Effective field theory for Higgs pair production

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General assembly LHC Higgs working group

Based on ongoing discussions with:
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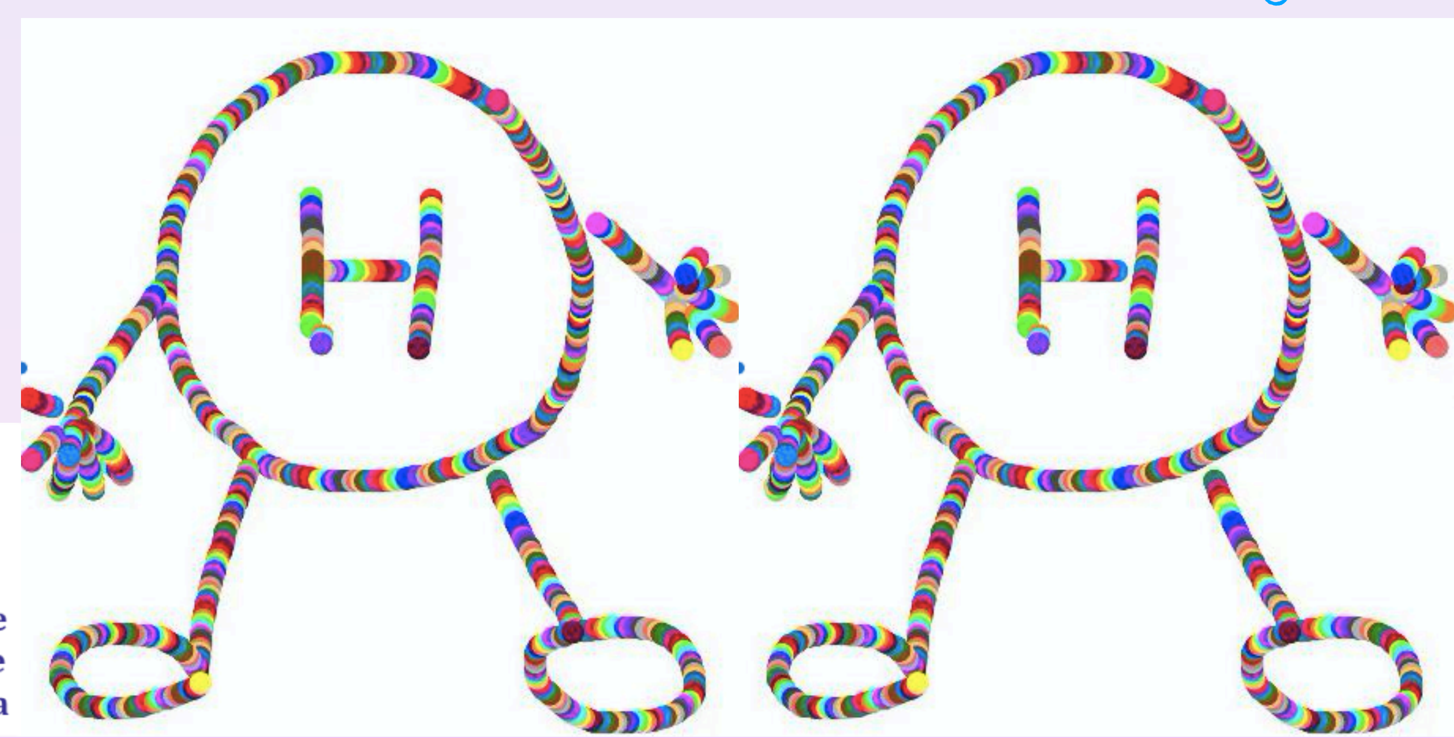

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Outline

- EFT for Higgs pair production

- Tools for EFT HH

- Open questions

Effective Theory for the Higgs boson

There exist two fundamentally different choices for an EFT.

SMEFT

The Higgs boson transforms in a SU(2) doublet. The Lagrangian contains all possible operators allowed by the symmetries. Ordering by operator dimension and suppression $(1/\Lambda)^n$

leading Higgs deviations for n=2.

Different choices of operators connected by equations of motion.

SILH basis

Warsaw basis

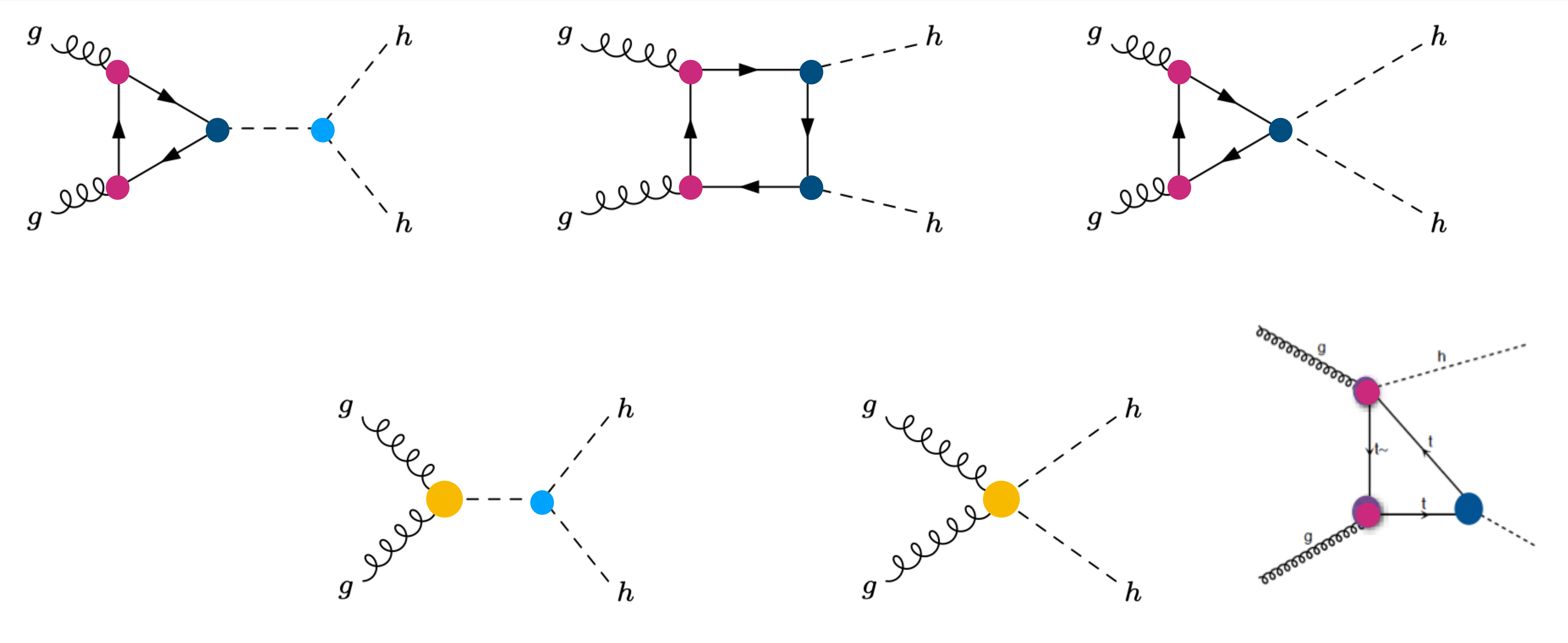
equivalent for HH

HEFT (or Electroweak Chiral Lagrangian)

Higgs transforms as gauge singlet.

Based on chiral perturbation theory.

Ordering of operators not unique but for instance by chiral dimension.

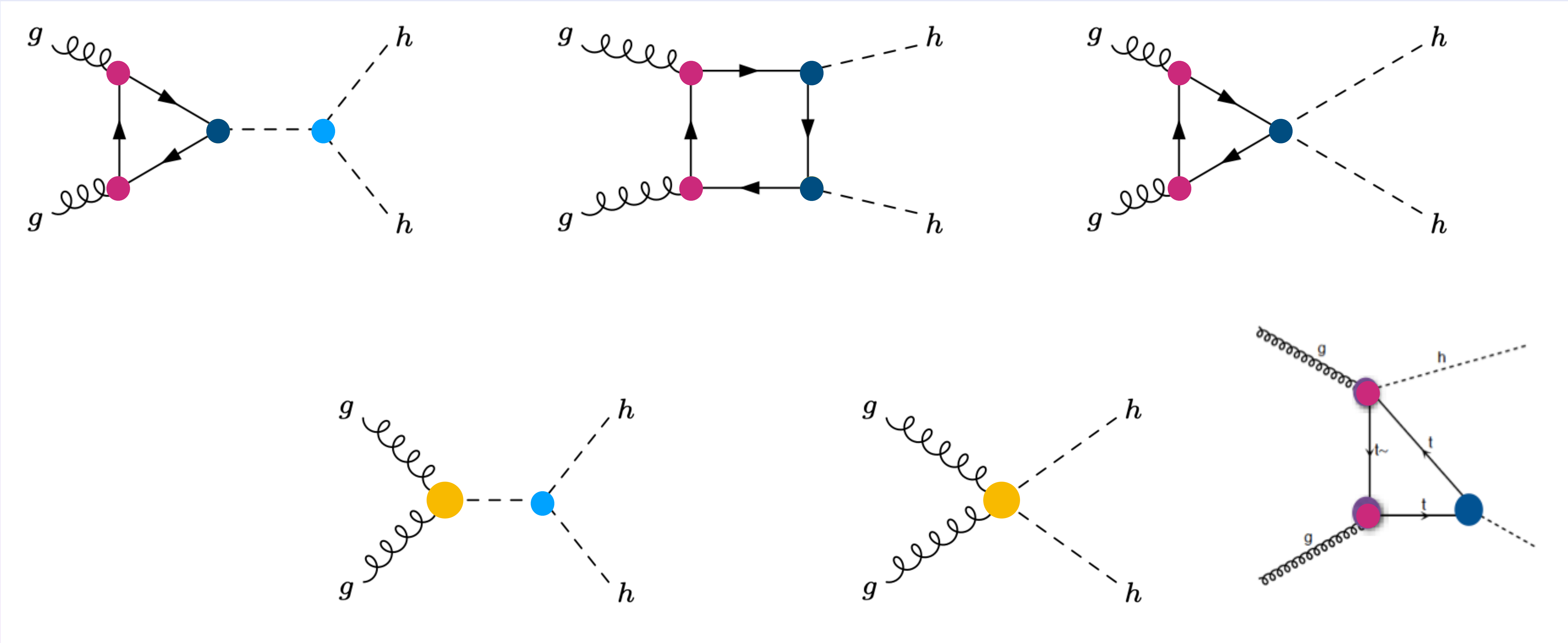


SMEFT:

$$\mathscr{L} = \frac{\bar{c}_H}{v^2}(H^\dagger \partial_\mu H)^2 - \frac{\bar{c}_6 \lambda}{v^2}|H|^6 + \frac{\bar{c}_g g_s^2}{m_W^2}|H|^2 G_{\mu\nu}G^{\mu\nu} + \frac{y_u \bar{c}_u}{v^2}\bar{Q}_L \tilde{H} t_R |H|^2 + h.c. + \frac{c_{tG}\alpha_s}{v^2}\bar{Q}_L \sigma_{\mu\nu} T^a \tilde{H} t_R G^a_{\mu\nu} + h.c.$$

SILH basis

Non-resonant HH production



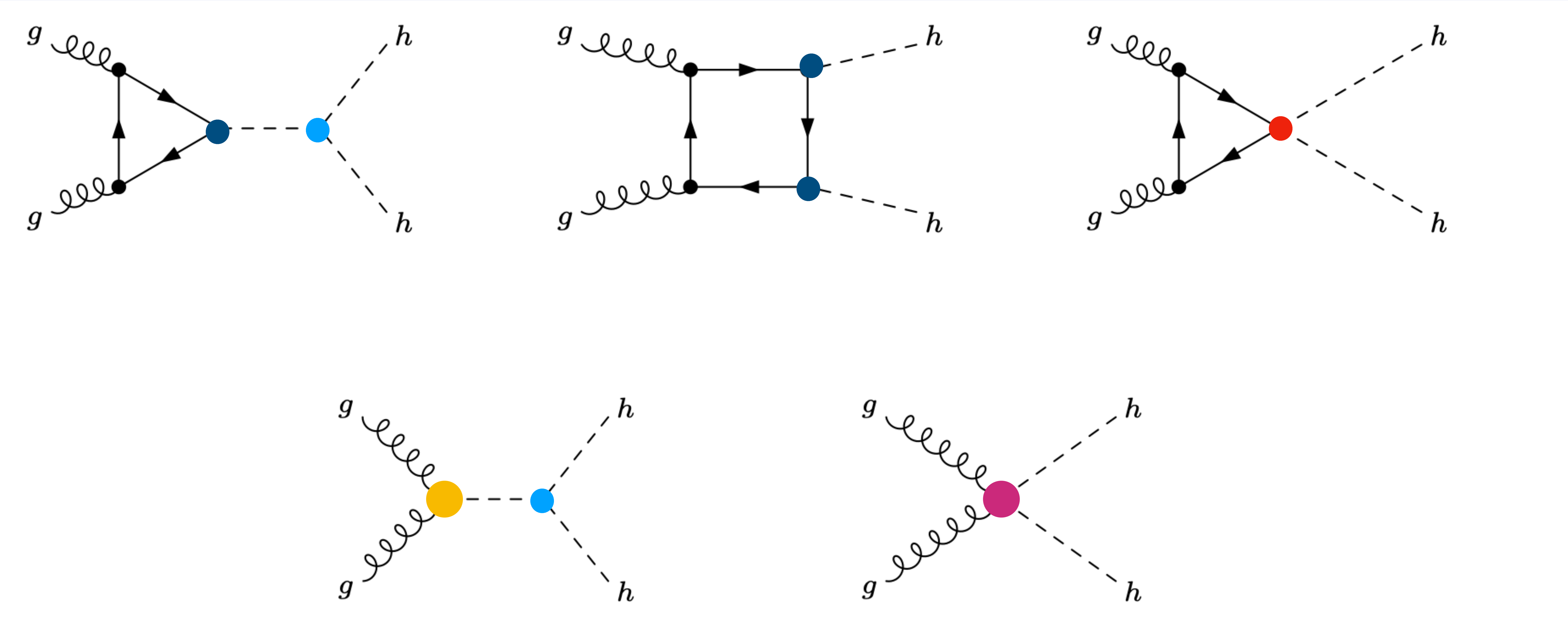
SMEFT:

$$\mathscr{L} = C_{H,\Box}(H^\dagger H)\Box(H^\dagger H) + C_{HD}D_\mu(H^\dagger H)D^\mu(H^\dagger H)^* + C_H|H|^6 + C_{HG}|H|^2 G_{\mu\nu}G^{\mu\nu} + C_{uH}\bar{Q}_L\tilde{H}t_R|H|^2 + h.c. + C_{uG}\bar{Q}_L\sigma_{\mu\nu}T^a\tilde{H}t_R G^a_{\mu\nu} + h.c.$$

Warsaw basis

coefficients of $\mathcal{O}(1/\Lambda^2)$

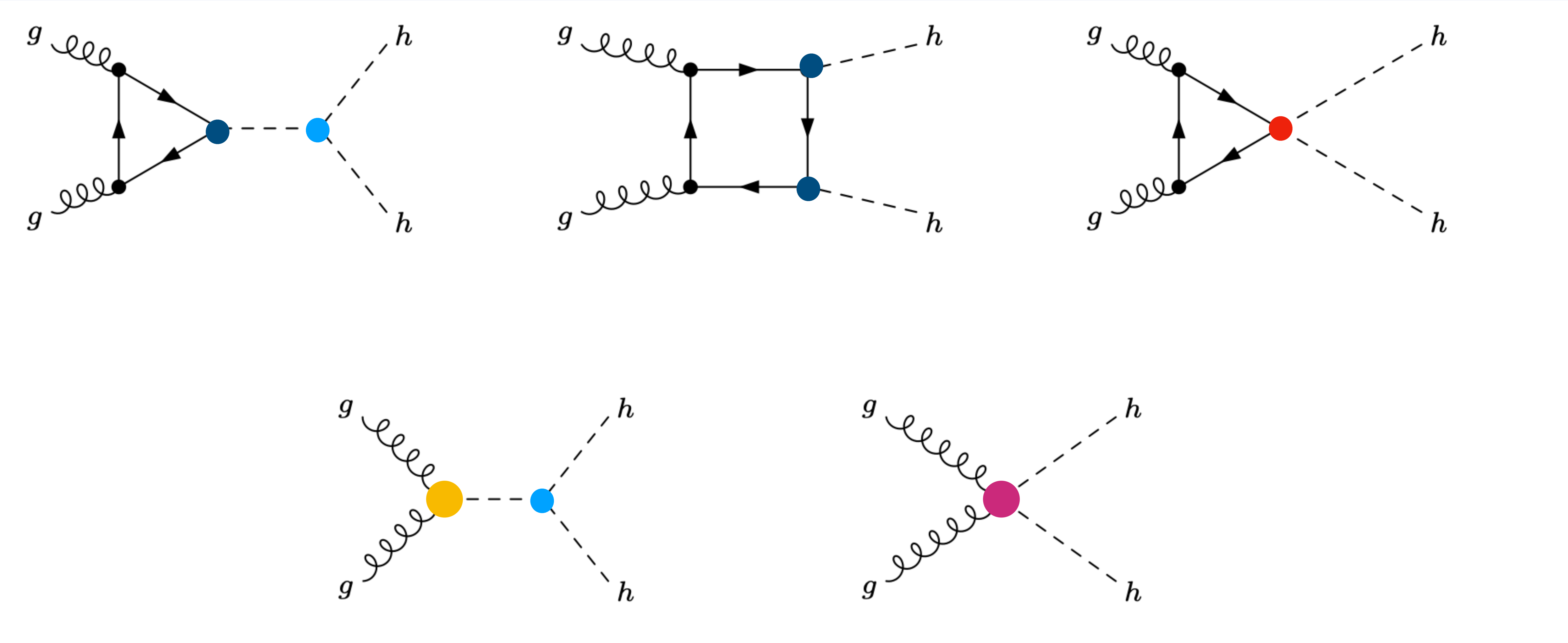
Effective Theory for HH



HEFT:

$$\mathcal{L} = -m_t \bar{t} t \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{v^2} \right) + \frac{\alpha_s}{8\pi} \left(c_g \frac{h}{v} + c_{gg} \frac{h^2}{v^2} \right) G^{\mu\nu} G_{\mu\nu} + c_{hhh} \frac{m_h^2}{2v} h^3$$

Effective Theory for HH



HEFT:

two Higgs couplings only to be probed in HH

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HEFT/SMEFT for HH?

HEFT	SMEFT
⊕ NLO results in full top mass dependence available [Buchalla et al '18; Heinrich et al '20]	⊕ Combination with single Higgs fits simpler
⊕ di-Higgs is THE place to probe differences in one or two Higgs couplings	
⊖ several couplings only in appearing HH: degeneracies?	
⊖ UV models that don't linearise to SMEFT?	

Chromomagnetic dipole operator: present in SMEFT at LO in EFT but with power counting rules should be suppressed
in HEFT appears at higher order in EFT expansion

Tools for HH production

HH production has large QCD corrections

Complicated to compute due to various mass scales.

Full top mass dependent computations for NLO QCD available numerically.

[Borowka et al. '16, Baglio et al. '19]

POWHEG implementation of HEFT HH @ NLO QCD available.

[Buchalla et al '18; Heinrich et al '20]

SMEFT @ LO available in MG5_MC@NLO,
SMEFT@ NLO only in heavy top mass limit [RG, Mühlleitner, Spira, Streicher '15]

HEFT @ NNLO in approximative top mass dependence available in

[de Florian, Fabre, Heinrich, Mazzitelli, Scyboz '21]

[more later on by Ludovic]

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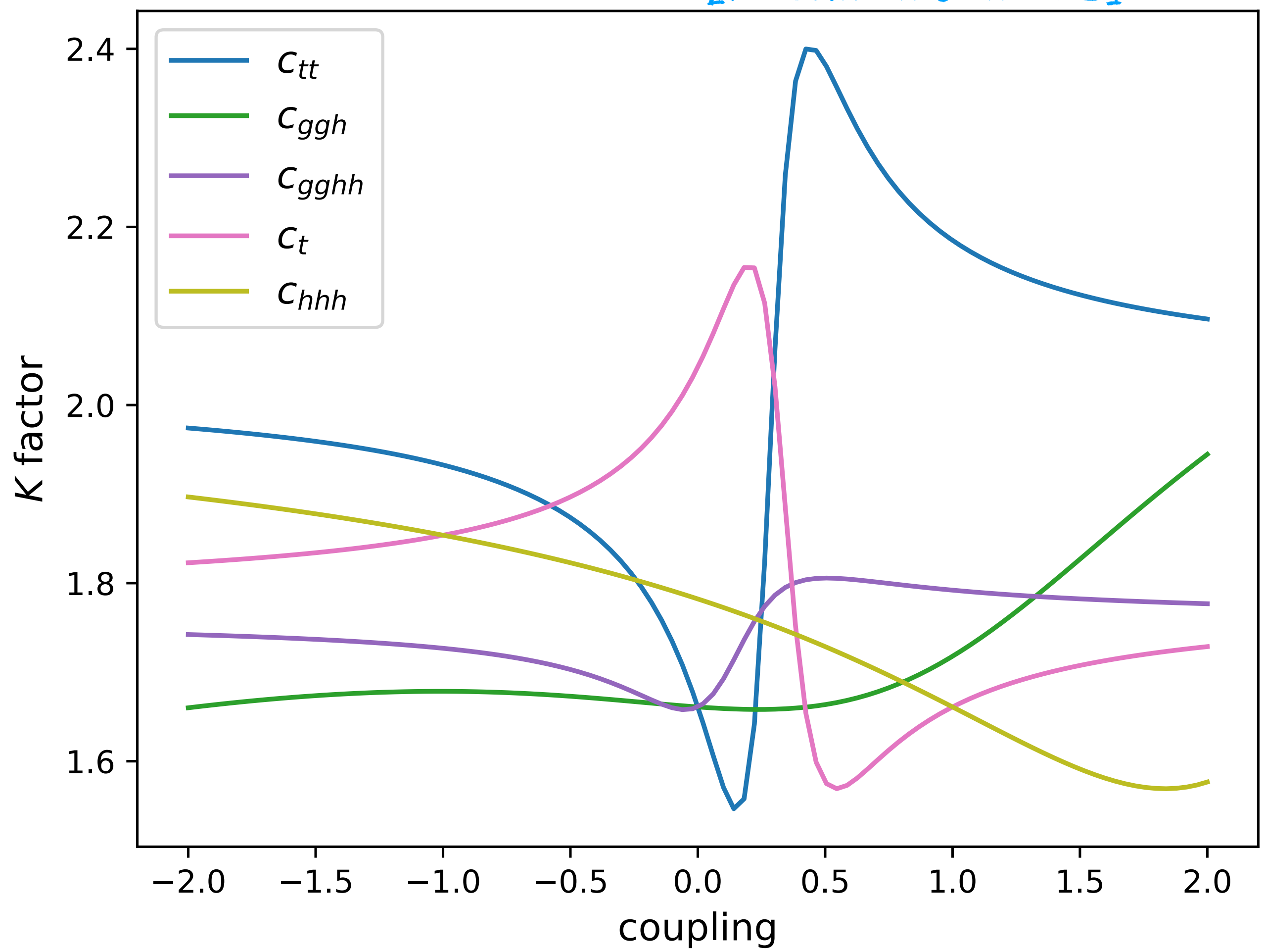

Strong dependence on EFT coefficient!

Translation HEFT/SMEFT

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

translation table holds at Lagrangian level

attention with Higgs gluon coupling and α_s

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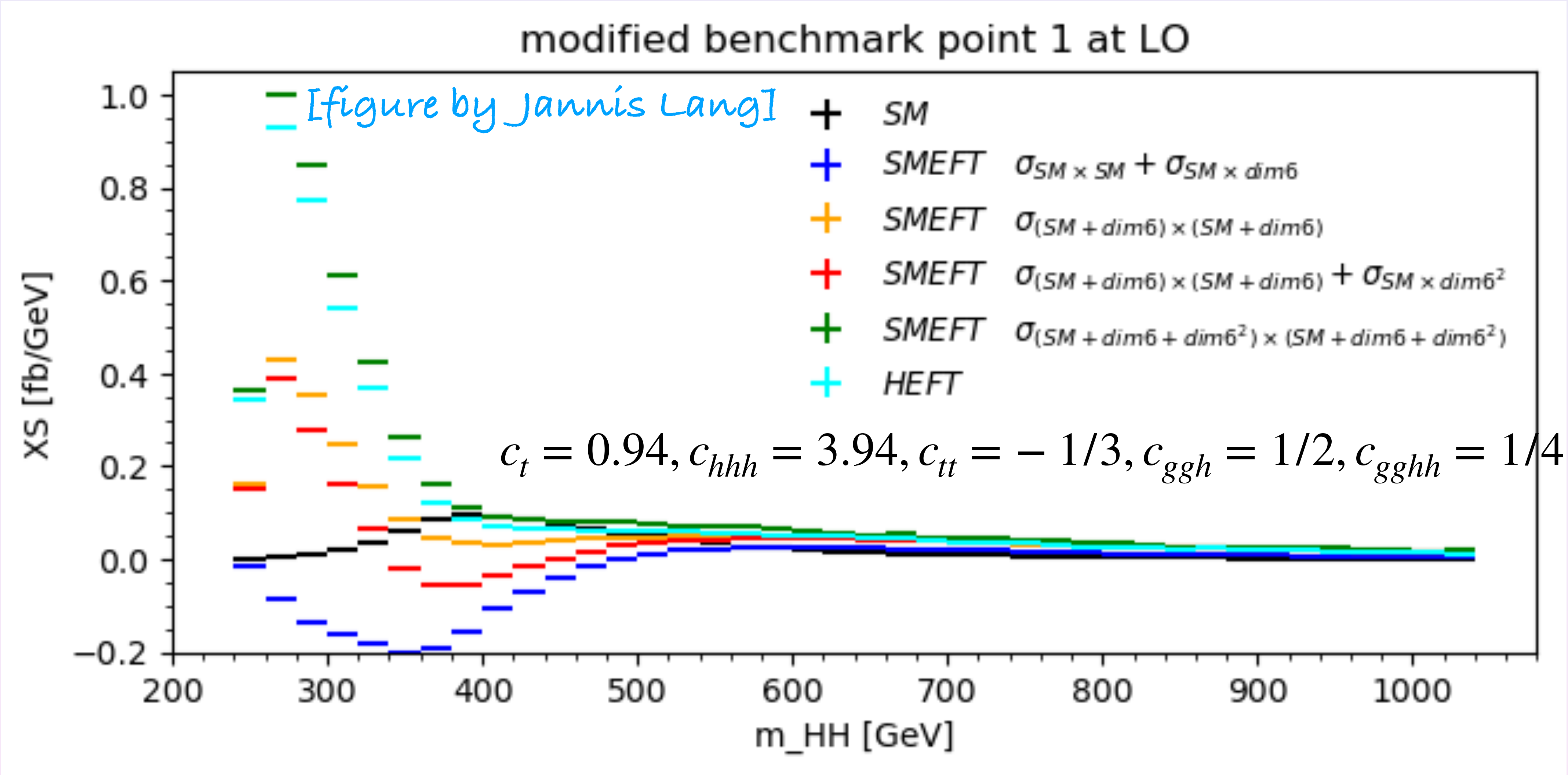
But on level of matrix element squared non-trivial



Open questions

Uncertainties on the specific EFT point?

- SM suffers from large uncertainties associated to the top quark mass renormalization scheme [Baglio et al. '19, Baglio et al. '20]

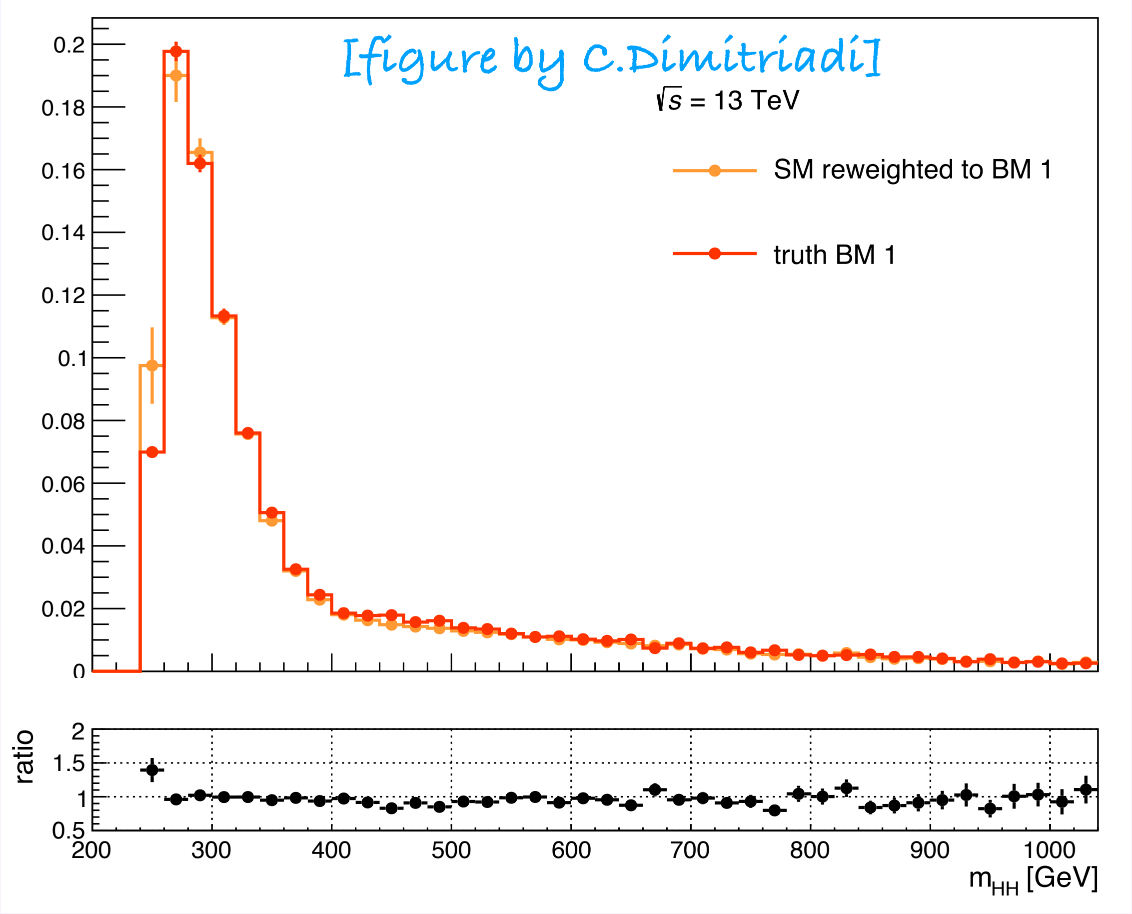
dependence on EFT coefficients?

Uncertainties on the specific EFT point?

- SM suffers from large uncertainties associated to the top quark mass renormalization scheme [Baglio et al. '19, Baglio et al. '20]

dependence on EFT coefficients?

- if the EFT point leads to distributions (very) different from the SM ones: what are the errors on the bins (in dependence on the EFT point)?



Reweighting

Scans in EFT space with New Monte Carlo events for each EFT point?

In practise not achievable, too computing time intensive!

Reweighting!

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Reweighting!

[Buchalla et al '18] provides

$$\sigma^{\mathrm{NLO}}/\sigma^{\mathrm{NLO}}_{SM} = A_1\, c_t^4 + A_2\, c_{tt}^2 + A_3\, c_t^2 c_{hhh}^2 + A_4\, c_{ggh}^2 c_{hhh}^2 + A_5\, c_{gghh}^2 + A_6\, c_{tt} c_t^2 + A_7\, c_t^3 c_{hhh}$$
$$+ A_8\, c_{tt} c_t\, c_{hhh} + A_9\, c_{tt} c_{ggh} c_{hhh} + A_{10}\, c_{tt} c_{gghh} + A_{11}\, c_t^2 c_{ggh} c_{hhh} + A_{12}\, c_t^2 c_{gghh}$$
$$+ A_{13}\, c_t c_{hhh}^2 c_{ggh} + A_{14}\, c_t c_{hhh} c_{gghh} + A_{15}\, c_{ggh} c_{hhh} c_{gghh}$$
$$+ A_{16}\, c_t^3 c_{ggh} + A_{17}\, c_t c_{tt} c_{ggh} + A_{18}\, c_t c_{ggh}^2 c_{hhh} + A_{19}\, c_t c_{ggh} c_{gghh}$$
$$+ A_{20}\, c_t^2 c_{ggh}^2 + A_{21}\, c_{tt} c_{ggh}^2 + A_{22}\, c_{ggh}^3 c_{hhh} + A_{23}\, c_{ggh}^2 c_{gghh}\,.$$

A's are numerical coefficients

Reweighting

Scans in EFT space with New Monte Carlo events for each EFT point?

In practise not achievable, too computing time intensive!

Reweighting!

[Buchalla et al '18] provides

$$Poly(c_i) = \frac{\sigma_{HEFT}(c_i)}{\sigma_{SM}}$$

$$Poly(c_i, m_{hh}) = \frac{\sigma_{HEFT}(c_i, m_{hh})}{\sigma_{SM}(m_{hh})}$$

Introduce a weight $w(c_i) = Poly(c_i, m_{hh})$ such that $\sigma_{HEFT} = w(c_i)\sigma_{SM}$

sometimes better though to disentangle normalisation from shape (i.e. to account for the "best" SM value)

How?

$$w'(c_i) = \frac{Poly(c_i, m_{hh})}{Poly(c_i)}$$

or normalise reweighted distribution?

Conclusions

- di-Higgs allows to probe various EFT operators
- can potentially distinguish between SMEFT and HEFT
- recommendations for HH EFT necessary
- various open questions
- discussions towards a recommendation underway

together with
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Thanks for your attention!