On the analytic two-loop corrections to double Higgs production in the SM

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Partially based on arXiv:1603.00385,
G. Degrassi, P.P.G., R. Gröber
\[ V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \]

\[ V(h) = \frac{1}{2} M_h^2 h^2 + \frac{M_h^2}{2v} h^3 + \frac{M_h^2}{8v^2} h^4 \]

In the SM the self coupling is fixed once the h-mass and the vev are known.

Trilinear coupling could be measured at LHC from Higgs Pair Production.

The quartic coupling will not be measured at LHC nor at ILC/CLIC.
New Physics

In general new physics affects the trilinear Higgs coupling:

- New Higgs bosons (e.g. 2HDM).
- New Particles in Loops (e.g. Susy).
- Modified couplings (e.g. Composite).

Adding a single scalar also would do the job.

\[
V(\phi, S) = -\mu^2 (\phi^\dagger \phi) + \lambda (\phi^\dagger \phi)^2 - m^2 S^2 + k_S (\phi^\dagger \phi) S^2 + \lambda_S S^4
\]
From $gg \rightarrow hh$ we can obtain information on NP.

- We need a calculation of the NLO corrections.
- NLO corrections are “large”.

- Large number of Amplitudes!
- Very complicated Integrals!

Programs like FIRE or REDUZE can solve the first problem.
Numerical approach

Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert and Zirke, arXiv: 1604.06447

$$\sigma^{NLO} = 32.80^{+13\%}_{-12\%} \text{ fb} \pm 0.4\%(\text{stat.}) \pm 0.1\%(\text{int.})$$

- Total cross section including the full top-quark dependence.
- 16 dual NVIDIA Tesla K20X GPGPU nodes.
- 4680 GPGPU hours.
- 665 phase space points.
Analytical approach

- Too many scales involved!
  \[ P_1^2 = P_2^2 = 0 \quad P_3^2 = P_4^2 = M_h^2 \]
  \[ s_c = (P_1 + P_2)^2 \quad p_t^2 = \frac{(P_1 \cdot P_3)(P_2 \cdot P_3)}{s_c} - M_h^2 \]

- Taylor expansion doesn’t work: IR divergences.

- Asymptotic expansion for “large” parameters!

\[
\begin{align*}
\text{Diagram expression} & = \left( \begin{array}{c}
\text{Diagram 1} + \text{Diagram 2} \\
\end{array} \right) + \left( \begin{array}{c}
\text{Diagram 3} + \text{Diagram 4} + \text{Diagram 5} \\
\end{array} \right)
\end{align*}
\]

Berends, Davydychev, Smirnov, Tausk ’95;
Berends, Davydychev, Smirnov, ’96; V.A. Smirnov’s books.
Large Top Mass

- Grigo, Hoff, Melnikov, and Steinhauser, arXiv:1305.7340
- Grigo, Melnikov, and Steinhauser, arXiv:1408.2422
- Grigo, Hoff, and Steinhauser, arXiv:1508.00909
- G. Degrassi, PPG, R Gröber, arXiv:1603.00385

Very good approximation in the region of validity.
Simple formulas for MC.

The expansion works well only in the region where $m_t^2$ is larger than the other parameters...

We need something else for the other region!
Large s

- No nice graph representation for this one.
- Rampant Collinear divergences!
- Expansion by “Regions”.

\[
\frac{1}{(k + P_1)^2 - m_t^2} \sim \frac{1}{2k \cdot P_1}
\]

However it seems to work pretty well for the LO already already for \(1/s_c^2\).
This seems to be the right way to follow!
Conclusions

The double Higgs production can be useful in investigating NP.
The NLO corrections will be necessary to this end.
The numerical calculation is impressive but hardly flexible.
For now, the analytic computations are done only for a very large top mass!
More work is needed!