FlexibleDecay: Towards an automated computation of Higgs boson decays

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Motivation

- The Higgs is the only measurement we can do in BSM models

Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.27×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$	2.62×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$	2.14×10^{-1}	$^{+4.3\%}_{-4.2\%}$
$H \to \tau^+\tau^-$	6.27×10^{-2}	$^{+5.7\%}_{-5.7\%}$
$H \to b\bar{b}$	5.84×10^{-1}	$^{+3.2\%}_{-3.3\%}$
$H \to Z\gamma$	1.53×10^{-3}	$^{+9.0\%}_{-8.9\%}$
$H \to \mu^+\mu^-$	2.18×10^{-4}	$^{+6.0\%}_{-5.9\%}$

- Different channels require different level of precision
- Experiments measure branching ratios. Theorists calculates widths. The largest width has to computed with highest precision. Those turn out to be the tree-level decays.

Tree decays into heavy quarks

- Most important channels are h→ZZ, h→$W^+ W^-$, h→$b\bar{b}$
  - h→ZZ, h→$W^+ W^-$: pure tree-level, including single off-shell contributions. Possibility to include double off-shell contributions if needed.
  - h→$b\bar{b}$: mixed on-shell/$\overline{\text{MS}}$ calculation including mass effects up to NLO in α_s
- One-loop calculation with massive quarks

$$\Gamma(X \to q\bar{q}) = \frac{\sqrt{\lambda\left(1, \frac{m_q^2}{m_X^2}, \frac{m_q^2}{m_X^2}\right)}}{16\pi m_H} |\mathcal{A}_{X\to FF}|^2 \left(1 + C_F \frac{\alpha}{\pi} \Delta_X\right)$$

$$\Delta_H(\beta) = \frac{1}{\beta} A(\beta) + \frac{1}{16\beta^3}(3 + 34\beta^2 - 13\beta^4) \log \frac{1+\beta}{1-\beta} + \frac{3}{8\beta^2}(7\beta^2 - 1)$$

$$\mathrm{A}(\beta) = (1+\beta^2)\left[4\left(\tfrac{1-\beta}{1+\beta}\right) + 2\left(-\tfrac{1-\beta}{1+\beta}\right) - 3\log\left(\tfrac{1+\beta}{1-\beta}\right)\log\tfrac{2}{1+\beta}\right.$$
$$\left. -2\log\tfrac{1+\beta}{1-\beta}\log\beta\right] - 3\beta\log\tfrac{4}{1-\beta^2} - 4\beta\log\beta$$

- This work well if β≃0. For β≃1

$$\Delta_H \approx \tfrac{9}{4} - \tfrac{3}{2}\log\tfrac{m_H^2}{m_q^2}$$

Tree-level decays into light quarks

- Generic expression

$$\Gamma^{\text{light}}(X \to q_i \bar{q}_i) = \frac{\sqrt{\lambda\left(1, \frac{\hat{m}_q^2}{m_X^2}, \frac{\hat{m}_q^2}{m_X^2}\right)}}{16\pi m_H} |\mathcal{A}_{X\to q_i\bar{q}_i}|^2 (1 + \Delta_{qq}^{\text{QCD}} + \Delta_{qq}^{\text{QED}} + \Delta_X^2)$$

- 4-loop corrections in massless QCD [Chetyrkin, Baikov, Kühn]

$$\Delta_{qq}^{\text{QCD}} = \frac{17}{3}\frac{\alpha_s}{\pi} + (35.94 - 1.36 N_f)\frac{\alpha_s^2}{\pi^2} + (164.14 - 25.77 N_f + 0.259 N_f^2)\frac{\alpha_s^3}{\pi^3}$$
$$+ (39.34 - 220.9 N_f + 9.685 N_f^2 - 0.0205 N_f^3)\frac{\alpha_s^4}{\pi^4}$$

- Chiral breaking corrections

$$\Delta_H^2 = \frac{\alpha_s^2(m_H)}{\pi^2}\left(1.57 - \frac{2}{3}\log\frac{m_H^2}{m_q^2} + \frac{1}{9}\log^2\frac{m_q^2}{m_H^2}\right)$$

Mixed on-shell/$\overline{\text{MS}}$ expression

- Interpolation between two regimes [HDECAY]

$$\Gamma(X \to qq) = \left(1 - \frac{4m_q^2}{m_X^2}\right) \Gamma^{\text{light}}(X \to qq) + \frac{4m_q^2}{m_X^2} \Gamma^{\text{heavy}}(X \to qq)$$

  - where for light quarks

$$\Gamma^{\text{light}}(X \to qq) = \frac{\sqrt{\lambda\left(1, \frac{\hat{m}_q^2}{m_X^2}, \frac{\hat{m}_q^2}{m_X^2}\right)}}{16\pi m_H} |\mathcal{A}_{S\to FF}|^2 \left(1 + C_F \frac{\alpha_s}{\pi} \Delta_X(\hat{\beta}) + \Delta_X^{\text{mass}} + \Delta_X^{\text{QED}} \right.$$
$$\left. + \Delta_X^{\text{QCD}\geqslant 2\text{-loop}} + \Delta_X^{\text{BSM}}\right)$$

  - with

$$\Delta_X^{\text{mass}} = 2\frac{1-10\hat{x}}{1-4\hat{x}} \left(\frac{m_q}{\hat{m}_q^{\text{1-loop}}} - 1\right)$$

  - heavy quarks

$$\Gamma^{\text{heavy}}(X \to qq) = \frac{\sqrt{\lambda\left(1, \frac{m_q^2}{m_X^2}, \frac{m_q^2}{m_X^2}\right)}}{16\pi m_H} |\mathcal{A}_{S\to FF}|^2 \left(1 + \left[C_F \frac{\alpha_s}{\pi} + \frac{\alpha}{\pi}\right] \Delta_X + \Delta_X^{\text{BSM}}\right)$$

Loop-induced decays

- In principle straightforward (only 10 1-loop topologies)
- Generic Analytical expression at the level of particle types like S, F, V, etc… created with FeynArts/FormCalc (4000+ lines of generated code)
- Strategy:
  - Generate appropriate insertions at classes level in MATHEMATICA stage
  - map them to amplitudes at the C++ level
  - Introduce colour factors using modified version of ColorMath package from Malin Sjödahl

Renormalization scheme

- Need for a dedicated renormalization scheme since BSM is heavy
  - On-shell scheme most natural but it's not how spectrum generators work
  - $\overline{\text{MS}}/\overline{\text{DR}}$ features non-decoupling effects
- Dedicated scheme with explicit decoupling properties
  - BSM parameters equal by definition to their SM counterparts at the scale of decaying particle mass
  - no RGEs
- Decay module is agnostic of the scheme. They can be selected at run time.

Our TODO list

- The implementation of tree-level like decays is finished.
- The infrastructure for loop-induced decays is in place. Some corner cases need to be dealt with still.
- Study of the decoupling scheme is not yet started
- FlexibleSUSY has built only 1- and 2-point loop function. For decays we rely on LoopTools. It's not clear how good is it for our use case. There's an independent group working on abstracting away and implementing interfaces to other libraries (e.g. Collier).