Higgs Pair Production in gluon fusion at NLO with full top mass dependence

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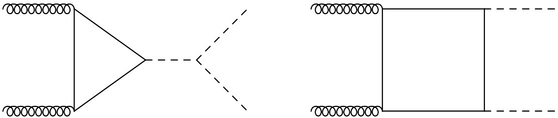
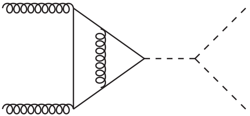
Higgs-boson pair production in gluon fusion

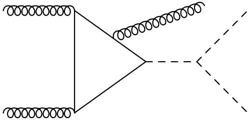
- all characteristics of the scalar particle found in 2012 are so far consistent with the Standard Model Higgs boson expectation
- further, we want to verify if the Higgs potential is as expected
- largest cross section expected in gluon fusion
- the leading order is loop induced Glover, van der Bij '88



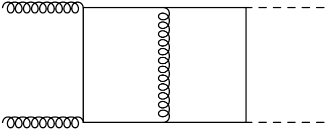
NLO with full top mass dependence

- NLO involves the computation of two-loop and one-loop diagrams with one additional radiation





- unknown two-loop integrals (with 4 independent mass scales: $\hat{s}$, $\hat{t}$, m_t^2, m_h^2, 3 ratios), e.g.



  appear as well
- analytic result for many integrals not available so far
- reduction of virtual 2-loop amplitude to master integrals is highly non-trivial

Higher-order approximations using HEFT

- NLO $m_t \to \infty$ limit
  Plehn, Spira, Zerwas '96; Dawson, Dittmaier, Spira '98
- NLO $m_t \to \infty$, supplemented with $1/m_t$ expansion
  Grigo, Hoff, Melnikov, Steinhauser '13; Degrassi, Giardino, Gröber 16
- NNLO $m_t \to \infty$ limit De Florian, Mazzitelli '13
- NNLO $m_t \to \infty$ + all matching coefficients
  Grigo, Melnikov, Steinhauser '14
- Full mass dependence in real radiation part + matching to parton shower Frederix, Hirschi, Mattelaer, Maltoni, Torrielli, Vryonidou, Zaro '14; Maltoni, Vryonidou, Zaro '14
- NNLO $m_t \to \infty$ + all matching coefficients + top quark mass effects Grigo, Hoff, Steinhauser '15
- NNLO $m_t \to \infty$ + NNLL threshold resummation
  De Florian, Mazzitelli '15

NEW: Full top-mass dependence at NLO

Virtual two-loop amplitude

- virtual amplitude generated with GoSam-2L
  - diagram generation with Qgraf Nogueira '93 (≈10000 different integrals before accounting for symmetries)
  - further processed with FORM Vermaseren '00; Kuipers, Ueda, Vermaseren '12
  - python interface to Reduze von Manteuffel, Studerus '12
- reduction up to non-planar 6- and 7-propagator topologies with Reduze, partially transformed into finite basis Panzer '14; von Manteuffel, Panzer, Schabinger '14
  $\rightarrow$ 228 planar master integrals
- 99 non-planar integrals
- integrals calculated numerically with SecDec 3 SB, Heinrich, Jones, Kerner, Schlenk, Zirke '15 using a dedicated integration setup

Numerical evaluation of Feynman integrals

- SecDec is a tool to numerically compute

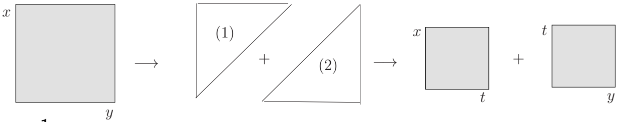
Feynman graph — or — parametric function

  - General **Feynman** integrals for **arbitrary** kinematics and with numerators
  - Integrals **matching** a Feynman integral **structure**
  - More general **parametric** functions

- SecDec is based on the method of sector decomposition

The sector decomposition idea

- Idea and method of sector decomposition pioneered by
  Hepp '66, Denner & Roth '96, Binoth & Heinrich '00



$$
\begin{aligned}
&\int_0^1 dx_1 \int_0^1 dx_2 \; \frac{1}{(x_1 + x_2)^{2+\epsilon}} \\
&= \int_0^1 dx_1 \int_0^1 dx_2 \; \frac{1}{(x_1 + x_2)^{2+\epsilon}} \left(\theta(x_1 - x_2) + \theta(x_2 - x_1)\right) \\
&= \int_0^1 dx_1 \int_0^{x_1} dx_2 \; \frac{1}{(x_1 + x_2)^{2+\epsilon}} + \int_0^1 dx_2 \int_0^{x_2} dx_1 \; \frac{1}{(x_1 + x_2)^{2+\epsilon}} \\
&= \int_0^1 dx_1 \int_0^1 dt \; \frac{x_1}{(x_1 + x_1 t)^{2+\epsilon}} + \int_0^1 dx_2 \int_0^1 d\tilde{t} \; \frac{1}{x_2^{1+\epsilon}(\tilde{t} + 1)^{2+\epsilon}}
\end{aligned}
$$

- iterative sector decomposition is highly automatable

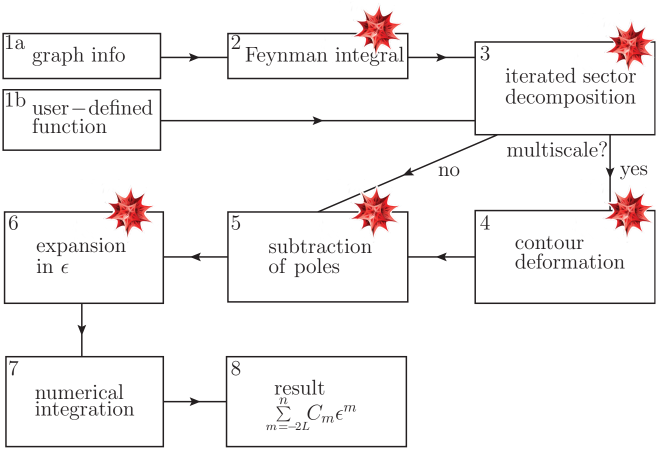
Public codes using the sector decomposition method

Public codes:

- sector_decomposition (uses GiNaC) Bogner & Weinzierl '07
  supplemented with CSectors Gluza, Kajda, Riemann, Yundin '10
  for construction of integrand in terms of Feynman parameters
- FIESTA* (uses Mathematica, C) A.V. Smirnov, V.A. Smirnov, Tentyukov '08 '09, A.V. Smirnov '13
- SecDec* (uses Mathematica, Fortran/C++)
  Carter & Heinrich '10; SB, Carter, Heinrich '12; SB & Heinrich '13; SB, Heinrich, Jones, Kerner, Schlenk, Zirke '15

*Multi-scale integrals not limited to the Euclidean region
SB, J. Carter & G. Heinrich '12; A.V. Smirnov '13

Outline of the program SecDec



numerical integration: CUBA library Hahn '04, NIntegrate Wolfram

Numerical integration of two-loop amplitude

So far SecDec has been used for...

- fast evaluation of massive bubbles (34 mass topologies, up to 5 scales) to calculate $\mathcal{O}(\alpha_s \alpha_t)$ self-energy contributions to the MSSM Higgs-boson masses

  SB, Hahn, Heinemeyer, Heinrich, Hollik '14

- checks of analytically calculated integrals

NEW:
use SecDec as a library to numerically compute all 327 integrals contributing to the Higgs-pair production amplitude

Numerical integration of two-loop amplitude

Important new steps:

- evaluate integrals with Quasi Monte Carlo integrator
  Dick, Kuo, Sloan '13; Li, Wang, Zan, Zhao '15
- use GPUs
- set number of sampling points dynamically for each integral
- target accuracy is set at amplitude level (3% for one form factor, ≈10% for the other, depending on the ratio of the two)

Real radiation at NLO

- four real radiation channels

$$gg \to hh + g \; , \quad gq \to hh + q \; ,$$
$$g\bar{q} \to hh + \bar{q} \; , \quad q\bar{q} \to hh + g$$

- 1-loop amplitudes generated and processed with GoSam
  Cullen, van Deurzen, Greiner, Heinrich, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Reiter, Schlenk, von Soden-Fraunhofen, Tramontano; '11 '14
- Catani-Seymour dipole formalism used for IR subtraction
  Catani, Seymour '96
- numerical integration using Vegas Lepage '80 of CUBA library Hahn '04

Checks and result

Checks:

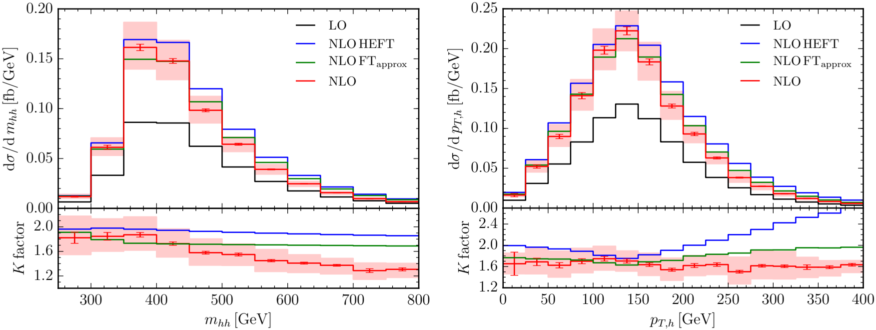
- independent calculation of (unreduced) amplitude
- checked invariance under exchange of $\hat{t}$ and $\hat{u}$
- two-loop integrals recomputed with Vegas
- single Higgs production reproduced, comparison to SusHi
  Harlander, Liebler, Mantler '13 '16
- pole cancellation
- independence of dipole parameter α Nagy '03
- comparison of $1/m_t$ expansion with Jens Hoff
  Grigo, Hoff, Steinhauser '15
- comparison of HEFT result to MG5_aMC@NLO
  Maltoni, Vryonidou, Zaro '14 '15

Resulting cross section at 14 TeV:

$$\sigma^{\text{NLO}} = 32.80^{+13.4\%}_{-12.5\%}\,\text{fb} \pm 0.4\%\,(\text{stat.}) \pm 0.1\%\,(\text{int.})$$

$$\sigma^{\text{NLO}}_{\text{HEFT}} = 38.29^{+18.1\%}_{-14.8\%}\,\text{fb}, \qquad \sigma^{\text{LO}} = 19.85^{+28\%}_{-21\%}\,\text{fb}$$

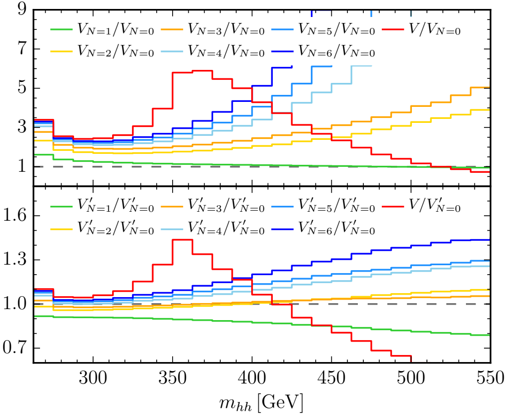
Comparison I: full result to HEFT approximations



- 665 phase-space points with ∼16 dual GPU nodes
  → total of ∼6 days runtime
- NLO HEFT good approximation for $m_{hh} < 2m_t$
- scale uncertainties of HEFT and FT_{approx} do not enclose central value of full result in m_{hh} tail → HEFT breaks down

Comparison II: full result to $1/m_t^{2\rho}$ approximations

V_N: ren. virtual amp. of HEFT result, in $1/m_t^{2N}$ expansion
V'_N: ren. virtual amp. of Born-improved HEFT, $1/m_t^{2N}$ expansion



$N < 4$ Tom Zirke,

$N = 4, 5, 6$ thanks to Jens Hoff

$\rightarrow$ deviations large and shapes very different beyond $m_{hh} \sim 2m_t$

Summary

- We calculated the total cross section for Di-Higgs production in gluon fusion at NLO with full top-quark mass dependence.
- evaluation of integrals done fully numerically using SecDec in dedicated integration setup
- total cross section is $\sim$14% smaller than Born-improved HEFT approximation
- m_{hh} distribution: for $m_{hh} \gtrsim 500\,\text{GeV}$, the top mass effects lead to reduction of differential cross section $\sim 20 - 30\%$ wrt. Born-improved HEFT approximation, and $\sim 10 - 20\%$ wrt. FT_{approx} result
- inclusion of the full top-quark mass dependence vital for reliable Higgs-boson pair production predictions over full invariant mass range