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Effective Field Theory descriptions of Higgs boson pair production

EFT for H+HH meeting
29 March 2023

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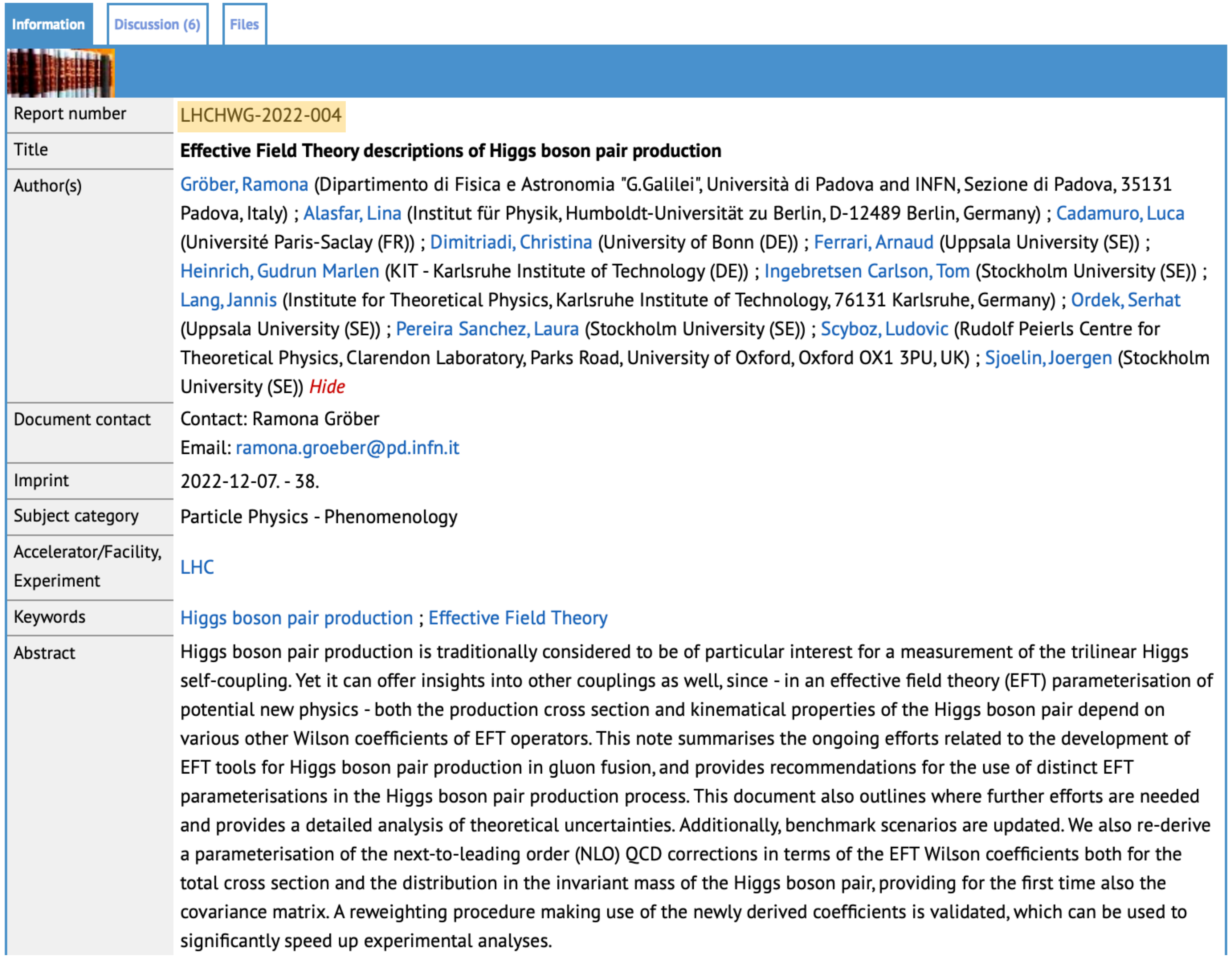
Outline

- Motivation
- SMEFT vs. HEFT
- Available MC tools
- Updated benchmarks
- Theoretical uncertainties
- Reweighting



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Title	**Effective Field Theory descriptions of Higgs boson pair production**
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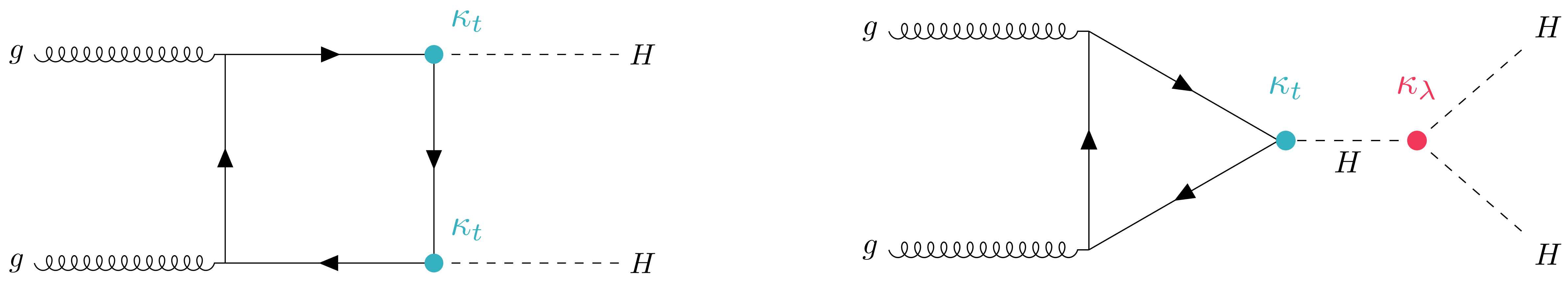
Keywords	Higgs boson pair production ; Effective Field Theory
Abstract	Higgs boson pair production is traditionally considered to be of particular interest for a measurement of the trilinear Higgs self-coupling. Yet it can offer insights into other couplings as well, since - in an effective field theory (EFT) parameterisation of potential new physics - both the production cross section and kinematical properties of the Higgs boson pair depend on various other Wilson coefficients of EFT operators. This note summarises the ongoing efforts related to the development of EFT tools for Higgs boson pair production in gluon fusion, and provides recommendations for the use of distinct EFT parameterisations in the Higgs boson pair production process. This document also outlines where further efforts are needed and provides a detailed analysis of theoretical uncertainties. Additionally, benchmark scenarios are updated. We also re-derive a parameterisation of the next-to-leading order (NLO) QCD corrections in terms of the EFT Wilson coefficients both for the total cross section and the distribution in the invariant mass of the Higgs boson pair, providing for the first time also the covariance matrix. A reweighting procedure making use of the newly derived coefficients is validated, which can be used to significantly speed up experimental analyses.

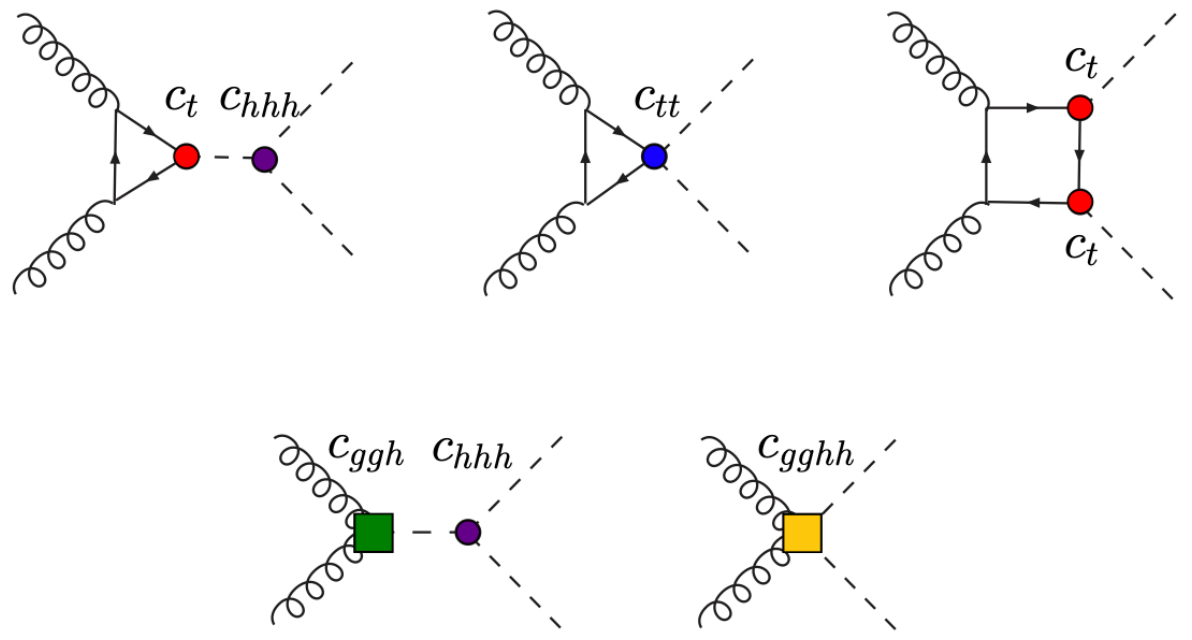
Motivation

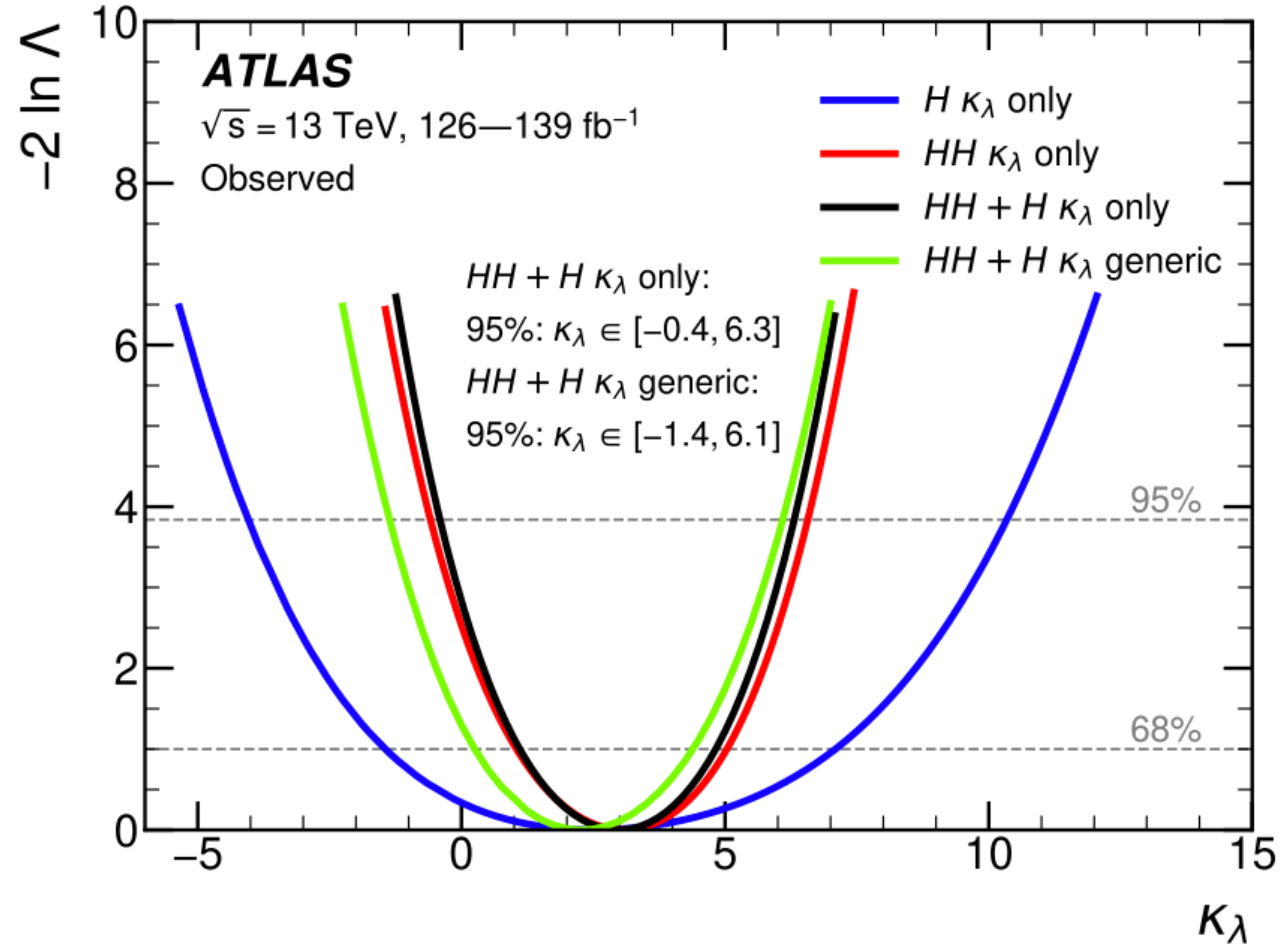
- HH production is of great interest for the Higgs self-coupling measurement



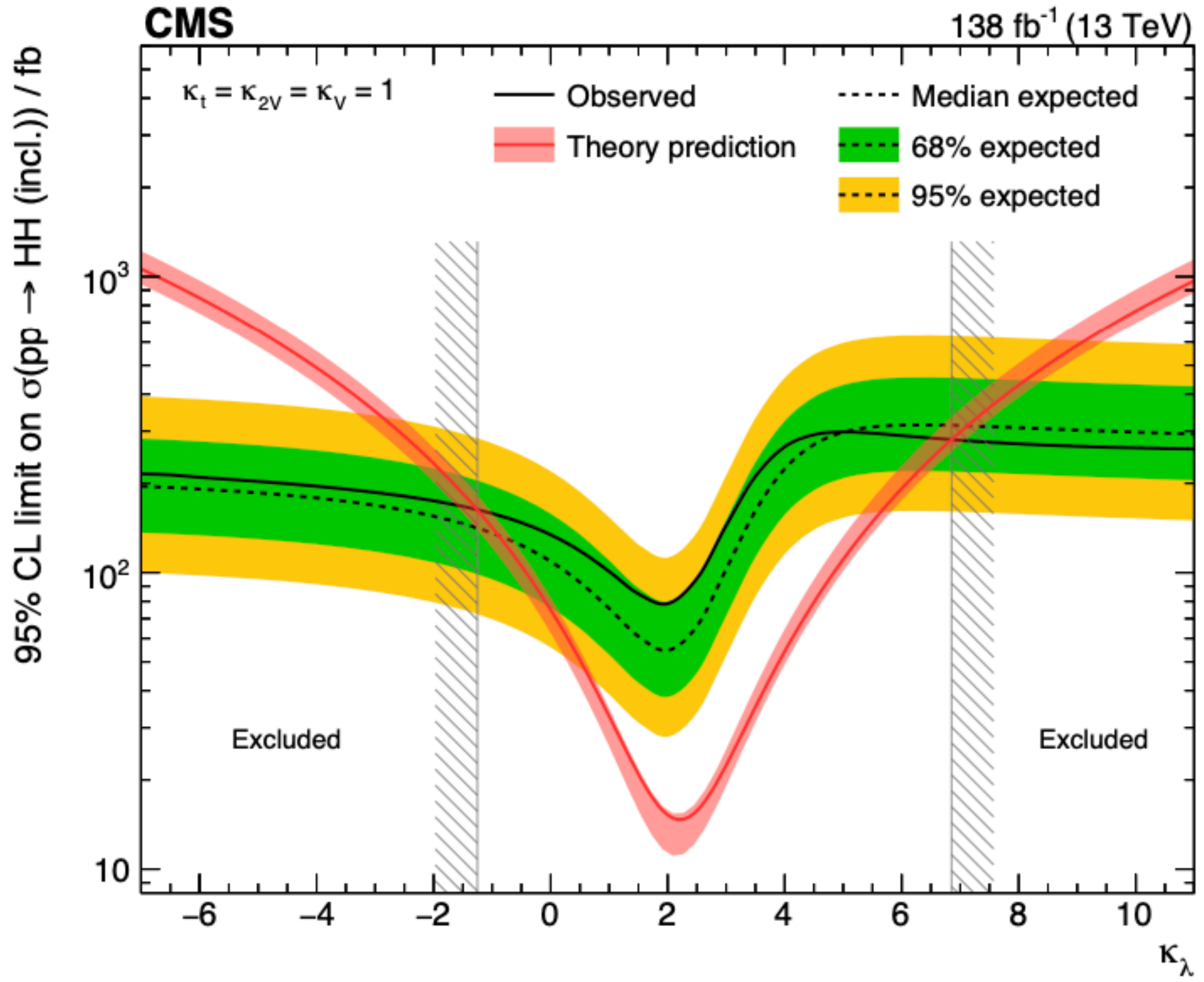
- SM HH rate very small, but many models predict alternative cross-sections and kinematics

- Effective operators can modify the $gg \to HH$ production in various ways



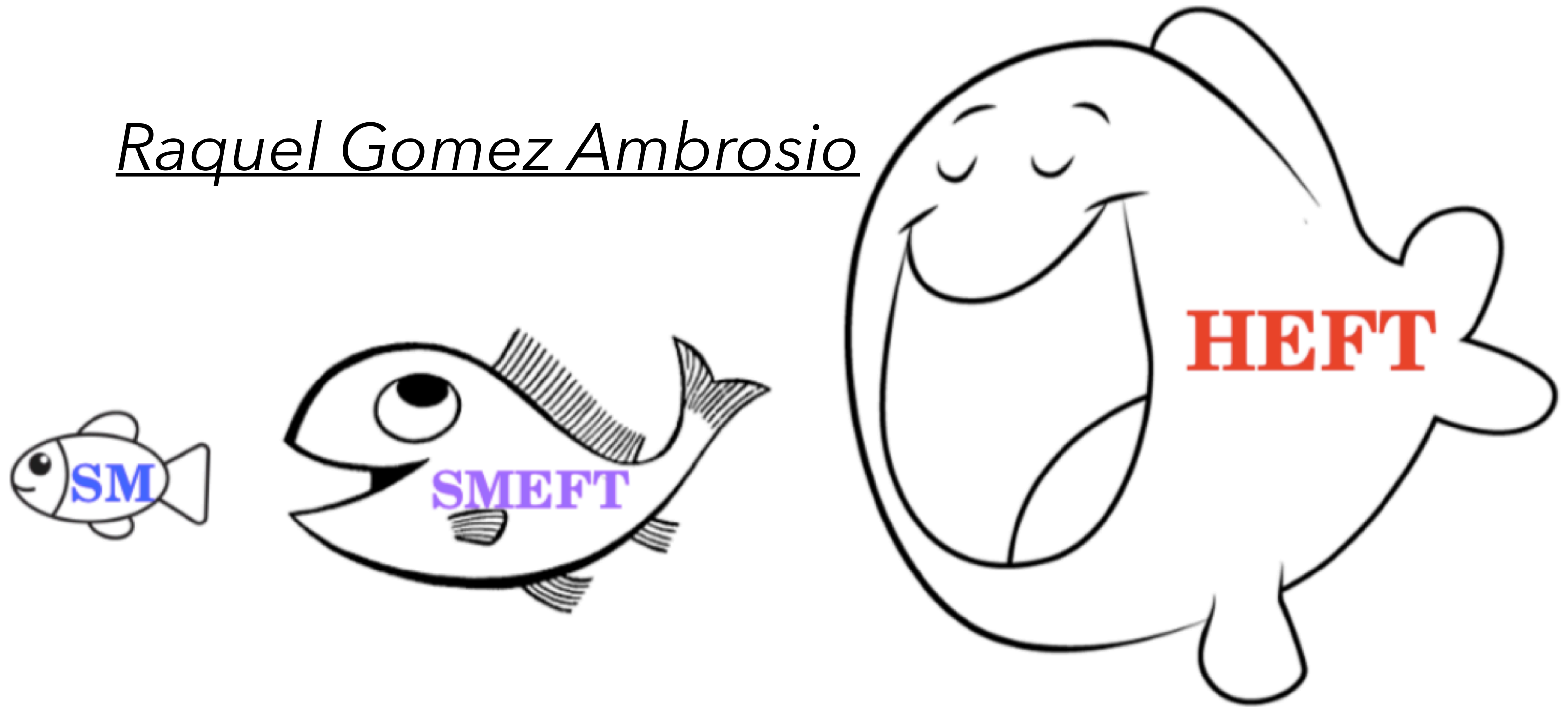


arXiv:2211.01216



arXiv:2207.00043

EFT frameworks



Raquel Gomez Ambrosio

SMEFT

- Canonical counting, expansion in $1/\Lambda$

$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_{n,i} \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathscr{O}_i^{(n)}$$

- SM symmetries and fields, traditional EWSB mechanism (Higgs field: $SU(2)_L$ doublet)
- More restrictive (correlated Wilson coefficients)

HEFT

- No power-counting like in SMEFT, more similar to chiral perturbation theory

$$\mathscr{L}_{d_\chi} = \mathscr{L}_{(d_\chi=2)} + \sum_{L=1}^{\infty} \sum_{i} \left(\frac{1}{16\pi^2} \right)^{L} c_i^{(L)} O_i^{(L)}$$

- Higgs field: EW singlet
- Much more general (independent couplings)

SMEFT vs. HEFT

SMEFT

$$\Delta\mathscr{L}_{\text{Warsaw}} = \frac{C_{H,\Box}}{\Lambda^2}(\phi^\dagger\phi)\Box(\phi^\dagger\phi) + \frac{C_{HD}}{\Lambda^2}(\phi^\dagger D_\mu\phi)^*(\phi^\dagger D^\mu\phi) + \frac{C_H}{\Lambda^2}(\phi^\dagger\phi)^3 + (\frac{C_{uH}}{\Lambda^2}\phi^\dagger\phi\bar{q}_L\tilde{\phi}\, t_R + \text{h.c.}) + \frac{C_{HG}}{\Lambda^2}\phi^\dagger\phi G^a_{\mu\nu}G^{\mu\nu,a} + \frac{C_{uG}}{\Lambda^2}(\bar{q}_L\sigma^{\mu\nu}T^aG^a_{\mu\nu}\tilde{\phi}\, t_R + \text{h.c.})$$

$$\Delta\mathscr{L}_{\text{SILH}} = \frac{\bar{c}_H}{2v^2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi) + \frac{\bar{c}_u}{v^2}y_t(\phi^\dagger\phi\,\bar{q}_L\tilde{\phi}t_R + \text{h.c.}) - \frac{\bar{c}_6}{2v^2}\frac{m_h^2}{v^2}(\phi^\dagger\phi)^3 + \frac{\bar{c}_{ug}}{v^2}g_s(\bar{q}_L\sigma^{\mu\nu}G_{\mu\nu}\tilde{\phi}\, t_R + \text{h.c.}) + \frac{4\bar{c}_g}{v^2}g_s^2\phi^\dagger\phi\, G^a_{\mu\nu}G^{a\mu\nu}$$

HEFT

$$\Delta\mathscr{L}_{\text{HEFT}} = -m_t(c_t\frac{h}{v} + c_{tt}\frac{h^2}{v^2})\,\bar{t}\,t - c_{hhh}\frac{m_h^2}{2v}h^3 + \frac{\alpha_s}{8\pi}(c_{ggh}\frac{h}{v} + c_{gghh}\frac{h^2}{v^2})\,G^a_{\mu\nu}G^{a,\mu\nu}$$

Naive translation after field redefinition up to $\mathcal{O}(\Lambda^{-2})$ in Lagrangian ($C_{H,\text{kin}} = C_{H,\Box} - \frac{1}{4}C_{HD}$)

- ❗ Different assumptions, different EFT validity range
- ❗ Translation contains α_s which is a running parameter, typically evaluated at $\mu_0 = m_{hh}/2$
- ❗ Not generally applicable in practical calculations

HEFT	SILH	Warsaw
c_{hhh}	$1 - \frac{3}{2}\bar{c}_H + \bar{c}_6$	$1 - 2\frac{v^2}{\Lambda^2}\frac{v^2}{m_h^2}C_H + 3\frac{v^2}{\Lambda^2}C_{H,\text{kin}}$
c_t	$1 - \frac{\bar{c}_H}{2} - \bar{c}_u$	$1 + \frac{v^2}{\Lambda^2}C_{H,\text{kin}} - \frac{v^2}{\Lambda^2}\frac{v}{\sqrt{2}m_t}C_{uH}$
c_{tt}	$-\frac{\bar{c}_H + 3\bar{c}_u}{4}$	$-\frac{v^2}{\Lambda^2}\frac{3v}{2\sqrt{2}m_t}C_{uH} + \frac{v^2}{\Lambda^2}C_{H,\text{kin}}$
c_{ggh}	$128\pi^2\bar{c}_g$	$\frac{v^2}{\Lambda^2}\frac{8\pi}{\alpha_s}C_{HG}$
c_{gghh}	$64\pi^2\bar{c}_g$	$\frac{v^2}{\Lambda^2}\frac{4\pi}{\alpha_s}C_{HG}$

SMEFT truncations

- Amplitude: $\mathcal{M} = \mathcal{M}_{\text{SM}} + \underbrace{\mathcal{M}_{\text{dim6}}}_{\text{Single dim-6 operator insertions}} + \underbrace{\mathcal{M}_{\text{dim6}^2}}_{\text{Double dim-6 operator insertions}}$

➡ Same order as the dim-8 operators (neglected) and the $\mathcal{O}(\Lambda^{-4})$ terms following field redefinition

- Amplitude squared:

$$\sigma \simeq \begin{cases} \sigma_{\text{SM}\times\text{SM}} + \sigma_{\text{SM}\times\text{dim6}} \\ \sigma_{(\text{SM+dim6})\times(\text{SM}+\text{dim6})} \\ \sigma_{(\text{SM+dim6})\times(\text{SM}+\text{dim6})} + \sigma_{\text{SM}\times\text{dim6}^2} \\ \sigma_{\left(\text{SM+dim6+dim6}^2\right)\times\left(\text{SM}+\text{dim6}+\text{dim6}^2\right)} \end{cases}$$

Truncation options

(a) LO of an expansion of the cross-section in Λ^{-2} (linearised SMEFT)

(b) LO of an expansion of the amplitude in Λ^{-2}, which is then squared

(c) All terms of $\mathcal{O}(\Lambda^{-4})$ from single and double dim-6 insertions (ambiguous definition)

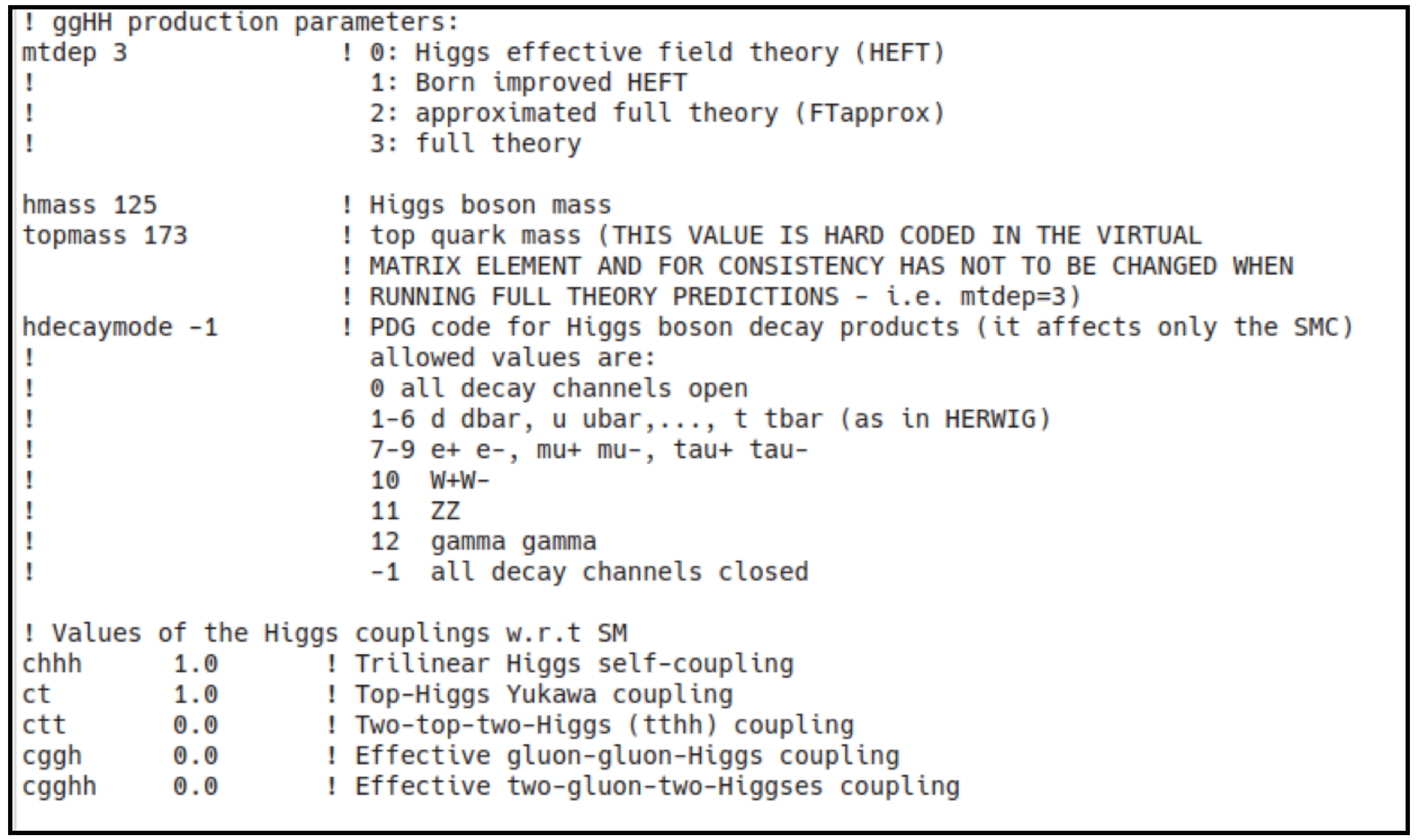
(d) Naive translation from HEFT to SMEFT

- Typically only options (a) and (b) are used for predictions based on SMEFT

Available MC tools (including full m_t dependence at NLO)

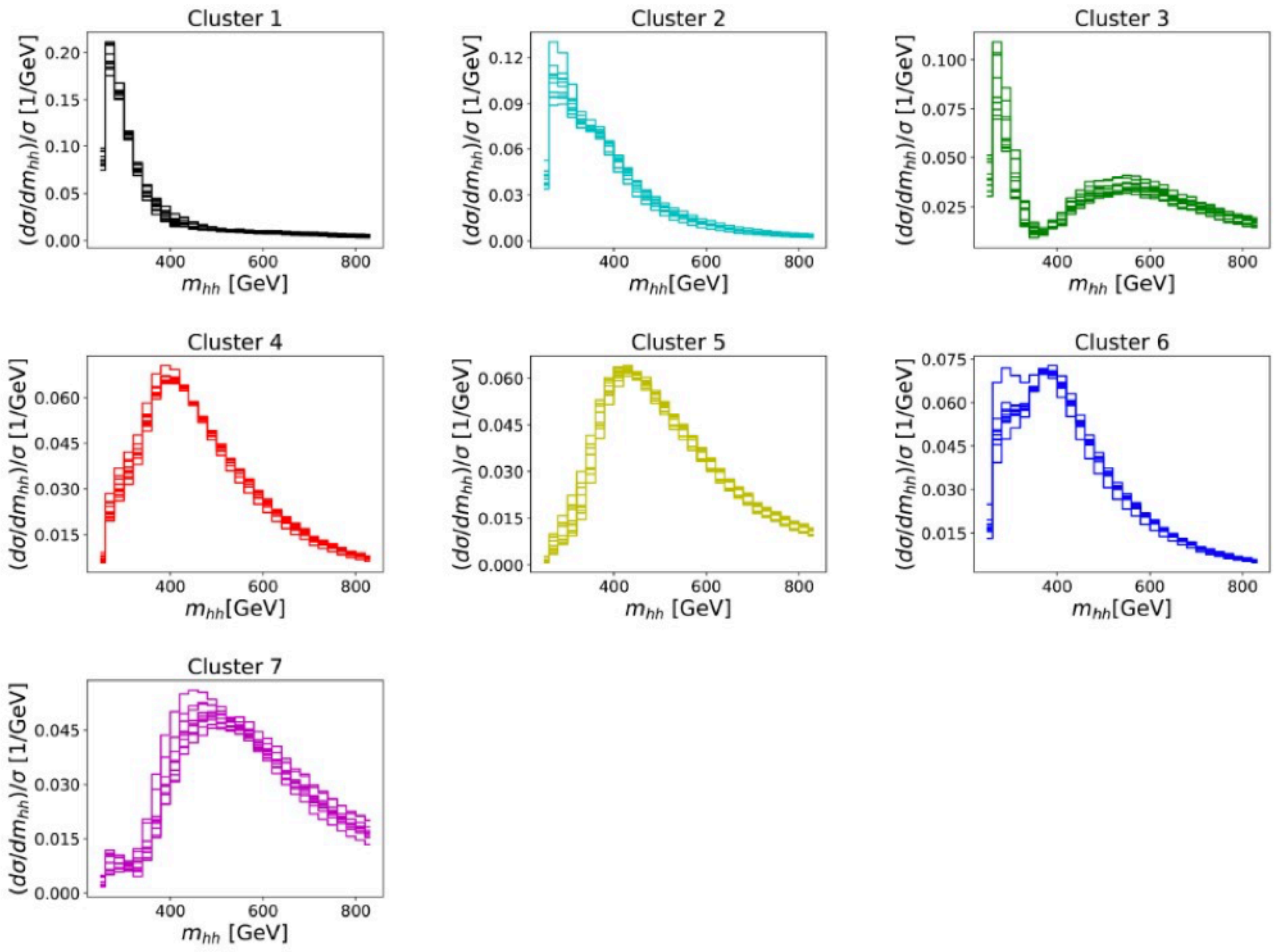
`POWHEG` code `ggHH` (https://powhegbox.mib.infn.it/)

- Update HEFT benchmarks
    - Originally defined in arXiv:1908.08923 based on clustering of m_{hh} shapes using unsupervised ML
    - Apply tighter constraints $0.83 \leq c_t \leq 1.17$ ($|c_{tt}| < 0.05$ for benchmark 1*)



```
! ggHH production parameters:
mtdep 3                 ! 0: Higgs effective field theory (HEFT)
!                         1: Born improved HEFT
!                         2: approximated full theory (FTapprox)
!                         3: full theory

hmass 125               ! Higgs boson mass
topmass 173             ! top quark mass (THIS VALUE IS HARD CODED IN THE VIRTUAL
                        ! MATRIX ELEMENT AND FOR CONSISTENCY HAS NOT TO BE CHANGED WHEN
                        ! RUNNING FULL THEORY PREDICTIONS - i.e. mtdep=3)
hdecaymode -1           ! PDG code for Higgs boson decay products (it affects only the SMC)
!                         allowed values are:
!                         0 all decay channels open
!                         1-6 d dbar, u ubar,..., t tbar (as in HERWIG)
!                         7-9 e+ e-, mu+ mu-, tau+ tau-
!                         10  W+W-
!                         11  ZZ
!                         12  gamma gamma
!                         -1  all decay channels closed

! Values of the Higgs couplings w.r.t SM
chhh       1.0        ! Trilinear Higgs self-coupling
ct         1.0        ! Top-Higgs Yukawa coupling
ctt        0.0        ! Two-top-two-Higgs (tthh) coupling
cggh       0.0        ! Effective gluon-gluon-Higgs coupling
cgghh      0.0        ! Effective two-gluon-two-Higgses coupling
```

benchmark (* = modified)	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}
SM	1	1	0	0	0
1*	5.11	1.10	0	0	0
2*	6.84	1.03	$\frac{1}{6}$	$-\frac{1}{3}$	0
3	2.21	1.05	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{2}$
4*	2.79	0.90	$-\frac{1}{6}$	$-\frac{1}{3}$	$-\frac{1}{2}$
5	3.95	1.17	$-\frac{1}{3}$	$\frac{1}{6}$	$-\frac{1}{2}$
6*	−0.68	0.90	$-\frac{1}{6}$	$\frac{1}{2}$	0.25
7	−0.10	0.94	1	$\frac{1}{6}$	$-\frac{1}{6}$



Available MC tools (including full m_t dependence at NLO)

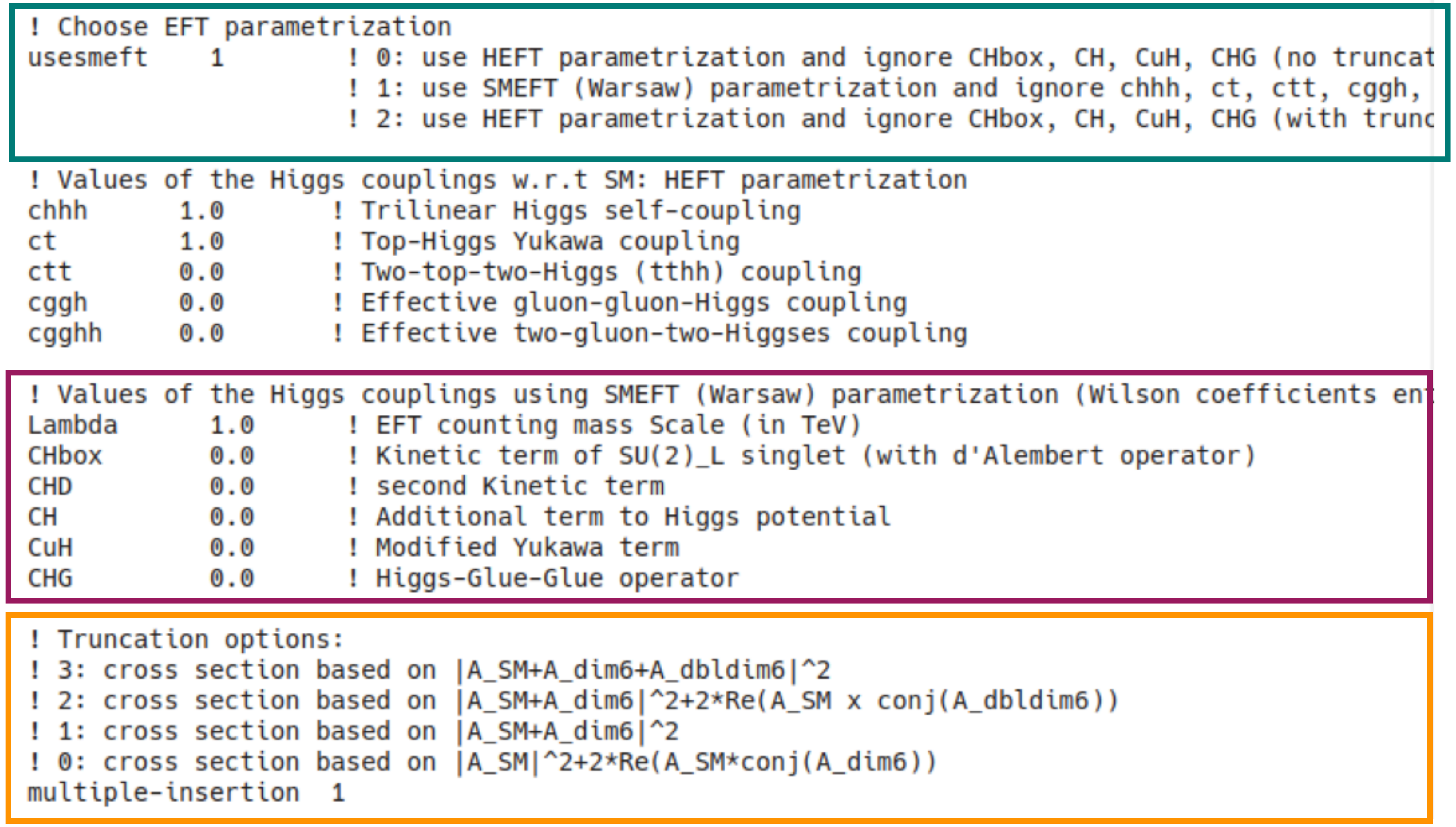
`POWHEG` **code** `ggHH_SMEFT` - Warsaw basis (https://powhegbox.mib.infn.it/)

- Built on NLO HEFT `ggHH` (very similar usage)

`usesmeft 0 (1)` for HEFT (SMEFT) operators

Vary values of Wilson coefficients

`multiple-insertion 0-3` corresponding to truncation options (a)-(d)



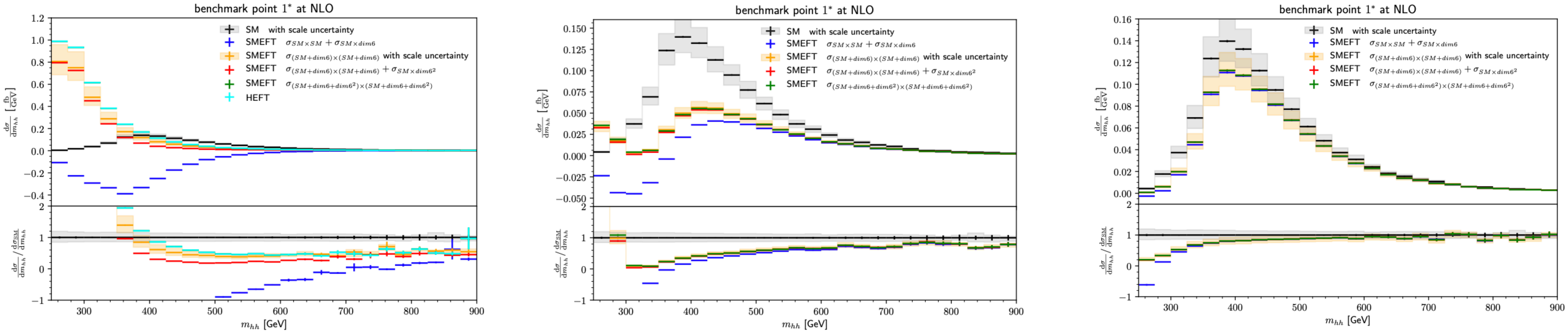
```
! Choose EFT parametrization
usesmeft    1        ! 0: use HEFT parametrization and ignore CHbox, CH, CuH, CHG (no truncat
                     ! 1: use SMEFT (Warsaw) parametrization and ignore chhh, ct, ctt, cggh,
                     ! 2: use HEFT parametrization and ignore CHbox, CH, CuH, CHG (with trunc

! Values of the Higgs couplings w.r.t SM: HEFT parametrization
chhh      1.0       ! Trilinear Higgs self-coupling
ct        1.0       ! Top-Higgs Yukawa coupling
ctt       0.0       ! Two-top-two-Higgs (tthh) coupling
cggh      0.0       ! Effective gluon-gluon-Higgs coupling
cgghh     0.0       ! Effective two-gluon-two-Higgses coupling

! Values of the Higgs couplings using SMEFT (Warsaw) parametrization (Wilson coefficients en
Lambda      1.0      ! EFT counting mass Scale (in TeV)
CHbox       0.0      ! Kinetic term of SU(2)_L singlet (with d'Alembert operator)
CHD         0.0      ! second Kinetic term
CH          0.0      ! Additional term to Higgs potential
CuH         0.0      ! Modified Yukawa term
CHG         0.0      ! Higgs-Glue-Glue operator

! Truncation options:
! 3: cross section based on |A_SM+A_dim6+A_dbldim6|^2
! 2: cross section based on |A_SM+A_dim6|^2+2*Re(A_SM x conj(A_dbldim6))
! 1: cross section based on |A_SM+A_dim6|^2
! 0: cross section based on |A_SM|^2+2*Re(A_SM*conj(A_dim6))
multiple-insertion  1
```

SMEFT truncation effects

Benchmark shape 1*
Enhanced low-m_{hh} region

benchmark (* = modified)	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}	$C_{H,\text{kin}}$	C_H	C_{uH}	C_{HG}
SM	1	1	0	0	0	0	0	0	0
1*	5.11	1.10	0	0	0	4.95	−6.81	3.28	0

Naive benchmark translation
HEFT ↔ SMEFT

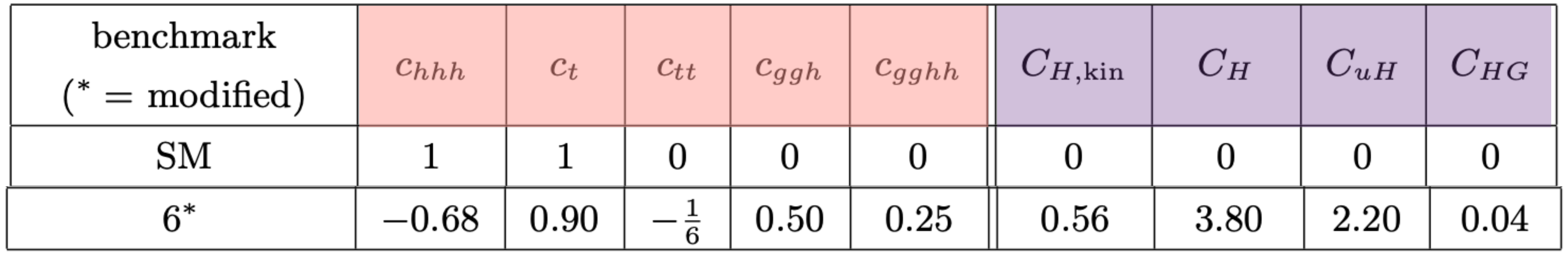


$\Lambda = 1\,\text{TeV}$ $\Lambda = 2\,\text{TeV}$ $\Lambda = 4\,\text{TeV}$

- A valid point in HEFT can become unphysical in SMEFT with the naive translation – negative differential cross-section for truncation (a)
- Increasing Λ reduces the differences between the truncations – convergence towards the SM

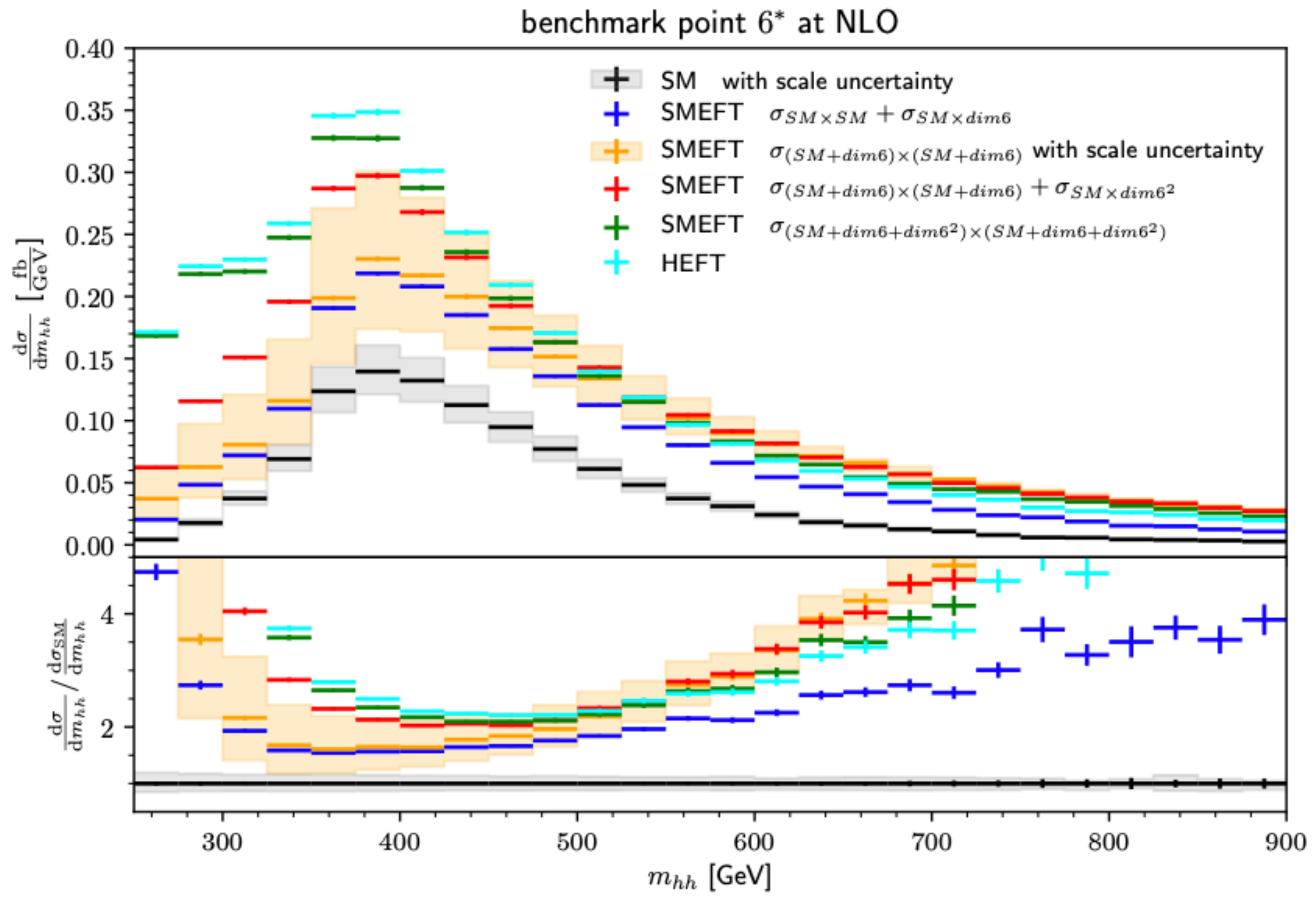
SMEFT truncation effects

Benchmark shape 6*
Shoulder left of the peak

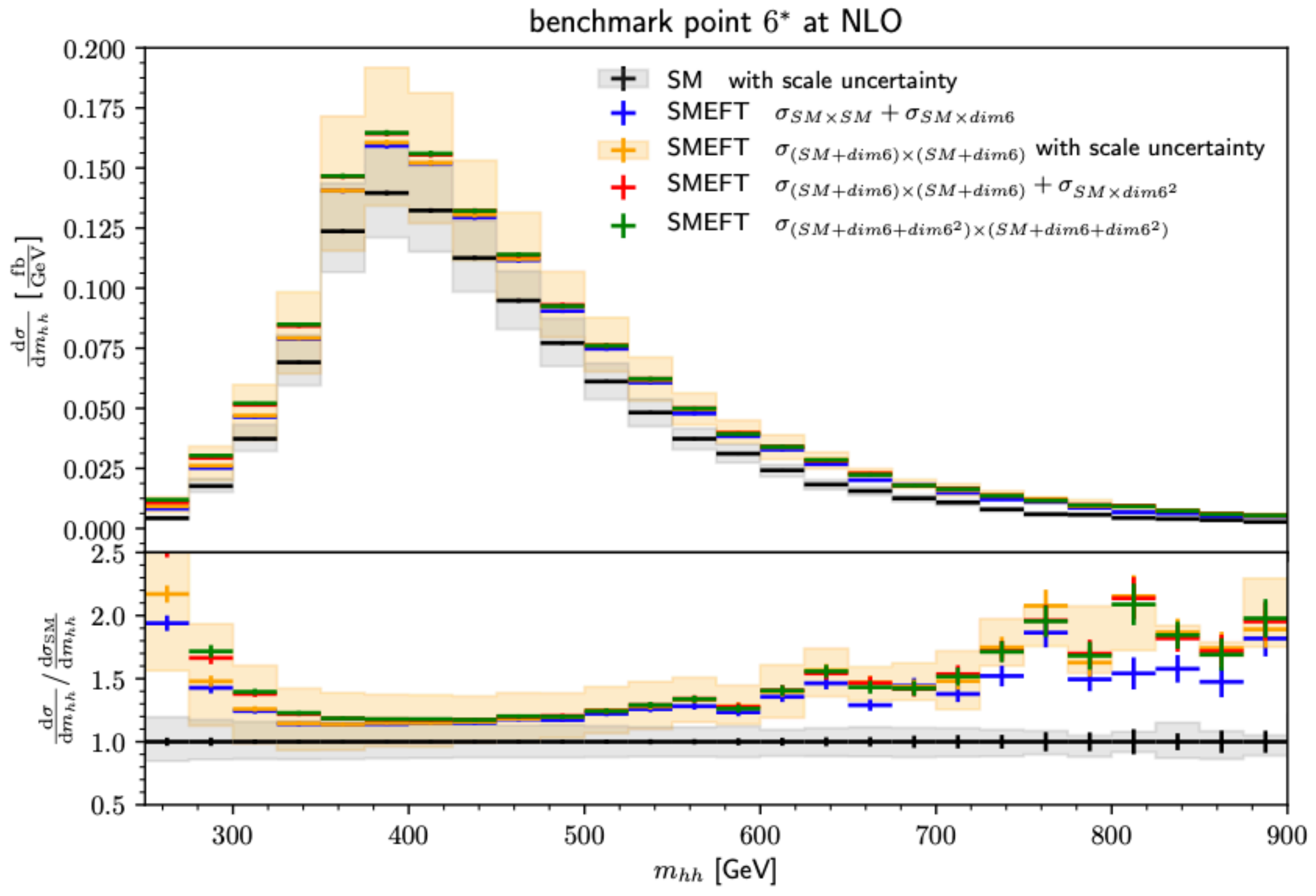


benchmark (* = modified)	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}	$C_{H,\mathrm{kin}}$	C_H	C_{uH}	C_{HG}
SM	1	1	0	0	0	0	0	0	0
6*	-0.68	0.90	$-\frac{1}{6}$	0.50	0.25	0.56	3.80	2.20	0.04

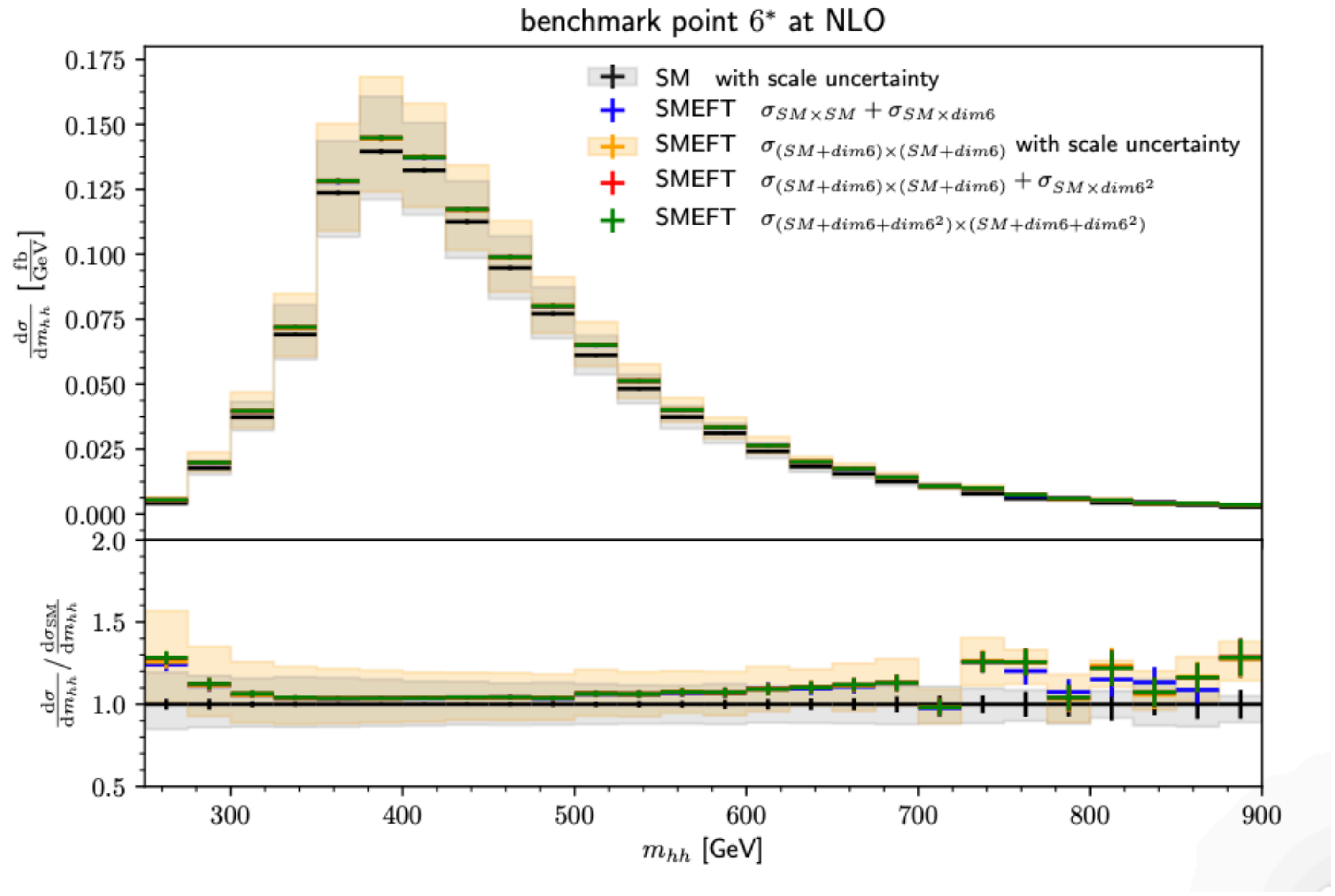
Naive benchmark translation
HEFT ↔ SMEFT



$\Lambda = 1\,\mathrm{TeV}$



$\Lambda = 2\,\mathrm{TeV}$



$\Lambda = 4\,\mathrm{TeV}$

- No negative cross-section in SMEFT, but different interference pattern wrt HEFT leading to smaller cross-sections and modified shape (no shoulder)
- Increasing Λ reduces the differences between the truncations – convergence towards the SM

Theoretical uncertainties

Total unc. ≃ Scale + (PDF+α_s) + m_t renormalisation scheme + EW corrections + numerical grid

- Scale: Assessed by 7-point variation of $\mu_R = \mu_F = \{\frac{1}{2},1,2\} \cdot \mu_0$ and is of $\mathcal{O}(15\,\%)$ for SM and $\mathcal{O}(15-20\,\%)$ for SMEFT truncation (b) of benchmarks 1* and 6* at NLO QCD

- PDF+α_s: $\pm 3\,\%$ at NNLO (Born improved HTL using PDF4LHCNNLO), expected not to depend much on the benchmark

- m_t renormalisation scheme: Currently largest unc. on $\sigma_{hh}^{\mathrm{SM}}$. Depends strongly on c_{hhh} and has to be evaluated for each EFT parameter point separately – not available at the moment

- Missing EW corrections: Full NLO EW corrections unknown, expected to be larger than the ones related to Yukawa-type ($\sim 0.2\,\%$)

- Accuracy of numerical computation of NLO QCD virtual corrections: Grids derived originally for SM, can't capture the EFT phase space accurately where SM cross-section contribution is small, possibly leading to sizeable uncertainties up to $\sim 75\,\%$ in the first m_{hh} bin (not covered by the MC generators)

HEFT reweighting

- Generating MC samples is computationally expensive ➡ **event reweighting** instead
- Cross-section can be parametrised at NLO as follows:

$$
\begin{aligned}
\sigma_{hh}^{\mathrm{NLO}}(c_{hhh}, c_t, c_{tt}, c_{ggh}, c_{gghh}) &= Poly(\mathbf{c}, \mathbf{A}) = \mathbf{c}^{\intercal} \cdot \mathbf{A} \\
&= A_1 c_t^4 + A_2 c_{tt}^2 + (A_3 c_t^2 + A_4 c_{ggh}^2) c_{hhh}^2 \\
&+ A_5 c_{gghh}^2 + (A_6 c_{tt} + A_7 c_t c_{hhh}) c_t^2 \\
&+ (A_8 c_t c_{hhh} + A_9 c_{ggh} c_{hhh}) c_{tt} + A_{10} c_{tt} c_{gghh} \\
&+ (A_{11} c_{ggh} c_{hhh} + A_{12} c_{gghh}) c_t^2 \\
&+ (A_{13} c_{hhh} c_{ggh} + A_{14} c_{gghh}) c_t c_{hhh} \\
&+ A_{15} c_{ggh} c_{gghh} c_{hhh} + A_{16} c_t^3 c_{ggh} \\
&+ A_{17} c_t c_{tt} c_{ggh} + A_{18} c_t c_{ggh}^2 c_{hhh} \\
&+ A_{19} c_t c_{ggh} c_{gghh} + A_{20} c_t^2 c_{ggh}^2 \\
&+ A_{21} c_{tt} c_{ggh}^2 + A_{22} c_{ggh}^3 c_{hhh} \\
&+ A_{23} c_{ggh}^2 c_{gghh}
\end{aligned}
$$

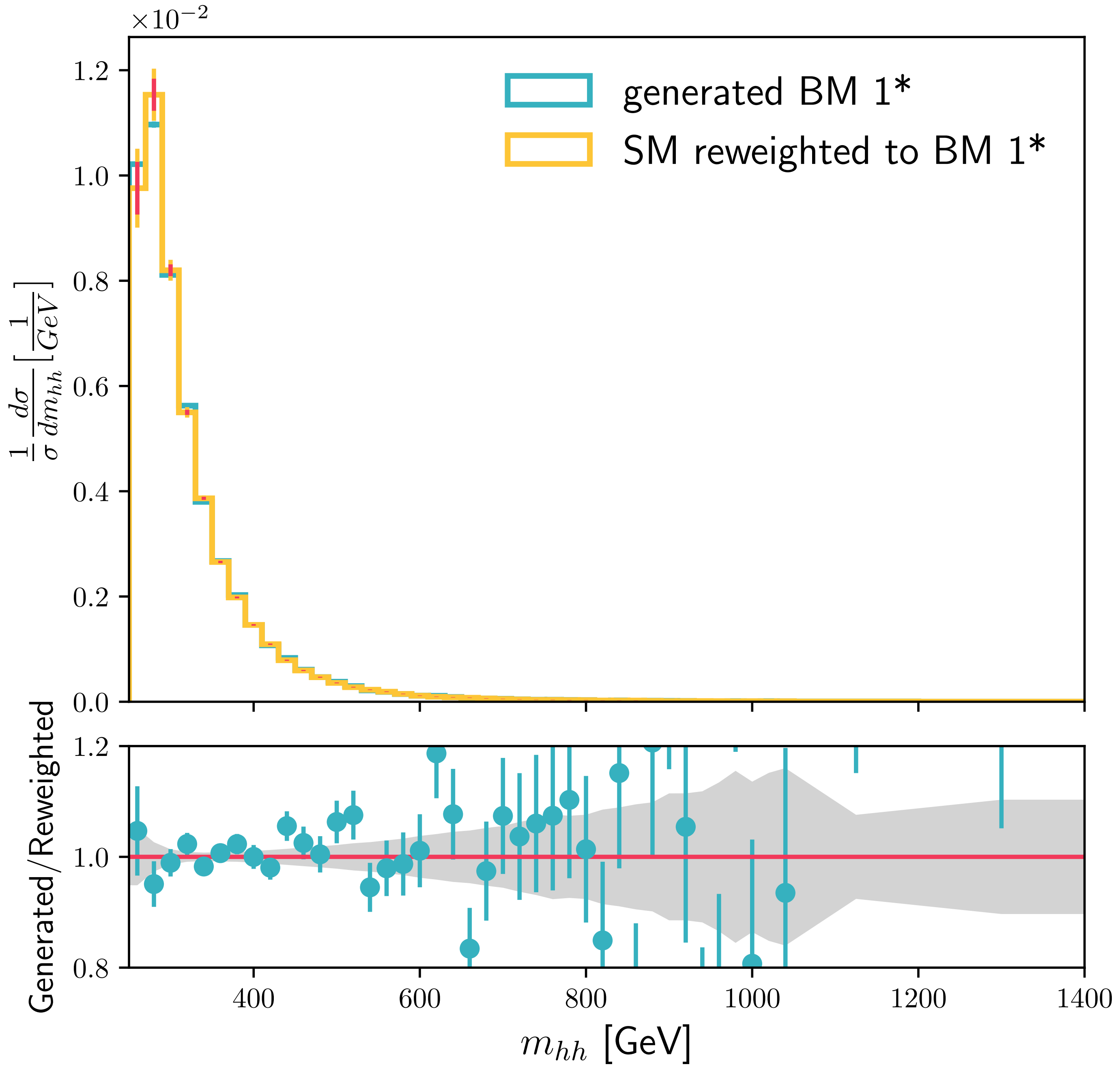
- 🆕 set of **A** and (differential in m_{hh}) d**A** coefficients (for $\sqrt{s} = 13\,\mathrm{TeV}$) derived using a weighted least square fit
  - Lower statistical uncertainty (more simulated HH MC events)
  - Cover a larger kinematic range (up to $m_{hh} = 1400\,\mathrm{GeV}$)
- Weights obtained as

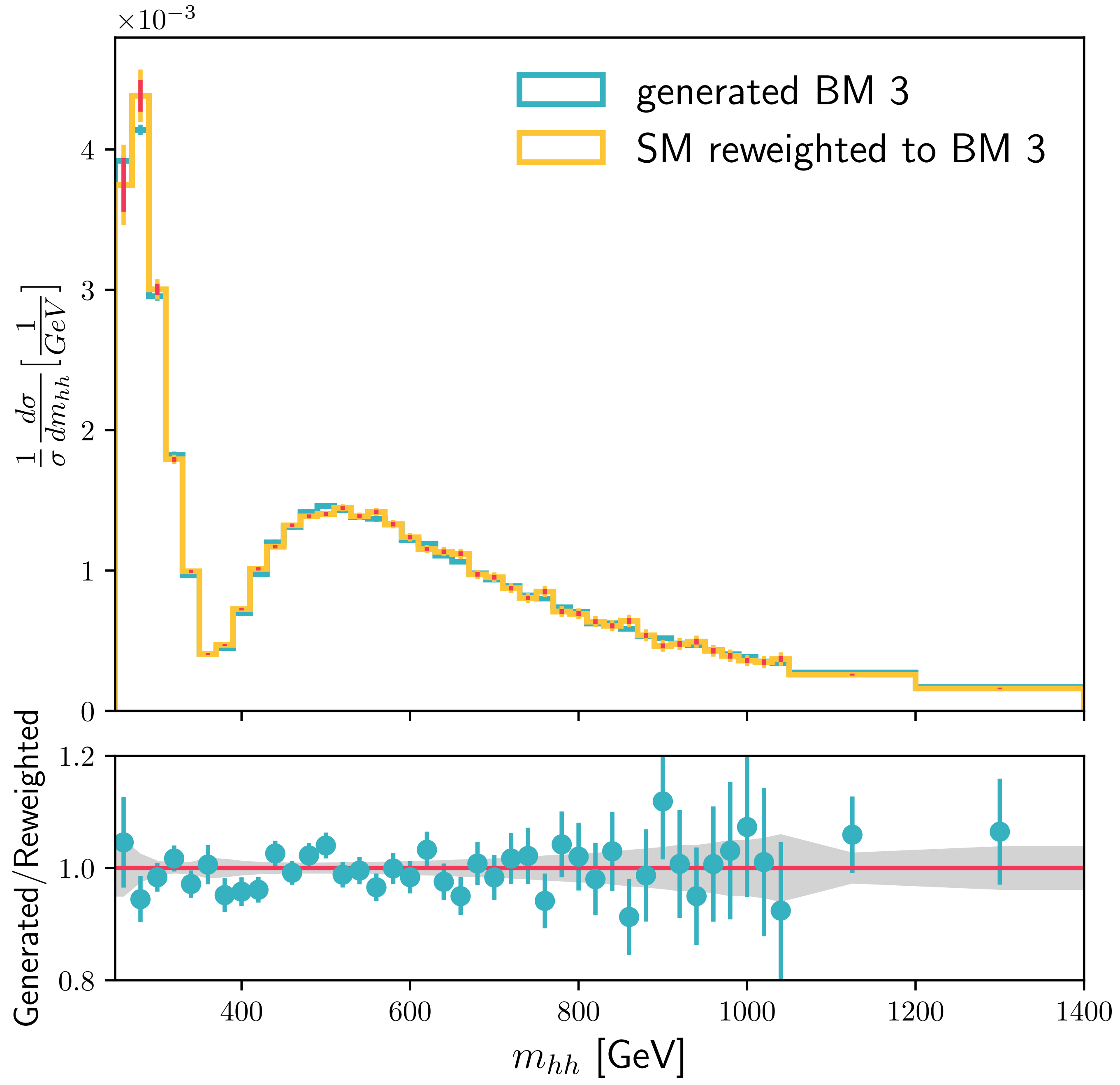
$$
w_{\mathrm{HEFT}} = \frac{Poly(\mathbf{c}, d\mathbf{A}\,|\,m_{hh})}{Poly(\mathbf{c}_{\mathrm{SM}}, d\mathbf{A}\,|\,m_{hh})}
$$

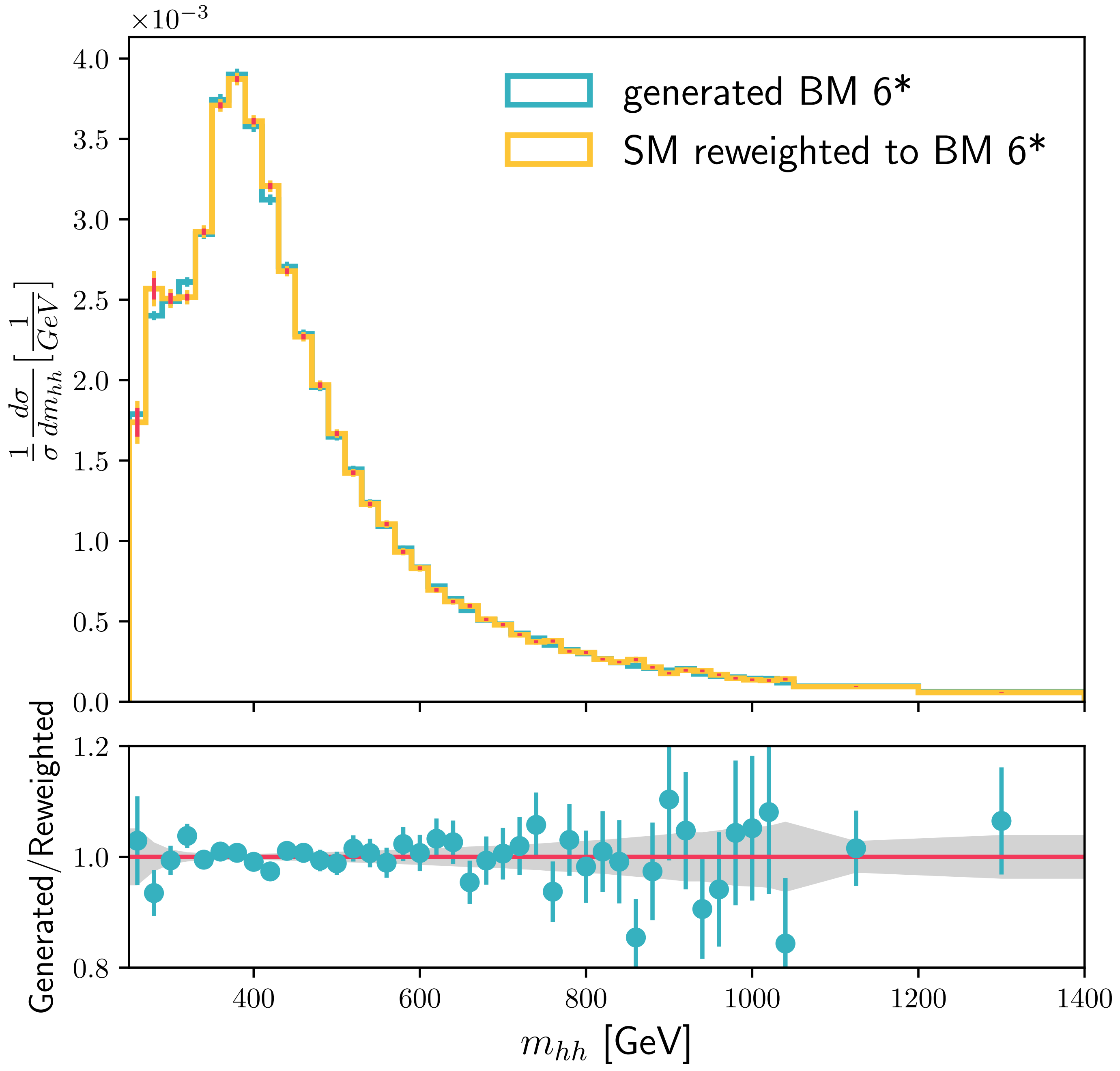
- Provided uncertainties:
  - Covariance matrices Σ_{A} and $\Sigma_{d\mathrm{A}}$ used to obtain the statistical uncertainty on the weights
  - 3 sets of coefficients with scale variations $\mu_R = \mu_F = \{\frac{1}{2}, 1, 2\} \cdot \mu_0$

Validation plots (m_{hh})

- Reweighting SM sample to benchmarks 1*, 3 and 6*







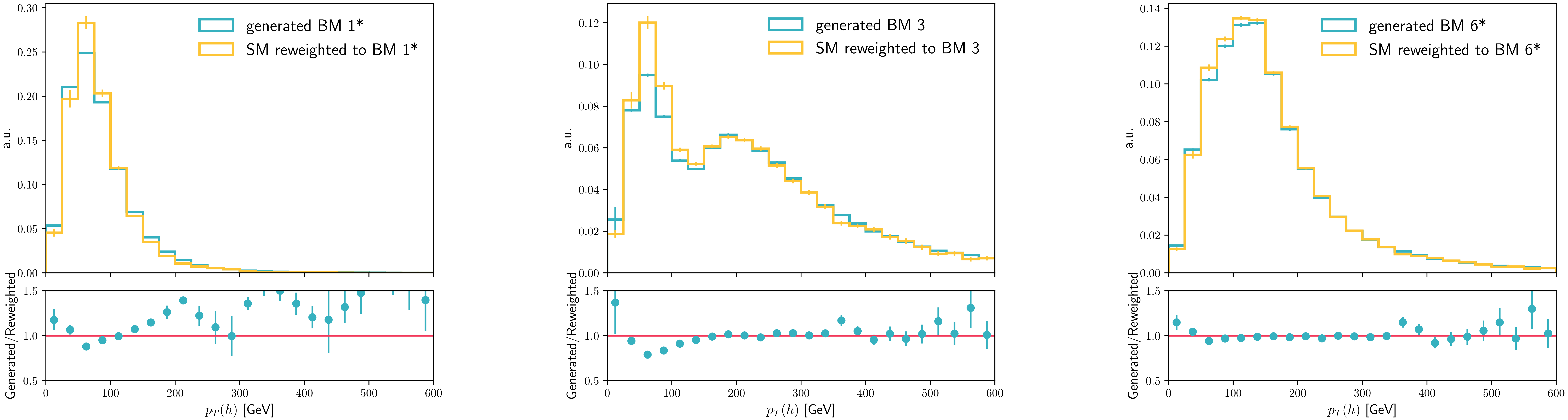
- Distributions account for varying bin width
- Uncertainty source: statistical + reweighting procedure

↪shown as red error bars (grey bands) in the upper (lower) panel

- Good closure for m_{hh} distributions

Validation plots ($p_T(h)$)

- Reweighting SM sample to benchmarks 1*, 3 and 6*



- General shape is reproduced, but discrepancies up to ~40% (BM 1*)
- Reweighting performed based on m_{hh}, hence not accounting for additional jet radiation

Summary

Overview of the LHCHWG-2022-004 note

- Discuss $gg \to HH$ production in **HEFT** and **SMEFT** at NLO (with full m_t dependence)
- Recap how to use existing `POWHEG` implementations
- Updated list of **benchmarks**
- Investigate potential **translation** between HEFT and SMEFT
    - List issues to be considered and advise studying each EFT interpretation separately
- Outline **theory uncertainties**
- Present HEFT **reweighting** method and **validation**
    - Coefficients and set of covariance matrices to be made publicly available in arXiv submission/HEPData

Back-up

Available MC tools

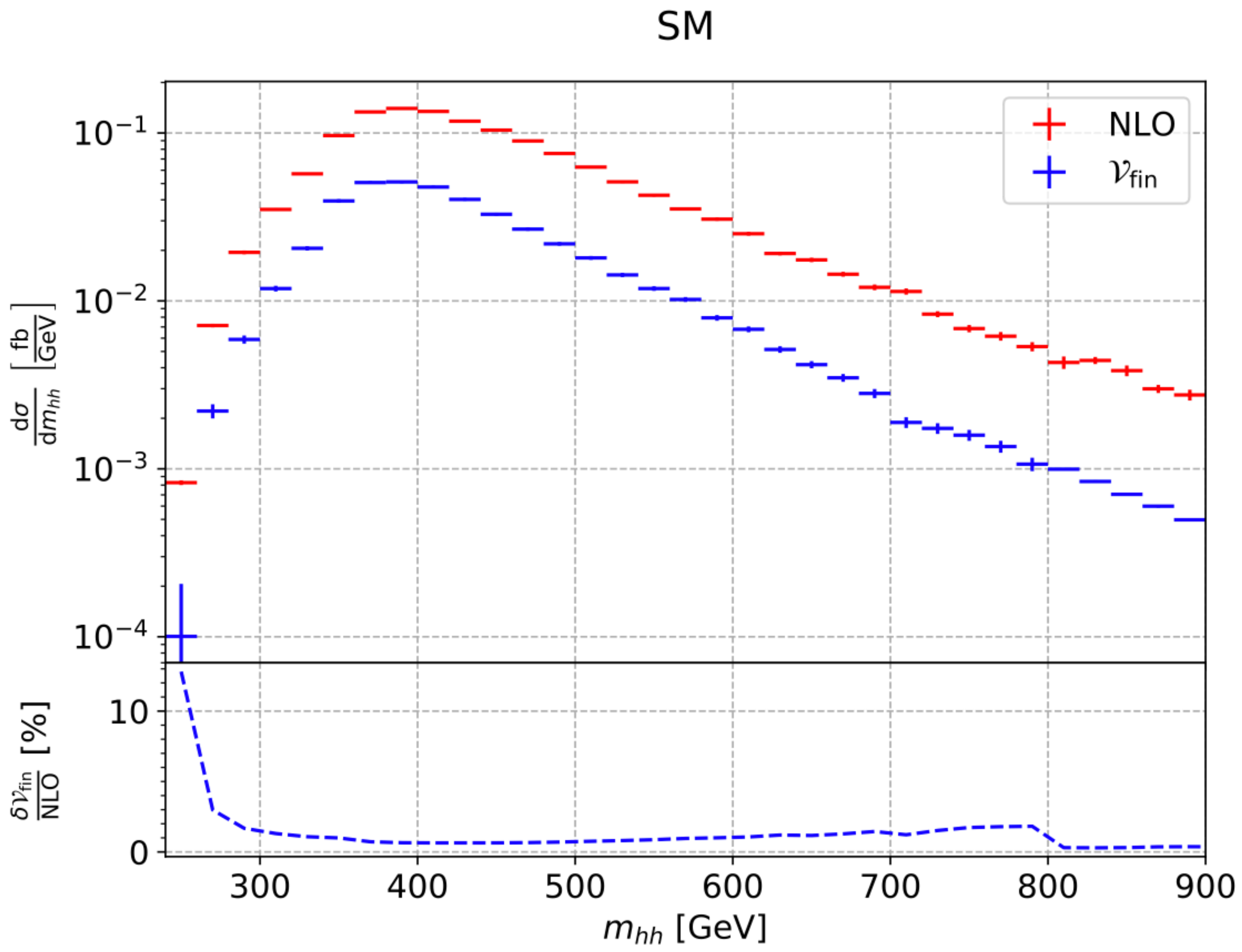
HEFT

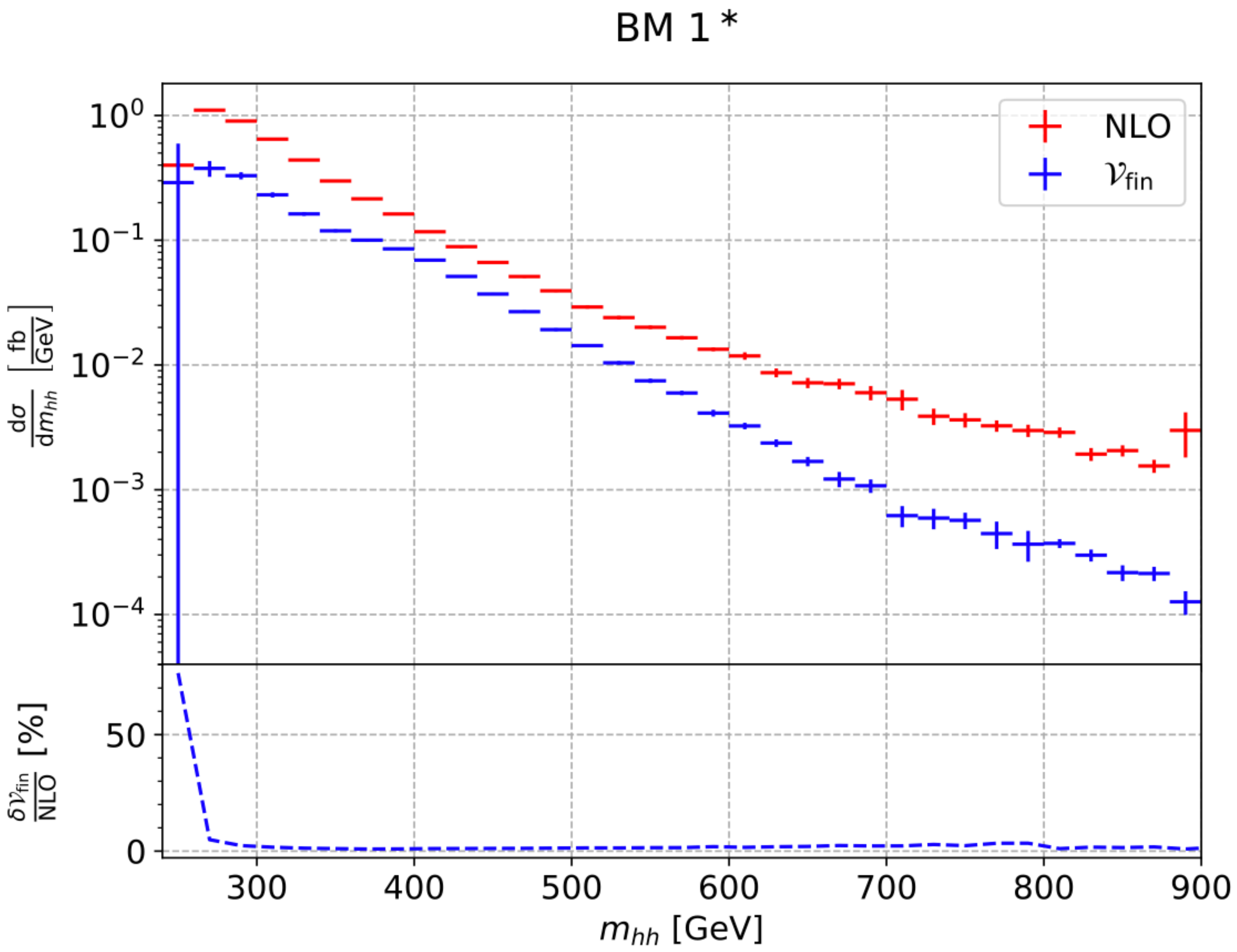
- LO and NLO QCD HTL HPAIR [link]
- Full m_t NLO QCD POWHEG-BOX-V2/ggHH [links 1, 2, 3, 4]
- NNLO' QCD HEFT (combination of full m_t NLO QCD and NNLO QCD in HTL) [link]

SMEFT

- LO and NLO QCD HTL HPAIR [link]
- SMEFT@NLO in MG5_aMC@NLO [link]
- SMEFTsim and SmeftFR built on Feynrules [links 1, 2]
- Full m_t NLO QCD POWHEG-BOX-V2/ggHH_SMEFT with truncation options [link]

Numerical grids uncertainty





- $\mathcal{O}(12\,\%)$ for SM in the first bin, much worse for scenarios with enhanced low-m_{hh} region

HEFT weights and statistical uncertainties

- Differential coefficients have been derived for $m_{hh} \in [250{,}1400]\,\mathrm{GeV}$ with bins of $20\,\mathrm{GeV}$ for $m_{hh} \in [250{,}1050]\,\mathrm{GeV}$ and with two broader bins in the range $m_{hh} \in [1050{,}1200]\,\mathrm{GeV}$ and $m_{hh} \in [1200{,}1400]\,\mathrm{GeV}$

- Weights calculated as $w_{\mathrm{HEFT}} = \dfrac{Poly(\mathbf{c}, d\mathbf{A}\,|\,m_{hh})}{Poly(\mathbf{c}_{\mathrm{SM}}, d\mathbf{A}\,|\,m_{hh})}$

- Corresponding uncertainty calculated using $\delta_{w_{\mathrm{HEFT}}} = \sqrt{\mathbf{J}_w \Sigma_{d\mathbf{A}} \mathbf{J}_w^{\intercal}}$, with $\mathbf{J}_w = \dfrac{\mathbf{c}^{\intercal}}{Poly(\mathbf{c}_{\mathrm{SM}}, d\mathbf{A}|m_{hh})} - \dfrac{Poly(\mathbf{c}, d\mathbf{A}|m_{hh}) \cdot \mathbf{c}_{\mathrm{SM}}^{\intercal}}{Poly(\mathbf{c}_{\mathrm{SM}}, d\mathbf{A}|m_{hh})^2}$

- Total stat. unc. in bin *j* when reweighting simulated SM HH events is as follows:

$$\delta^j = N^j \sqrt{\left(\frac{\delta^j_{w_{\mathrm{HEFT}}}}{w^j_{\mathrm{HEFT}}}\right)^2 + \left(\frac{\delta^j_{\mathrm{SM}}}{N^j_{\mathrm{SM}}}\right)^2},$$

with N^j being the sum of weighted events,
N^j_{SM} the sum of weighted SM events,
w^j_{HEFT} the weight and δ^j_{SM} the weighted stat. unc. for SM events