

# Higgs Boson Pair Production via Gluon Fusion: Full NLO QCD Corrections



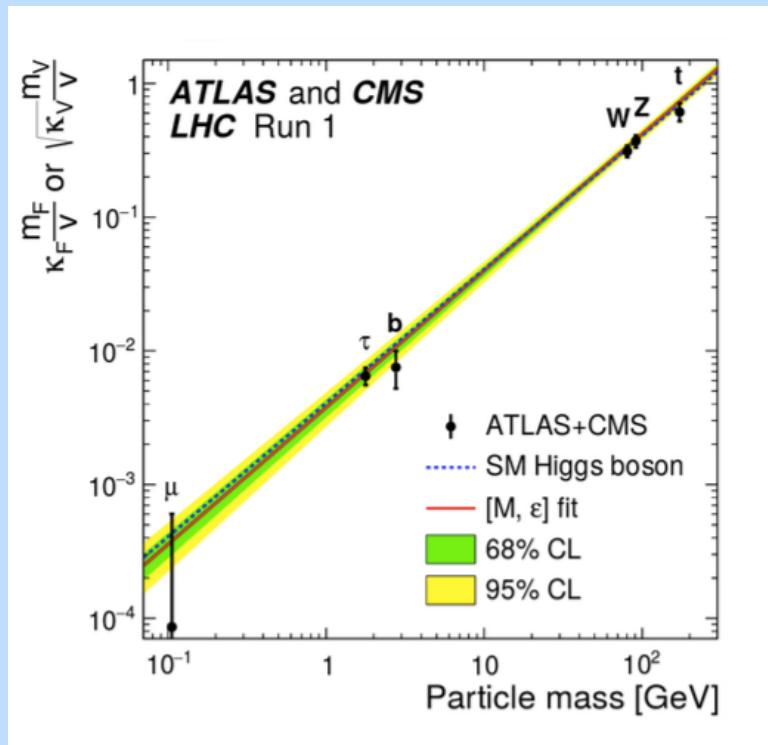
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# Motivation

- Detection of a Higgs boson with a mass  $\sim 125$  GeV
- Higgs mass, coupling strengths, spin and CP already determined
- Self-coupling strength still unknown



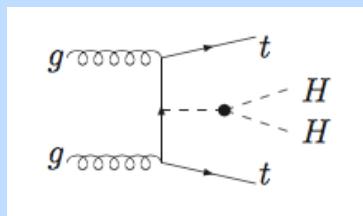
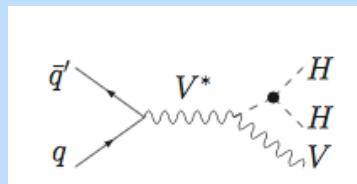
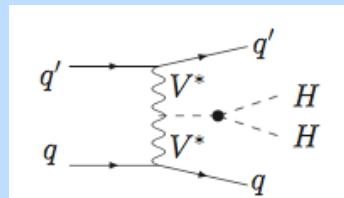
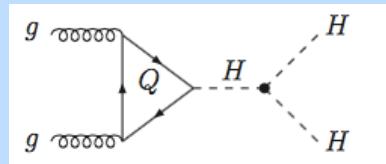
$$V(\phi) = \frac{\lambda}{2} \left\{ |\phi|^2 - \frac{v^2}{2} \right\}^2$$

$$\lambda_{h^3} = 3 \frac{m_h^2}{v}$$

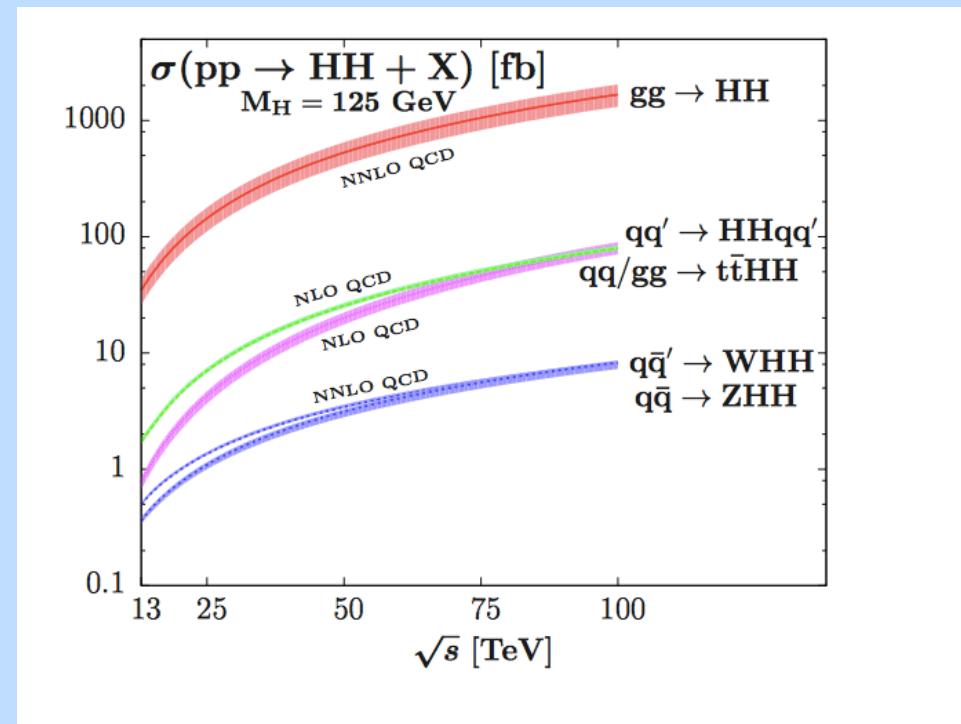
$$\lambda_{h^4} = 3 \frac{m_h^2}{v^2}$$

## Higgs boson pair production

### Production channels

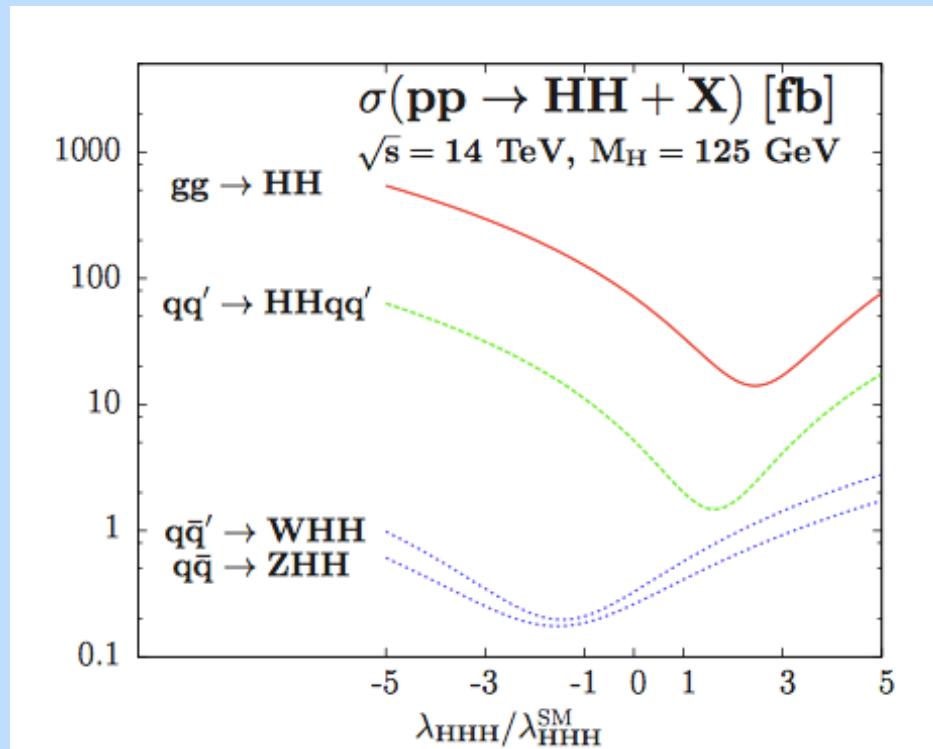


### Cross sections



Baglio, Djouadi, Quevillon

## Uncertainties:

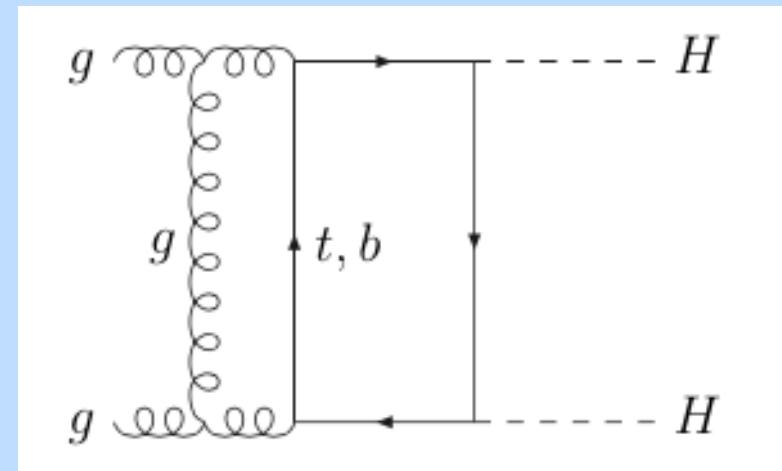


$$gg \rightarrow HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

Baglio, Djouadi, Gröber,  
Mühlleitner, Quevillon, Spira

Gluon fusion  $gg \rightarrow HH$ : loop induced

Complete calculation of the NLO QCD corrections (2-loop) considering the top mass dependences in the context of the Standard Model



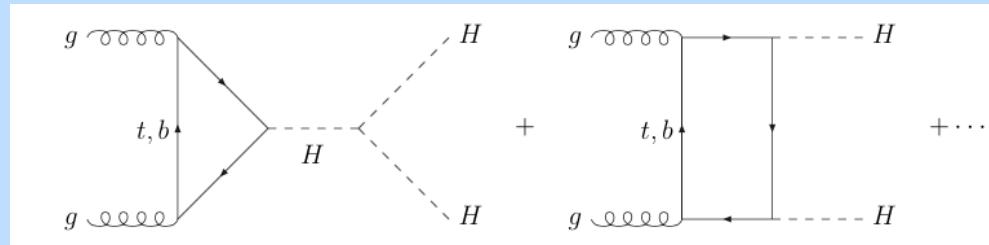
# Current Status

- Virtual & real (N)NLO QCD corrections in large top mass limit (HTL):  
~100%  
  
Dawson,Dittmaier,Spira  
de Florian,Mazzitelli  
Grigo,Melnikov,Steinhauser
- Large top mass expansion: ~  $\pm 10\%$   
  
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:  
- 15 % NLO mass effects  
  
Borowka, Greiner, Heinrich,  
Jones, Kerner, Schlenk, Schubert,  
Zirke  
  
Baglio,Campanario,SG,Mühlleitner,  
Spira,Streicher
- New expansion/extrapolation methods:
  - $1/m_t^2$  expansion & conformal mapping & Padé approximants  
Gröber,Maier,Rauh
  - $p_T^2$  expansion  
Bonciani,Degrassi,Giardino,Gröber
  - high-energy  
Davies,Mishima,Steinhauser,Wellmann

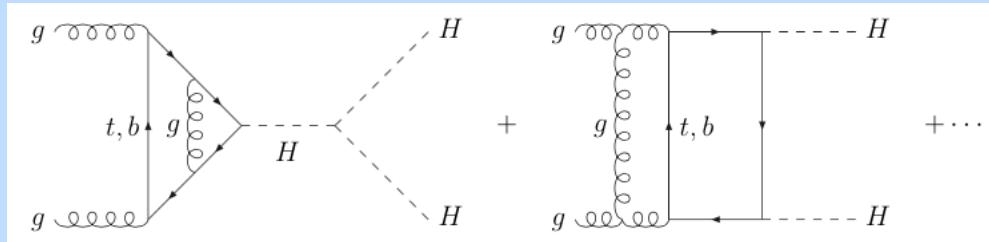
# NLO Corrections

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

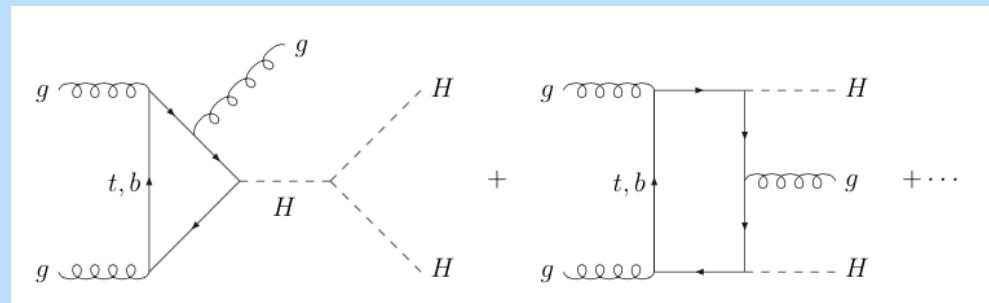
$\sigma_{\text{LO}}$ :



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



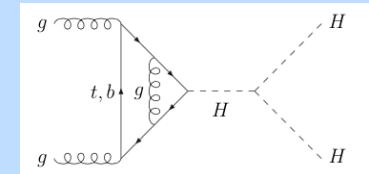
$\Delta\sigma_{ij}$ :



# Virtual Corrections

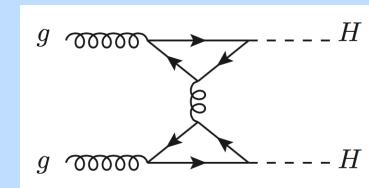
## Triangular diagrams

- Use existing results of single Higgs calculation



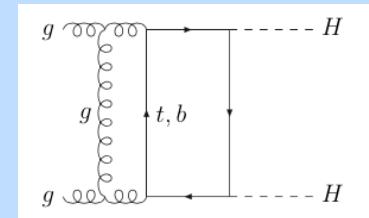
## One-particle reducible diagrams

- Use existing results of  $H \rightarrow Z\gamma$



## Box diagrams

- Treat every diagram individually (no reduction to master integrals)
- Extract the ultraviolet divergences of the matrix elements using endpoint subtractions
- Extract the infrared and collinear divergences using a ‘proper’ subtraction of the integrand
- Integration by parts due to numerical instabilities above the thresholds where  $m_{hh}^2 > 0$ ,  
 $m_{hh}^2 > 4m_t^2 \Rightarrow m_t^2 \rightarrow m_t^2(1 - i\bar{\epsilon})$  with  $\bar{\epsilon} \ll 1$



## Total virtual corrections

- Numerical evaluation using Vegas [\(P. Lepage\)](#)

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

$\frac{d\mathcal{L}^{gg}}{d\tau}$  = gluon luminosity

$\hat{\sigma}_{virt}$  = virtual part of the partonic cross section

$$(Q^2 = m_{HH}^2)$$

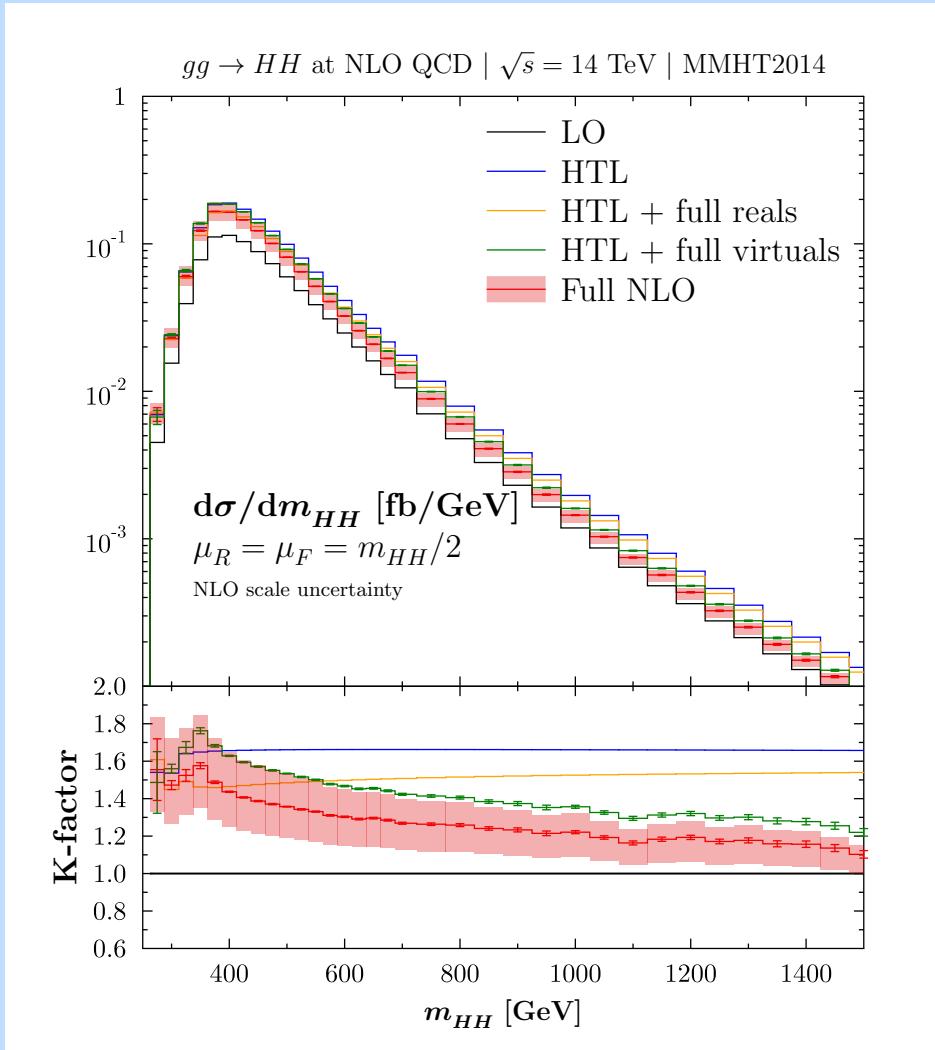
- Renormalization:  $\alpha_s$  in  $\overline{MS}$  with  $N_F = 5$  and  $m_t$  on shell (central value)
- Subtraction of HTL  $\rightarrow$  IR finite top mass effects
- Numerical instabilities due to the small imaginary parts of the top mass above the thresholds: *Richardson extrapolation*

## Real corrections

- Full matrix elements generated with FeynArts and FormCalc
- Matrix element in the HTL (massive LO) subtracted  $\rightarrow$  IR finite top mass effects

# Results

## Differential cross section



## K-factor

$$K = \frac{\sigma_{\text{NLO}}}{\sigma_{\text{LO}}}$$

## Total hadronic cross section ( $\sqrt{s} = 14 \text{ TeV}$ , $m_t = 172.5 \text{ GeV}$ )

	PDF4LHC15	MMHT2014
$\sigma_{LO}$	19.80 fb	23.75 fb
$\sigma_{NLO}^{HTL}$	38.66 fb	39.34 fb
$\sigma_{NLO}$	32.78(7) fb	33.33(7) fb

(only numerical error!)

→ - 15 % NLO mass effects compared to HTL result

Borowka et al.:  $\sigma_{NLO} = (32.91^{+13.6\%}_{-12.6\%}) \text{ fb}$  using PDF4LHC15 PDFs ( $m_t = 173 \text{ GeV}$ )

## Factorisation / renormalisation scale dependence

varying both scales by a factor of two around central value of  $\mu_F = \mu_R = m_{hh}/2$

Differential cross section:

$$\frac{d\sigma(gg \rightarrow HH)}{dQ} \Big|_{Q=300 \text{ GeV}} = 0.02978(8)^{+15.3\%}_{-13.0\%} \text{ fb/GeV}$$

$$\frac{d\sigma(gg \rightarrow HH)}{dQ} \Big|_{Q=400 \text{ GeV}} = 0.1609(4)^{+14.4\%}_{-12.8\%} \text{ fb/GeV}$$

$$\frac{d\sigma(gg \rightarrow HH)}{dQ} \Big|_{Q=600 \text{ GeV}} = 0.03204(9)^{+10.9\%}_{-11.5\%} \text{ fb/GeV}$$

$$\frac{d\sigma(gg \rightarrow HH)}{dQ} \Big|_{Q=1200 \text{ GeV}} = 0.000435(4)^{+7.1\%}_{-10.6\%} \text{ fb/GeV}$$

Total cross section:

$$\sigma(gg \rightarrow HH) = 32.78(7)^{+13.5\%}_{-12.5\%} \quad (\text{PDF4LHC15})$$

$(\sqrt{s} = 14 \text{ TeV})$

## Uncertainty due to $m_t$ : differential cross section

- uncertainty related to the scheme and scale choice of the top mass
- calculated the total NLO results for the differential cross section for the  $\overline{MS}$  top mass at different scale choices
- $\overline{MS}$  top mass in the range  $[Q/4, Q]$ ,  $m_t$

$$\frac{d\sigma(gg \rightarrow HH)}{dQ} \Big|_{Q=300 \text{ GeV}} = 0.02978(7)^{+6\%}_{-34\%} \text{ fb/GeV}$$

$$\frac{d\sigma(gg \rightarrow HH)}{dQ} \Big|_{Q=400 \text{ GeV}} = 0.1609(4)^{+0\%}_{-13\%} \text{ fb/GeV}$$

$$\frac{d\sigma(gg \rightarrow HH)}{dQ} \Big|_{Q=600 \text{ GeV}} = 0.03204(9)^{+0\%}_{-30\%} \text{ fb/GeV}$$

$$\frac{d\sigma(gg \rightarrow HH)}{dQ} \Big|_{Q=1200 \text{ GeV}} = 0.000435(4)^{+0\%}_{-35\%} \text{ fb/GeV}$$

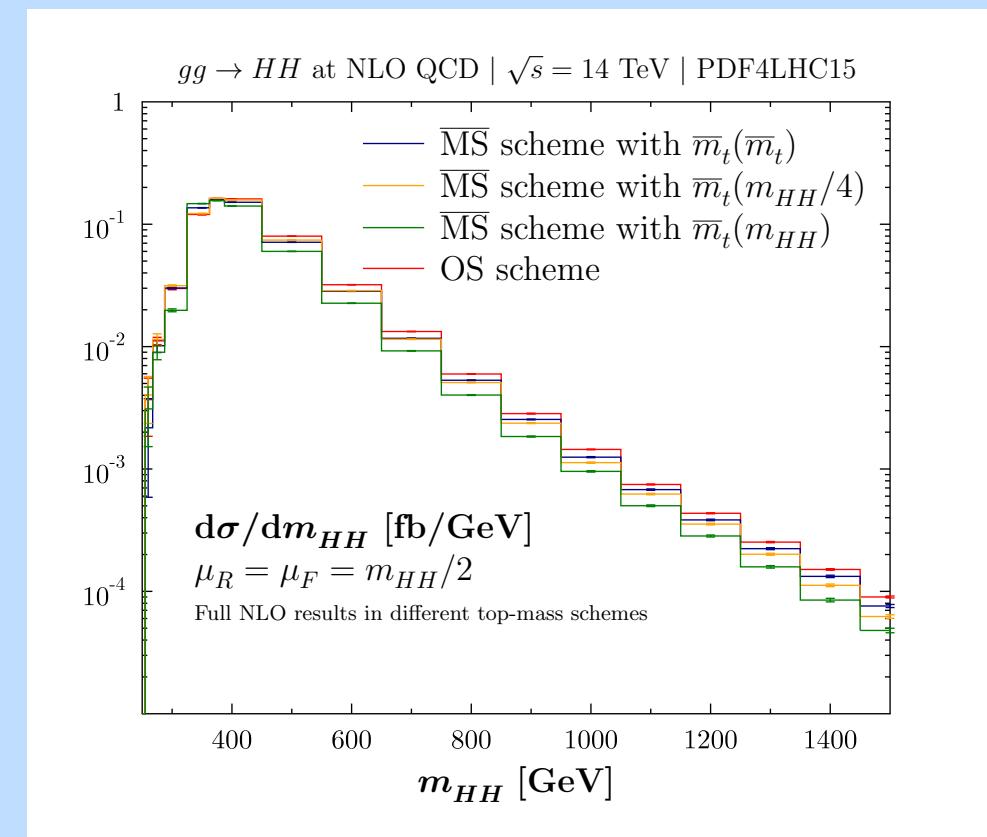
$(\sqrt{s} = 14 \text{ TeV})$

## Uncertainty due to $m_t$ : total hadronic cross section

Take for individual Q values the maximum / minimum differential cross section and integrate

$$\sigma(gg \rightarrow HH) = 32.78(7)^{+4.0\%}_{-17\%}$$

with PDF4LHC15



# Conclusions

- Higgs pair production via gluon fusion at NLO including the top mass
- NLO top mass effects of  $\sim -15\%$  compared to HTL result
- Factorisation / renormalisation scale dependence:  $\sim 15\%$  uncertainties
- Top mass scheme and scale uncertainties:  $\lesssim 30\%$   
total cross section at 14 TeV:  $\sigma(gg \rightarrow HH) = 32.78(7)^{+4.0\%}_{-17\%}$

# BACK-UP

# NLO Corrections

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

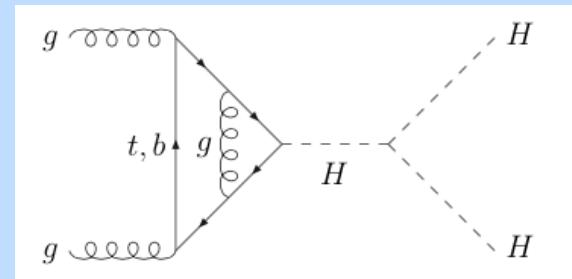
$$\begin{aligned}
 \sigma_{\text{LO}} &= \int_{\tau_0}^1 d\tau \frac{d\mathcal{L}^{gg}}{d\tau} \hat{\sigma}_{\text{LO}}(Q^2 = \tau s) \\
 \Delta\sigma_{\text{virt}} &= \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^1 d\tau \frac{d\mathcal{L}^{gg}}{d\tau} \hat{\sigma}_{\text{LO}}(Q^2 = \tau s) \ C \\
 \Delta\sigma_{gg}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

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

47 two-loop **box diagrams** + 8 triangular diagrams + 2 one-particle reducible diagrams

## Triangular Diagrams

← single Higgs case

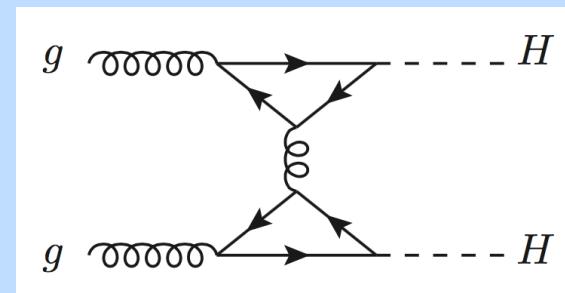


## One-particle reducible diagrams

→ analytical results for  $C_{\Delta\Delta}$

$(H \rightarrow Z\gamma)$

see e.g. [Degrassi, Giardino, Gröber](#)



## Box diagrams

- Generate matrix element form factors for all possible diagrams using Feynman rules (by hand → *Reduce*, *Mathematica*, *Form*)
- Perform Feynman parametrisation → additional 6-dimensional integrals
- Extract the ultraviolet divergences of the matrix elements using endpoint subtractions of the 6-dimensional Feynman integrals

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

- Extract the infrared and collinear divergences using a ‘proper’ subtraction of the integrand (based on HTL calculation)
- Integration by parts due to numerical instabilities at the thresholds

$$m_{hh}^2 > 4m_t^2 \Rightarrow m_t^2 \rightarrow m_t^2(1 - i\bar{\epsilon}) \text{ with } \bar{\epsilon} \ll 1$$

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

## Differential cross section

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

$\frac{d\mathcal{L}^{gg}}{d\tau}$  = gluon luminosity

$\hat{\sigma}_{virt}$  = virtual part of the partonic cross section

- 7 dimensional integrals (6 Feynman and one phase space integration)
- use Vegas for numerical integration (P. Lepage)
- numerical instabilities due to the small imaginary parts of the top mass above the thresholds: Richardson extrapolation

## Renormalisation

$\alpha_s$  and  $m_t$  need to be renormalised

- $\alpha_s$  in  $\overline{MS}$  with  $N_F = 5$
- $m_t$  on shell (→ central prediction)

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

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

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

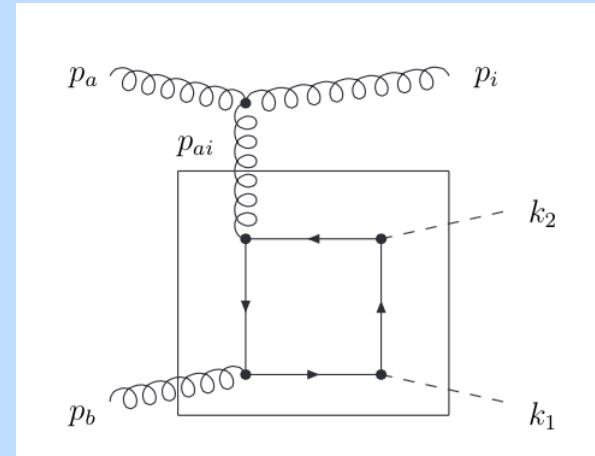
Adding back the results in the heavy-top limit (HPAIR)

$$C = C_{HTL} + \Delta C_{mass}$$

↑  
HPAIR

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

- Full matrix elements generated with FeynArts and FormCalc
- Matrix elements in the heavy-top limit rescaled locally by massive LO matrix elements → subtracted → free of divergences  
(appropriate mapping on LO kinematics ← Catani Seymour)
- Adding back the results in the heavy-top limit (HPAIR)



## Box diagrams

- Generate matrix element form factors for all possible diagrams using Feynman rules (by hand → *Reduce*, *Mathematica*)
- Use dimensional regularisation:  $D = 4 - 2\epsilon$
- Perform Feynman parametrisation → additional 6-dimensional integrals

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

- Substitution to obtain integrals from 0 to 1
- Evaluating momentum integrals using:

$$\int \frac{d^D k}{(2\pi)^D} \frac{1}{(k^2 - M^2 + i\epsilon)^N} = i \frac{(-1)^N}{(4\pi)^{D/2}} \frac{\Gamma(N - \frac{D}{2})}{\Gamma(N)} \frac{1}{(M^2 - i\epsilon)^{N - \frac{D}{2}}}$$

$$\int \frac{d^D k}{(2\pi)^D} \frac{k_\mu k_\nu}{(k^2 - M^2 + i\epsilon)^N} = \frac{i}{2} \frac{(-1)^{N-1}}{(4\pi)^{D/2}} \frac{\Gamma(N - 1 - \frac{D}{2})}{\Gamma(N)} \frac{g_{\mu\nu}}{(M^2 - i\epsilon)^{N-1 - \frac{D}{2}}} \quad \text{etc.}$$

## Divergences

- Integration by parts due to numerical instabilities at the thresholds

$$m_{hh}^2 > 4m_t^2 \Rightarrow m_t^2 \rightarrow m_t^2(1 - i\bar{\epsilon}) \text{ with } \bar{\epsilon} \ll 1$$

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

(more involved for second order polynomials)

further integration by parts not successful since new divergences are created (investigated further)

## Divergences

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

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

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

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

denominator:	$N = ar^2 + br + c$	$a = \mathcal{O}(\rho)$	$\rho_s = \frac{\hat{s}}{m_Q^2}$
	$N_0 = br + c$	$b = 1 + \mathcal{O}(\rho)$	
		$c = -\rho_s x(1-x)(1-s)t$	

$$\int_0^1 d\vec{x} dr \frac{rH(\vec{x}, r)}{N^{3+2\epsilon}} = \int_0^1 d\vec{x} dr \left\{ \left( \frac{rH(\vec{x}, r)}{N^{3+2\epsilon}} - \frac{rH(\vec{x}, 0)}{N_0^{3+2\epsilon}} \right) + \frac{rH(\vec{x}, 0)}{N_0^{3+2\epsilon}} \right\}$$

↑ Taylor expansion in  $\epsilon$       ↑ analytical r-integration

## Richardson extrapolation

→ sequence acceleration method to obtain a better convergence behaviour

Approximation polynomial

$$M_{i+1}(h) = \frac{t^{k_i} M_i(\frac{h}{t}) - M_i(h)}{t^{k_i} - 1}$$

$h$  and  $h/t$  the two step sizes and  $k_i$  the truncation error

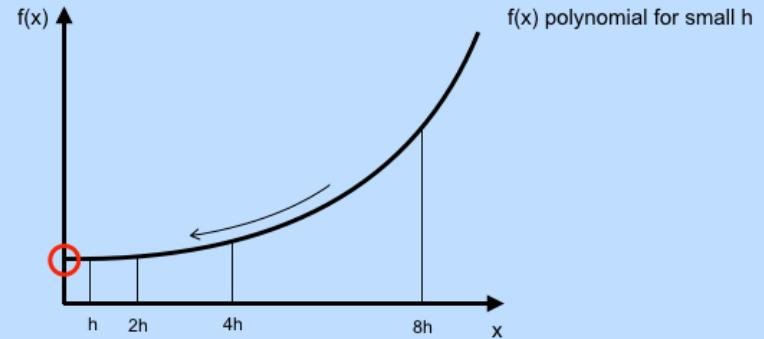
$$M_2[f(h), f(2h)] = 2f(h) - f(2h) = f(0) + \mathcal{O}(h^2)$$

$$M_4[f(h), f(2h), f(4h)] = (8f(h) - 6f(2h) + f(4h))/3 = f(0) + \mathcal{O}(h^3)$$

$$M_8[f(h), f(2h), f(4h), f(8h)] = (64f(h) - 56f(2h) + 14f(4h) - f(8h))/21 = f(0) + \mathcal{O}(h^4)$$

In our case  $h = \bar{\epsilon}$  and  $\bar{\epsilon}_n = 0.05 \times 2^n$   $n = 0 \dots 9$

Theoretical error from Richardson extrapolation estimated by the difference of the fifth and the



## Numerical Instabilities

1. due to phase-space integration over Mandelstam variable  $t$

→ cut-off at  $t = 10^{-8}$  for individual diagrams (total sum finite)

→ logarithmic substitution with  $y = \log \frac{t - t_-}{m_t^2}$

2. due to the small imaginary parts  $\bar{\epsilon}$  of the top mass above the thresholds, where

$$m_t^2 \rightarrow m_t^2(1 - i\bar{\epsilon})$$

need value in narrow width approximation where  $\bar{\epsilon} \rightarrow 0$

calculate partonic cross section for different  $\bar{\epsilon} \rightarrow$  Richardson extrapolation

# Real Corrections

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

- Full matrix elements generated with FeynArts and FormCalc
- Matrix elements in the heavy-top limit rescaled locally by massive LO matrix elements → subtracted → free of divergences

$$\frac{|\mathcal{M}^R(p_i, k_j)|^2}{|\mathcal{M}_{LO}(\tilde{p}_i, \tilde{k}_j)|^2} - \frac{|\mathcal{M}_{HTL}^R(p_i, k_j)|^2}{|\mathcal{M}_{LO}(\tilde{p}_i, \tilde{k}_j)|^2} = \frac{\Delta^{RM}(p_i, k_j)}{|\mathcal{M}_{LO}(\tilde{p}_i, \tilde{k}_j)|^2}$$

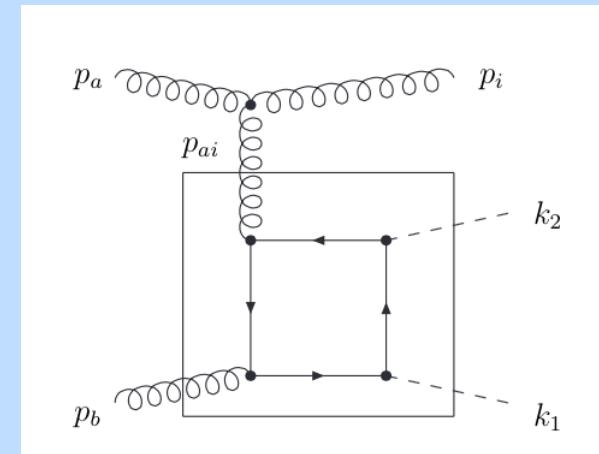
$\mathcal{M}^R(p_i, k_j)$  = real NLO matrix element

$\mathcal{M}_{HTL}^R(p_i, k_j)$  = real NLO matrix element in the HTL

$\mathcal{M}_{LO}(\tilde{p}_i, \tilde{k}_j)$  = LO matrix element

$\Delta^{RM}(p_i, k_j)$  = remaining finite part of the NLO matrix element

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



## Total hadronic cross section

Range 275-300 GeV:

- extension of Boole's rule ( $h$  step size of 5 GeV)

$$\int_{x_0}^{x_5} f(x)dx \approx \frac{5h}{288}[19f(x_0) + 75f(x_1) + 50f(x_2) + 50f(x_3) + 75f(x_4) + 19f(x_5)]$$

error:  $-\frac{275}{12096}h^7f(x_6)$       ( $x_0 < x_6 < x_5$ )

Range 300-1500 GeV:

- Richardson extrapolation for differential cross sections with bin sizes of 50, 100, 200 and 400 GeV
- Trapezoidal rule

$$\int_a^b f(x)dx \approx \frac{\Delta x}{2}[f(x_0) + 2f(x_1) + \dots + 2f(x_{n-1}) + f(x_n)]$$

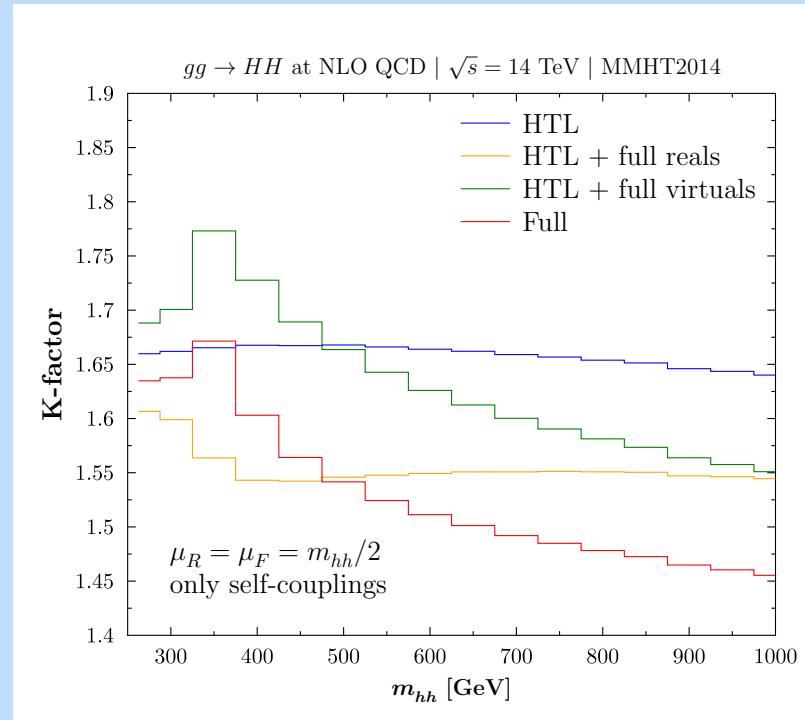
error:  $-\frac{nh^3}{12}f''(\zeta)$       ( $a < \zeta < b$ )

# Results

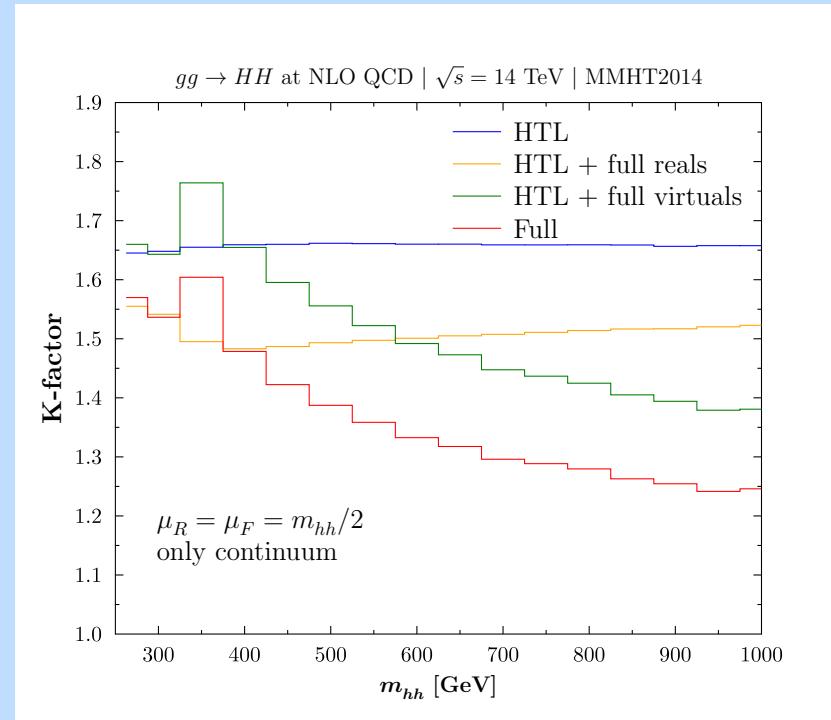
## K-factor distribution

$$K = \frac{\sigma_{\text{NLO}}}{\sigma_{\text{LO}}}$$

### Triangular contributions

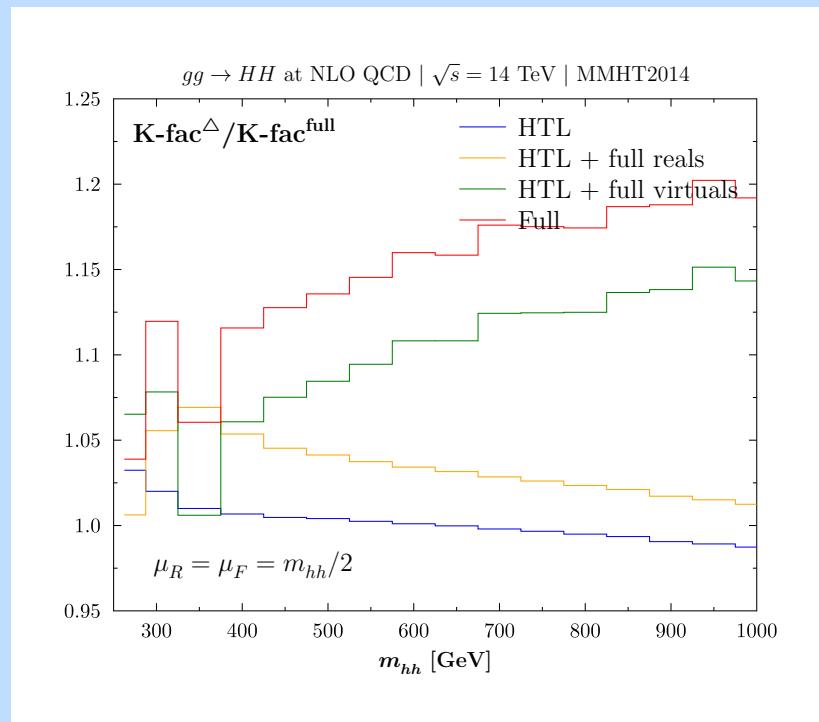


### Box contributions

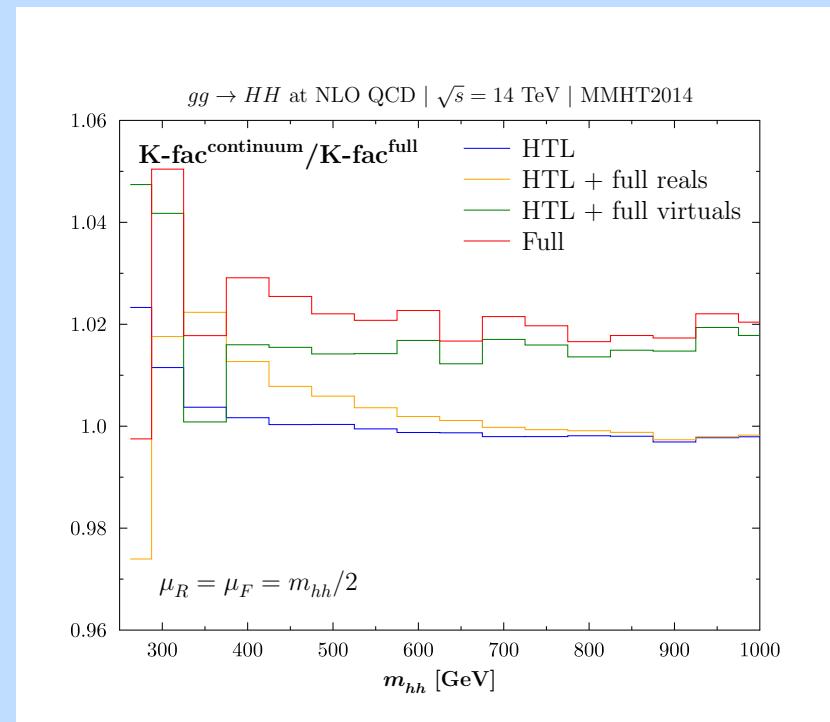


# Results

## Triangular contributions



## Box contributions



## Uncertainty due to $m_t$ for single Higgs

→  $\overline{MS}$  top mass in the range  $[Q/4, Q]$

$$\sigma(gg \rightarrow H) \Big|_{m_H=125\text{ GeV}} = 42.17^{+0.4\%}_{-0.5\%} \text{ pb}$$

$$\sigma(gg \rightarrow H) \Big|_{m_H=300\text{ GeV}} = 9.85^{+7.5\%}_{-0.3\%} \text{ pb}$$

$$\sigma(gg \rightarrow H) \Big|_{m_H=400\text{ GeV}} = 9.43^{+0.1\%}_{-0.9\%} \text{ pb}$$

$$\sigma(gg \rightarrow H) \Big|_{m_H=600\text{ GeV}} = 1.97^{+0.0\%}_{-15.9\%} \text{ pb}$$

$$\sigma(gg \rightarrow H) \Big|_{m_H=900\text{ GeV}} = 0.230^{+0.0\%}_{-22.3\%} \text{ pb}$$

$$\sigma(gg \rightarrow H) \Big|_{m_H=1200\text{ GeV}} = 0.0402^{+0.0\%}_{-26.0\%} \text{ pb}$$