anyH3 and di-Higgs production with loop-corrected trilinear couplings in the 2HDM

Kateryna Radchenko Serdula

based on arXiv: 2305.03015 (H. Bahl, J. Braathen, M. Gabelmann, G. Weiglein),

arXiv: 2403.14776 (S. Heinemeyer, M. Mühlleitner, K. R. , G. Weiglein)

and work in progress (H. Bahl, J. Braathen, M. Gabelmann, K. R. , G. Weiglein)

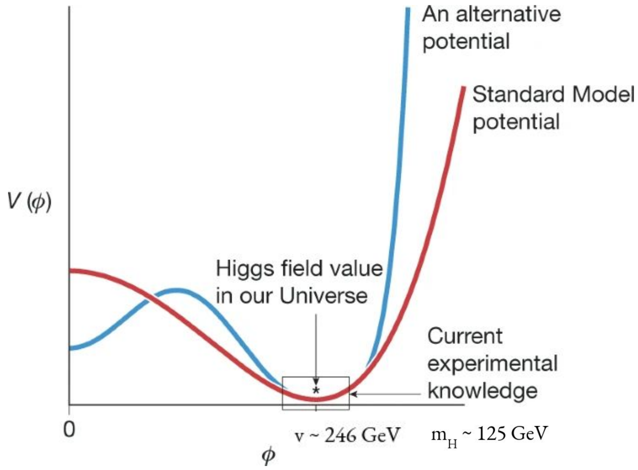
KUTS 2024

27.06.2024

Motivation

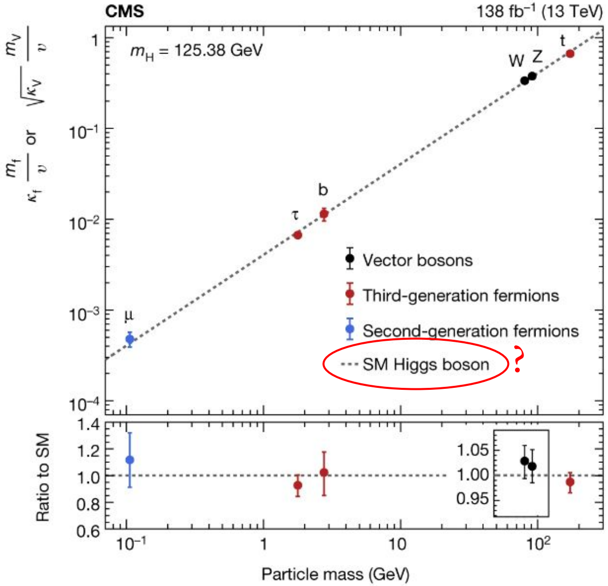
Couplings to fermions and bosons: $m_i = \lambda_i v/2$
(λ_i are renormalizable parameters that cannot be predicted in the SM)

→ proof of the Brout-Englert-Higgs mechanism 



The new particle seems to be **a** Higgs boson … but is it **the SM** Higgs boson?

Without the measurement of the **triple Higgs coupling (THC)** the shape of the potential is unknown!



[Nature 2022]

A potential barrier requires large deviations in the trilinears and can be related to a **strong first order electroweak phase transition**

[Kanemura, Okada, Senaha: arxiv: 0411354, Noble, Perelstein: arXiv: 0711.3018]

Outline

1. Trilinear Higgs self-coupling (λ_{hhh})
   - theoretical status and experimental constraints → potential to probe BSM models

2. Generalization to **any BSM model** (anyH3)
   - methodology, user input, applications

3. Generalization to **any BSM trilinear scalar coupling** (anyH3 v2)

4. Future prospects: insertion in gluon fusion **double Higgs production**
   - developments, applications, impact on constraints, ongoing work

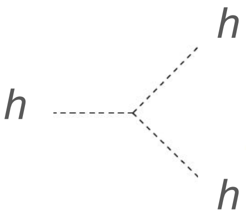
Higgs self coupling measurements

[ATLAS: arXiv: 2211.01216]

- Motivation: probe of **Higgs potential** and a **window to BSM**
- Can have **large deviations** from SM predictions in BSM while the couplings to gauge bosons and fermions are very close to the SM values (in agreement with existing constraints)
- Improving limits already impact the phenomenology

Notation:

$$\kappa_\lambda = \lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}(0)}$$



$$\lambda_{hhh}^{\mathrm{SM}(0)} = 3m_h/v$$

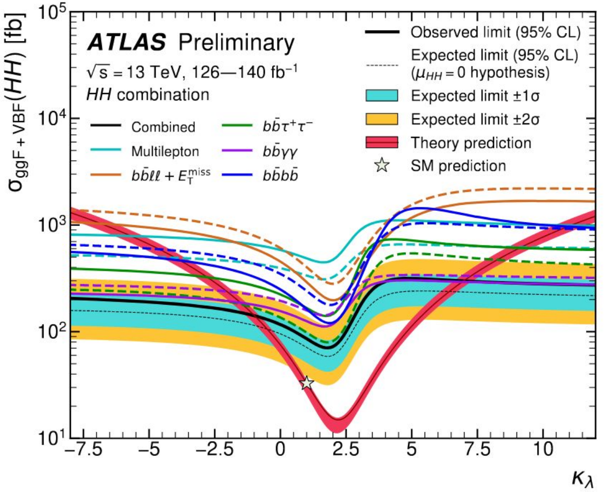
→ in the SM it is fully fixed by m_h (125 GeV) and v (246 GeV)

Experimental status:

- access through **Higgs pair production**

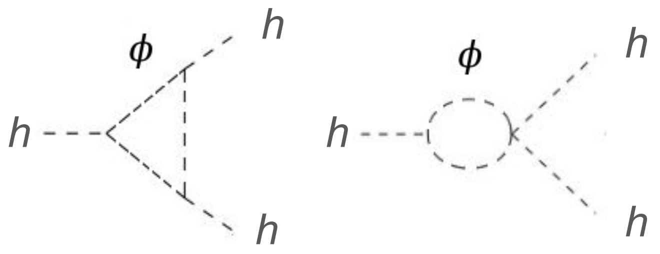
$$\mu_{hh} \leq 2.4$$

[$-1.2 < \kappa_\lambda < 7.2$] (95% CL at LHC Run II)



Radiative corrections to the trilinear couplings

- These become extremely important in BSM theories because of the effect of heavy New Physics: ϕ



- Theoretical predictions of the 1 loop results of the trilinear already exist in many models:

SM + singlet [Kanemura et al. '16]; ***2HDMs*** [Kanemura et al. '04], [Basler et al. '17]; ***N2HDM (2HDM + singlet)*** [Basler et al. '19]; ***triplet extensions*** [Aoki et al. '12], [Chiang et al. '18]; ***MSSM*** [Hollik, Penaranda '04]; ***NMSSM*** [Dao et al. '13]; ***models with classical scale invariance*** [Hashino, Kanemura, Orikasa '16], etc.

[List taken from J. Braathen]

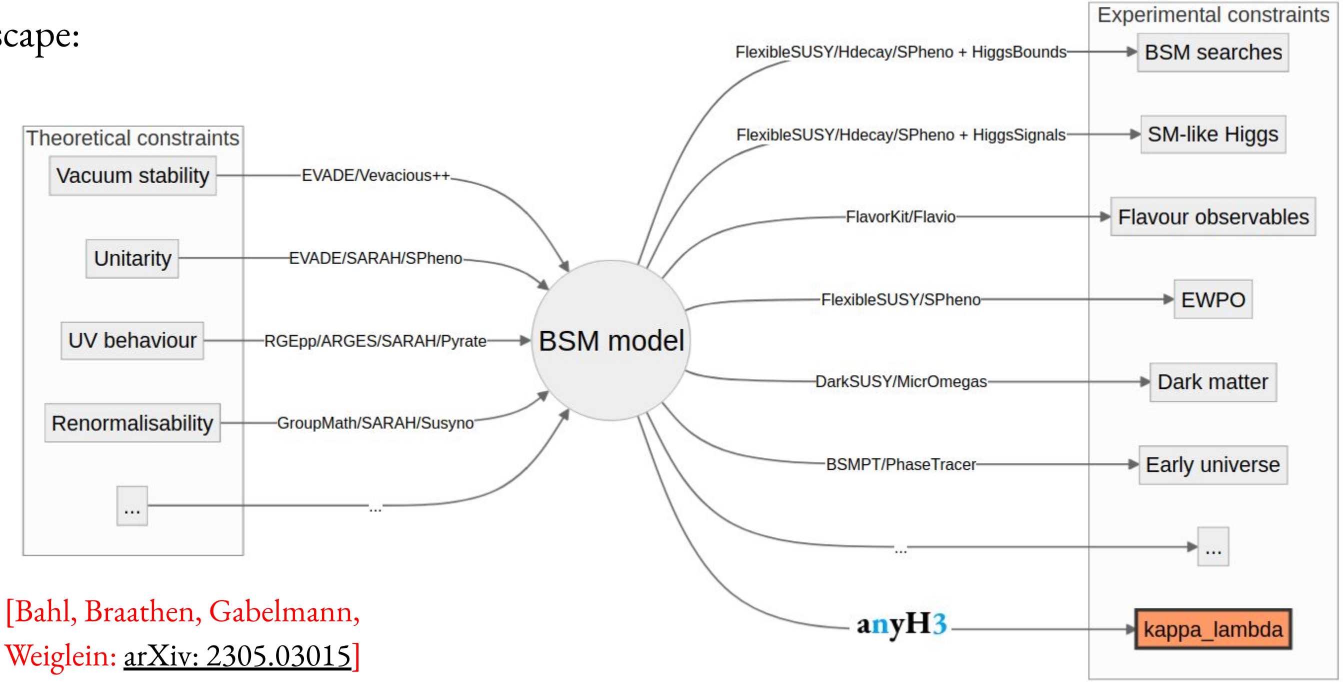
- .. and also at 2 loops [See talk by M. Gabelmann on Friday]

- Would be useful to automate the prediction of this parameter in any BSM model → **anyH3**

anyH3 purpose

- Close the gap regarding κ_λ predictions in the landscape of BSM tool-boxes:

- The landscape:

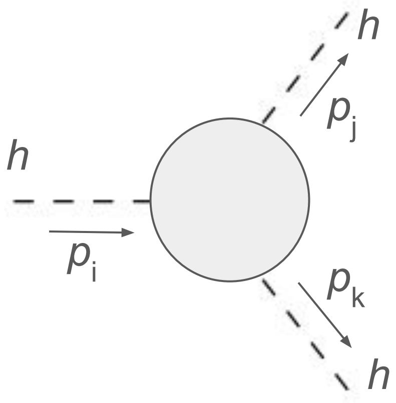


[Bahl, Braathen, Gabelmann, Weiglein: arXiv: 2305.03015]

Generic predictions for the trilinear couplings

Trilinear Higgs couplings (generic approach)

- Trilinear couplings = renormalized 3 point functions : $\lambda_{hhh} = -\hat{\Gamma}_{hhh}(p_1^2, p_2^2, p_3^2)$



Possible topologies:

$$= \lambda^{(0)}_{hhh} + \delta^{(1)}_{\mathrm{genuine}}\lambda_{hhh} + \delta^{(1)}_{\mathrm{tadpoles}}\lambda_{hhh} + \delta^{(1)}_{\mathrm{WFR}}\lambda_{hhh} + \delta^{(1)}_{\mathrm{CT}}\lambda_{hhh}$$

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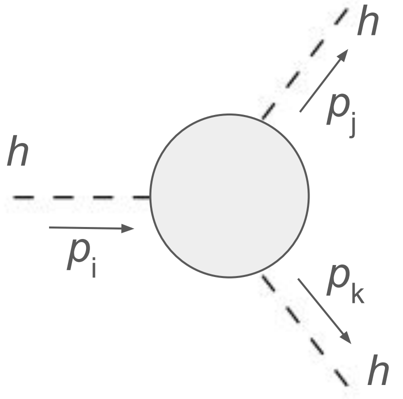

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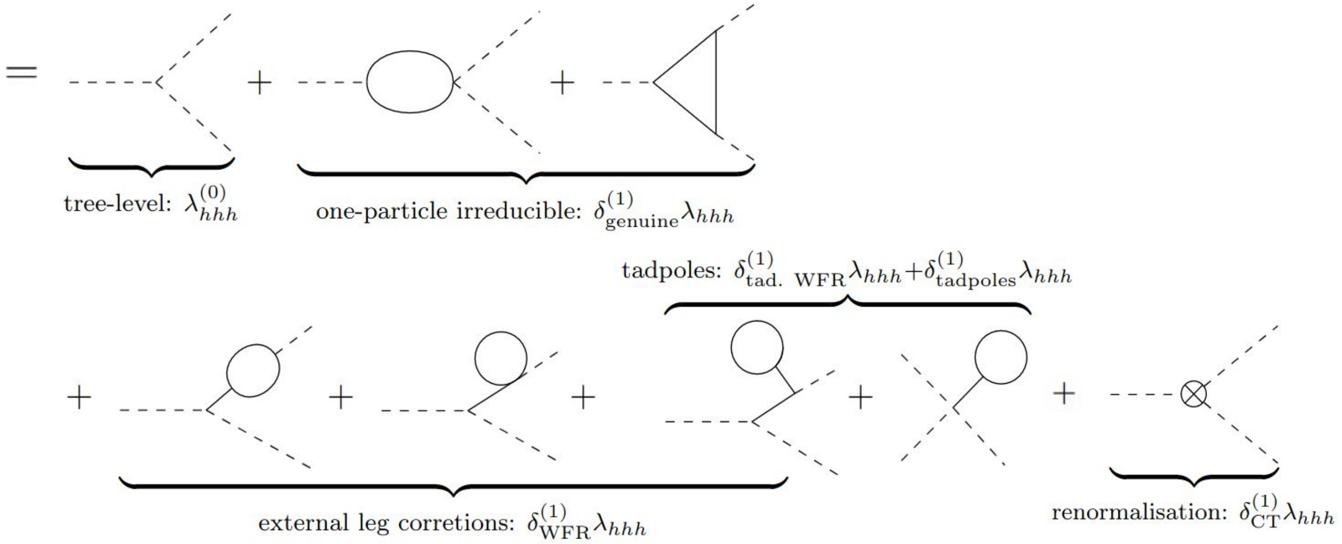

note: solid line here means generic field

Automation methodology

1. Identify all possible Feynman diagram **topologies** contributing to the three point function
2. Insert all allowed fields (**S** = scalar, **V** = vector, **F** = fermion, **U** = ghost)
3. Substitute in the general analytic expressions (`FeynArts` + `FormCalc`) → calculated from generic Lagrangian in terms of couplings (C_i), masses of the particles in the loop (m_i) and the external leg momenta (p_i)

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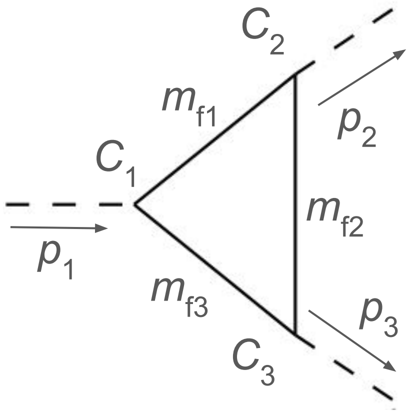


$$
\begin{aligned}
= {} & 2\mathbf{B0}(p_3^2, m_2^2, m_3^2)(C_1^L(C_2^L C_3^R m_{f_1} + C_2^R C_3^R m_{f_2} + C_2^R C_3^L m_{f_3}) + C_1^R(C_2^R C_3^L m_{f_1} + \\
& C_2^L C_3^L m_{f_2} + C_2^L C_3^R m_{f_3})) + m_{f_1}\mathbf{C0}(p_2^2, p_3^2, p_1^2, m_1^2, m_3^2, m_2^2)((C_1^L C_2^L C_3^R + \\
& C_1^R C_2^R C_3^L)(p_1^2 + p_2^2 - p_3^2) + 2(C_1^L C_2^L C_3^L + C_1^R C_2^R C_3^R) m_{f_2} m_{f_3} + \\
& 2m_{f_1}(C_1^L(C_2^L C_3^R m_{f_1} + C_2^R C_3^R m_{f_2} + C_2^R C_3^L m_{f_3}) + C_1^R(C_2^R C_3^L m_{f_1} + C_2^L C_3^L m_{f_2} + \\
& C_2^L C_3^R m_{f_3}))) + \mathbf{C1}(p_2^2, p_3^2, p_1^2, m_1^2, m_3^2, m_2^2)(2p_2^2(C_1^L C_3^R(C_2^L m_{f_1} + C_2^R m_{f_2}) + \\
& C_1^R C_3^L(C_2^R m_{f_1} + C_2^L m_{f_2})) + (p_1^2 + p_2^2 - p_3^2)((C_1^L C_2^L C_3^R + C_1^R C_2^R C_3^L) m_{f_1} + \\
& (C_1^L C_2^R C_3^L + C_1^R C_2^L C_3^R) m_{f_3})) + \mathbf{C2}(p_2^2, p_3^2, p_1^2, m_1^2, m_3^2, m_2^2)((p_1^2 + p_2^2 - \\
& p_3^2)(C_1^L C_3^R(C_2^L m_{f_1} + C_2^R m_{f_2}) + C_1^R C_3^L(C_2^R m_{f_1} + C_2^L m_{f_2})) + 2p_1^2((C_1^L C_2^L C_3^R + \\
& C_1^R C_2^R C_3^L) m_{f_1} + (C_1^L C_2^R C_3^L + C_1^R C_2^L C_3^R) m_{f_3}))
\end{aligned}
$$

$$C_i = C_i^L P_L + C_i^R P_R \,, \text{ where } P_{L,R} \equiv \frac{1}{2}(1 \mp \gamma_5)$$

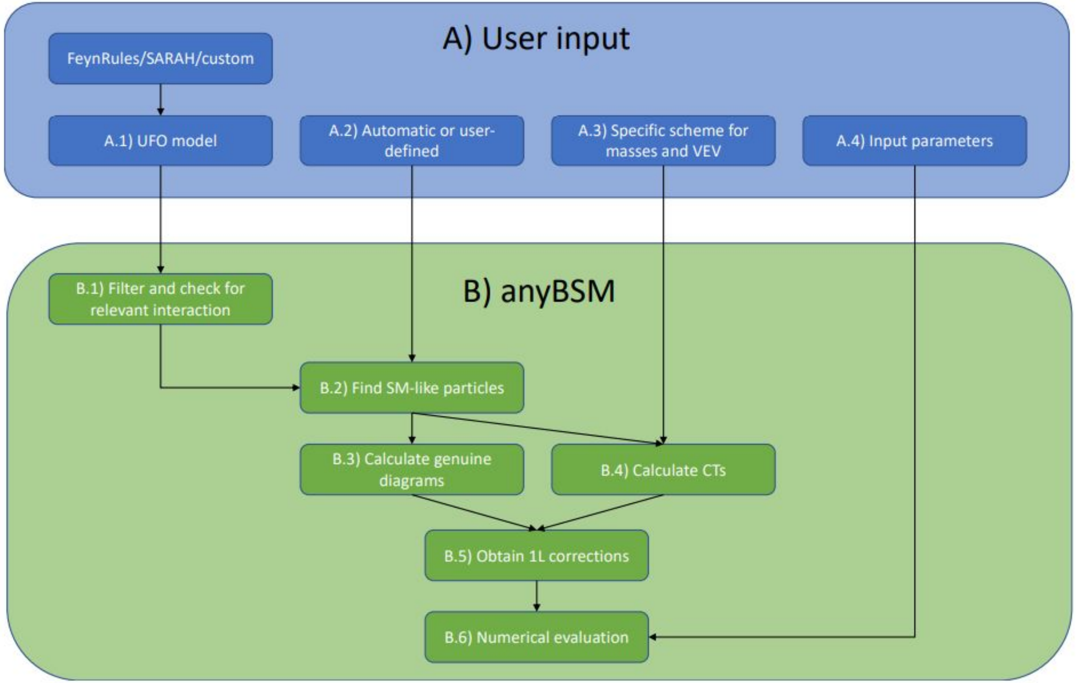
*loop integrals evaluated with `pyCollier` (original Fortran code: `COLLIER` [Denner, Dittmaier, Hofer: arXiv: 1604.06792])

User input

- anyH3 takes as input **UFO model files** that can be generated by `SARAH`, `FeynRules`, etc.
(this sets particles, parameters, couplings, vertices, lorentz structures in the model)

- to convert to `anyH3` notation one can use the inbuilt tool, which will map to the corresponding conventions automatically

- optionally, the user can provide a renormalisation scheme for the model

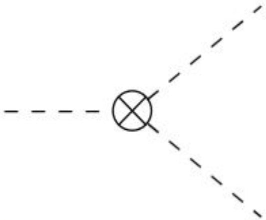


Renormalisation

- The trilinear coupling is not an observable!

- Easily automated schemes like $\overline{\text{MS}}$ or $\overline{\text{DR}}$ can lead to artificially large corrections and other issues
[See previous talk by Andrii Dashko]

- Many options in `anyH3`:
  * SM sector: fully OS or $\overline{\text{MS}}/\overline{\text{DR}}$
  * BSM sector masses: fully OS or $\overline{\text{MS}}/\overline{\text{DR}}$, BSM sector fields: OS or $\overline{\text{MS}}/\overline{\text{DR}}$
  * BSM sector couplings and vevs: custom or $\overline{\text{MS}}$



$$\delta^{(1)}_{\text{CT}}\lambda_{hhh} = \sum_i \frac{\partial}{\partial m_i^2}\lambda^{(0)}_{hhh}\cdot\delta^{(1)}_{\text{CT}}m_i^2 + \frac{\partial}{\partial v}\lambda^{(0)}_{hhh}\cdot\delta^{(1)}_{\text{CT}}v + \delta^{(1)}_{\text{custom-CT}}\lambda_{hhh}$$

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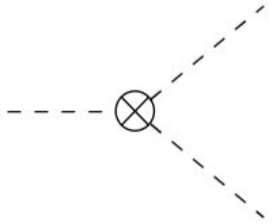

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$\boxed{m_\text{i}} = m_\text{h}$(SM), m_ϕ(BSM)

$$\boxed{\delta^{(1)}_{\text{custom}-\text{CT}}\lambda_{hhh}} = \sum_{\alpha_i} \frac{\partial}{\partial \boxed{\alpha_i}}\lambda^{(0)}_{hhh} \cdot \delta^{(1)}_{\text{CT}}\alpha_i$$

$\boxed{\alpha_\text{i}}$ = BSM parameters (mixing angles, indep. couplings, etc.)

What does OS (on-shell) mean?

- Counterterms in this expression: $\delta^{(1)}_{\mathrm{CT}}\lambda_{hhh} = \sum_i \frac{\partial}{\partial m_i^2}\lambda^{(0)}_{hhh} \cdot \boxed{\delta^{(1)}_{\mathrm{CT}} m_i^2} + \frac{\partial}{\partial v}\lambda^{(0)}_{hhh} \cdot \boxed{\delta^{(1)}_{\mathrm{CT}} v} + \boxed{\delta^{(1)}_{\text{custom-CT}}\lambda_{hhh}}$

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- On shell **vev**: $v^{\mathrm{OS}} \equiv \frac{2M_W}{e}\sqrt{1-\frac{M_W^2}{M_Z^2}} \quad \rightarrow \quad \frac{\boxed{\delta^{(1)}_{\mathrm{CT}} v}}{v^{\mathrm{OS}}} = \frac{\delta^{(1)} M_W^2}{2M_W^2} + \frac{\cos^2\theta_w}{2\sin^2\theta_w}\left(\frac{\delta^{(1)} M_Z^2}{M_Z^2} - \frac{\delta^{(1)} M_W^2}{M_W^2}\right) - \frac{\delta^{(1)} e}{e}$

- On shell **tadpoles**: $\boxed{\delta^{(1)}_{\mathrm{custom-CT}}\lambda_{hhh}} = \frac{\partial}{\partial t_h}\lambda^{(0)}_{hhh} \cdot \delta t_h^{\mathrm{OS}},\ \delta t_h^{\mathrm{OS}} = -T_h$ = unrenormalised scalar one point function

(should be defined as custom CT otherwise Fleischer–Jegerlehner $\overline{\mathrm{MS}}$ tadpole scheme will be used)

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$$\boxed{\frac{\delta^{(1)}M_V^2}{M_V^2}} = \frac{\text{Re}\Sigma^T_{VV}}{M_V^2}(p^2 = M_V^2)\,,\ (V = W, Z) \qquad \boxed{\frac{\delta^{(1)}e}{e}} = \left(\frac{1}{2}\Pi_\gamma\ (p^2 = 0) + \text{sng}(s_{\theta_w})\frac{s_{\theta_w}}{M_Z^2 c_{\theta_w}}\Sigma^T_{\gamma Z}\ (p^2 = 0)\right)$$

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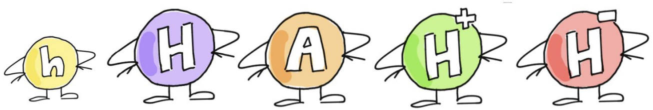
- On shell **fields**: $\delta Z_{hh}^{\mathrm{OS}} = \left.\frac{-\partial\Sigma_{hh}(p^2)}{\partial p^2}\right|_{p^2=m_h^2}$ included in $\delta^{(1)}_{\mathrm{WFR}}\lambda_{hhh}$

BSM Example: 2HDM

[T. D. Lee (1973) Physical Review , Branco, Ferreira et al: arXiv: 1106.0034]

- **CP conserving** 2HDM with two complex doublets: $\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1+\rho_1+i\eta_1}{\sqrt{2}} \end{pmatrix}, \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2+\rho_2+i\eta_2}{\sqrt{2}} \end{pmatrix}$



- **Softly broken $\mathbb{Z}_2$ symmetry** ($\Phi_1 \to \Phi_1$; $\Phi_2 \to -\Phi_2$) entails 4 Yukawa types

- Potential:

$$\boxed{\begin{aligned} V_{\text{2HDM}} = m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \\ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}((\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2), \end{aligned}}$$

- Free parameters:

$$m_h,\ m_H,\ m_A, m_{H^\pm},\ M,\ c_{\beta-\alpha},\ t_\beta,\ v$$

$$\boxed{\begin{aligned} &\tan\beta = v_2/v_1 \\ &v^2 = v_1^2 + v_2^2 \sim (246\ \text{GeV})^2 \end{aligned}}$$

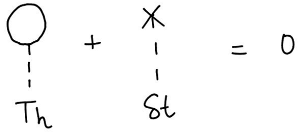
$c_\theta \equiv \cos\theta,\ s_\theta \equiv \sin\theta,\ t_\theta \equiv \tan\theta$

$$M^2 = \frac{m_{12}^2}{c_\beta s_\beta}$$

OS renormalisation example: THDM

Conditions Counterterms

- **tadpoles**:



$$\hat{T}_h = \cancelto{0}{t_h} + T_h + \delta t \overset{!}{=} 0 \Rightarrow \boxed{\mathrm{CT}}: \delta t_h^{\mathrm{OS}} = -T_h$$

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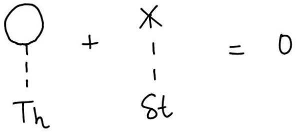
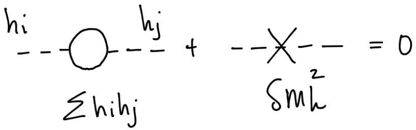
- **masses**:	$\text{Re}\,\hat{\Sigma}_{hh}\left(m_h^2\right) \stackrel{!}{=} 0 \Rightarrow$	$\boxed{\text{CT}}: \delta m_h^{2\,\text{OS}} = \text{Re}\left(\Sigma_{hh}\left(m_h^2\right)\right)$





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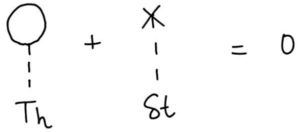

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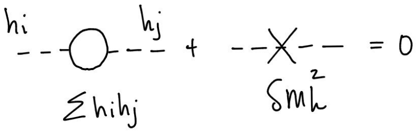

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- **fields**:

renormalized self energies:

$$\hat{\Sigma}_{hh}(p^2) = \Sigma_{hh}(p^2) - \delta m_h^2 + (p^2 - m_h^2)\delta Z_{hh}$$

$$\hat{\Sigma}_{hH}(p^2) = \Sigma_{hH}(p^2) + (p^2 - m_h^2)\frac{\delta Z_{hH}}{2} + (p^2 - m_H^2)\frac{\delta Z_{Hh}}{2}$$

$$\left.\frac{\partial \hat{\Sigma}_{hh} = 0}{\partial p^2}\right|_{p^2 = m_h^2} \overset{!}{=} 0 \Rightarrow \boxed{\text{CT}}: \delta Z_{hh}^{\text{OS}} = \left.\frac{-\partial \Sigma_{hh}(p^2)}{\partial p^2}\right|_{p^2 = m_h^2}$$

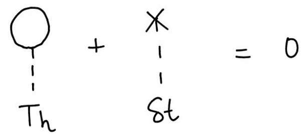
$$\hat{\Sigma}_{hH}\left(m_h^2\right) \overset{!}{=} 0 \Rightarrow \boxed{\text{CT}}: \delta Z_{Hh} = -2\frac{\Sigma_{hH}\left(m_h^2\right)}{m_h^2 - m_H^2}$$

$$\hat{\Sigma}_{hH}\left(m_H^2\right) \overset{!}{=} 0 \Rightarrow \boxed{\text{CT}}: \delta Z_{hH} = 2\frac{\Sigma_{hH}\left(m_H^2\right)}{m_h^2 - m_H^2}$$

OS renormalisation example: THDM

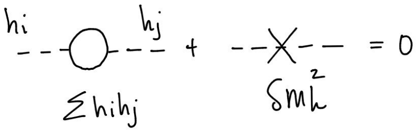
Conditions | Counterterms

- **tadpoles**:



$$\hat{T}_h = \cancelto{0}{t_h} + T_h + \delta t \overset{!}{=} 0 \Rightarrow \boxed{\mathrm{CT}}: \delta t_h^{\mathrm{OS}} = -T_h$$

- **masses**:



$$\mathrm{Re}\,\hat{\Sigma}_{hh}\left(m_h^2\right) \overset{!}{=} 0 \Rightarrow \boxed{\mathrm{CT}}: \delta m_h^{2\,\mathrm{OS}} = \mathrm{Re}\left(\Sigma_{hh}\left(m_h^2\right)\right)$$

- **fields**:

renormalized self energies:

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$$\hat{\Sigma}_{hH}\left(m_H^2\right) \overset{!}{=} 0 \Rightarrow \boxed{\mathrm{CT}}: \delta Z_{hH} = 2\frac{\Sigma_{hH}\left(m_H^2\right)}{m_h^2 - m_H^2}$$

- **other parameters**: δM^2 can be defined through some physical process or another parameter (e.g. independent couplings) [See morning talk by Kei Yagyu and next talk by Alain Verduras]

Renormalisation example: THDM user defined scheme

- **tadpoles**: $\frac{\partial V}{\partial \rho_1} = \Big|_{\substack{\Phi_1=<\Phi_1>,\\ \Phi_2=<\Phi_2>}} \stackrel{!}{=} t_1, \qquad \frac{\partial V}{\partial \rho_2} = \Big|_{\substack{\Phi_1=<\Phi_1>,\\ \Phi_2=<\Phi_2>}} \stackrel{!}{=} t_2$

user defined:

$$\boxed{\begin{aligned} t_1 &= \cos\alpha\, t_H - \sin\alpha\, t_h \\ t_2 &= \sin\alpha\, t_H + \cos\alpha\, t_h \end{aligned}}$$

these terms need to be kept in the UFO file so that all parameters depend on t_1, t_2, including the trilinears

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- **masses and fields**: automatic
- **mixing angles** (through off diagonal self energies):

$$\begin{pmatrix} H_0 \\ h_0 \end{pmatrix} = \begin{pmatrix} 1+\frac{1}{2}\delta Z_{HH} & \frac{1}{2}Z_{Hh}+\delta\alpha \\ \frac{1}{2}Z_{hH}-\delta\alpha & 1+\frac{1}{2}\delta Z_{HH} \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

user defined:

$$\boxed{\begin{aligned} \delta\alpha &= \frac{\Sigma_{hH}(m_h^2)+\Sigma_{hH}(m_H^2)}{2(m_H^2-m_h^2)} \\ \delta\beta &= -\frac{\Sigma_{G^{(0)}A}(0)+\Sigma_{G^{(0)}A}(m_A^2)}{2m_A^2} \end{aligned}}$$

→ this is a version of an OS scheme, see also:
[Krause et al. 1605.04853
Denner et al. 1808.03466
Kanemura et al. 1705.05399]

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$\rightarrow$ this is a version of an OS scheme, see also:
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Denner et al. 1808.03466
Kanemura et al. 1705.05399]

- other parameters:

user defined:

$$\boxed{\begin{aligned} \delta M =& \frac{M}{32\pi^2 v^2}\Bigg\{-3\left(2M_W^2+M_Z^2\right)+6\left(\frac{m_u^2+m_c^2+m_t^2}{t_\beta^2}+\left(m_d^2+m_s^2+m_b^2\right)t_\beta^2\right) \\ &+2t_\beta^2\left(m_e^2+m_\mu^2+m_\tau^2\right)-\frac{s_{2\alpha}}{s_{2\beta}}\left(M_h^2-M_H^2\right)+4M^2-2M_{H^\pm}^2-M_A^2\Bigg\}\log\left(\frac{4Q^2}{(M+m_t)^2}\right) \end{aligned}}$$

Renormalisation example: THDM user defined scheme

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$$t_1 = \cos\alpha\, t_H - \sin\alpha\, t_h$$
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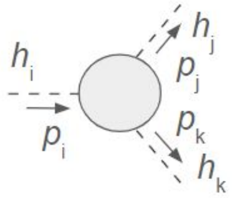
$$\left. +2t_\beta^2\left(m_e^2+m_\mu^2+m_\tau^2\right)\right) - \frac{s_{2\alpha}}{s_{2\beta}}\left(M_h^2 - M_H^2\right) + 4M^2 - 2M_{H^\pm}^2 - M_A^2\Big\}\log\left(\frac{4Q^2}{(M+m_t)^2}\right)$$

Other examples: RxSM [See next talk by Alain Verduras]

Applications of anyH3

- Compute loop corrected trilinears in a user defined model (14 BSM models already implemented)
- Track the momentum dependence of the coupling
- Use the result for theoretical predictions in the double Higgs (hh) production cross section
- Estimate higher order uncertainties
- Phenomenology and powerful exclusion potential of the parameter space of BSM models → easily incorporated in large parameter scans

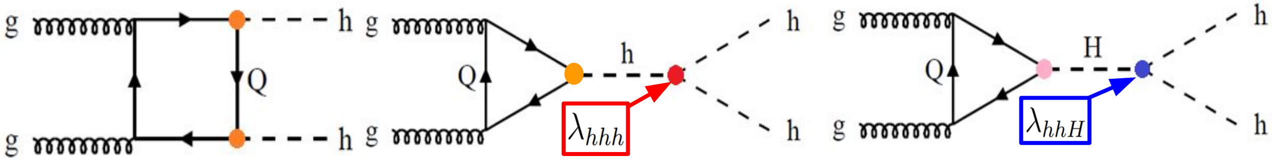
Generalization to BSM trilinear Higgs couplings



anyH3 v2: [Bahl, Braathen, Gabelmann, KR, Weiglein: TBP]

- An **additional argument** can be set in the calculation of the three point functions which is the **fields** involved in the external legs
- Relevant for resonant Higgs pair production processes

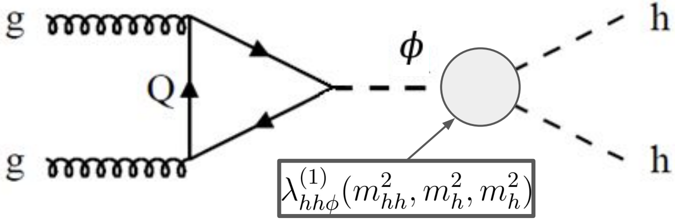
Example: 2HDM gghh production



We include corrections to this process by means of effective trilinear Higgs couplings assuming that the largest contribution comes from this type of diagrams and others can be neglected (eg. double box diagram):

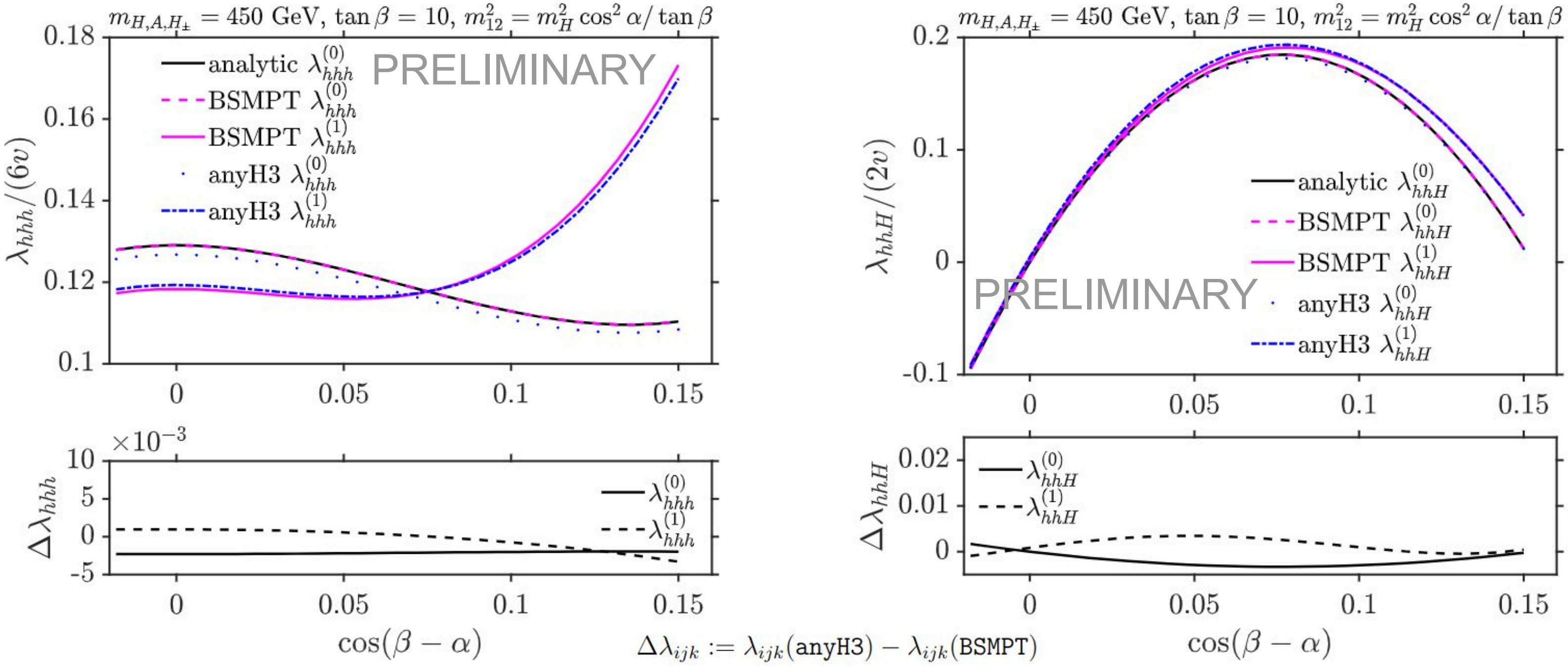
- Is this reasonable? -> modifications of λ_{hhh} are the leading source of deviations of non resonant hh production cross section

[Bahl, Braathen, Weiglein : arXiv: 2202.03453]



Comparison to other tools

THDM II



Agreement of the corrections to the trilinear couplings λ_{hhh} and λ_{hhH} with `BSMPT`
Note: `BSMPT` uses V_{eff} + different renormalization schemes + different vevs!

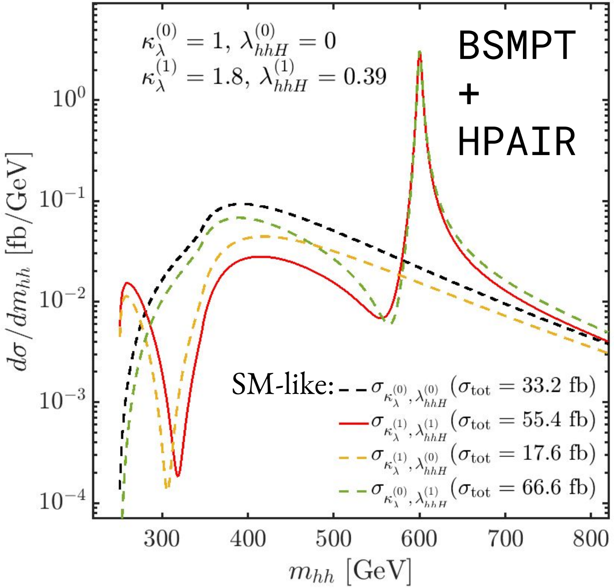
[Basler, Biermann, Mühlleitner, Müller, Santos, Viana: arXiv: 2404.19037]

Example applications

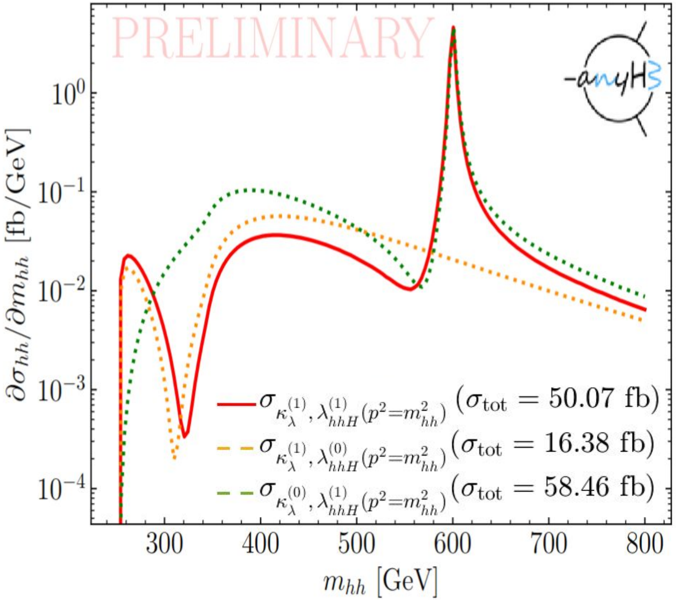
- Impact of loop corrections to the trilinear is very sizable in Higgs pair production searches!
- Existing analysis in 2HDM can be easily reproduced in any model with `anyBSM`

HPAIR:
[Plehn, Spira, Zerwas : arXiv: 9603205]
[Dawson, Dittmaier, Spira: arXiv:9805244]
[Abouabid, Arhrib, Azevedo, El Falaki, Ferreira, Mühlleitner, Santos: arXiv: 2112.12515]

[Heinemeyer, Mühlleitner, K.R., Weiglein: arXiv: 2403.14776]



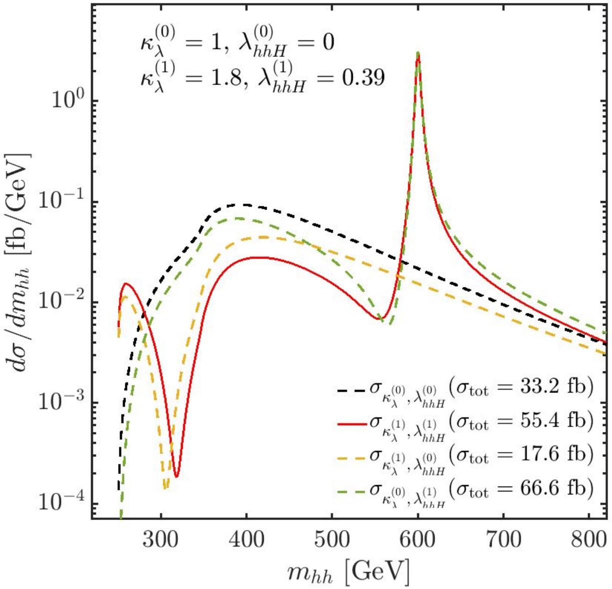
[Bahl, Braathen, Gabelmann, KR, Weiglein: TBP]



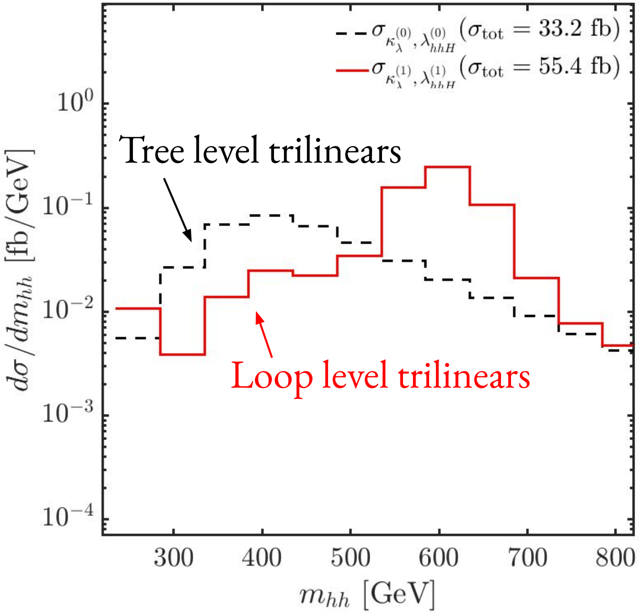
$$\tan\beta = 2,\ M_{A,H,H^+} = 600\ \text{GeV},\ M = 400\ \text{GeV},\ \alpha = \beta - \pi/2$$

Difference in the experimental results

- Differential cross section measurements are affected by the finite resolution of particle detectors → observed spectrum is "**smeared**" → we mimic this effect by introducing *ad hoc* **Gaussian uncertainties** in m_{hh}
- Experimental data is gathered in **bins**

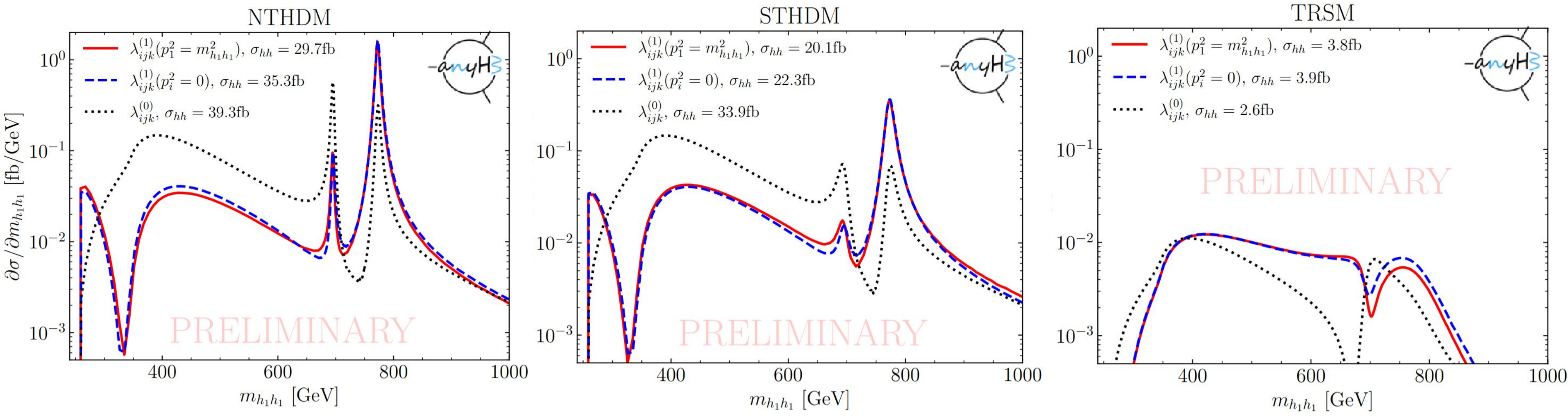


Realistic distribution:



Results in other models

- Results in many models can be obtained for the first time with an OS scheme for the couplings



Conclusions

- We presented a novel tool for calculation of the **trilinear couplings** in **arbitrary renormalizable QFTs**

  → including full **1 loop** calculation
  → including **momentum** dependence
  → flexible choices of **renormalisation** schemes → predefined or by user

- Convenient features: UFO model inputs , analytical results (Python, Mathematica), fast numerical results (with caching): SM(~0.2s); MSSM(~0.5s)

- **`anyBSM`** framework, currently under development but good agreement with existent codes

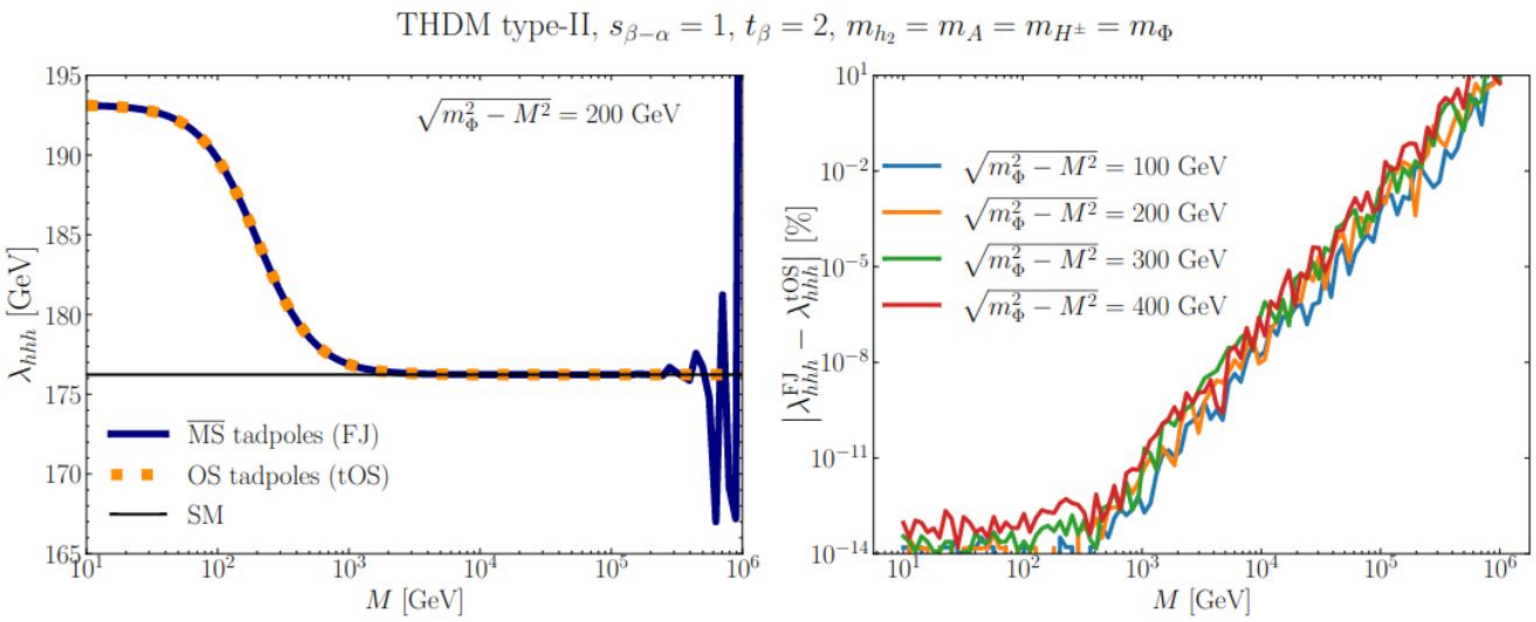
  → generalisation of the above to any scalar trilinear coupling
  → large impact on Higgs pair production
  → leading to interesting phenomenology within reach of HL-LHC

Thank you for your attention!

Backup

OS vs FJ tadpole treatment

[Slide by M. Gabelmann]



Backup

A cross-check: the decoupling limit

[Slide by J. Braathen]

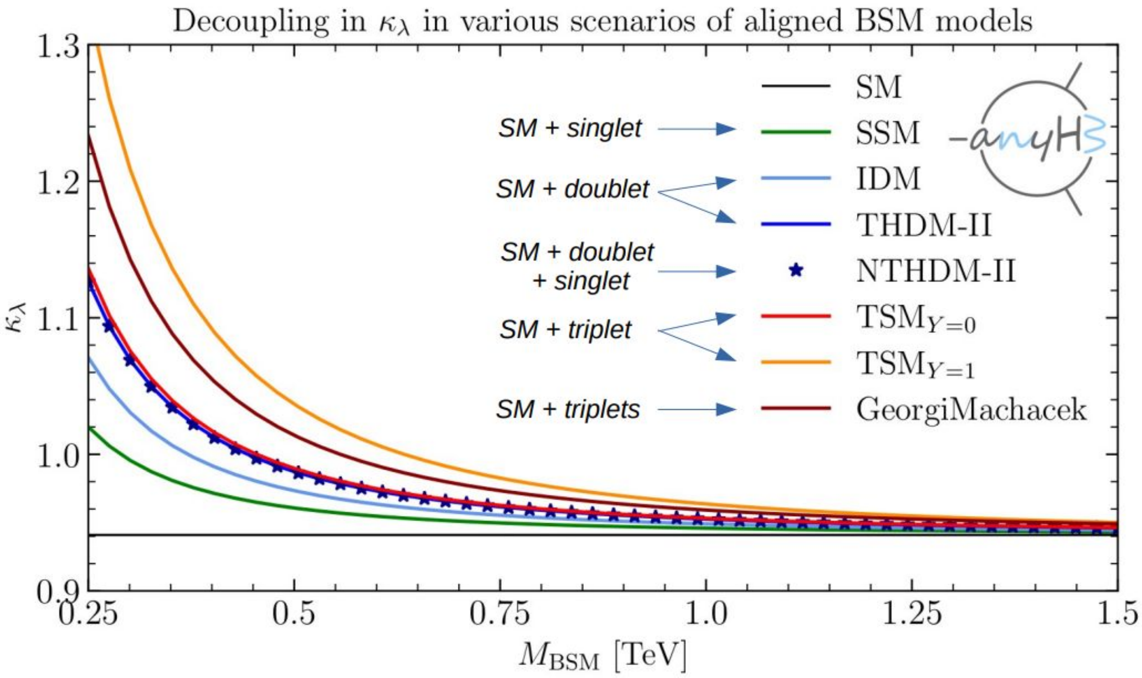
- Consider the decoupling limit in several BSM models

$$M_{\mathrm{BSM}}^2 = \mathcal{M}^2 + \tilde{\lambda} v^2$$

$\mathcal{M}$: BSM mass scale
$\tilde{\lambda}$: Quartic couplings

- Increase BSM mass scale
$$\mathcal{M} \to \infty$$

- BSM corrections to should vanish (c.f. decoupling theorem [Appelquist, Carrazone '75])



Backup

New results I: mass-splitting effects in various BSM models

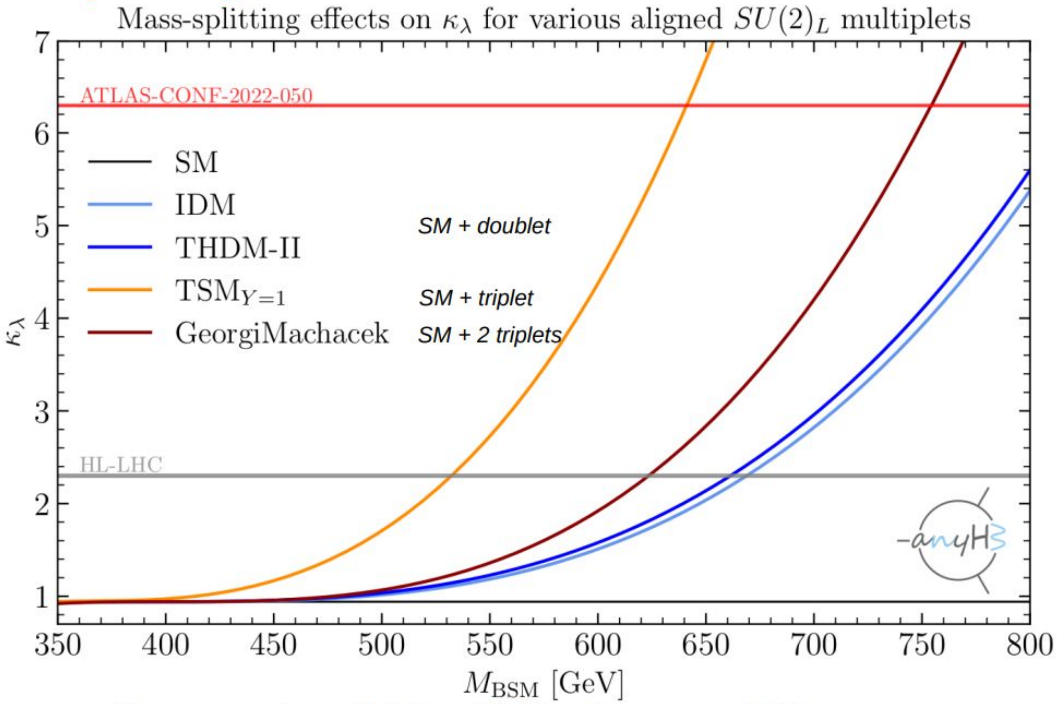
- Consider the non-decoupling limit in several BSM models

$$M^2_{\text{BSM}} = \mathcal{M}^2 + \tilde{\lambda} v^2$$

- Increase M_{BSM}, keeping $\mathcal{M}$ fixed
  → large mass splittings
  → **large BSM effects!**

- Perturbative unitarity checked with `anyPerturbativeUnitarity`

- **Constraints on BSM parameter space!**

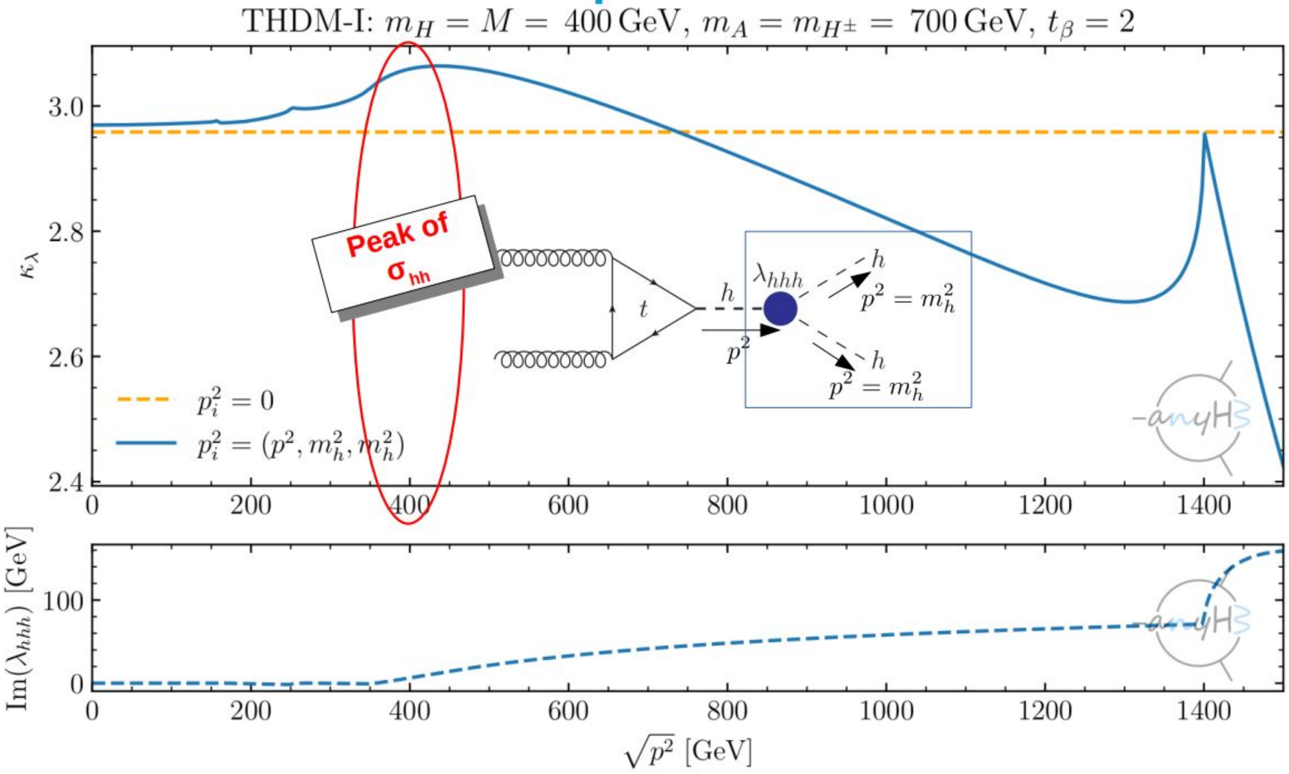


Here: scenarios with lightest BSM scalar mass + BSM mass param. at 400 GeV; other BSM scalar masses = M_{BSM}

[Slide by J. Braathen]

Backup

New results II: momentum dependence in the 2HDM



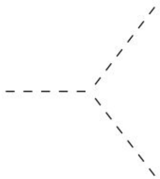
[Slide by J. Braathen]

Effective potential approach

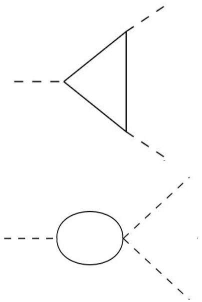
[Coleman, Weinberg: (1973) Physical Review]

$$V_{\text{eff}} = V_{\text{tree}} + V_{\text{CW}} + V_{\text{CT}}$$

$$\lambda_{hhh}^{\text{eff}} = \left.\frac{\partial^3 V_{\text{eff}}}{\partial h^3}\right|_{h=0} =$$



$+$



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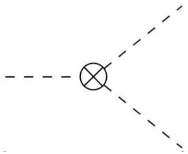

* zero external momentum
* no external leg corrections

Treatment of external leg corrections

$$\delta^{(1)}\lambda^{\mathrm{WFR}}_{hhh} = \sum_i \left(\frac{1}{2}\Sigma'_{hh}(p_i^2)\lambda^{(0)}_{hhh} + \sum_{j,h_j\neq h} \frac{\Sigma_{hh_j}(p_i^2)}{p_i^2 - m^2_{h_j}}\lambda^{(0)}_{h_jhh} \right)$$
$$\equiv \sum_i \left(\frac{1}{2}\delta^{(1)}Z_h(p_i^2)\lambda^{(0)}_{hhh} + \sum_{j,h_j\neq h} \delta^{(1)}Z_{hh_j}(p_i^2)\lambda^{(0)}_{h_jhh} \right) ,$$

$$\delta^{(1)}\lambda^{\mathrm{WFR}}_{112}(p_1^2,p_2^2,p_3^2) = \frac{1}{2}\delta^{(1)}Z_{11}(p_1^2)\lambda^{(0)}_{112} + \frac{1}{2}\delta^{(1)}Z_{11}(p_2^2)\lambda^{(0)}_{112} + \frac{1}{2}\delta^{(1)}Z_{22}(p_3^2)\lambda^{(0)}_{112}$$
$$+ \delta^{(1)}Z_{12}(p_1^2)\lambda^{(0)}_{122} + \delta^{(1)}Z_{12}(p_2^2)\lambda^{(0)}_{122} + \delta^{(1)}Z_{21}(p_3^2)\lambda^{(0)}_{111} ,$$