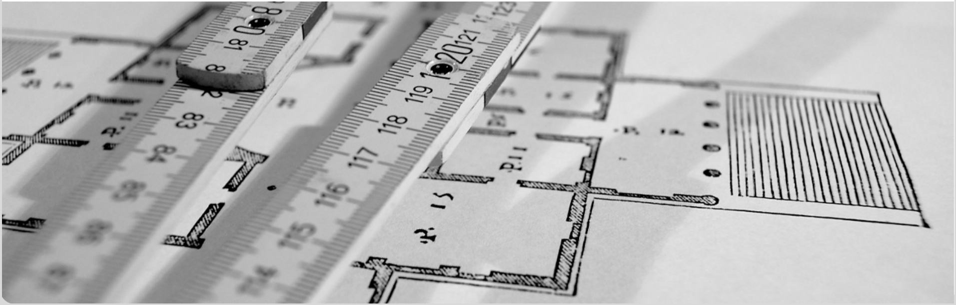
Karlsruher Institut für Technologie

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

GK Workshop 2015

Juraj Streicher, in collab. with R. Gröber, M. Mühlleitner and M. Spira | 28. September 2015

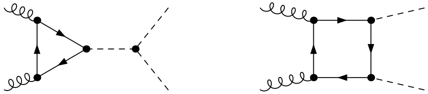
INSTITUT FÜR THEORETISCHE PHYSIK



Outline:

Motivation: Why Higgs Pairs?

- The Higgs self-coupling is accessible in double Higgs production processes, with major production channel being gluon fusion ($\sigma \sim 30-40\ fb$).
- LO cross section first calculated in 1988. [Glover, van der Bij]
- NLO corrections in the heavy top quark limit: $\sigma_{\rm LO}$ enhanced by $60-100\%$. [Dawson, Dittmaier, Spira (1998)]
- NNLO QCD corrections: Add $+20\%$ atop of $\sigma_{\rm NLO}$. [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 $\sigma_{\rm NLO}$. [Shao, Li, Li, Wang (2013)]



Motivation: Why EFT?

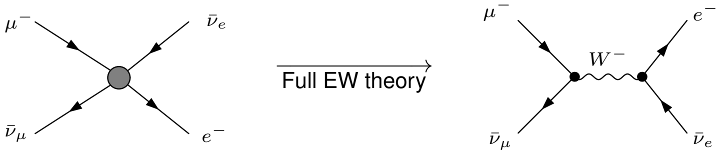
- The Higgs boson discovery provides interesting opportunities for new physics searches.
- In the SM the trilinear Higgs self-coupling is uniquely determined by the Higgs mass, yet difficult to determine experimentally at the LHC.
- Significant deviations of the self-coupling are possible in BSM models,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

Framework: EFT

- EFTs describe the influence of heavy BSM particles on SM observables.
- Effects parametrised by coefficients of SM interactions and higher-dimensional operators.
- Matching of coefficients to experiment allows for model independent limits on BSM physics.
- Historical example: Fermi interaction.



Framework: EFT

- The higher dimensional contributions relevant for the analysis are summarised in the non-linear EFT Lagrangian, [Contino, Grojean, et al, (2010)]

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

giving rise to effective *tthh*, *ggh*, and *gghh* couplings, as well as modifications to the *tth* and *hhh* coupling.

- The SM limit is recovered for

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

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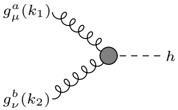
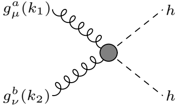
Framework: Heavy top limit

- 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 the Higgs-gluon couplings,



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



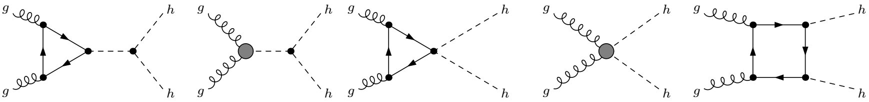
$$i\delta^{ab}\frac{\alpha_s}{3\pi v^2}\left[k_1^\nu k_2^\mu-(k_1\cdot k_2)g^{\mu\nu}\right]\left[(c_{tt}-c_t^2)\left(1+\frac{11}{4}\frac{\alpha_s}{\pi}\right)+12c_{gg}\right] .$$

Calculation: Leading Order

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

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

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

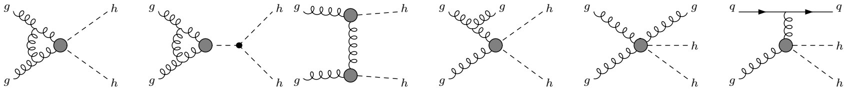


Calculation: NLO Corrections

- 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.

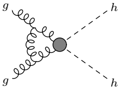


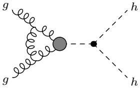
Calculation: $\Delta\sigma_{\text{virt}}$

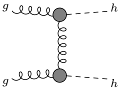
- In direct analogy to the SM and MSSM, $\Delta\sigma_{\text{virt}}$ is found to be,

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

$$C = \pi^2 + \frac{33 - 2N_F}{6} \log \frac{\mu_R^2}{\hat{s}} + \frac{11}{2}$$
$$+ \text{Re} \frac{\int_{\hat{t}_-}^{\hat{t}_+} d\hat{t} \mathcal{A}_1 \left[-C_\triangle^* 44 c_g - 44 c_{gg} + \frac{4}{9}(c_t + 12 c_g)^2 \right]}{\int_{\hat{t}_-}^{\hat{t}_+} d\hat{t} \left[|\mathcal{A}_1|^2 + |\mathcal{A}_2|^2 \right]}$$
$$+ \text{Re} \frac{\int_{\hat{t}_-}^{\hat{t}_+} d\hat{t} \mathcal{A}_2 \left[\frac{p_T^2}{2\hat{t}\hat{u}} (2M_h^2 - \hat{s}) \frac{4}{9} (c_t + 12 c_g)^2 \right]}{\int_{\hat{t}_-}^{\hat{t}_+} d\hat{t} \left[|\mathcal{A}_1|^2 + |\mathcal{A}_2|^2 \right]}$$







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

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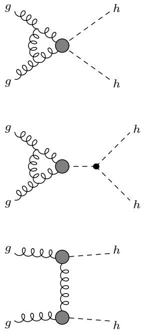

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Numerical Analysis:

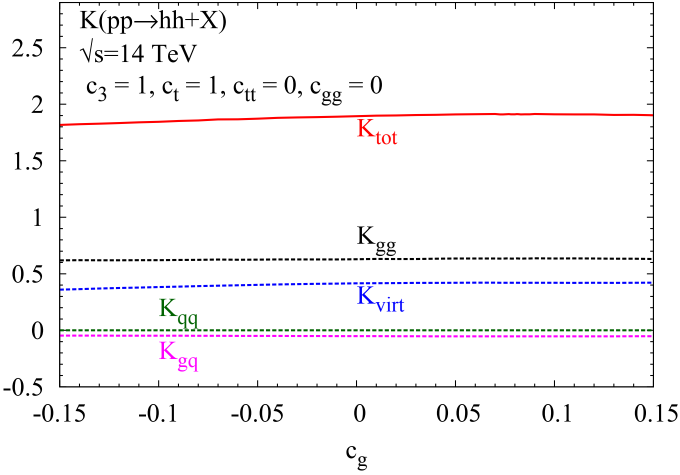
- The results of the calculation were implemented in the Fortran code `HPAIR`.
- Influence of new couplings on $K^{\text{EFT}} = \frac{\sigma^{\text{EFT}}_{\text{NLO}}}{\sigma^{\text{EFT}}_{\text{LO}}}$.
- Determine maximal K-factor deviation,

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

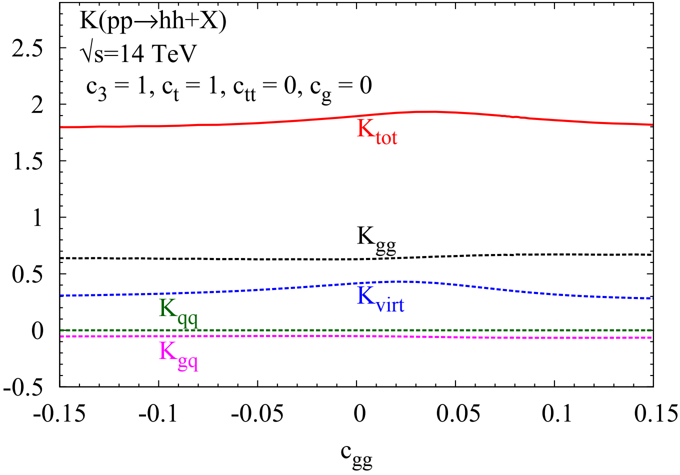
- Analysis performed for $\sqrt{s} = 14$ TeV and $\sqrt{s} = 100$ TeV using MSTW08 PDFs and the SM parameters set to,

$$M_h = 125\,\text{GeV}\,, \quad m_t = 173.2\,\text{GeV}\,, \quad m_b = 4.75\,\text{GeV}\,,$$
$$\alpha_S^{\text{LO}}(M_Z) = 0.13939\,, \quad \alpha_S^{\text{NLO}}(M_Z) = 0.12018\,.$$

Numerical Analysis: c_g



Numerical Analysis: c_{gg}



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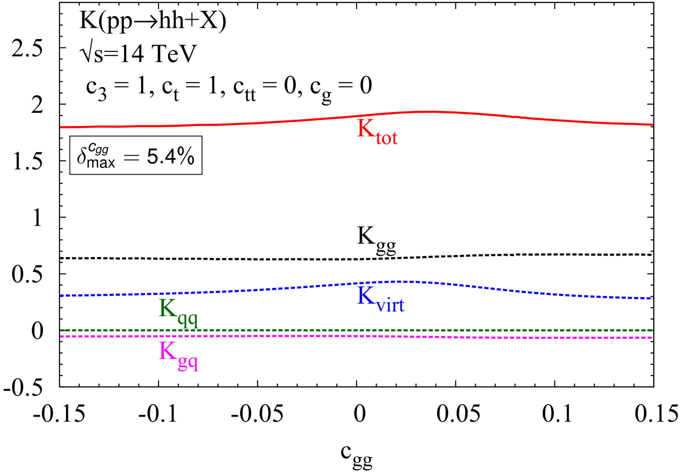
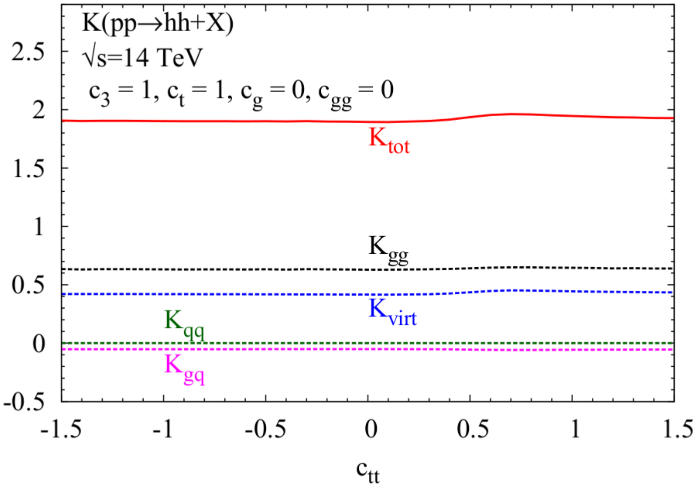


Numerical Analysis: c_{tt}



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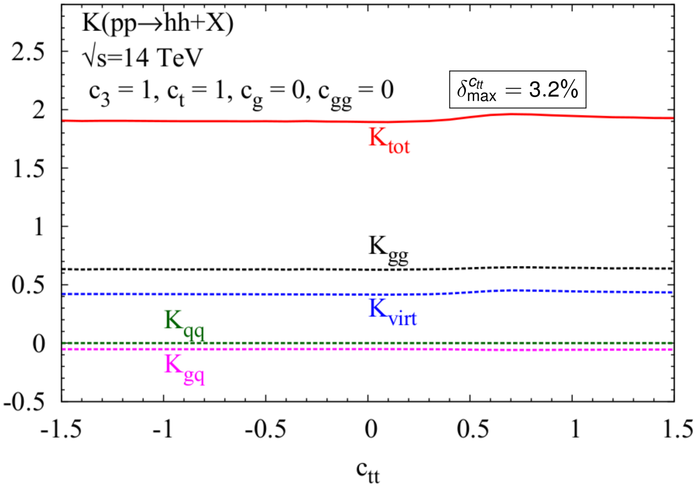

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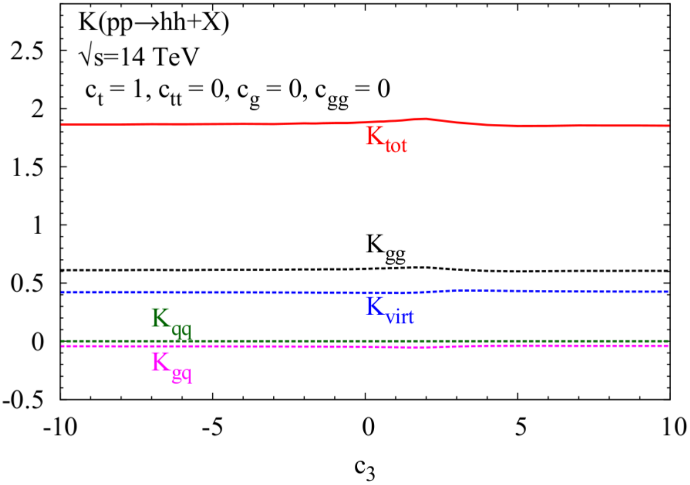

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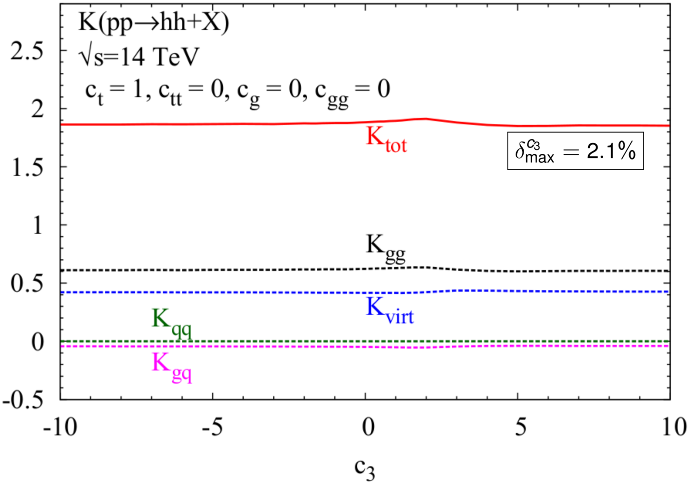

Conclusion and Outlook:

- 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.
- NLO corrections are crucial for precise predictions of the cross sections.
- Further details and discussion of the SILH approximation can be found in

`JHEP 1509 (2015) 092`.

Thank you for your attention!