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TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

Top Quark Mass Effects in Higgs Boson Production at four-loop order: Virtual Corrections

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based on [Davies, FH, Steinhauser PRL 124 (2020) 11, 112002]

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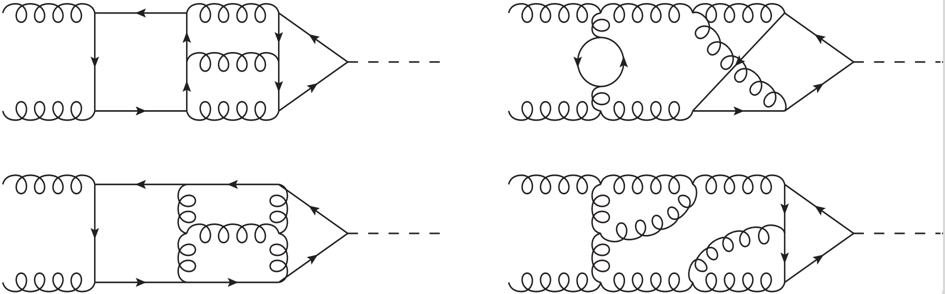
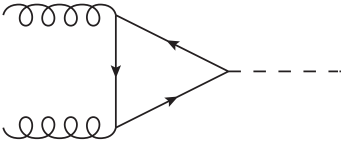
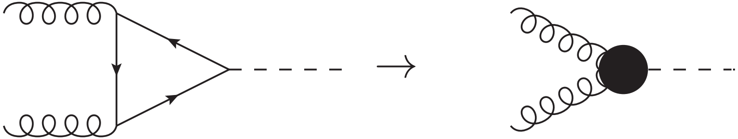


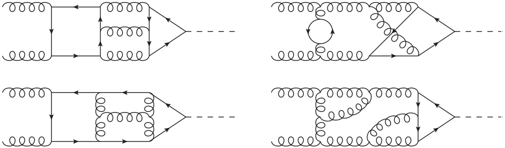
Introduction



- Gluon fusion is the dominant process for Higgs boson production at Hadron colliders
- Computation including full quark mass dependence challenging
- First step is typically the limit of an infinitely heavy top quark
- At NNLO the total cross section is known including mass suppressed terms [Harlander, Ozeren '09],[Pak, Rogal, Steinhauser '10]
- At N^{3}LO only the approximation of an infinitely heavy top quark available [Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger '16, Mistlberger '18]



Introduction



- Already at three loops the calculations is very challenging
- Light fermionic contributions recently computed exactly and analytically [Harlander, Prausa, Usovitch '19]
- LME known up to $1/m_t^{14}$ [Davies, Steinhauser '19]
- Recently two exact numerical results have been obtained:
  - by combining LME and a threshold expansion using Pade approximants [Davies, Gröber, Maier, Rauh, Steinhauser '19]
  - by performing a full IBP reduction, evaluating the master integrals numerically [Niggetiedt, Czakon '19]
- Virtual corrections known at four loops for $m_t \to \infty$ [Baikov, Chetyrkin, Smirnov, Smirnov, Steinhauser '09], [Gehrmann, Glover, Huber, Ikizlerli, Studerus '10]

$\to$ First step beyond infinite top mass limit at four loops [Davies, FH, Steinhauser '19]

Structure

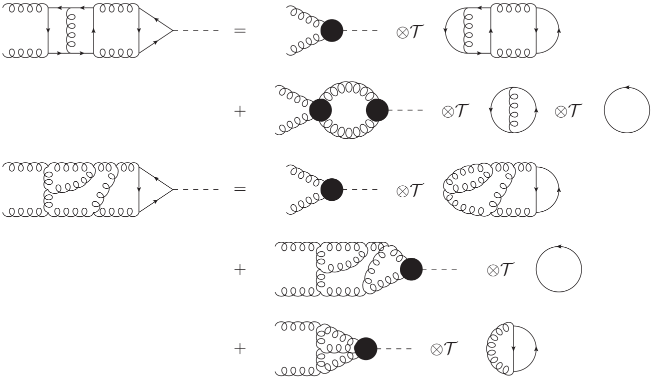
- The amplitude for $gg \to H$ can be written as

$$\mathcal{A}_{gg\to H} = \mathcal{A}_0 h(\rho) \left(q_1 \cdot q_2 g^{\mu\nu} - q_1^\nu q_2^\mu\right)$$

- $\mathcal{A}_0 = T_F \frac{2\alpha_s}{3v\pi}$
- $\rho = \frac{m_H^2}{m_t^2} \approx 0.5$
- Project $\mathcal{A}_{gg\to H}$ onto $h(\rho)$
- Since $\rho \ll 1$ we expand $h(\rho)$ for small ρ
- Small ρ expansion is an asymptotic expansion in the large top quark mass
- Our aim was to compute $h(\rho)$ through four loops up to ρ^2

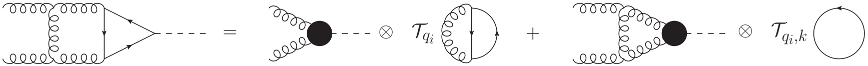
Asymptotic expansion

- The asymptotic expansion of h in ρ is performed using the method of expansion by subgraph
  $\rightarrow$ decomposes each diagram into hard subgraphs and co-subgraphs



- Automated in `exp`

- Massive vacuum integrals up to four loops
- Massless three-point integrals up to three loops
- We end up with tensor integrals
- Two-loop example:



$$I(\rho) \approx \int \left[\mathrm{d}^d k\right] \left[\mathrm{d}^d l\right] \frac{P(q_i \cdot k, q_i \cdot l)}{(k^2)^{a_1} \left((k-l)^2 - m_t^2\right)^{a_2} \left(l^2 - m_t^2\right)^{a_3}} + \int \left[\mathrm{d}^d k\right] \frac{1}{(k^2)^{a_1} \left((k+q_1)^2\right)^{a_2} \left((k-q_2)^2\right)^{a_3}} \int \left[\mathrm{d}^d l\right] \frac{Q(q_i \cdot l, k \cdot l)}{\left(l^2 - m_t^2\right)^{a_4}}$$

- Vacuum integrals: tensor structure composed of $g^{\mu\nu}$

IBP reduction and MIs

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- Up to two loops there are algorithms for arbitrary ranks, implemented in `MATAD` [Steinhauser '01]
- At three and four loops we implemented tensor reduction up to rank 8
- After tensor reduction: 4 million vacuum integrals and 1 million three-point integrals
- IBP reduction using `LiteRed` [Lee '14] and `FIRE` [Smirnov, Chuharev '14]
- Leads to 25 GB of `FORM` tablebases
  $\rightarrow$ bug in `FORM` related to tables with many entries found and fixed
- Master integrals for four-loop tadpoles from [Schroder, Vuorinen '05], [Chetyrkin, Faisst, Sturm, Tentyukov '06], [Lee, Terekhov '11]
- Master integrals for three-loop three-point functions from [Baikov, Chetyrkin, Smirnov, Smirnov, Steinhauser '09], [Heinrich, Huber, Kosower, Smirnov '09], [Gehrmann, Glover, Huber, Ikizlerli, Studerus '10, '10], [Lee, Smirnov, 11]

UV renormalization

- Renormalize m_t and α_s in the $\overline{\mathrm{MS}}$ scheme: Z_{α_s} and Z_m
- Renormalize external gluons in the on-shell scheme: $Z_3^{(OS)} = \frac{1}{\zeta_3^0}$
- Decouple the top quark: $\alpha_s^{(6)} = \frac{1}{\zeta_{\alpha_s}} \alpha_s^{(5)}$
- In addition: use $\overline{\mathrm{MS}}$-OS relation to also get results in terms of on-shell top mass
- Important note: we need ζ_3^0, ζ_{α_s} and the $\overline{\mathrm{MS}}$-OS relation at three loops, including higher order ϵ terms
  $\rightarrow$ available from [Gerlach, FH, Steinhauser '18] and [Marquard, Smirnov, Smirnov, Steinhauser, Wellmann '16]

IR structure

- $h(\rho)$ still contains infrared poles
- Infrared poles of $\log(F)$ with

$$F = \frac{h(\rho)}{h^{(1)}(\rho)} = 1 + \mathcal{O}(\alpha_s)$$

  known
- Can be expressed in terms of three quantities only [Becher, Neubert '09], [Gehrmann, Glover, Huber, Ikizlerli, Studerus '10]:
  - QCD beta function
  - Cusp soft anomalous dimension
  - Gluon collinear anomalous dimension
- As a consequence the poles of $\log(F)$ do not depend on ρ (after writing everything in terms of $\alpha_s^{(5)}$)

Checks and Numerical effects

- Projected on both $g^{\mu\nu}$ and $q_1^\nu q_2^\mu$ independently
- Construct ρ^0 term by combining effective gluon coupling and form-factors from [Gehrmann, Glover, Huber, Ikizlerli, Studerus '10]
- Three-loop results agree with [Davies, Steinhauser '19]
- IR structure is in agreement with expectation
- For $m_t = 173\text{GeV}$ in the on-shell scheme and $m_H = 125\text{GeV}$ we get:

$$
\begin{aligned}
\log(F)_{\text{finite}} \approx & \frac{\alpha_s^{(5)}(m_t)}{\pi}\left((11.07 - i3.06) + 0.07 + 0.04\right) \\
& \left(\frac{\alpha_s^{(5)}(m_t)}{\pi}\right)^2 \left((22.59 + i13.24) + (1.02 + i0.13) + (0.07 + i0.01)\right) \\
& \left(\frac{\alpha_s^{(5)}(m_t)}{\pi}\right)^3 \left((-73.18 + i51.55) + (7.61 + i0.85) + (0.70 + i0.14)\right)
\end{aligned}
$$

- Convergence of LME similar for $\overline{\mathrm{MS}}$ renormalized top quark mass

Summary

- Computed four loop corrections to the gluon-Higgs amplitude up to $1/m_t^4$
- Computationally very challenging
- Convergence of LME very good
- Result on its own not physical, has to be combined with real corrections