Precise predictions for the trilinear Higgs coupling in arbitrary models

predicting κ_λ in *any* model at the one-loop order

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Outline

Motivation: theories and tools

$\lambda_{hhh}^{\text{BSM}}$ in any BSM model at the one-loop level

Outlook: beyond κ_λ

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The SM scalar sector

- SM: $\lambda_{hhh} h^3$ experimentally no (very well) known.
- BSM case: deformation of the scalar potential possible!

$$V_{\mathrm{BSM}}(h,\dots) = \frac{m_h^2}{2} h^2 + 3\frac{m_h^2}{v}\kappa_\lambda^{\mathrm{BSM}} h^3 + 3\frac{m_h^2}{v^2}\kappa_{2\lambda} h^4 + \dots$$

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$\kappa_\lambda^{\text{BSM}}$: describes deviation from SM: $\kappa_\lambda^{\text{BSM}} = \frac{\lambda_{hhh}^{\text{BSM}}}{\lambda_{hhh}^{\text{SM}}}$ in model "BSM".

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- Idea: use $-1 < \kappa_\lambda^{\text{exp.}} < 6.6$ [ATLAS-CONF-2021-052] to constraint "BSM" parameter space.
- Example: "BSM"=THDM (talk by Johannes Braathen)
  $\rightarrow$ **higher-order corrections important**

Higher-order corrections to $\lambda_{hhh}^{\text{BSM}}$

A few studies of the trilinear Higgs self-couplings (i.e. κ_λ) already exists:

- SM [Kanemura et al. '04]
- SM + singlet [Kanemura et al. '16]
- THDM[Kanemura et al. '04][Basler et al. '17][Braathen et al. '19]
- THDM + singlet [Basler et al. '19]
- Triplet extensions [Aoki et al. '18] [Chiang et al. '18]
- MSSM [Brucherseifer et al. '13]
- NMSSM [Dao et al. '13] [Dao et al. '15]

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However, there many more models to explore:

- THDM-variants
- singlet-variants
- extended gauge sectors
- extended fermion sectors
- non-minimal SUSY, e.g. seesaw extensions, dirac gauginos, SplitSUSY, ...
- (+ combinations)
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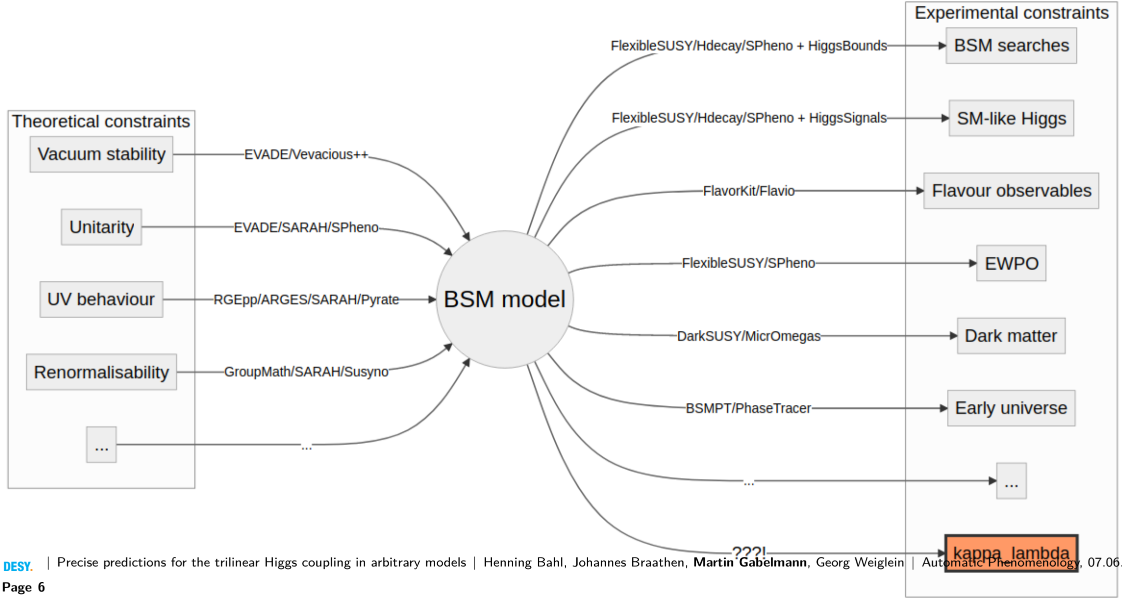
$\rightarrow$ **framework to calculate** $\lambda_{hhh}^{\text{BSM}}$ **for large class of "BSM's"**

$\lambda_{hhh}^{\mathrm{BSM}}$ in the landscape of generic BSM tool-boxes



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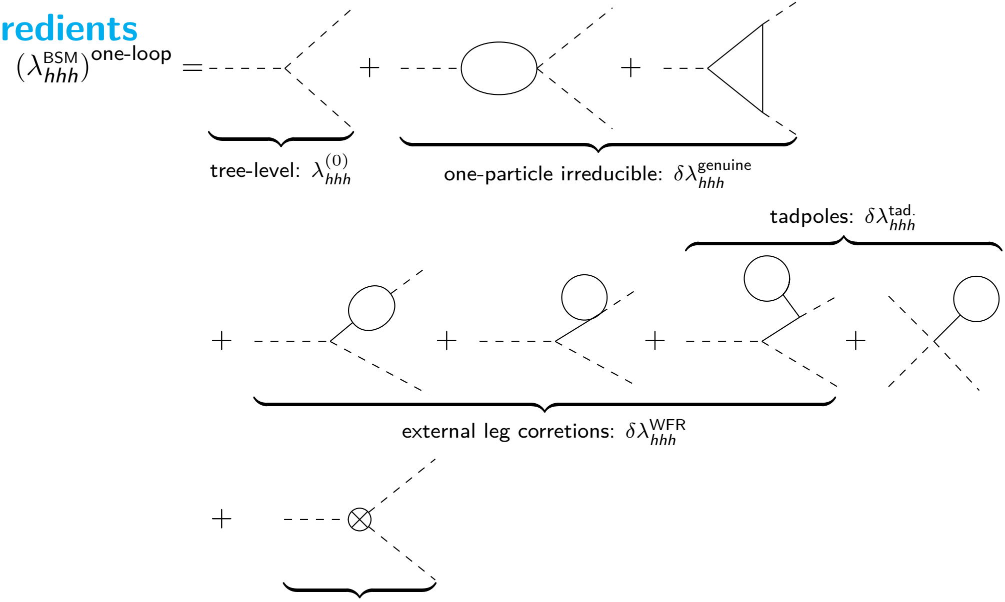
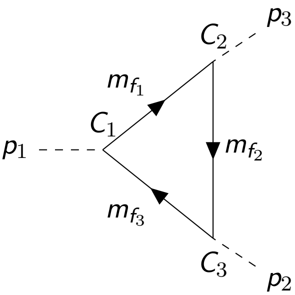
Outlook: beyond κ_λ

Ingredients



Example ingredient: generic fermion triangle

Idea: compute *generic* diagrams i.e. assume most generic



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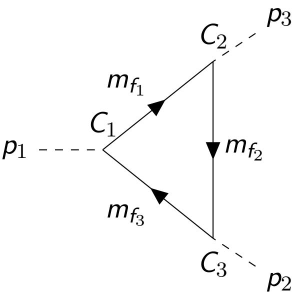

- couplings $C_i = P_L C_i^L + P_R C_i^R$, $P_{R/L} = \frac{1 \pm \gamma_5}{2}$
- as well as loop-masses m_{f_i} and
- external momenta p_i, $i = 1, 2, 3$.

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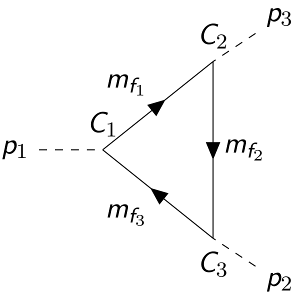

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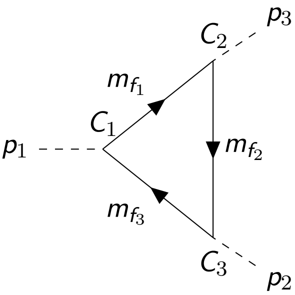

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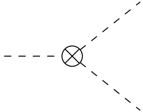
- insert concrete BSM model
- evaluate with the help of `COLLIER` [Denner et al. '16]

Another ingredient: Renormalisation of λ_{hhh}

$\delta\lambda^{\text{CT}}_{hhh} =$  $= \; ?$

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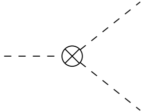
$\delta\lambda^{\mathsf{CT}}_{hhh} =$  $= \;\; ?$

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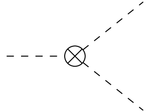
$\delta\lambda^{CT}_{hhh} =$  $= \ ?$

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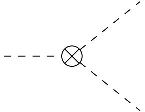
$\delta\lambda_{hhh}^{\text{CT}} =$  $= \ ?$

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$$\lambda_{hhh}^{(0),\text{BSM}} \equiv \lambda_{hhh}^{(0),\text{BSM}}(\underbrace{v^{\text{SM}}, m_h^{\text{SM}}}_{\text{SM Higgs sector}}, m_{H_i}^{\text{BSM}}, v_i^{\text{BSM}}, \ldots)$$

$m_{H_i}^{\text{BSM}}$ → BSM masses

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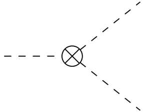
$$\delta\lambda^{\text{CT}}_{hhh} =$$  $$= \quad ?$$

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$m_{H_i}^{\text{BSM}}$ → BSM masses; v_i^{BSM} → vevs; $\ldots$ → couplings etc. (that can't be expressed in terms of masses)

- user's choice:
  - SM sector: fully OS **or** $\overline{\text{MS}}/\overline{\text{DR}}$
  - BSM masses: OS **or** $\overline{\text{MS}}/\overline{\text{DR}}$
  - additional couplings/vevs: most likely $\overline{\text{MS}}$ **but also custom ren. conditions possible!**

$$\delta\lambda^{\text{CT}}_{hhh} = \sum_x \frac{\partial\lambda^{(0),\text{BSM}}_{hhh}}{\partial x}\delta x,\;\; x = (m_h^{SM})^{\text{OS}/\overline{\text{MS}}},\, (v^{\text{SM}})^{\text{OS}/\overline{\text{MS}}},\, (m_{H_i}^{\text{BSM}})^{\text{OS}/\overline{\text{MS}}},\, (\ldots)^{\overline{\text{MS}}/\text{custom}}$$

(Default) Renormalization choice of $(v^{\mathrm{SM}})^{\mathrm{OS}}$ and $(m_i^2)^{\mathrm{OS}}$

- $v^{\mathrm{OS}} \equiv \frac{2M_W^{\mathrm{OS}}}{e}\sqrt{1-\frac{M_W^{2\,\mathrm{OS}}}{M_Z^{2\,\mathrm{OS}}}}$ with
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- attention *(i)*: $\rho^{\text{tree-level}} \neq 1 \rightarrow$ further CTs needed (depends on the model)

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All bosonic one- & two-point functions and their derivatives for general QFTs are required for flexible OS renormalisation.

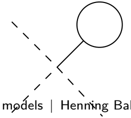
Tadpole contributions to λ_{hhh}

- In the SM: once λ_{hhh} is expressed in terms of *physical* input parameters, its result is independent of the treatment of the tadpoles:

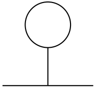
$$\delta^{(1)}\lambda_{hhh} \supset -\frac{3}{v^2}\delta^{(1)}t_{\text{finite}}$$

- However: `UFO` models do (often) **not** contain the explicit dependence on the tree-level/one-loop/one-loop-CT tadpoles.
- Thus: we choose the Fleischer-Jegerlehner treatment $t^{\text{tree-level}} = 0$ and renormalize $\delta^{(1)}t^{\text{CT}}|_{\text{finite}} = 0$ in the $\overline{\text{MS}}$ scheme per default (can also turn-off automatic tadpoles and implement own scheme).

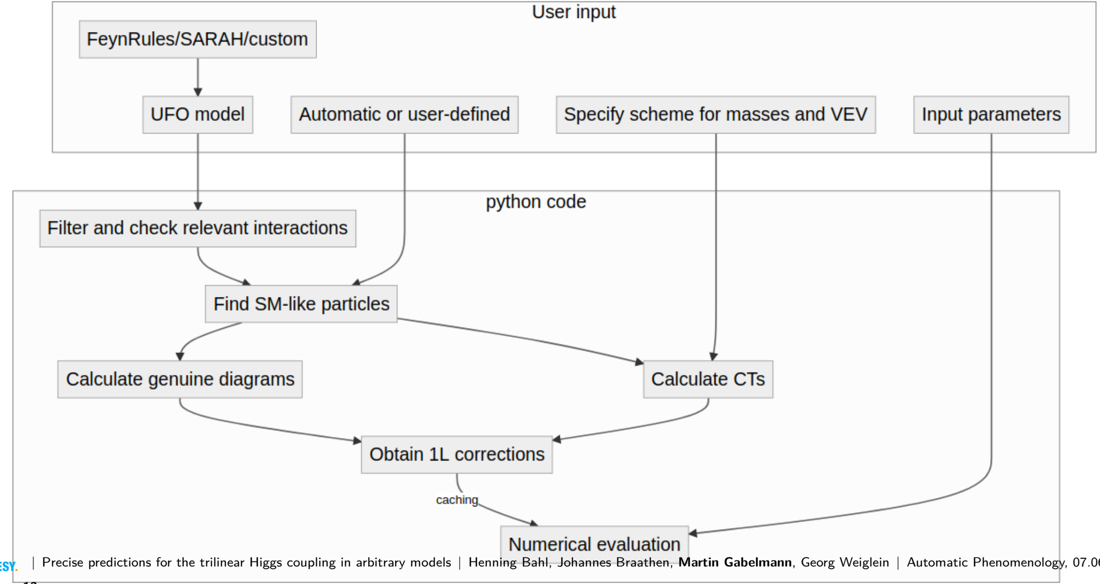
$\rightarrow$ only need to take into account tadpole contributions to all two- and three-point functions:



and

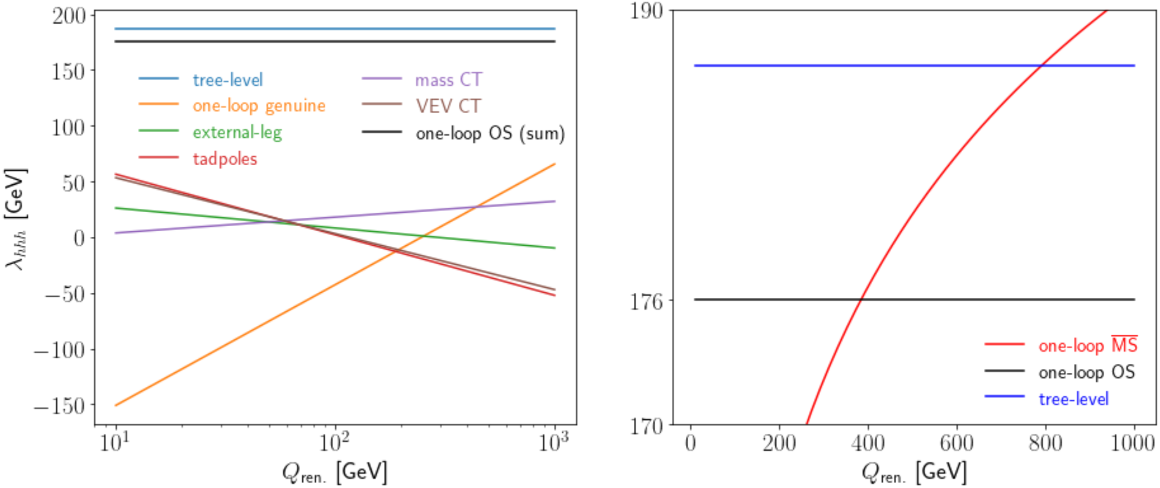


Workflow



User input
FeynRules/SARAH/custom
UFO model
Automatic or user-defined
Specify scheme for masses and VEV
Input parameters
python code
Filter and check relevant interactions
Find SM-like particles
Calculate genuine diagrams
Calculate CTs
Obtain 1L corrections
caching
Numerical evaluation

Simplest model to consider for cross-check: SM



Leading two-loop $\mathcal{O}(\alpha_t(\alpha_t + \alpha_s))^{\text{OS}}$: $\mathcal{O}(+1.4\%)$ [Senaha '18] [Braathen et al. '19]

Code demo

Feature list (so far)

- import/convert arbitrary UFO models
- definition of renormalisation schemes

```
# schemes.yml
renormalization_schemes:
  OS:
      mass_counterterms:
        h1: OS
        h2: OS
      VEV_counterterm: OS
  MS:
      mass_counterterms:
        h1: MS
        h2: MS
      VEV_counterterm: MS
```

- command line interface or python-library

```
from anyH3 import anyH3
myfancymodel = anyH3(
    'path/to/UFO/model',
    evaluation = 'numerical',
    scheme = 'OS')
result = myfancymodel.lambdahhh()
```

- optional: full p^2 dependence
- numerical / analytical / LaTeX outputs
- restrict to certain topologies
- restrict to certain particles in the loop
- ...

Motivation: theories and tools

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Outlook: beyond κ_λ

Electroweak precision observables

- M_W (via $\Delta r \approx \delta\rho$)
- $\sin\theta_W^{\text{eff.}}$
- Γ_Z
- $\dots$

Status: reproduced full one-loop result for $M_W/\delta\rho/\Delta r$ in the SM.

To Do: vertex + box diagrams for arbitrary QFTs (small in many extended Higgs sectors (+ alignment)); incorporation of higher-order SM results.

W Mass

- start with HO corrections to muon decay: $M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha_{\text{em}}}{\sqrt{2}G_F}\left[1+\Delta r\right]$
- and solve for: $M_W^2=M_Z^2\left[\frac{1}{2}+\sqrt{\frac{1}{4}-\frac{\pi\alpha_{\text{em}}}{\sqrt{2}G_F M_Z^2}(1+\Delta r)}\right]$
- with: $\Delta r^{(1)}=2\delta^{(1)}e+\frac{\Pi_W^{(1),T}(0)-\delta^{(1)}M_W^2}{M_W^2}-\frac{\delta^{(1)}\sin^2\theta_W}{\sin^2\theta_W}+\delta_{\text{vertex+box}}$
- and: $\frac{\delta^{(1)}\sin^2\theta_W}{\sin^2\theta_W}=\frac{\cos^2\theta_W}{\sin^2\theta_W}\left(\frac{\Pi_W^{(1),T}(M_W^2)}{M_W^2}-\frac{\Pi_W^{(1),T}(M_W^2)}{M_W^2}\right)$

It's all there but:

- $\delta^{\text{SM}}_{\text{vertex+box}}=-\frac{2\,\text{sign}(\sin\theta_W)}{\cos\theta_W\sin\theta_W M_Z^2}\Pi_{Z\gamma}(p^2=0)+\frac{\alpha_{QED}}{4\pi\sin^2\theta_W}\left(6+\frac{7-4\sin^2\theta_W}{2\sin^2\theta_W}\right)\log(\cos^2\theta_W)$
- $\delta^{\text{BSM}}_{\text{vertex+box}}=$ **needs to be implemented**

However:

- in many models $\Delta r\supset\frac{\delta\sin^2\theta_W}{\sin\theta_W}\approx\delta\rho$ is the dominant effect!

Other coupling modifiers

Question: how do you know that only $\kappa_\lambda \neq 1$ while e.g. $\kappa_t = 1$?

$$\mathcal{L}_{HH} = -\frac{3m_H^2}{v}(1+\kappa_\lambda)h^3 - \left[\frac{m_t}{v}(1+\kappa_t)\bar{t}_L t_R h + \text{h.c.}\right] + \ldots$$

Summary

- developed computer code for λ_{hhh} (and M_W as by-product) in arbitrary ren. QFTs
  - at the full one-loop order
  - with arbitrary choice of renormalization schemes
- reproduced SM results
- uses `UFO` input (generate with `SARAH`, `FeynRules` or use a custom one)
- analytical results; fast numerical results; SM: $\mathcal{O}(0.2\,\mathrm{s})$, MSSM: $\mathcal{O}(0.5\,\mathrm{s})$
- many models already implemented:
  SM, SM+**singlet, THDM, NTHDM**, various **triplet extensions, MSSM** and **NMSSM**

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Future ideas / todos:

- more models / cross-checks
- go beyond one-loop
- non-SM self-couplings (e.g. $\kappa_{\lambda_{hhH}}$)
- κ_t and κ_{tt}
- ...