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NLO QCD corrections to Higgs boson pair production via gluon fusion

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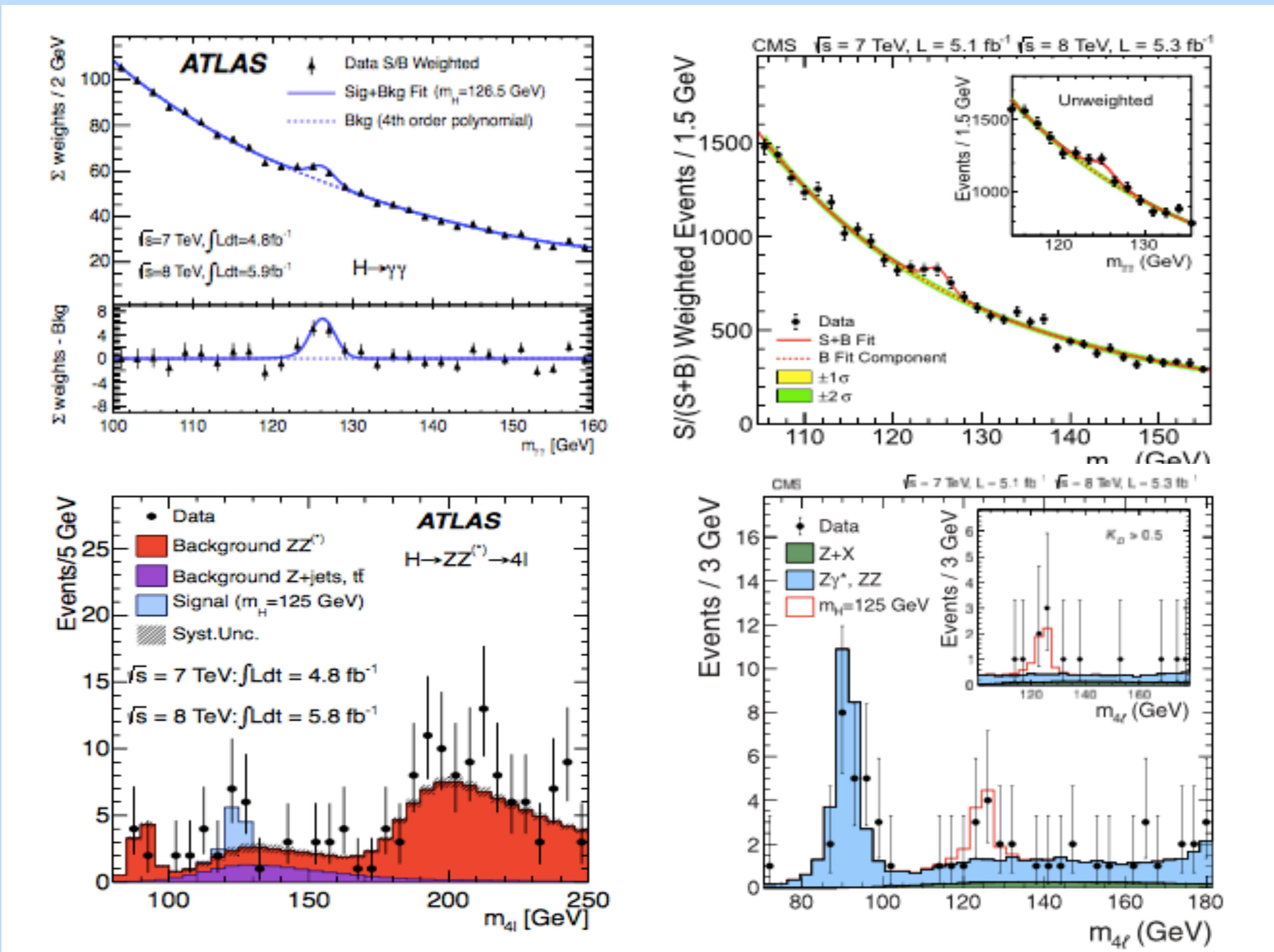
Outline

- Motivation
- Objective
- Previous work
- NLO Cross section
  - Virtual Corrections
  - Real Corrections
- Numerical Analysis
- Conclusions/Outlook

Motivation

Detection of a Higgs boson with a mass ~ 125 GeV

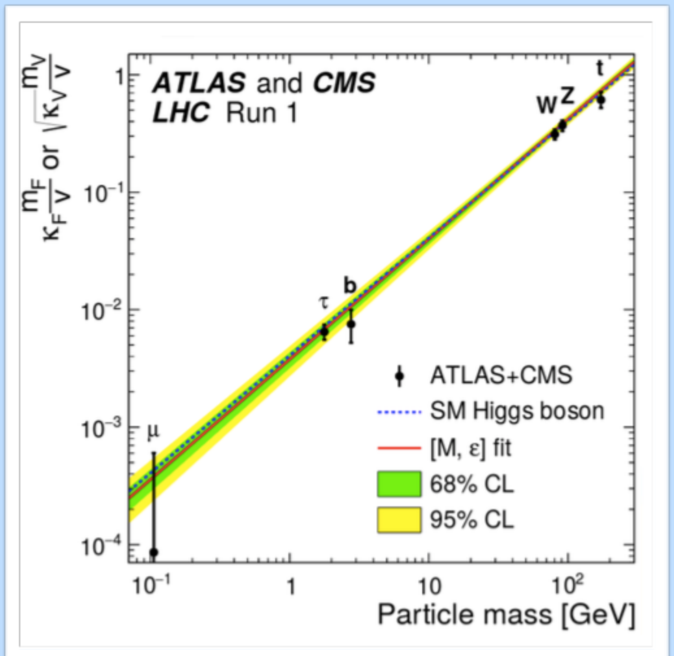


Motivation

- Further investigations of the properties of the detected particle for a unique association to a model

- Higgs mass, coupling strengths, spin and CP already determined

- self-coupling strength still unknown



$$V = \frac{\lambda}{2}\left(\phi^\dagger\phi - \frac{v^2}{2}\right)^2$$

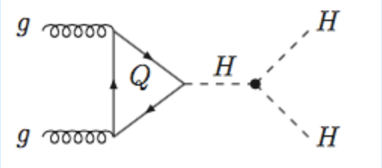
$$\lambda = \frac{M_H^2}{2v^2}$$

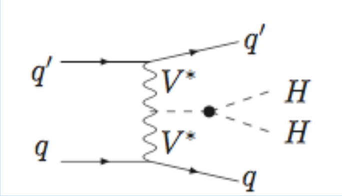
$$\lambda_{H^3} = 3\frac{M_H^2}{v} \qquad \lambda_{H^4} = 3\frac{M_H^2}{v^2}$$

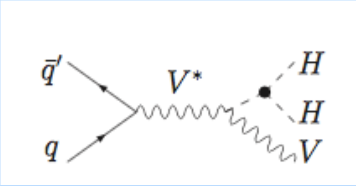
Motivation

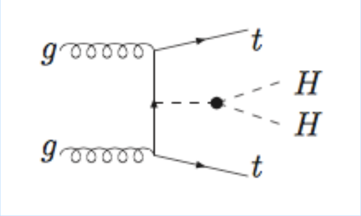
Higgs boson pair production

Production channel

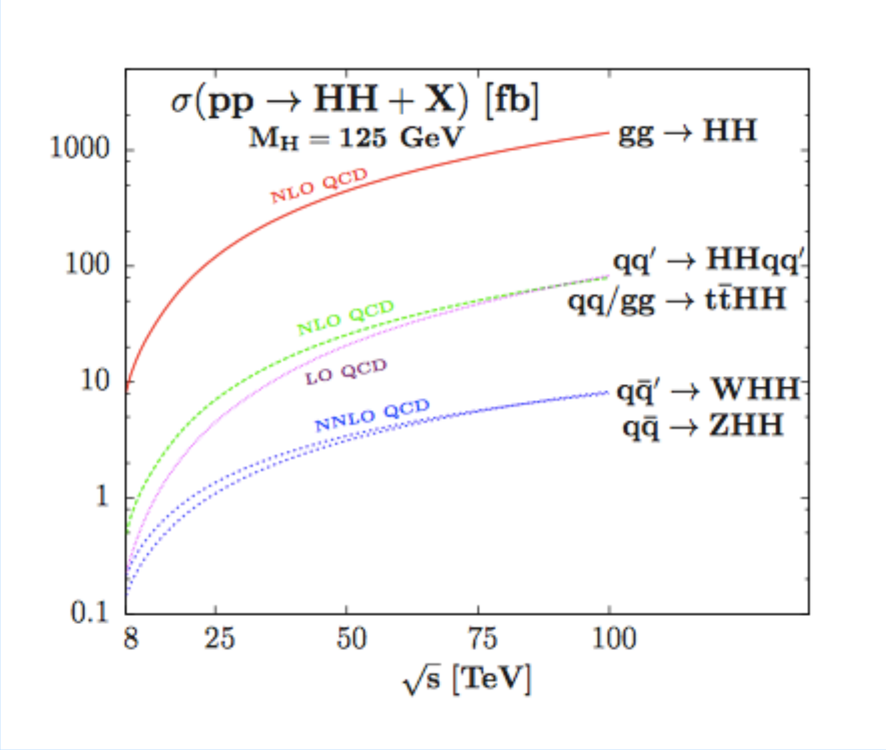








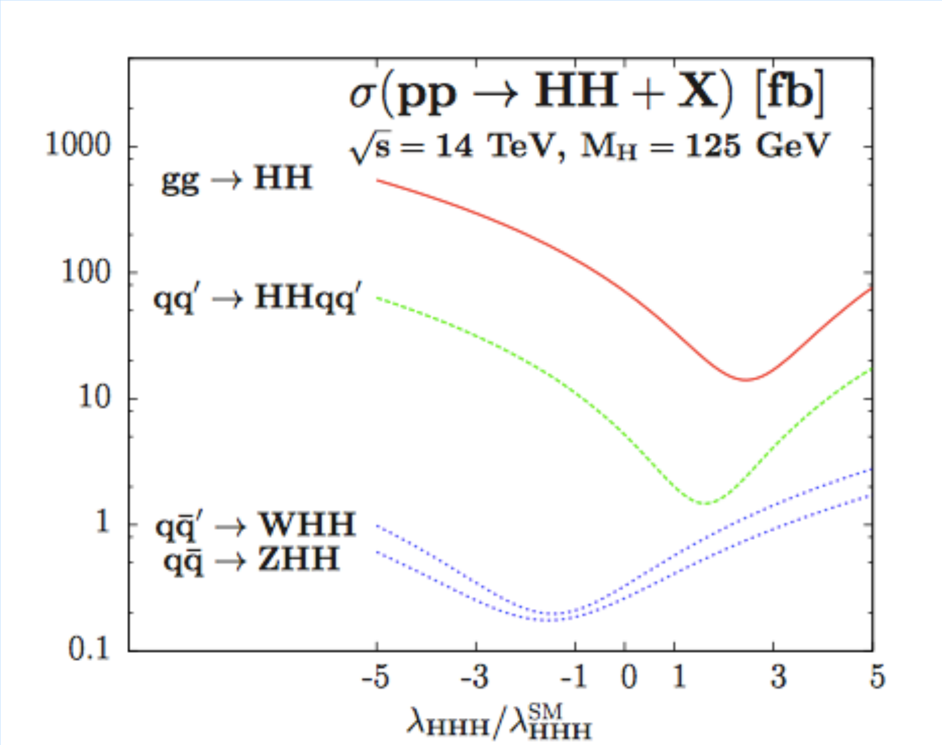
Cross section



Baglio, Djouadi, Gröber,
Mühlleitner, Quevillon, Spira

Motivation

Uncertainties:



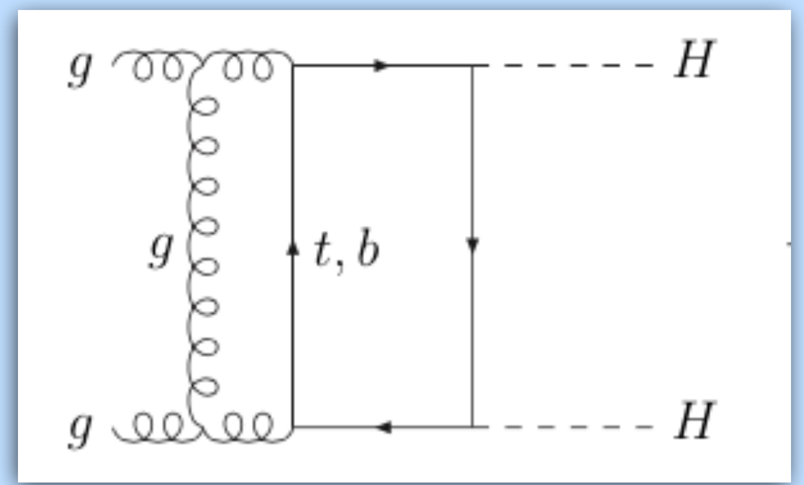
$$gg \to HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

Baglio, Djouadi, Gröber,
Mühlleitner, Quevillon, Spira

Objective

Gluon fusion gg → HH: loop induced

Complete calculation of the NLO QCD corrections (2-loop) considering the top- und bottom mass dependences in the context of the Standard Model → 2-loop integrals with 3 kinematical parameter ratios



Previous work

- Virtual & real (N)NLO QCD corrections in large top mass limit: ~100%

  Dawson,Dittmaier,Spira
  de Florian,Mazzitelli
  Grigo,Melnikov,Steinhauser

- Large top mass expansion: ~ ±10%

$$\sigma = \sigma_0 + \frac{\sigma_1}{m_t^2} + \cdots + \frac{\sigma_4}{m_t^8}$$

  Grigo, Hoff, Melnikov, Steinhauser

- NLO mass effects of the real NLO correction alone

  ~ -10 %

  Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torrielli, Vryonidou, Zaro

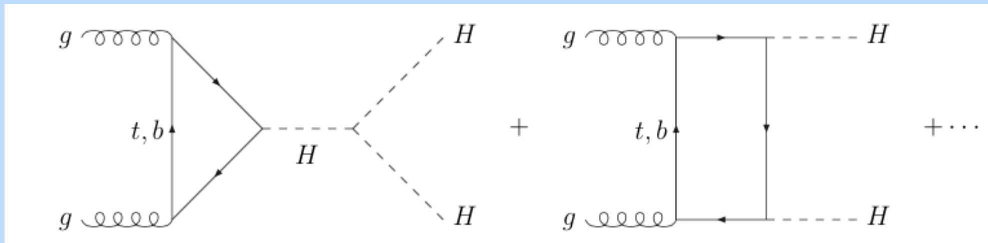
- NLO QCD corrections including the full top mass dependence

  Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke

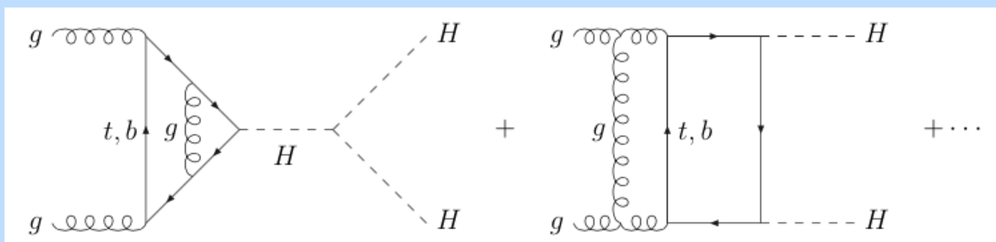
NLO Corrections

$$\sigma_{\mathrm{NLO}}(pp \to HH + X) = \sigma_{\mathrm{LO}} + \Delta\sigma_{\mathrm{virt}} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{q\bar{q}},$$

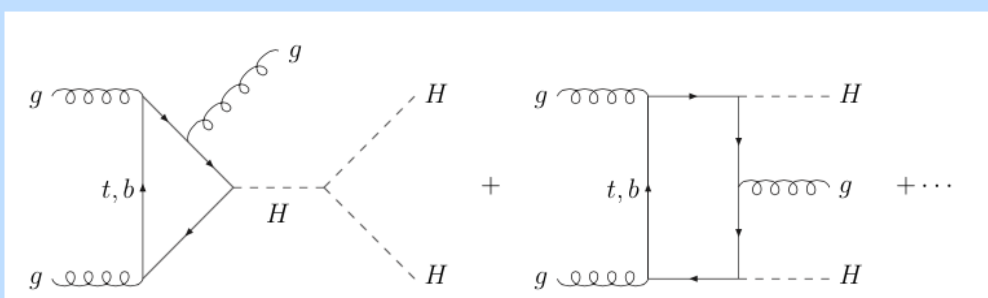
σ_{LO}:



$\Delta\sigma_{virt}$:



$\Delta\sigma_{ij}$:



NLO Corrections

$$\sigma_{\rm NLO}(pp \to HH+X) = \sigma_{\rm LO} + \Delta\sigma_{\rm virt} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{q\bar{q}},$$

$$\begin{aligned}
\sigma_{\rm LO} &= \int_{\tau_0}^1 d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \, \hat{\sigma}_{\rm LO}(Q^2=\tau s) \\
\Delta\sigma_{\rm virt} &= \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^1 d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \, \hat{\sigma}_{\rm LO}(Q^2=\tau s) \, C \\
\Delta\sigma_{gg} &= \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^1 d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \int_{\tau_0/\tau}^1 \frac{dz}{z} \, \hat{\sigma}_{\rm LO}(Q^2=z\tau s) \left\{ -zP_{gg}(z) \log\frac{M^2}{\tau s} \right. \\
&\qquad \left. + d_{gg}(z) + 6[1+z^4+(1-z)^4] \left(\frac{\log(1-z)}{1-z} \right)_+ \right\} \\
\Delta\sigma_{gq} &= \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^1 d\tau \sum_{q,\bar{q}} \frac{d\mathcal{L}^{gq}}{d\tau} \int_{\tau_0/\tau}^1 \frac{dz}{z} \, \hat{\sigma}_{\rm LO}(Q^2=z\tau s) \left\{ -\frac{z}{2} P_{gq}(z) \log\frac{M^2}{\tau s(1-z)^2} \right. \\
&\qquad \left. + d_{gq}(z) \right\} \\
\Delta\sigma_{q\bar{q}} &= \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^1 d\tau \sum_{q} \frac{d\mathcal{L}^{q\bar{q}}}{d\tau} \int_{\tau_0/\tau}^1 \frac{dz}{z} \, \hat{\sigma}_{\rm LO}(Q^2=z\tau s) \, d_{q\bar{q}}(z)
\end{aligned}$$

$$C \to \pi^2 + \frac{11}{2} + C_{\triangle\triangle}, \qquad d_{gg} \to -\frac{11}{2}(1-z)^3, \qquad d_{gq} \to \frac{2}{3}z^2 - (1-z)^2, \qquad d_{q\bar{q}} \to \frac{32}{27}(1-z)^3$$

Virtual Corrections

Set-up

- Associate the 47 two-loop box diagrams to similar topologies
- Generate matrix elements for all possible diagrams
  (by hand → *Reduce, Mathematica*)
- Use dimensional regularisation: n = 4 – 2ε
- Perform Feynman parametrisation → 6-dimensional integrals

$$\frac{1}{A_1^{\alpha_1}\cdots A_n^{\alpha_n}} = \frac{\Gamma(\alpha_1+\ldots+\alpha_n)}{\Gamma(\alpha_1)\cdots\Gamma(\alpha_n)}\int_0^1 du_1 \int_0^{1-u_1} du_2 \cdots \int_0^{1-u_1-\ldots-u_{n-2}} du_{n-1} \frac{u_1^{\alpha_1-1}\cdots u_{n-1}^{\alpha_{n-1}-1}(1-u_1-\ldots-u_{n-1})^{\alpha_n-1}}{[u_1A_1+\ldots+u_{n-1}A_{n-1}+(1-u_1-\ldots-u_{n-1})A_n]^{\alpha_1+\ldots+\alpha_n}},$$

Virtual Corrections

Divergences

- Extraction of the ultraviolet divergences of the matrix elements using endpoint subtractions of the 6-dimensional Feynman integrals

$$\int_0^1 dx\, \frac{f(x)}{(1-x)^{1-\epsilon}} = \int_0^1 dx\, \frac{f(1)}{(1-x)^{1-\epsilon}} + \int_0^1 dx\, \frac{f(x)-f(1)}{(1-x)^{1-\epsilon}}$$

$$= \frac{f(1)}{\epsilon} + \int_0^1 dx\, \frac{f(x)-f(1)}{1-x} + \mathcal{O}(\epsilon)$$

- Extraction of the infrared and collinear divergences using a proper subtraction of the integrand

denominator: $N = ar^2 + br + c \qquad a = \mathcal{O}(\rho) \qquad \rho_s = \frac{\hat{s}}{m_Q^2}$

$N_0 = br + c \qquad b = 1 + \mathcal{O}(\rho)$

$c = -\rho_s x(1-x)(1-s)t$

$$\int_0^1 \mathrm{d}\vec{x}\mathrm{d}r \frac{rH(\vec{x},r)}{N^{3+2\epsilon}} = \int_0^1 \mathrm{d}\vec{x}\mathrm{d}r \Big\{ \Big(\underbrace{\frac{rH(\vec{x},r)}{N^{3+2\epsilon}} - \frac{rH(\vec{x},0)}{N_0^{3+2\epsilon}}}_{\text{Taylor expansion in } \epsilon} \Big) + \underbrace{\frac{rH(\vec{x},0)}{N_0^{3+2\epsilon}}}_{\text{analytical r-integration}} \Big\}$$

Virtual Corrections

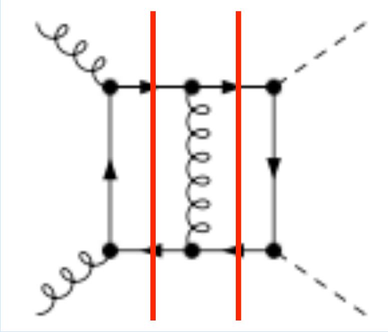
Divergences

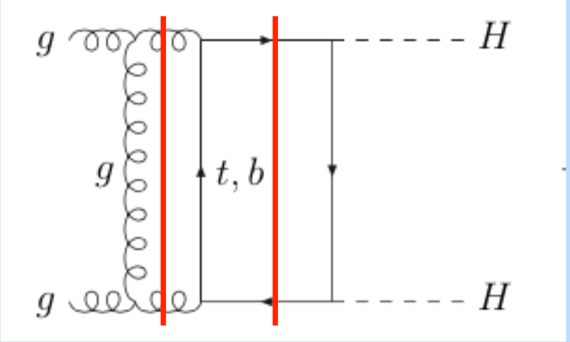
- Integration by parts due to numerical instabilities at the thresholds

$M_{HH}^2 > 4m_Q^2 \Rightarrow m_Q^2 \rightarrow m_Q^2(1 - i\bar{\epsilon})$ with $\bar{\epsilon} \ll 1$

$$\int_0^1 dx \frac{f(x)}{(a+bx)^3} = \frac{f(0)}{2a^2} - \frac{f(1)}{2(a+b)^2} + \int_0^1 dx \frac{f'(x)}{2(a+bx)^2}$$

- gluon rescattering: threshold for $M_{HH}^2 > 0$





Virtual Corrections

Renormalisation

α_s and m_q need to be renormalised

→ α_s in $\overline{MS}$ with $N_F = 5$

→ m_q on shell

$$\delta\sigma = \delta\alpha_s \frac{\delta\sigma_{LO}}{\delta\alpha_s} + \delta m_t \frac{\delta\sigma_{LO}}{\delta m_t}$$

Subtraction of the heavy-top limit → virtual mass effects only (infrared finite)

$$\Delta C_{mass} = C^0 - C^0_{HTL}$$

Adding back the results of HPAIR (heavy-top limit)

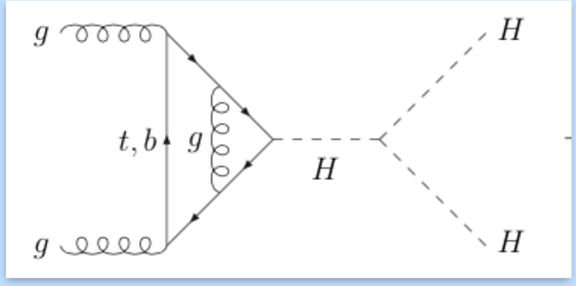
$$C = \underbrace{C_{HTL}}_{\text{HPAIR}} + \Delta C_{mass}$$

Virtual Corrections

Remaining Diagrams

Triangular diagrams

$\longleftarrow$ single Higgs case

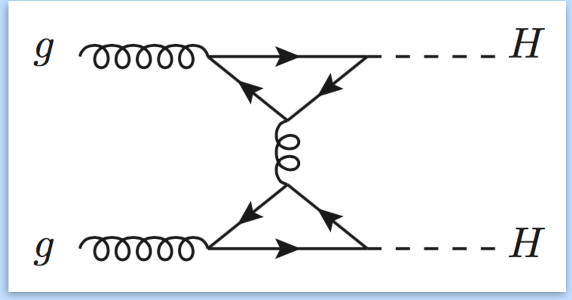


One-particle reducible diagrams

$\longrightarrow$ analytical results

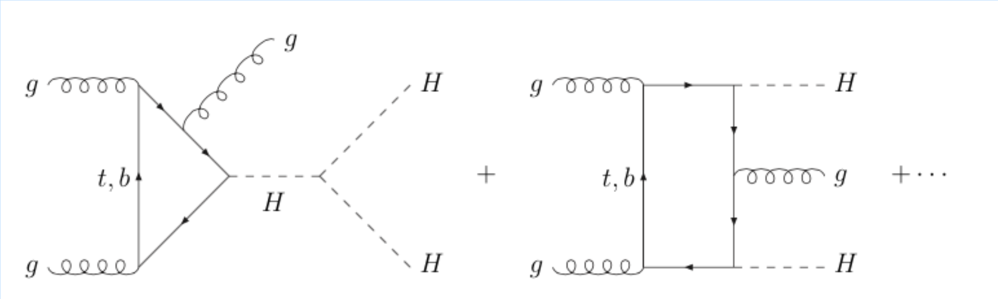
$(H \to Z\gamma)$

see e.g. Degrassi, Giardino, Gröber



Real Corrections

Processes: gg,q$\bar{q}$ → HHg; gq → HHq



- Full matrix elements generated with LoopTools
- Matrix elements in the heavy-top limit rescaled locally by massive LO matrix elements (with adjusted kinematics) → subtracted → free of divergences
- Adding back the results of HPAIR (heavy-top limit)

Numerical Analysis

- Use Vegas for numerical integration P. Lepage
- Calculation of differential cross section $\frac{d\sigma}{dQ^2}$, $(Q^2 = m^2_{HH})$

$$Q^2 \frac{d\Delta\sigma_{virt}}{dQ^2} = \tau \frac{d\mathcal{L}^{gg}}{d\tau} \hat{\sigma}_{virt}(Q^2)\Big|_{\tau=\frac{Q^2}{s}}$$

partonic cross section

(seven-dimensional integrals)

- Thresholds: $m_Q^2 \to m_Q^2(1 - i\bar{\epsilon})$

  different $\bar{\epsilon}$ $\longrightarrow$ Richardson extrapolation $\longrightarrow$ $\bar{\epsilon} = 0$ (NWA)

- Integration of real corrections straight forward

Conclusions and Outlook

- Full NLO calculation close to finalisation
  → numerical results soon
- NLO mass effects expected in the 10-20 % range
- Independent cross check of existing results

Outlook:

- Extension of the calculation to BSM-Higgs scenarios (dim 6, 2HDM)

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Back-up

Richardson Extrapolation

$$M_2[f(h), f(2h)] = 2f(h) - f(2h)$$

$$M_4[f(h), f(2h), f(4h)] = (8f(h) - 6f(2h) + f(4h))/3$$

$$M_8[f(h), f(2h), f(4h), f(8h)] = (64f(h) - 56f(2h) + 14f(4h) - f(8h))/21$$