VBF-HH at NLO QCD in HEFT

DESY theory seminar

Marius Höfer | 27 January 2025

with Jens Braun, Pia Bredt, Gudrun Heinrich

Outline

We found the Higgs ...

We found the Higgs ... Now we have to understand it!

Many parameters of the Higgs sector still poorly contrained
↳ relates to many open questions: origin of the Higgs mass, hierarchy problem, vacuum stability, ...

HL-LHC: exploring parameters of the Higgs sector, theory has to keep up

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Multi-Higgs couplings

Current bounds provide ample room for New Physics! How to measure?

- Single Higgs production at (at least) NLO EW
- Double and triple Higgs production at LO $\rightarrow$ cross section is extremely small

Higgs Pair production

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Most relevant channels: gluon fusion (ggF) and vector boson fusion (VBF)

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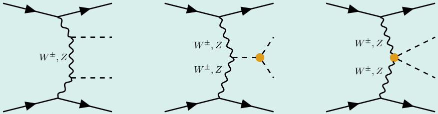
- Relatively clean wrt. QCD background
- Sensitive to $g_{hhvv} - g_{hvv}^2$: unitarity, HEFT vs SMEFT
- In SM: $\sigma_{VBF} \approx 1.7\mathrm{fb} \approx 5\%$ of σ_{ggF} (at 13 TeV)



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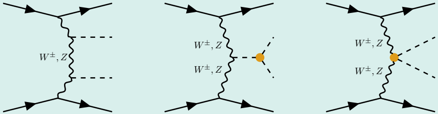

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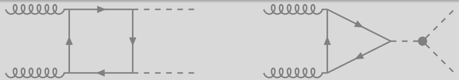

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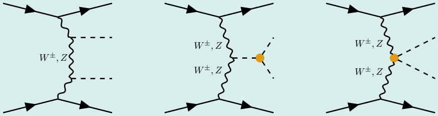

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Status of VBF-HH

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Experiment

- Bounds on prod. cross sec.: $\sigma^{exp.}_{VBF-HH} \lesssim \sigma^{\mathrm{SM}}_{VBF-HH} \times \begin{cases} 50 & \text{[ATLAS @ LHC-HWG'24]} \\ 91 & \text{[CMS PAS '24]} \end{cases}$
- Rather loose constraints on g_{hvv}, g_{hhvv} and g_{hhh} [ATLAS 2024][CMS 2024]

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Theory

$$\left.\begin{array}{l} \text{NNLO QCD + NLO EW [Dreyer et al. 2020]} \\ \text{N}^3\text{LO QCD [Dreyer et al. 2018]} \\ \text{NNLO QCD [Dreyer et al. 2019][Ling et al. 2014]} \\ \text{NLO QCD [Fidgy 2008][Baglio et al. 2013][Frederix et al. 2014]} \end{array}\right\} \text{Standard Model}$$

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} Standard Model

- In EFT context, at tree-level: g_{hhvv} only [Bishara et al. 2017], g_{hhvv} and g_{hhh} [Kilian et al. 2020]

New Physics hiding in VBF-HH?

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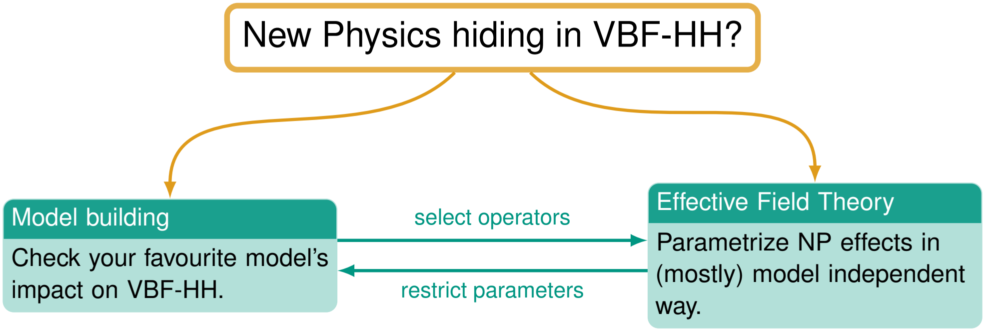
Model building

Check your favourite model's impact on VBF-HH.

Effective Field Theory

Parametrize NP effects in (mostly) model independent way.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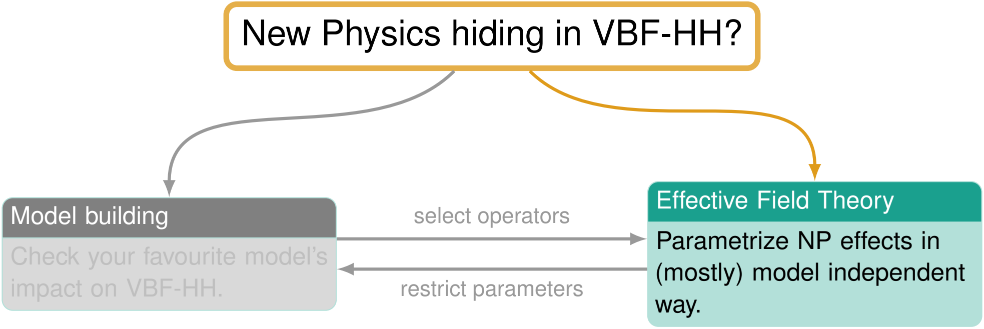
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The EFT approach to New Physics

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The SM as an EFT at the EW scale

General requirements:

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- Field content = SM fields

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Construction

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i C_i \mathcal{O}_i$$

- Coefficients C_i absorb unknown UV dynamics
- Systematic power counting organizes terms according to relevance (e.g. dim-6, dim-8, ... in SMEFT)

Two common EFT realizations

SMEFT

- EWSB realized as in SM, have ordinary Higgs doublet Φ
- Must have weakly coupled NP, NP decouples from EW scale physics
- Organization of power counting according to canonical dimension

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HEFT

- EWSB not necessarily SM-like, split Goldstone modes U and Higgs scalar h
- Can have strongly coupled NP in Higgs sector, does not decouple
- Organization of power counting in chiral dimension (loop counting)

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- Can have strongly coupled NP in Higgs sector, does not decouple
- Organization of power counting in chiral dimension (loop counting)
- Note: sometimes called the “Electroweak Chiral Lagrangian” (EWChL)

The HEFT-Lagrangian at LO

$$
\begin{aligned}
\mathcal{L}_{SM} = &-\frac{1}{2}\langle G_{\mu\nu}G^{\mu\nu}\rangle - \frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \bar{\psi}i\not{D}\psi \\
&+ \frac{1}{2}\partial_\mu h\partial^\mu h - v^2\left[\frac{m_h^2}{2}\left(\frac{h}{v}\right)^2 + \frac{m_h^2}{2}\left(\frac{h}{v}\right)^3 + \frac{m_h^2}{8}\left(\frac{h}{v}\right)^4\right] \\
&+ \frac{v^2}{4}\langle D_\mu U^\dagger D^\mu U\rangle\left[1 + 2\frac{h}{v} + \left(\frac{h}{v}\right)^2\right] \\
&- v\left[\bar{q}_L\left(Y_u + Y_u\frac{h}{v}\right)U\begin{pmatrix} u_R \\ 0 \end{pmatrix} + \text{h.c.} + \dots\right]
\end{aligned}
$$

- Goldstone bosons of EWSB:

  $$U = \exp\left(2i\frac{\varphi_\alpha t^\alpha}{v}\right)$$

- Higgs doublet:

  $$\Phi = U\begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}$$

  $\Rightarrow$ correlations between h-couplings

- Renormalizable in the classical sense

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&+ \frac{1}{2}\partial_\mu h\partial^\mu h - v^2\left[\frac{m_h^2}{2}\left(\frac{h}{v}\right)^2 + \sum_{i=3}^{\infty} V^{(i)}\left(\frac{h}{v}\right)^i\right] \\
&+ \frac{v^2}{4}\langle D_\mu U^\dagger D^\mu U\rangle\left[1 + \sum_{i=1}^{\infty} f_U^{(i)}\left(\frac{h}{v}\right)^i\right] \\
&- v\left[\bar{q}\left(Y_u + \sum_{i=1}^{\infty} Y_u^{(i)}\left(\frac{h}{v}\right)^i\right)U\begin{pmatrix}u_R\\0\end{pmatrix} + \text{h.c.} + \ldots\right]
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- Goldstone bosons of EWSB:
  $$U = \exp\left(2i\frac{\varphi_\alpha t^\alpha}{v}\right)$$
- h not part of a doublet
  $\Rightarrow$ no correlations
- h couples strongly to Goldstone sector $\Rightarrow$ arbitrary powers of h
- Non-renormalizable in the classical sense

HEFT power counting

- Characteristic scale of HEFT: v
  ↳ LO Lagrangian contains all terms of order $\sim v^4$
- Strong dynamics in scalar sector implies EFT cutoff: $\Lambda \sim 4\pi v$
- HEFT is constructed as an expansion in $\frac{v^2}{\Lambda^2} \sim \frac{1}{16\pi^2} \Rightarrow$ loop expansion

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Chiral dimension d_χ

$[A_\mu, \varphi, h]_\chi = 0, \quad [\partial, \bar{\psi}\psi, g, y]_\chi = 1 \quad \Rightarrow \quad [\mathcal{O}]_\chi = 2L + 2$ (L: loop order)

↪ LO Lagrangian $\mathcal{L}_2$ has $d_\chi = 2$ (0-loop order / tree level)

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Note: custodial symmetry breaking operator at $d_\chi = 2$: $\quad \mathcal{O}_{\beta_1} \sim v^2 \left\langle U^\dagger D_\mu U t^3 \right\rangle^2 F_{\beta_1}(h)$

- Highly constrained from EW T-parameter $\Rightarrow$ loop-suppressed $\Rightarrow$ NLO term

The HEFT Lagrangian at NLO

Construction of the NLO Lagrangian

- $\mathcal{L}_2$ renormalizable in the modern sense: introduction of counterterms order by order in loop expansion
- At NLO ($d_\chi = 4$): terms needed as counterterms for 1-loop diagrams constructed from $\mathcal{L}_2$
- From (momentum) power counting arguments: finite number of divergent diagrams at each order

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Operator classes

$UhD^4,\ g^2X^2Uh,\ gXUhD^2,\ y^2\psi^2UhD,\ y\psi^2UhD^2,\ y^2\psi^4Uh$

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Full set of 1-loop RGEs available since 2020 [Buchalla et al. 2020]

Parametrization of anomalous Higgs couplings

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HEFT for the practitioner

Not all Operators relevant for given processes: e.g. (double) Higgs production, Higgs decays

Assumptions:

- CP conservation
- Custodial symmetry conserved at LO (*Wh* couplings = *Zh* couplings)

$$\mathcal{L}_{eff} \supset \left(2c_V\frac{h}{v} + c_{2V}\frac{h^2}{v^2}\right)\left(m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2}m_Z^2 Z_\mu Z^\mu\right) - \sum_f m_f\left(c_f\frac{h}{v} + c_{2f}\frac{h^2}{v^2}\right)\bar{f}f + c_\lambda\frac{m_h^2}{2v}h^3$$
$$+\frac{\alpha}{8\pi}\left(c_{\gamma\gamma}\frac{h}{v} + c_{2\gamma\gamma}\frac{h^2}{v^2}\right)F_{\mu\nu}F^{\mu\nu} + \frac{\alpha_s}{8\pi}\left(c_{gg}\frac{h}{v} + c_{2gg}\frac{h^2}{v^2}\right)G^a_{\mu\nu}G^{a\mu\nu}$$

SM: $c_V = c_{2V} = c_f = c_\lambda = 1$, $c_{2f} = c_{\gamma\gamma} = c_{2\gamma\gamma} = c_{gg} = c_{2gg} = 0$

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hWW and hZZ couplings affected at tree level ($d_\chi = 2$)
$\Rightarrow$ operators $\sim h \langle W_{\mu\nu} W^{\mu\nu} \rangle$ from $\mathcal{L}_4$ subleading

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SM: $c_V = c$ …

h-photon and *h*-gluon interactions loop-induced
$\Rightarrow \mathcal{L}_4$ terms contribute to leading NP effects

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HEFT for the practitioner

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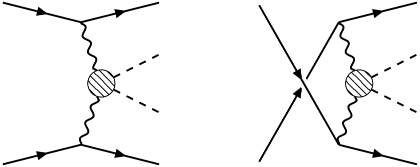
$$+\frac{\alpha}{8\pi}\left(c_{\gamma\gamma}\frac{h}{v} + c_{2\gamma\gamma}\frac{h^2}{v^2}\right)F_{\mu\nu}F^{\mu\nu} + \quad \leftarrow \quad \mathcal{L}_4$$

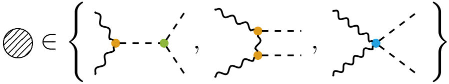
- At NLO QCD: No additional vertex structures! $\Rightarrow$ corresponds to κ-framework
- $\mathcal{L}_4$ becomes relevant at NLO EW

SM: $c_V = c_{2V} = c_\lambda = 1$

VBF-HH in HEFT: LO

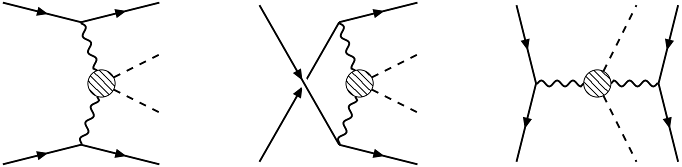
$$\mathcal{L}_{eff} \supset \left(2 c_V \frac{h}{v} + c_{2V} \frac{h^2}{v^2}\right)\left(m_W^2 W^+_\mu W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right) + c_\lambda \frac{m_h^2}{2v} h^3$$



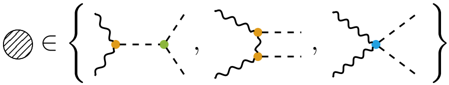


VBF-HH in HEFT: LO

$$\mathcal{L}_{eff} \supset \left(2 c_V \frac{h}{v} + c_{2V} \frac{h^2}{v^2}\right)\left(m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right) + c_\lambda \frac{m_h^2}{2v} h^3$$

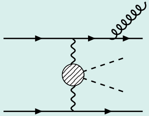


Same coupling order $\mathcal{O}(g_{ew}^4)$
$\Rightarrow$ included in our calculation,
suppressed by VBF-cuts:
large rapidity separation and
invariant mass in jet-system

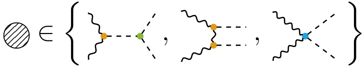


VBF-HH in HEFT: NLO QCD

Real corrections:



+ *u*- and *s*-channel crossings
+ process with gluon crossed into inital state



No QCD loop corrections to

$\Rightarrow$ renormalization as in SM

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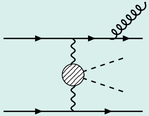

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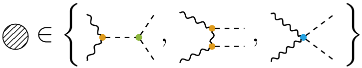

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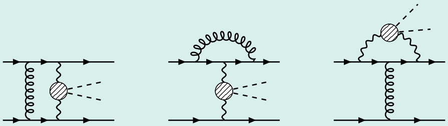
Virtual corrections:



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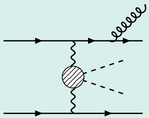

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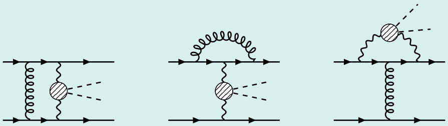

+ u- and s-channel crossings

Framework: Whizard + GoSam

- Use GoSam to generate amplitudes based on custom HEFT UFO model
- Whizard as Monte Carlo generator
- Implement flexible interface, usable for other processes

Whizard + GoSam

sindarin runcard:
define process, specify parameters

Whizard (Monte Carlo event generator)

GoSam (amplitude provider)

Whizard + GoSam

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UFO model

- Particles
- Vertices

Whizard (Monte Carlo event generator)

- Construct channel list & FKS subtraction terms

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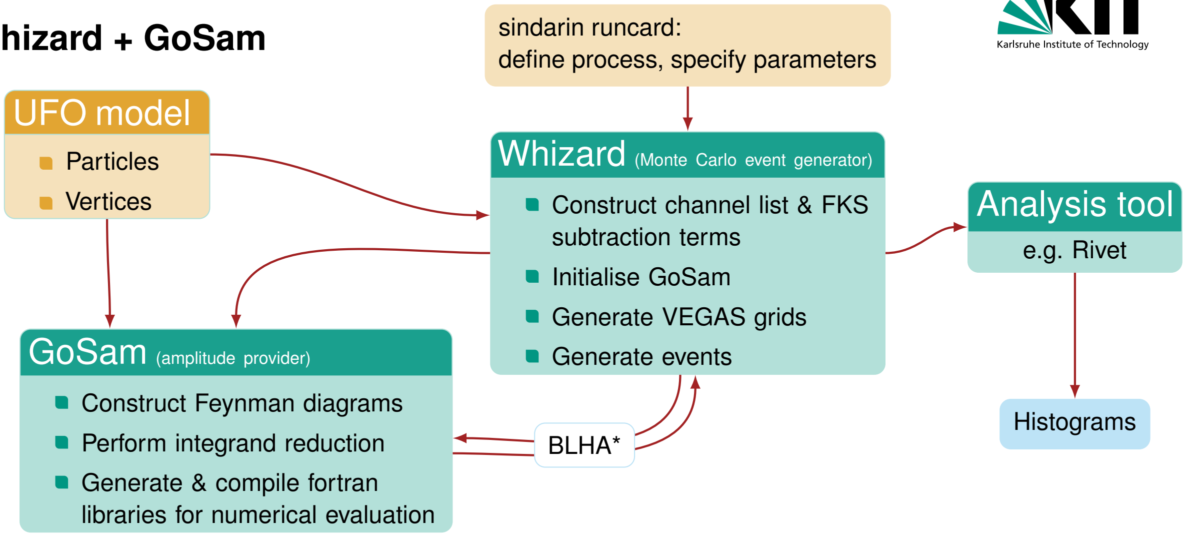
BLHA*

*Binoth Les Houches Accord

Whizard + GoSam



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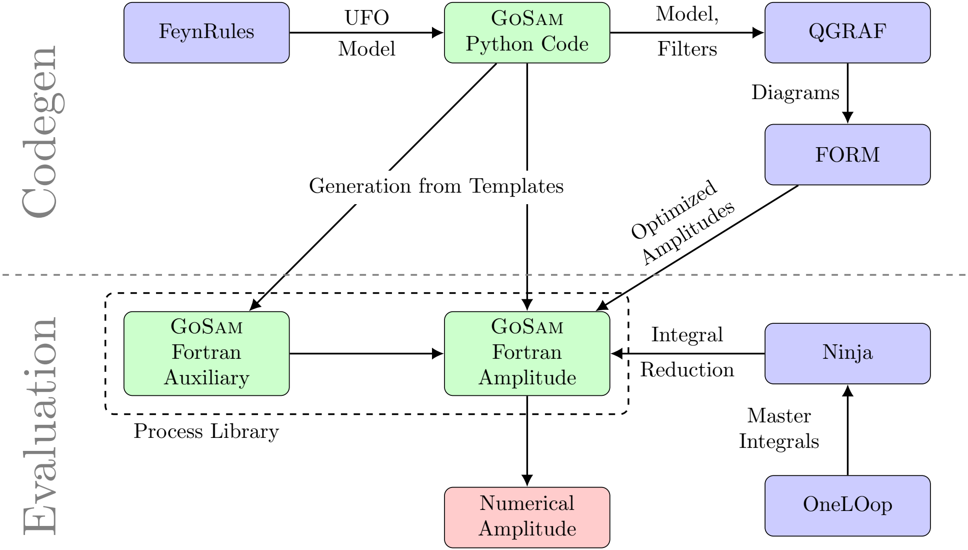
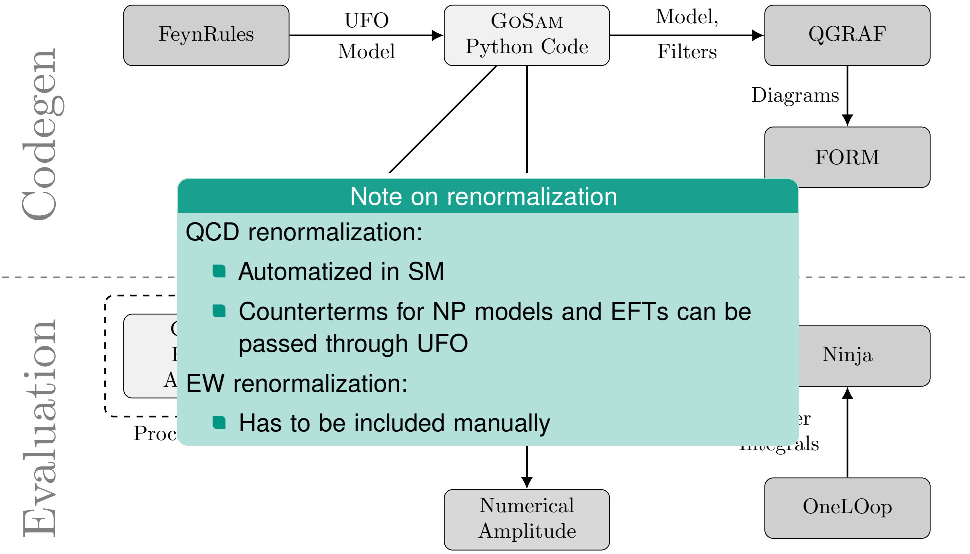


figure by Jens Braun



Note on renormalization

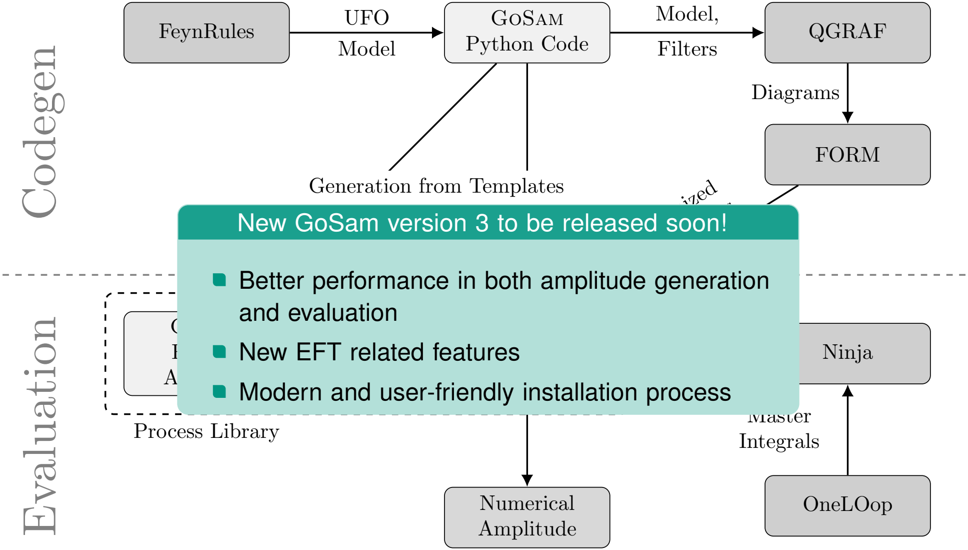
QCD renormalization:

- Automatized in SM
- Counterterms for NP models and EFTs can be passed through UFO

EW renormalization:

- Has to be included manually

figure by Jens Braun

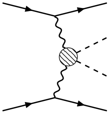


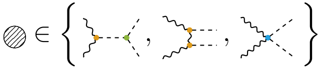
New GoSam version 3 to be released soon!

- Better performance in both amplitude generation and evaluation
- New EFT related features
- Modern and user-friendly installation process

figure by Jens Braun

VBF-HH: Process setup





$pp \to hh + 2$jets at $\mathcal{O}(\alpha_{ew}^4, \alpha_{ew}^4 \alpha_s)$ + c_V, c_{2V}, c_λ

- $\sqrt{s} = 13.6$TeV
- PDF set: `PDF4LHC21_mc`
- Central renormalization and factorization scale: $\mu_0 = \left(\frac{m_h^2}{4}\left(\frac{m_h^2}{4} + p_{T,hh}^2\right)\right)^{\frac{1}{4}}$
- 3-point scale variation $\mu_R = \mu_F = a\mu_0$ with $a = 0.5, 1, 2$
- Jets: anti-k_t with $R = 0.4$, at least two jets with $p_{T,j} > 20$GeV and $|y_j| < 4.5$
- VBF cuts: $m_{j_1 j_2} > 600$GeV and $\Delta\eta(j_1, j_2) > 4.0$

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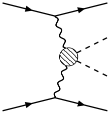

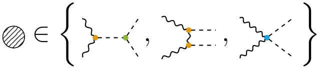

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For Validation:
$c_V = c_{2V} = c_\lambda = 1$ (SM)
$\mu_R = \mu_F = 2m_h$

VBF-HH: Validation

SM case ($c_V = c_{2V} = c_\lambda = 1$) can be validated against other tools.

- Matrix elements: check against OpenLoops2 for 10^6 random phase space points
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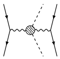
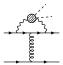
no  , 

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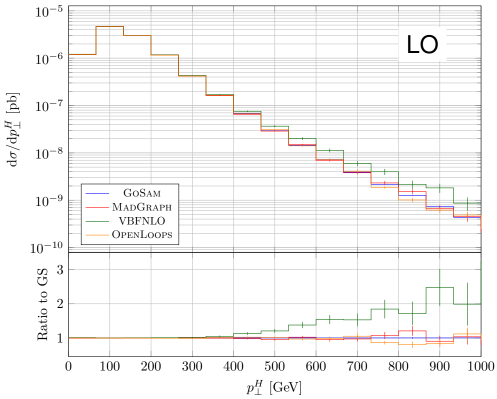
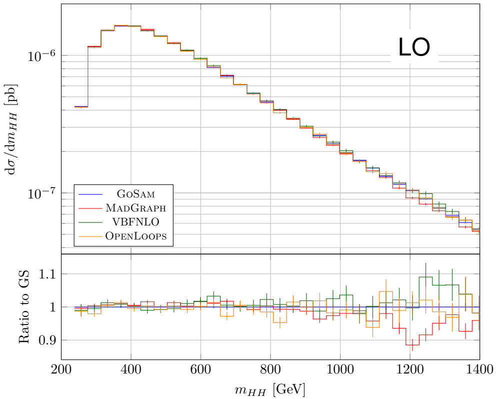
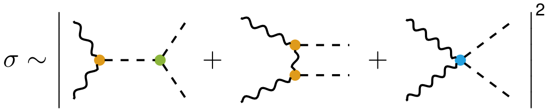




Phenomenology

Parametrization of the total cross section



$$\Rightarrow \quad \frac{\sigma}{\sigma_{\mathrm{SM}}} = A_0\ c_\lambda^2 c_V^2 + A_1\ c_V^4 + A_2\ c_{2V}^2 + A_3\ c_\lambda c_V^3 + A_4\ c_\lambda c_V c_{2V} + A_5\ c_V^2 c_{2V}$$

- Coefficients A_i can be determined by fit after calculating σ for different values of c_i
- No new A_i at NLO QCD, but different numerical values
- Note: $\sum_i A_i = 1$ by construction

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NLO coeff.	$\mu_F = \mu_r = \mu_0/2$	$\mu_F = \mu_r = \mu_0$	$\mu_F = \mu_r = 2\mu_0$
A_0	0.7011(46)	0.6889(35)	0.6830(30)
A_1	22.15(12)	21.71(9)	21.55(8)
A_2	11.86(7)	11.59(5)	11.55(4)
A_3	-6.139(42)	-6.025(33)	-5.984(27)
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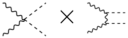
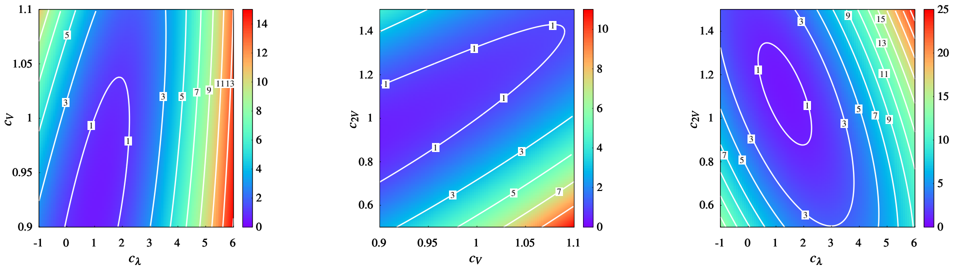
Destructive interferences:
 and 
Note: depends on signs of c_i

Total cross section

Parameter ranges are chosen roughly like current experimental bounds [ATLAS 2024][CMS 2024]

$$c_V \in [0.9, 1.1], \qquad c_{2V} \in [0.5, 1.5], \qquad c_\lambda \in [-1, 6]$$



σ / σ_{SM} (NLO),
one c_i fixed to SM

- Can have increase of cross section by more than a factor of 20.
- Current best exp. bound: $\sigma^{exp.}_{VBF-HH} \lesssim 50\sigma^{SM}_{VBF-HH}$ [ATLAS @ LHC-HWG'24]

Total cross section

Karlsruhe Institute of Technology

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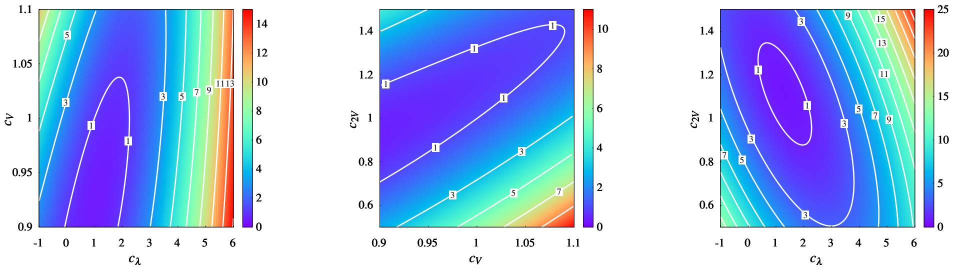

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When all three c_i allowed to float: up to factor $\sim$ 130 possible

Total cross section: K-factors

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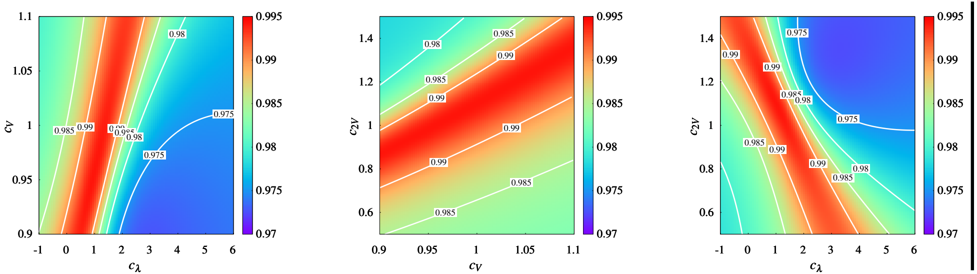

σ_{NLO}/σ_{LO},
one c_i fixed to SM

- NLO QCD K-factor mostly flat: structure of EFT contributions unaffected by QCD

Distributions

Parametrization with A_i in principle possible with distributions, but:

- Requires very high statistics in each bin
- Detailed analysis of correlations for uncertainty estimation

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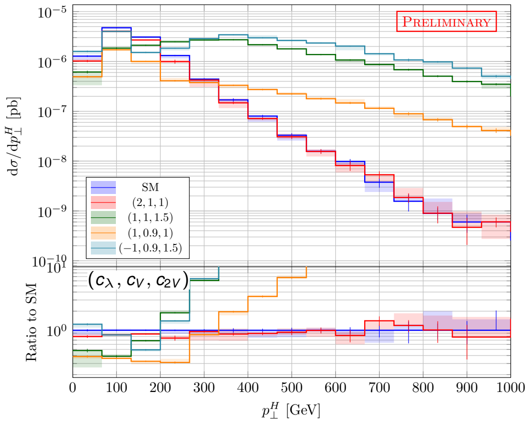
Alternative: distributions for 12 benchmark points (c_λ, c_V, c_{2V}) incl. SM

c_λ	1	0	1	1	1	2	-1	-1	2	3	4	6
c_V	1	1	0.9	1	1	1	0.9	1.05	0.9	1.1	0.95	1.1
c_{2V}	1	1	1	0.5	1.5	1	1.5	1.3	1.4	0.5	0.5	1

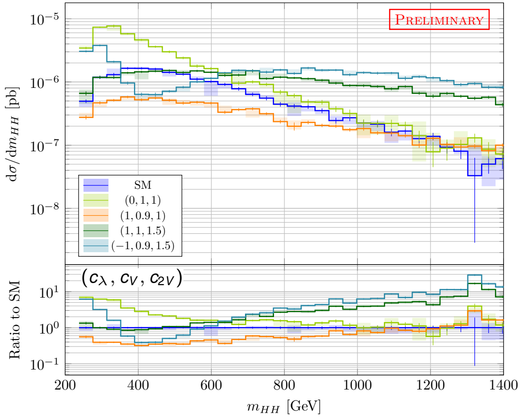
Distributions: Higgs-p_T



Note: p_T of any Higgs $\Rightarrow$ two histrogram entries per event

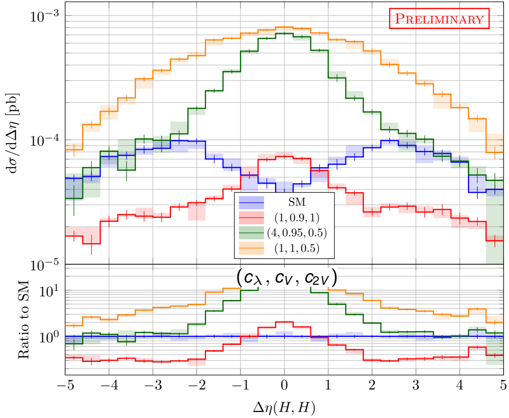
- SM: Max. around 100 GeV, exponentially falling tail.
- Doubling c_λ has no significant effect, slight reduction for low p_T.
- $c_{2V} = 1.5$ (upper exp. bound) enhances tail drastically. Reduction in low p_T. Shifts maximum.
- $c_V = 0.9$ (lower exp. bound) similar as previous, does not shift maximum.
- All c_i at exp. boundaries: enhancements in tail and in first bin, reduction in second and third bin.

Distributions: Higgs pair invariant mass



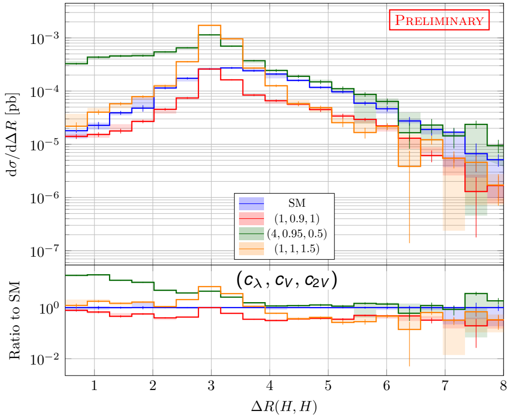
- SM: broad max. around 400 GeV, exponentially falling tail.
- Switching of triple h coupling has almost no effect on tail. Increases low m_{hh} significantly.
- $c_{2V} = 1.5$ (upper exp. bound) flattens distribution. Large enhancements in the tail.
- $c_V = 0.9$ (lower exp. bound) similar as previous, but ovearll reduction of the cross-section, except for high m_{hh}
- All c_i at exp. boundaries: enhancements for low and high m_{hh}. Dip around 400 GeV.

Distributions: Higgs pair rapidity separation



- SM: low rap.-separation suppressed, peaks around ± 2.5.
- $c_V = 0.9$ (lower exp. bound) very different from SM. Low rapidity-separation favoured.
- Larger c_λ, smaller c_V, c_{2V}: similar as previous, much larger peak.
- $c_{2V} = 0.5$ (lower exp. bound) even larger shape distortions, large overall enhancement.

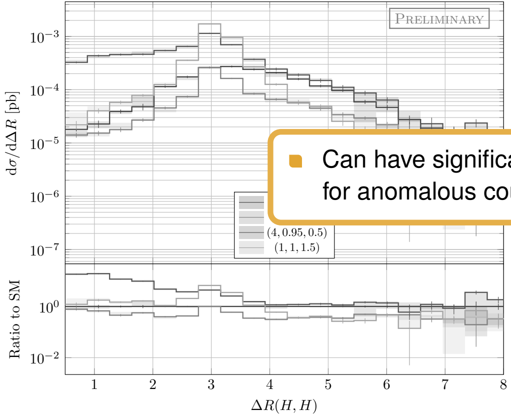
Distributions: Higgs pair separation



$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\Phi^2}$$

- SM: form of $\Delta\eta$ distr. decisive: low ΔR suppressed, peak at $\Delta R \approx 3.5$.
- $c_V = 0.9$ (lower exp. bound): clear peak at $\Delta R \approx 3$, overall suppression.
- $c_{2V} = 1.5$ (upper exp. bound) clear peak at $\Delta R \approx 3$, enhancement for low ΔR, suppression for high ΔR.
- Larger c_λ, smaller c_V, c_{2V}: high ΔR comparable to SM, but low ΔR region enhanced.

Distributions: Higgs pair separation



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- Can have significant and interesting shape distortions for anomalous couplings within experimental bounds.

Conclusions

- Identified leading HEFT operators for VBF-HH at NLO QCD
  ↳ Three anomalous couplings c_λ, c_V, c_{2V} (corresponds to κ-framework)
  ↳ Sub-leading operators will be relevant at NLO EW
- Updated Whizard-GoSam interface to investigate HEFT effects
- Determined set of coefficients A_i: total cross section for arbitrary values of the anom. couplings
  ↳ Large enhancements wrt. SM cross section possible
- Observe significant shape distortions in distributions for anomalous couplings within allowed range

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Possible further studies

- Consider possible constraints from unitarity
- Add Higgs decays
- Add NLO EW (a lot of work...)

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