

Probing the trilinear Higgs boson coupling in di-Higgs production at NLO QCD in Powheg

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Max-Planck-Institut für Physik

Introduction

Probing the Higgs sector

- EW symmetry breaking is a cornerstone of the Standard Model

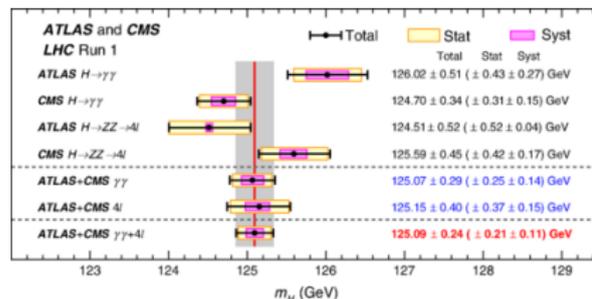
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- Higgs boson properties (mass, spin, ...) experimentally well measured



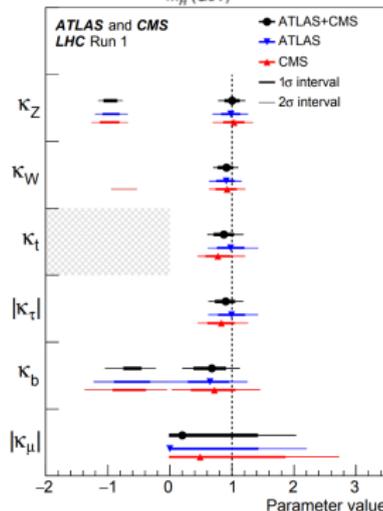
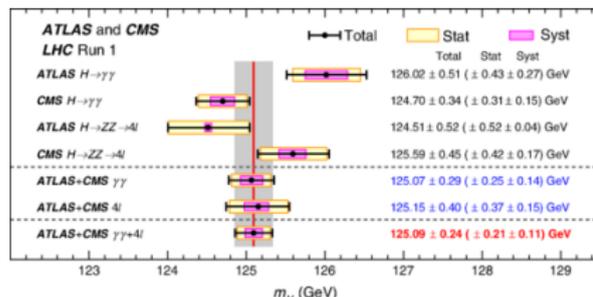
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$$V(h) = \frac{1}{2}m_h^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$

- Higgs boson properties (mass, spin, ...) experimentally well measured
- Higgs couplings to light fermions and self-coupling still largely unconstrained

$$-5.0 \leq \kappa_\lambda \leq 12.1 \text{ (95\% CL) ATLAS}$$



Theoretical advances: di-Higgs production

Ladder of approximations to the m_t -dependent NLO QCD corrections:

- **HEFT**: heavy-top limit $m_t \rightarrow \infty$

Heavy-top limit



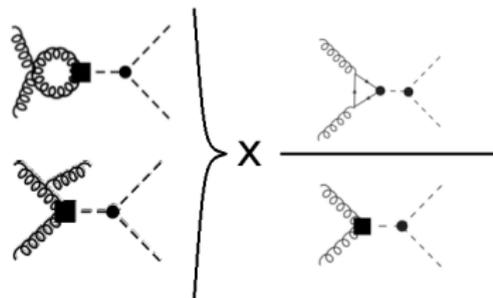
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[Dawson, Dittmaier, Spira '98]

Born-improved (B.-i.)



Theoretical advances: di-Higgs production

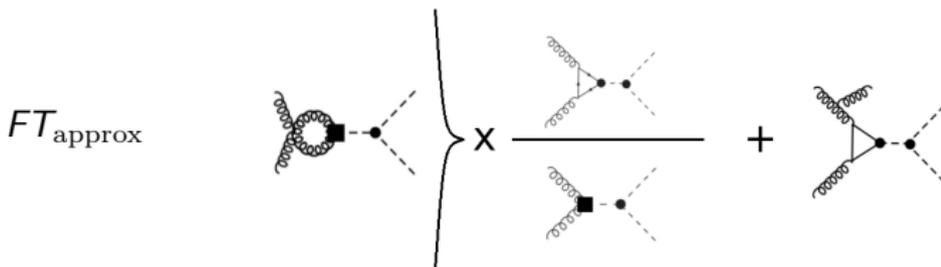
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- $\text{FT}_{\text{approx}}$: full m_t -dependence in the real radiation

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State-of-the-art:

- NNLO $\text{FT}_{\text{approx}} + \text{NNLL}$
[De Florian, Mazzitelli '18]
- Full NLO m_t -dependent QCD corrections
[Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke '16], [Baglio et al. '18]
- NNLO $\text{FT}_{\text{approx}} + \text{full NLO QCD corrections}$
[Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, Mazzitelli '18]

Full NLO

Numerical two-loop calculation

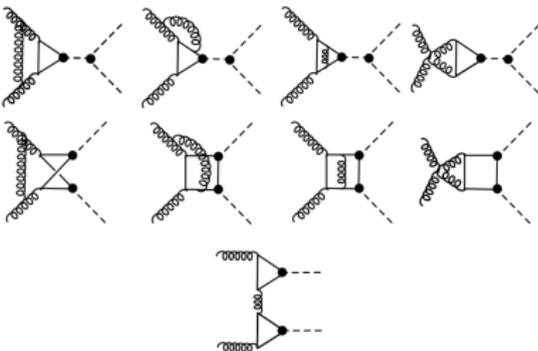
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Varying the Higgs couplings

Full m_t –dependence:

- Full NLO QCD for hh within a non-linear EFT

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- 5 anomalous couplings:

$$\mathcal{L} \supset -m_t \left(y_t \frac{h}{v} + c_{tt} \frac{h^2}{v^2} \right) \bar{t} t - \kappa_\lambda \frac{m_h^2}{2v} h^3$$

$$+ \frac{\alpha_s}{8\pi} \left(c_{ggh} \frac{h}{v} + c_{gggh} \frac{h^2}{v^2} \right) G_{\mu\nu}^a G^{a,\mu\nu}$$

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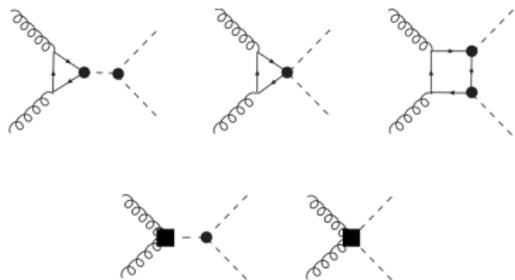
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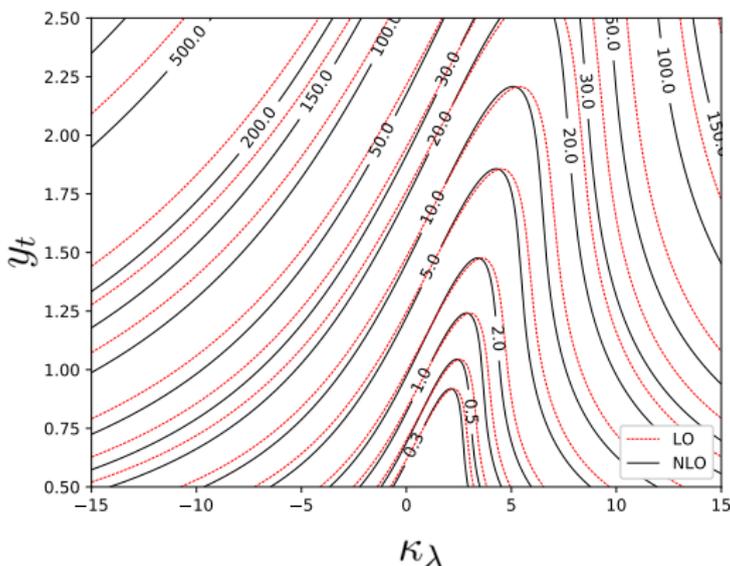
LO diagrams



Results: NLO inclusive cross-section

- Can lead to **sizeable enhancements** compared to SM xsec
 - $\sigma/\sigma_{SM} \sim \mathcal{O}(10 - 100)$
- **Large NLO corrections** to the ratio across parameter space
 - K -factors $\sim \mathcal{O}(1.6 - 2.4)$
 - Important dependence on the couplings

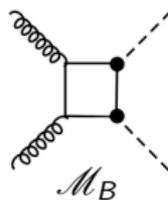
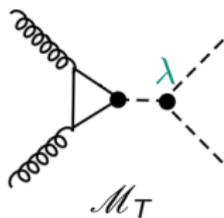
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Powheg implementation & Results

κ_λ variations in Powheg

- Full top-mass dependence at NLO QCD implemented in Powheg-Box-V2



- Interference between triangle- and box-type diagrams (holds at all orders in QCD)

$$|\mathcal{M}|^2 = [\mathcal{M}_B \mathcal{M}_B^* + \lambda(\mathcal{M}_B \mathcal{M}_T^* + \mathcal{M}_T \mathcal{M}_B^*) + \lambda^2 \mathcal{M}_T \mathcal{M}_T^*].$$

$$\rightarrow M_\lambda = |\mathcal{M}|^2 = M_0(1 - \lambda^2) + \frac{M_1}{2}(\lambda + \lambda^2) + \frac{M_{-1}}{2}(-\lambda + \lambda^2)$$

κ_λ variations in Powheg

- Virtual 2-loop amplitude for 3398 (s_i, t_i) -points at $\kappa_\lambda \in \{-1, 0, 1\}$

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- $\sqrt{s} \in \{13, 14, 27\}$ TeV, pdf41hc15_nlo_30_pdfas, $\mu = m_{hh}/2$

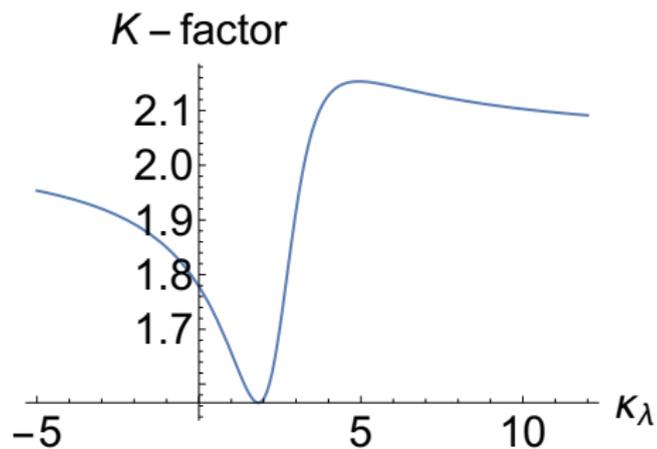
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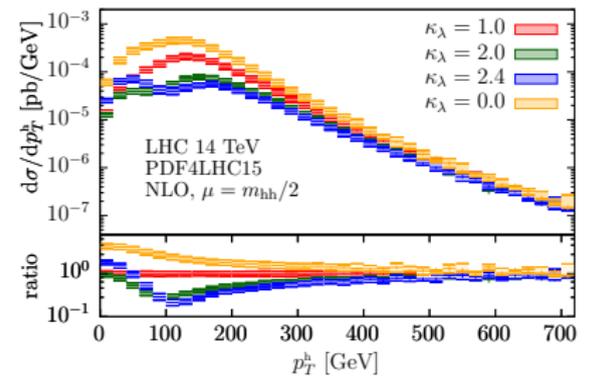
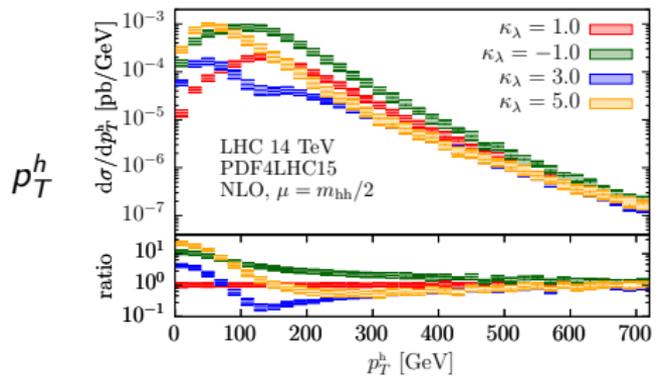
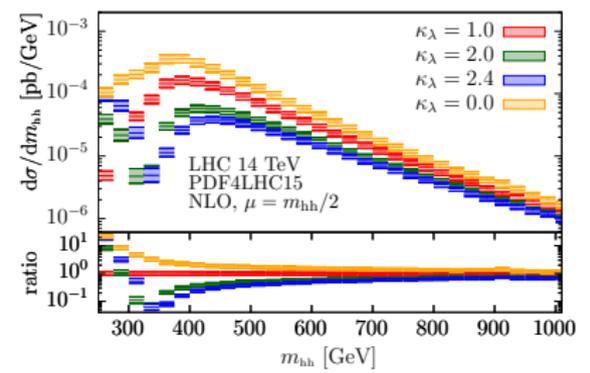
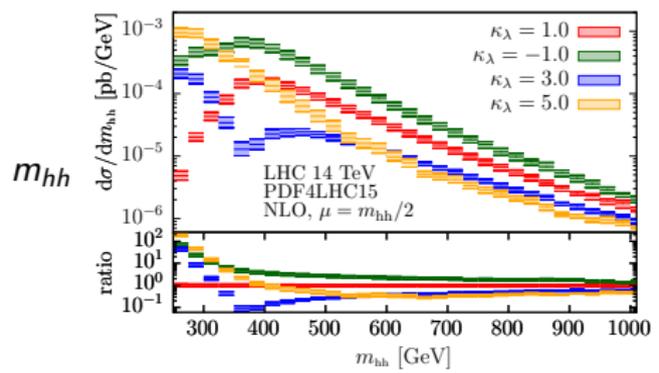
κ_λ	$\sigma_{\text{NLO}}@13\text{TeV}$ [fb]	$\sigma_{\text{NLO}}@14\text{TeV}$ [fb]	$\sigma_{\text{NLO}}@27\text{TeV}$ [fb]	K-factor@14TeV
-1	116.71 ^{+16.4%} _{-14.3%}	136.91 ^{+16.4%} _{-13.9%}	504.9	1.86
0	62.51 ^{+15.8%} _{-13.7%}	73.64 ^{+15.4%} _{-13.4%}	275.29	1.79
1	27.84^{+11.6%}_{-12.9%}	32.88^{+13.5%}_{-12.5%}	127.7^{+11.5%}_{-10.4%}	1.66
2	12.42 ^{+13.1%} _{-12.0%}	14.75 ^{+12.0%} _{-11.8%}	59.10	1.56
2.4	11.65 ^{+13.9%} _{-12.7%}	13.79 ^{+13.5%} _{-12.5%}	53.67	1.65
3	16.28 ^{+16.2%} _{-15.3%}	19.07 ^{+17.1%} _{-14.1%}	69.84	1.90
5	81.74 ^{+20.0%} _{-15.6%}	95.22 ^{+19.7%} _{-11.5%}	330.61	2.14

K -factor dependence on κ_λ

- In HEFT: K -factor $\sigma_{\text{NLO}}/\sigma_{\text{LO}} \sim$ flat w.r.t couplings variation
- Sizeable variation of the K -factor in full NLO prediction

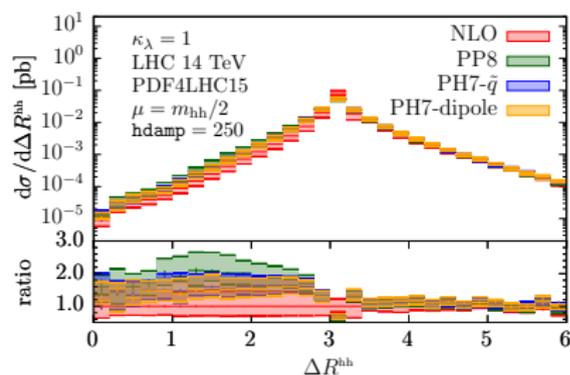
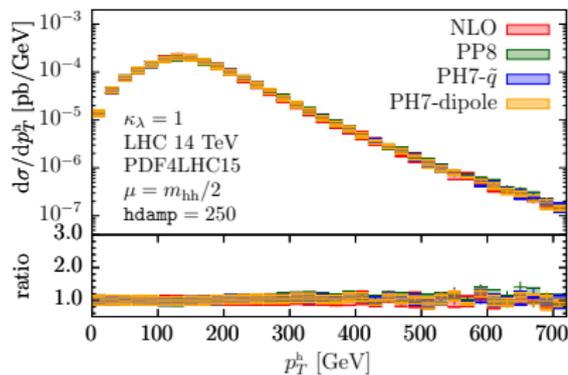


Differential distributions: fixed-order



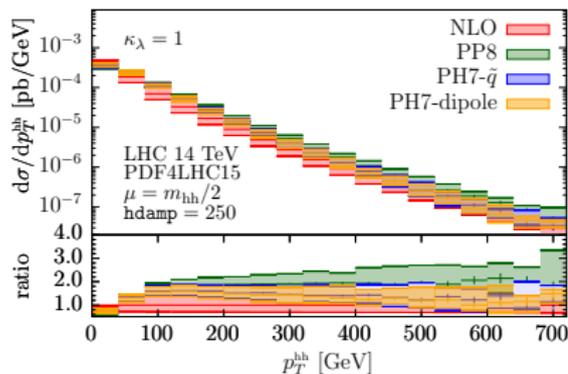
Showered results

- Fixed-order NLO result matched to Pythia8, Herwig7
- Both showers from Herwig: angular-ordered \tilde{q} , dipole showers

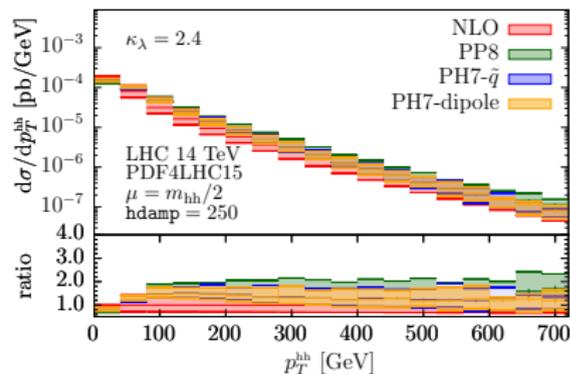


Showered results

- Pythia8 generates much **harder radiation** in the high- p_T^{hh} tail
- **Very similar results** for both Herwig showers



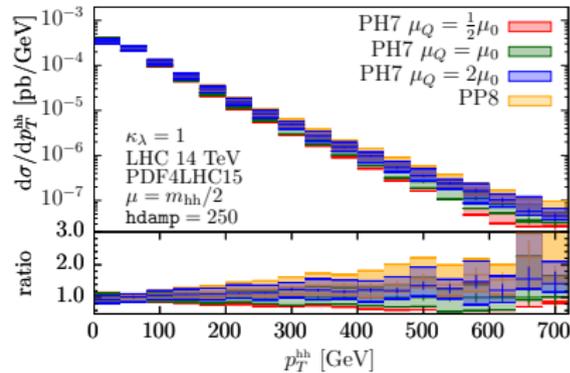
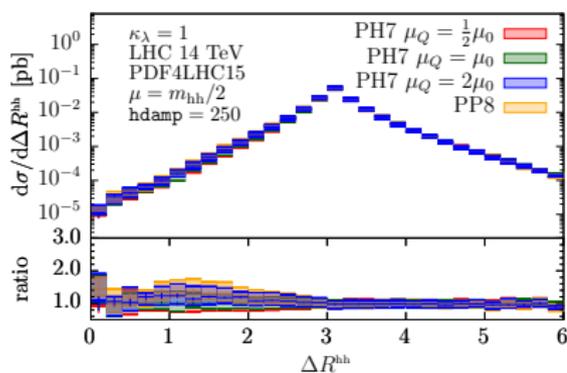
$$\kappa_\lambda = 1.0$$



$$\kappa_\lambda = 2.4$$

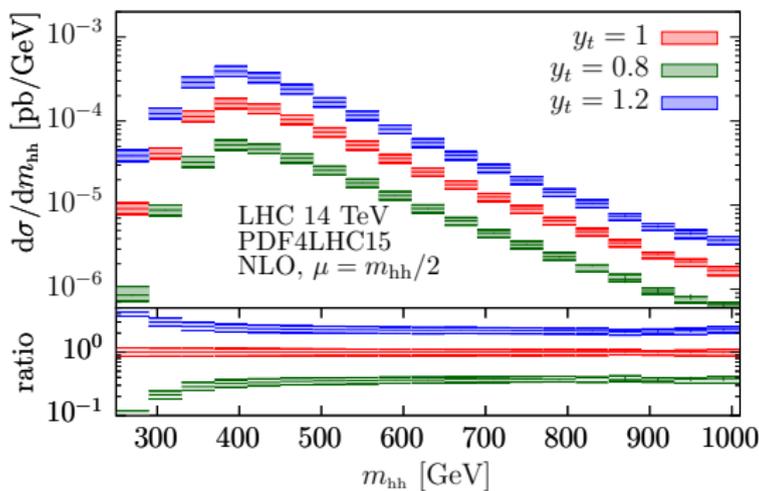
Shower scale variation

- Herwig shower hard scale μ_Q varied by $\{\frac{1}{2}, 2\}$
- High sensitivity to the shower scale uncertainties
- Differences Pythia - Herwig covered by the shower uncertainties



Variation of the Higgs-top Yukawa coupling

$$|\mathcal{M}|^2 = y_t^4 \left[\mathcal{M}_B \mathcal{M}_B^* + \frac{\lambda}{y_t} (\mathcal{M}_B \mathcal{M}_T^* + \mathcal{M}_T \mathcal{M}_B^*) + \frac{\lambda^2}{y_t^2} \mathcal{M}_T \mathcal{M}_T^* \right].$$



e.g. $\sigma(y_t = 1.2, \lambda = 1) = (1.2)^4 \cdot \sigma(y_t = 1, \lambda = 1/1.2)$

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Full m_t -dependent NLO QCD corrections to Higgs pair production

- Variation of κ_λ and y_t
- Public Powheg-BOX-V2 package:
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 - Higgs decays
 - Hadronization, ...

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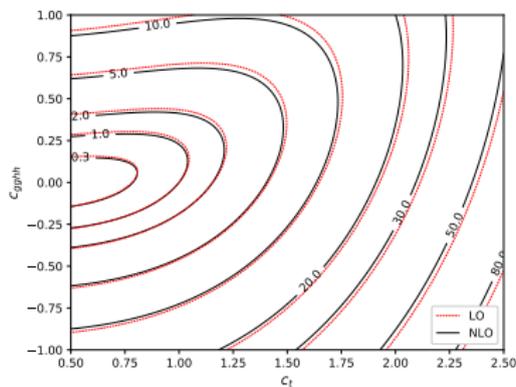
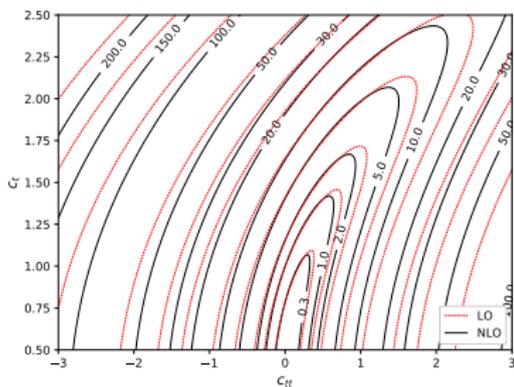
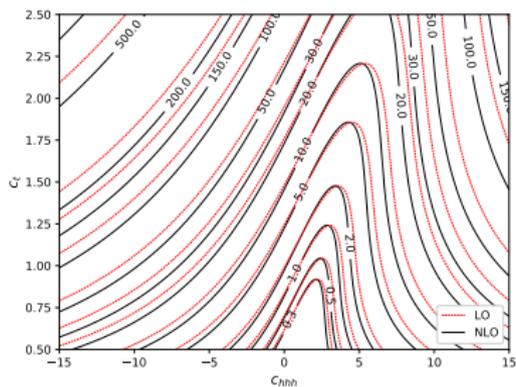
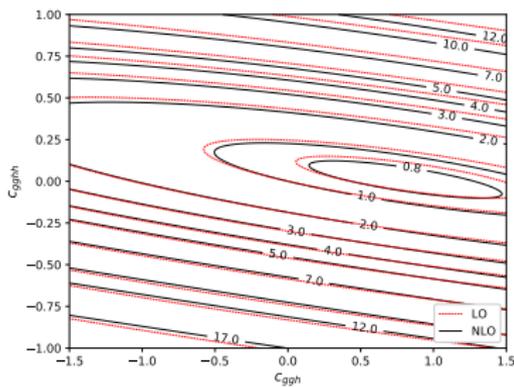
Thank you!

Backup

Powheg shower matching

- Standard [UserHooks](#) to match Powheg to Pythia shower: `main31`
- [Different definitions](#) of hardness and emission vetoing possible:
default parameters
 - `POWHEG:veto = 1`
 - `POWHEG:pThard = 0`
 - `POWHEG:pTemt = 0`
 - `POWHEG:pTdef = 1`

Other iso-contours



Electroweak Chiral Lagrangian

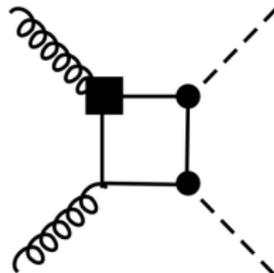
- To leading order:

$$\begin{aligned}
 \mathcal{L}_2 = & -\frac{1}{2}\langle G_{\mu\nu}G^{\mu\nu}\rangle - \frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \sum_{\psi=q_L,l_L,u_R,d_R,e_R} \bar{\psi}i\not{D}\psi \\
 & + \frac{v^2}{4}\langle D_\mu U^\dagger D^\mu U\rangle (1 + F_U(h)) + \frac{1}{2}\partial_\mu h\partial^\mu h - V(h) \\
 & - v \left[\bar{q}_L \left(Y_u + \sum_{n=1}^{\infty} Y_u^{(n)} \left(\frac{h}{v}\right)^n \right) UP_+ q_R + \bar{q}_L \left(Y_d + \sum_{n=1}^{\infty} Y_d^{(n)} \left(\frac{h}{v}\right)^n \right) \right. \\
 & \quad \left. + \bar{l}_L \left(Y_e + \sum_{n=1}^{\infty} Y_e^{(n)} \left(\frac{h}{v}\right)^n \right) UP_- l_R + \text{h.c.} \right].
 \end{aligned}$$

- Order defined by counting of **chiral dimensions** d_χ , as opposed to canonical orders of $1/\Lambda$

Chromo-magnetic operator

- $O_{tG} = y_t g_s \bar{t}_L \sigma_{\mu\nu} G^{\mu\nu} t_R$
- $d_\chi(O_{tG}) \geq 4 \sim 1\text{-loop order}$



- Contribution to $gg \rightarrow HH$ at least of two-loop order
- New Physics sector likely to couple weakly to t_L and t_R
- \rightsquigarrow contribution at least of order $d_\chi \geq 6$

[Deutschmann, Duhr, Maltoni, Vryonidou '17]

- \rightarrow effects of O_{tG} in SMEFT

Effective Lagrangian

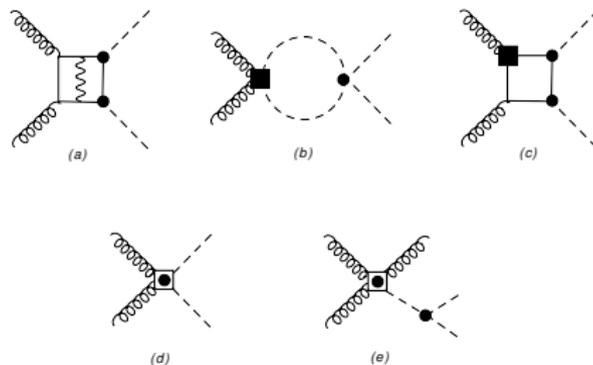
- Chiral counting:

$$d_{\chi}(A_{\mu}, \varphi, h) = 0, \quad d_{\chi}(\partial, \bar{\psi}\psi, g, y) = 1.$$

- Equivalent to counting **loop orders**:

$$d_{\chi} = 2L + 2$$

- Consistently neglected** corrections in the calculation:



EWChL to SMEFT

- 6-dimensional operators in SMEFT:

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

- Linear gauge relations between BSM coefficients:

$$\begin{aligned} c_t = 1 - \frac{\bar{c}_H}{2} - \bar{c}_u, \quad c_{tt} = -\frac{\bar{c}_H + 3\bar{c}_u}{4}, \quad c_{hhh} = 1 - \frac{3}{2}\bar{c}_H + \bar{c}_6 \\ c_{ggh} = 2c_{gggh} = 128\pi^2\bar{c}_g \end{aligned}$$