD+EW}_{\beta\to 1} = \left(\frac{v_T}{\Lambda_{\mathrm{NP}}}\right)^2 \left(\boxed{-5.46}\frac{\bar{C}_{bH}}{y_b} + \right.$$

QCD corrections N4LO

[P.A. Baikov, K.G. Chetyrkin, J.H. Kühn - 0511063

$$\kappa_{\mathrm{QCD}} = 1 + 0.208 + 0.039 + 0.002 - 0.001$$

$$\boxed{0.03 \sim \frac{\sqrt{2}G_F}{(4\pi)^2}\left(12m_H^2 + (6N_c - 3)m_t^2\right) ln\left[\frac{m_t}{m_H}\right]}$$

Summary of QCD + ~EW corrections

- QCD corrections for C_{bH} = those in SM (known to N4LO)
  [P.A. Baikov, K.G. Chetyrkin, J.H. Kühn - 0511063]

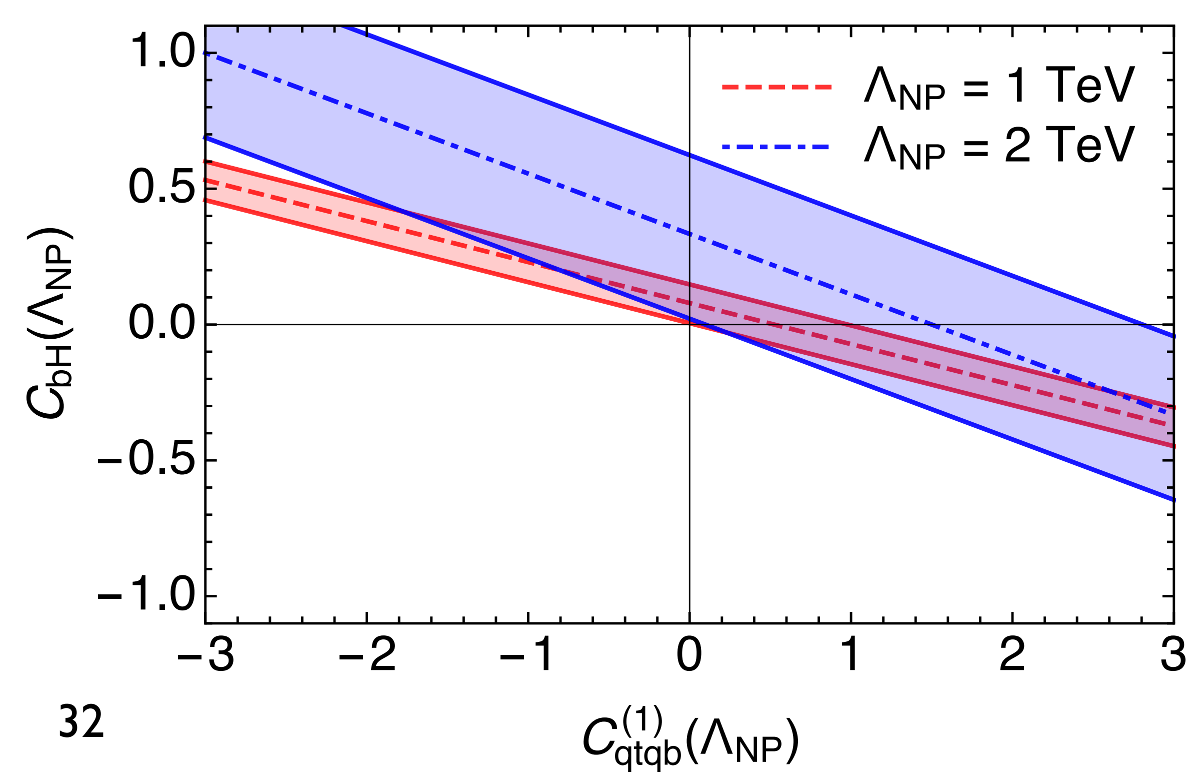
  and implemented in eHDecay
  [R. Cotino et al. - 1403.3381, 1303.3876]

- Yukawa and Lambda corrections for C_{bH} ~ N2LO QCD ones
  [RG et al. - 1512.02508]

- Under the assumption of MFV-like scaling of C_{bH}, the NLO corrections involving operators such as C_{HG}, C_{bG} important
  A scaling of the effective Hbb-vertex (kappa) not appropriate
  [RG et al. - 1607.06354]

- Else: Higgs signal strength measurement already constrains $C_{bH}(m_H)$

Can interpret this in terms of
$C_{bH}(\Lambda_{\rm NP}), C^{(1)}_{qtqb}(\Lambda_{\rm NP})$



Other progress in SMEFT at NLO

Automation: QCD corrections with MG5_aMC@NLO:

[O. B. Bylund, C. Degrande, G. Durieux, D. B. Franzosi, F. Maltoni, I. Tsinikos, E. Vryonidou, J. Wang, C. Zhang] - see ICHEP talk of Cen Zhang here (focus on top-quark sector)

Other QCD corrections:

Double Higgs production [R. Grober, M. Muhlleitner, M. Spira, J. Steircher - 1504.06577]

Progress in full/partial electroweak corrections:

$\mu \to e\gamma$ [G. M. Pruna, A. Signer - 1408.3565]

$h \to \gamma\gamma$ [C. Hartmann, M. Trott - 1505.02646, 1507.03568]

$h \to VV^{(*)}$ [M. Ghezzi, R. Gomez-Ambrosio, G. Passarino, S. Uccirati - 1505.0370]

$h \to b\bar{b}(\tau\bar{\tau})$ [RG, B. D. Pecjak, D. J. Scott - 1512.02508, 1607.06354], vanishing g1, g2

$gg \to h$ [M. Gorbahn, U. Haisch - 1607.03773], lambda dependence@2-loop

$h \to \gamma\gamma$

. . . If I have missed some, apologies and please let me know!

Haven't even mentioned:

- Several partial/complete SMEFT anomalous dimension calculations
- Global fits, and several important works on input parameter schemes choices

See yellow report for review [G. Passarino, M. Trott - cds.cern.ch/record/2138031]

Back-ups

Relevant generalities of the SMEFT

Usual SM relations between parameters altered

For example, the shape of the scalar potential

$$V(H) = \lambda \left(H^\dagger H - \frac{v^2}{2} \right)^2 - C_H \left(H^\dagger H \right)^3$$

Yielding the minimum:

$$\langle H^\dagger H \rangle = \frac{v^2}{2} \left(1 + \frac{3 C_H v^2}{4\lambda} \right) \equiv \frac{v_T^2}{2}$$

Higgs field in general gauge:

$$H(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} -\sqrt{2} i \phi^+(x) \\ \left[1 + C_{H,\text{kin}}\right] h(x) + i \left[1 - \frac{v^2}{4} C_{HD}\right] \phi^0(x) + v_T \end{pmatrix}$$

*Normalisation of fields in $H(x)$ to fix Higgs kinetic terms

$$C_{H,\text{kin}} \equiv \left(C_{H\Box} - \frac{1}{4} C_{HD} \right) v_T^2$$

Choice of input parameters/vev

$$\frac{1}{v_T} = \frac{1}{\hat{v}_T} + \frac{\hat{c}_W}{\hat{s}_W}\left(C_{HWB} + \frac{\hat{c}_W}{4\hat{s}_W}C_{HD}\right)\hat{v}_T$$

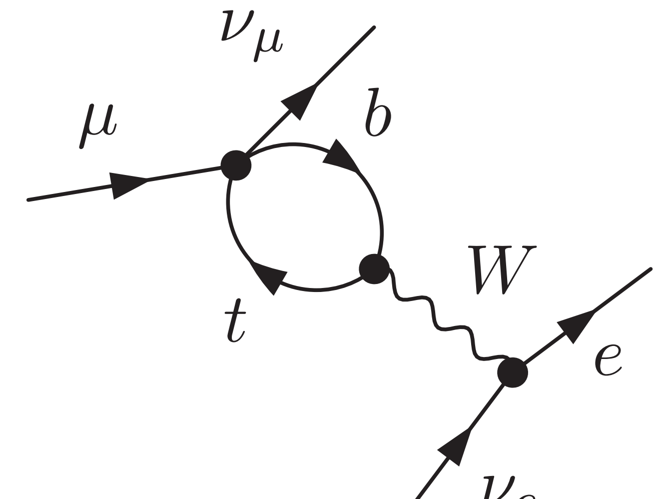
where $\hat{v}_T \equiv \frac{2M_W\,\hat{s}_w}{\bar{e}}$; $\hat{s}^2_w \equiv 1 - \frac{M_W^2}{M_Z^2}$, $\hat{c}^2_w \equiv 1 - \hat{s}^2_w$

Renormalise vev with $\{M_W, M_Z, \bar{e}, C_{HWB}, C_{HD}\}$ RC

In practice, eliminate MW dependence in favour GFermi using the precise measurement from Muon decay

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

At NLO, must also compute finite matching corrections! Partial results in 1512.02508



The running b-quark mass

In Higgs decay, resum the Log[mb/mh] with the running b-mass

- Convert decay rate into MSbar for b-quark mass (drop finite del m)
- Find the LL solution for the b-quark mass. Eg: for the QCD corrections

Pole/MSbar conversion: $m_b = \overline{m}_b(\mu)\left(1 - \delta_m(\mu)\right)$

$$\delta_m^{(4)}(\mu) = -\frac{\alpha_s C_F}{\pi}\left(1 + \frac{3}{4}\ln\left[\frac{\mu^2}{\overline{m}_b^2}\right]\right)$$

SM

$$\delta_m^{(6)}(\mu) = -\frac{\alpha_s C_F}{\pi}\frac{v_T \overline{m}_b}{\sqrt{2}} C_{bG}\left(1 + 3\ln\left[\frac{\mu^2}{\overline{m}_b^2}\right]\right)$$

EFT

Must solve: $$\frac{d\,\overline{m}_b}{d\ln(\mu)} = -\frac{\alpha_s C_F}{\pi}\frac{3}{2}\overline{m}_b\left(1 + 2\sqrt{2} v_T \overline{m}_b C_{bG}\right) + \mathcal{O}(\alpha_s^2)$$

Find solution for CbG, then we find simple analytic formula

$$\overline{m}_b(\mu) = \overline{m}_b(\mu_0)\left(\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\right)^{\frac{\gamma_m^0}{\beta_0}}\left(1 + \frac{2\sqrt{2}v_T}{\gamma_m^0 + \gamma_c^0}\left[\overline{m}_b^{(4)}(\mu)C_{bG}(\mu) - \overline{m}_b^{(4)}(\mu_0)C_{bG}(\mu_0)\right]\right)$$

$$\gamma_C^0 = -\frac{5C_F - 2N_c}{4} \qquad \gamma_m^0 = \frac{3}{4}C_F$$

Anomalous dimension example

QCD corrections

$$\delta C_{bH} = \frac{\alpha_s C_F}{\pi} \frac{3}{v_T^2} \frac{1}{\hat{\epsilon}} \times \left(2m_b^2 C_{bG} + v_T \left(\sqrt{2} m_b C_{HG} - \frac{v_T}{4} C_{bH} \right) \right)$$

Yukawa and Lambda corrections

$$\begin{aligned}
\frac{v_T^2}{\sqrt{2}} \delta C_{bH} = \frac{1}{\epsilon} \frac{1}{v_T} \Bigg[& - m_b \left(6m_b^2 + m_H^2\right) \frac{C_{H,\mathrm{kin}}}{v_T^2} + \frac{1}{4} m_b \left(2m_b^2 - m_H^2\right) C_{HD} \\
& + \frac{v_T}{2\sqrt{2}} \Big((10N_c + 21) m_b^2 + 12 m_H^2 + (6N_c - 3) m_t^2 + 6 m_\tau^2 \Big) C_{bH} \\
& - \frac{(3 - 2N_c) v_T m_b m_t C_{tH}}{\sqrt{2}} + \sqrt{2} v_T m_b m_\tau C_{\tau H} - 4 m_b m_\tau^2 C_{H\tau}^{(3)} \\
& - m_b \left(4N_c m_b^2 - 3m_H^2 + (4N_c - 6) m_t^2\right) C_{Hq}^{(3)} + m_b \left(2m_b^2 + m_H^2\right) \left(C_{Hq}^{(1)} - C_{Hb} \right) \\
& - m_t \left(-4N_c m_b^2 + m_H^2 + 2m_t^2\right) C_{Htb} \Bigg] + \frac{v_T^2}{\sqrt{2}} \delta C_{bH}^{(4f)}
\end{aligned}$$