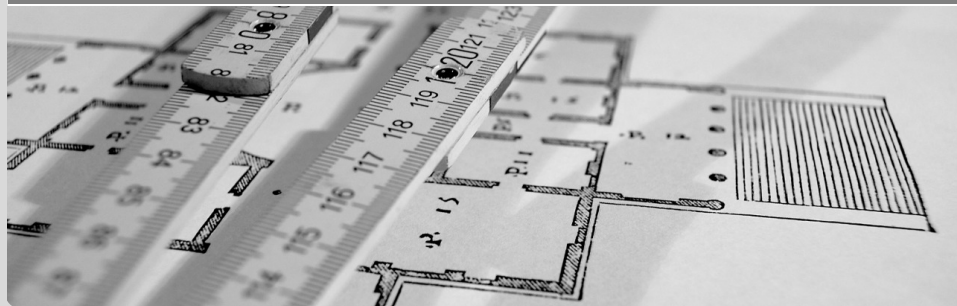


NLO QCD Corrections to Higgs Pair Production including Dimension-6 Operators

9th Annual Meeting of the Helmholtz Alliance "Physics at the Terascale"

Juraj Streicher, in collab. with R. Gröber, M. Mühlleitner and M. Spira | 18. November 2015

INSTITUT FÜR THEORETISCHE PHYSIK



Motivation: Why Higgs Pairs?

- Higgs pair production gives access to the Higgs self-coupling, with major production channel being gluon fusion ($\sigma \sim 30\text{--}40\text{ fb}$ at 14 TeV). [Djouadi, Kilian, Muhlleitner, Zerwas (1999)]
- LO cross section first calculated in 1988. [Glover, van der Bij (1988)]
- NLO corrections in the heavy top quark limit: σ_{LO} enhanced by 60–100%. [Dawson, Dittmaier, Spira (1998)]
- NNLO QCD corrections: Add +20% atop of σ_{NLO} . [de Florian, Mazzitelli (2013)]
- NLO QCD top mass expansion: mass effects of $\mathcal{O}(10\%)$. [Grigo, Hoff, Melnikov, Steinhauser (2014)]
- NNLL resummation: +(20–30)% atop of σ_{NLO} . [Shao, Li, Li, Wang (2013)]



Motivation: Why EFT?

- The Higgs boson discovery provides interesting opportunities for new physics searches.
- The SM trilinear Higgs self-coupling is uniquely determined by the Higgs mass, yet difficult to determine experimentally at the LHC.
- Large deviations of the self-coupling are possible in BSM models, varying the signal strengths significantly. [Azatov, Contino, Panico, Son (2015)]
- The **Effective Field Theory** framework enables a **rather model independent** description of BSM effects in terms of higher dimensional operators.

Motivation: Why NLO?

- NLO QCD effects expected to have a significant impact ($K \equiv \sigma_{\text{NLO}}/\sigma_{\text{LO}} \sim 2$).
- Gluon fusion receives large NLO QCD corrections, so far only known in the heavy top quark limit.
- Previous works on inclusion of higher dimensional operators relied on multiplication of the **LO EFT** result with the overall K -factor given by the **SM** NLO QCD cross section.
- In this work we validate these approximative results by including the higher dimensional EFT operators **directly in the NLO calculation**.

Framework: EFT

- BSM effects parametrised by coefficients of SM interactions and higher-dimensional operators.
- Matching of coefficients to experiment allows for model independent limits on BSM physics.
- The higher dimensional contributions relevant for the analysis are summarised in the non-linear EFT Lagrangian,

[Contino, Grojean, et al, (2010)]

$$\Delta\mathcal{L}_{\text{non-lin}} \supset -m_t \bar{t} t \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{2v^2} \right) - c_3 \left(\frac{m_h^2}{2v} \right) h^3 + \frac{\alpha_s}{\pi} G^{a\mu\nu} G_{\mu\nu}^a \left(c_g \frac{h}{v} + c_{gg} \frac{h^2}{2v^2} \right),$$

giving rise to effective $t\bar{t}hh$, ggh , and $gghh$ couplings, as well as modifications to the $t\bar{t}h$ and hhh coupling.

- The SM limit is recovered for

$$c_t \rightarrow 1, \quad c_{tt} \rightarrow 0, \quad c_3 \rightarrow 1, \quad c_g \rightarrow 0 \quad \text{and} \quad c_{gg} \rightarrow 0.$$

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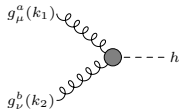
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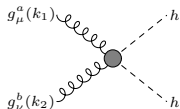
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Framework: Heavy top limit

- The effective Lagrangian for Higgs boson interactions in the heavy top limit can be derived in the low-energy limit of vanishing Higgs four-momentum.
- Together with the EFT contributions, the effective Lagrangian leads to the Higgs-gluon couplings,



$$i\delta^{ab} \frac{\alpha_s}{3\pi v} [k_1^\nu k_2^\mu - (k_1 \cdot k_2) g^{\mu\nu}] \left[c_t \left(1 + \frac{11}{4} \frac{\alpha_s}{\pi} \right) + 12c_g \right] ,$$



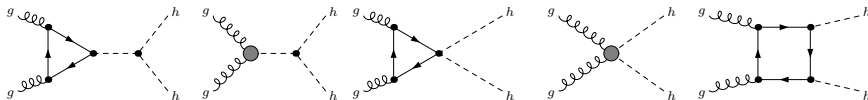
$$i\delta^{ab} \frac{\alpha_s}{3\pi v^2} [k_1^\nu k_2^\mu - (k_1 \cdot k_2) g^{\mu\nu}] \left[(c_{tt} - c_t^2) \left(1 + \frac{11}{4} \frac{\alpha_s}{\pi} \right) + 12c_{gg} \right] .$$

Calculation: Leading Order

- As in the SM case, the LO partonic cross section can be written in terms of form factors as,

$$\hat{\sigma}_{\text{LO}} = \int_{\hat{t}_-}^{\hat{t}_+} d\hat{t} \frac{G_F^2 \alpha_s^2(\mu_R)}{512(2\pi)^3} \left[\underbrace{\left| C_\Delta (c_t F_\Delta + 8c_g) + c_{tt} F_\Delta + 8c_{gg} + c_t^2 F_\square \right|^2}_{\mathcal{A}_1} + \underbrace{\left| c_t^2 G_\square \right|^2}_{\mathcal{A}_2} \right].$$

- F_Δ , F_\square and G_\square are the SM form factors containing the full quark mass dependence.
- C_Δ contains the trilinear Higgs self-coupling.

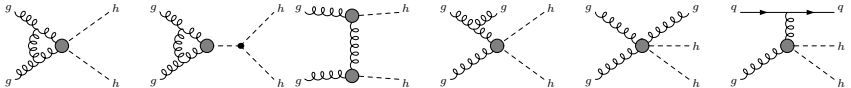


Calculation: NLO Corrections

- The finite hadronic NLO cross section can be organised as,

$$\sigma_{\text{NLO}} = \sigma_{\text{LO}} + \Delta\sigma_{\text{virt}} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{q\bar{q}}.$$

- The **relative** real corrections in $\Delta\sigma_{gg}$, $\Delta\sigma_{gq}$ and $\Delta\sigma_{q\bar{q}}$ remain unaltered by higher-dimensional operators.
- The virtual corrections $\Delta\sigma_{\text{virt}}$ are altered due to additional contributions from novel vertices and coupling modifications of the Yukawa and trilinear self-coupling.



Calculation: $\Delta\sigma_{\text{virt}}$

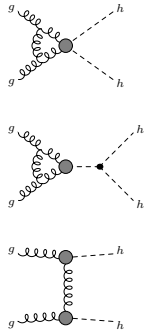
- In direct analogy to the SM and MSSM, $\Delta\sigma_{\text{virt}}$ is found to be,

$$\Delta\sigma_{\text{virt}} = \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_0}^1 d\tau \frac{d\mathcal{L}^{gg}}{d\tau} \hat{\sigma}_{\text{LO}}(\hat{s} = \tau s) C, \quad \text{with}$$

$$C = \pi^2 + \frac{33 - 2N_F}{6} \log \frac{\mu_R^2}{\hat{s}} + \frac{11}{2}$$

$$+ \text{Re} \frac{\int_{\hat{t}_-}^{\hat{t}_+} d\hat{t} \mathcal{A}_1 [-C_\Delta^* 44c_g - 44c_{gg} + \frac{4}{9}(c_t + 12c_g)^2]}{\int_{\hat{t}_-}^{\hat{t}_+} d\hat{t} [|\mathcal{A}_1|^2 + |\mathcal{A}_2|^2]}$$

$$+ \text{Re} \frac{\int_{\hat{t}_-}^{\hat{t}_+} d\hat{t} \mathcal{A}_2 [\frac{\rho_T^2}{2i\hat{u}} (2M_h^2 - \hat{s}) \frac{4}{9}(c_t + 12c_g)^2]}{\int_{\hat{t}_-}^{\hat{t}_+} d\hat{t} [|\mathcal{A}_1|^2 + |\mathcal{A}_2|^2]}$$



- The various contributions to Higgs pair production are affected differently by the QCD corrections.

Calculation: $\Delta\sigma_{\text{virt}}$

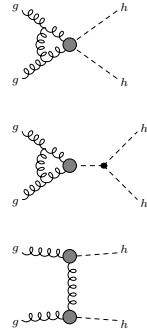
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Numerical Analysis:

- The results of the calculation were implemented in the Fortran code HPAIR.
- Influence of new couplings on $K^{\text{EFT}} = \frac{\sigma_{\text{NLO}}^{\text{EFT}}}{\sigma_{\text{LO}}^{\text{EFT}}}$.
- Determine maximal K -factor deviation,

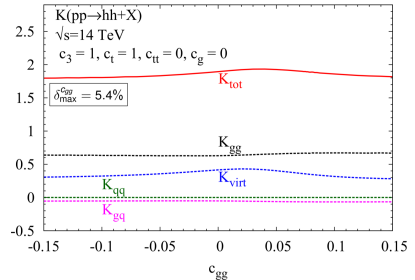
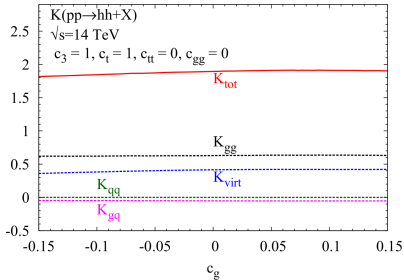
$$\delta_{\text{max}} = \frac{\max|K^{\text{EFT}} - K^{\text{SM}}|}{K^{\text{SM}}}.$$

- Analysis performed for $\sqrt{s} = 14 \text{ TeV}$ and $\sqrt{s} = 100 \text{ TeV}$ using MSTW08 PDFs and the SM parameters set to,

$$M_h = 125 \text{ GeV}, \quad m_t = 173.2 \text{ GeV}, \quad m_b = 4.75 \text{ GeV},$$

$$\alpha_S^{\text{LO}}(M_Z) = 0.13939, \quad \alpha_S^{\text{NLO}}(M_Z) = 0.12018.$$

Numerical Analysis: c_g and c_{gg}

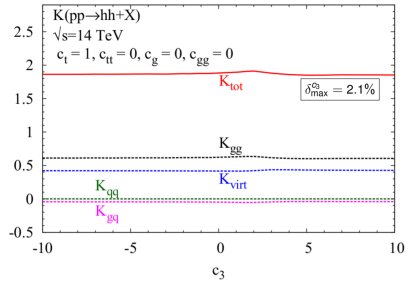
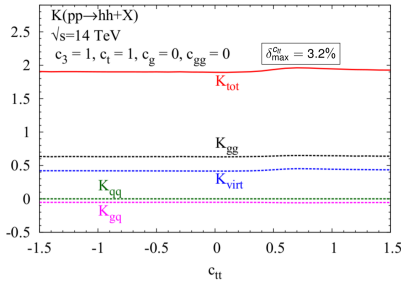


- Variation range of the coefficients is chosen in agreement with the experimental limits, except for c_g .
- The c_g variation is suppressed due the additional Higgs propagator.
- The effect of the c_{gg} variation is small, but the impact on the cross section is huge.

[Azatov, Contino Panico, Son (2015)]

$$\max |\sigma^{c_{gg}} - \sigma^{SM}| / \sigma^{SM} = 5.8$$

Numerical Analysis: c_{tt} and c_3



- For $c_{tt} \approx 0.7$ the LO cross section is minimised, causing a maximum of K_{tot} .
- c_3 can be varied over a broad range, however the impact of the variation is small.
- Not shown are the variation for c_t and the corresponding analysis for $\sqrt{s} = 100 \text{ TeV}$.

Conclusion and Outlook:

- The various contributions to Higgs pair production are affected differently by the QCD corrections.
- One by one variation of EFT parameters leads to K -factor deviations of several per cent.
- Minor impact confirms the dominance of soft and collinear gluon effects.
- Large deviations from σ^{SM} are still possible within the experimental limits on the EFT parameters.
- Further details and discussion of the SILH approximation can be found in

JHEP 1509 (2015) 092.

Thank you for your attention!