EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Institut für Theoretische Physik

Two-loop top mass effects in Higgs pair production at NLO QCD

RPP 2019, LPC Clermont-Ferrand

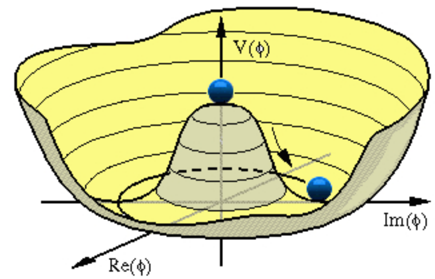
[in collaboration with F. Campanario, S. Glaus, M. M. Mühlleitner, M. Spira, and J. Streicher (arXiv:1811.05692)]

23/01/2019, Julien Baglio

The SM ultimate test: probing the scalar potential

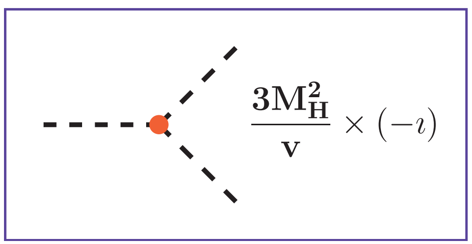
From the scalar potential before EWSB (ϕ as the Higgs field):

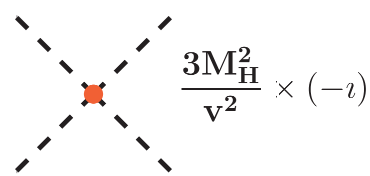
$$V(\phi) = -m^2|\phi|^2 + \lambda|\phi|^4$$



To $V(\phi)$ after EWSB, with $M_H^2 = 2m^2$, $v^2 = m^2/\lambda$:

$$\phi = \begin{pmatrix} 0 \\ \frac{v + H(x)}{\sqrt{2}} \end{pmatrix} \Rightarrow V(H) = \frac{1}{2}M_H^2 H^2 + \frac{1}{2}\frac{M_H^2}{v} H^3 + \frac{1}{8}\frac{M_H^2}{v^2} H^4 + \text{constant}$$





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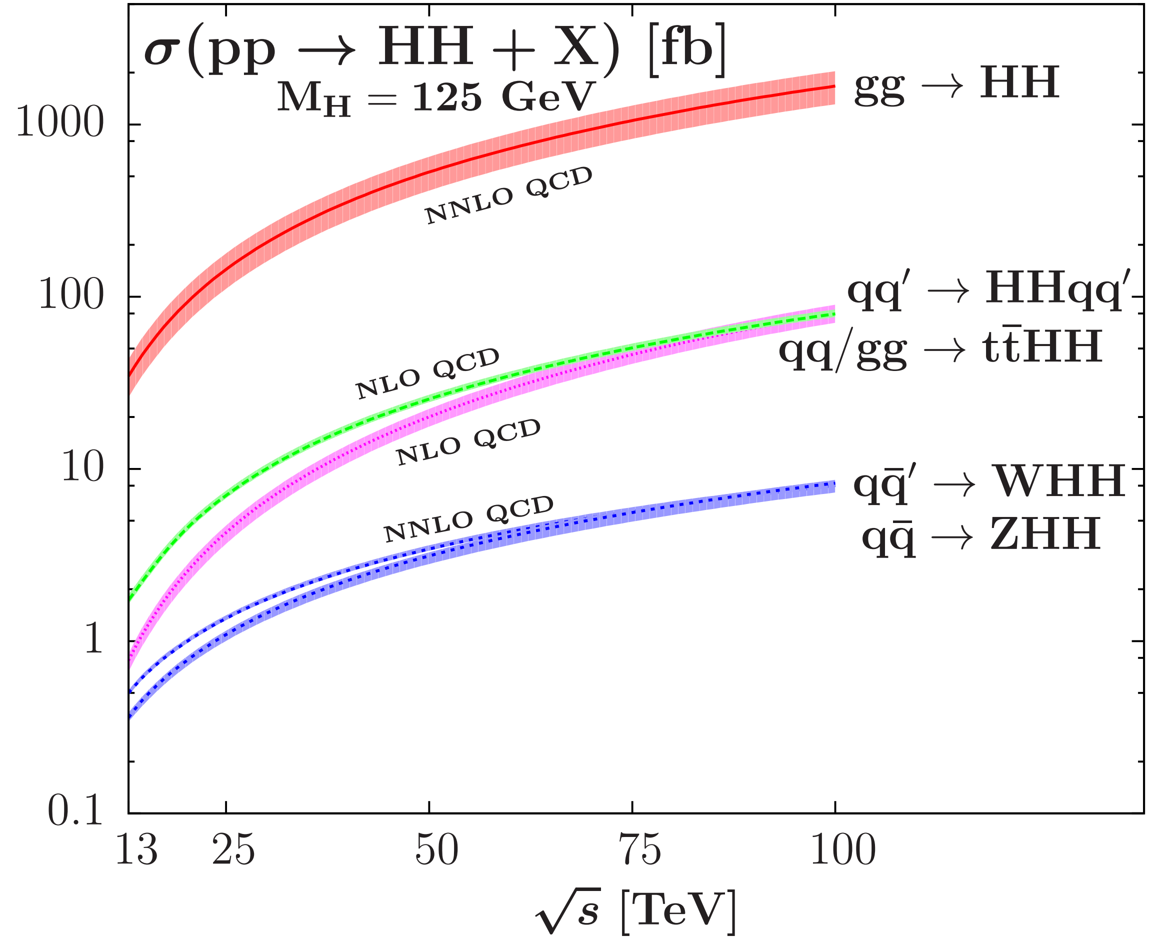
Overview *HH* production channels

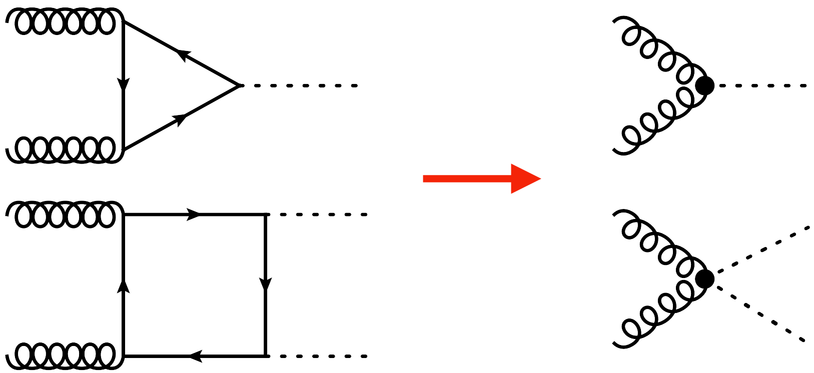


[from **J.B.**, Djouadi, Quevillon, Rept.Prog.Phys. 79 (2016) 116201]

Heavy top-quark limit (HTL) calculation

HTL $\equiv m_t \to +\infty$

$\to$ Effective tree-level *ggH* and *ggHH* couplings
$\to$ Reduce the number of loop by one at each perturbative order



- HTL valid for $\hat{s} \ll 4m_t^2$, but *HH* production threshold $4M_H^2 \leq \hat{s}$
  $\Rightarrow$ narrow energy range for which HTL is valid!
- **Born-improved NLO QCD HTL:** improve HTL result with

$$d\sigma_{\rm NLO} \simeq d\sigma_{\rm NLO}^{\rm HTL} \times \frac{d\sigma_{\rm LO}^{\rm full}}{d\sigma_{\rm LO}^{\rm HTL}}$$ [Dawson, Dittmaier, Spira, PRD 58 (1998) 115012]

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Gluon fusion: Where we stand in 2019

- **LO QCD (1-loop):** Dominated by top-quark loops [Eboli, Marques, Novaes, Natale, PLB 197 (1987) 269; Glover, van der Bij, NPB 309 (1988) 282; Dicus, Kao, Willenbrock, PLB 203 (1988) 457]
- **NLO QCD HTL (1-loop):** $+93\%$ correction

  [Dawson, Dittmaier, Spira, PRD 58 (1998) 115012]
- **Toward full NLO QCD (2-loop):**

  $\to$ $\mathrm{NLOFT}_{\mathrm{approx}}$, m_t-effects in real radiation: -10%

  [Frederix *et al*, PLB 732 (2014) 079, Maltoni, Vryonidou, Zaro, JHEP 1411 (2014) 079]

  $\to$ $\mathcal{O}(1/m_t^{12})$ terms in virtual amplitudes: $\pm 10\%$

  [see e.g. Grigo, Hoff, Steinhauser, NPB 900 (2015) 412]
- **NNLO QCD HTL (2-loop):** $+20\%$ on total cross section

  [De Florian, Mazzitelli, PLB 724 (2013) 306; PRL 111 (2013) 201801]
- **Latest NNLO QCD:** full NLO QCD + NNLO HTL + NNLO exact reals $\Rightarrow$ $+10\%$ to $+20\%$ in distributions

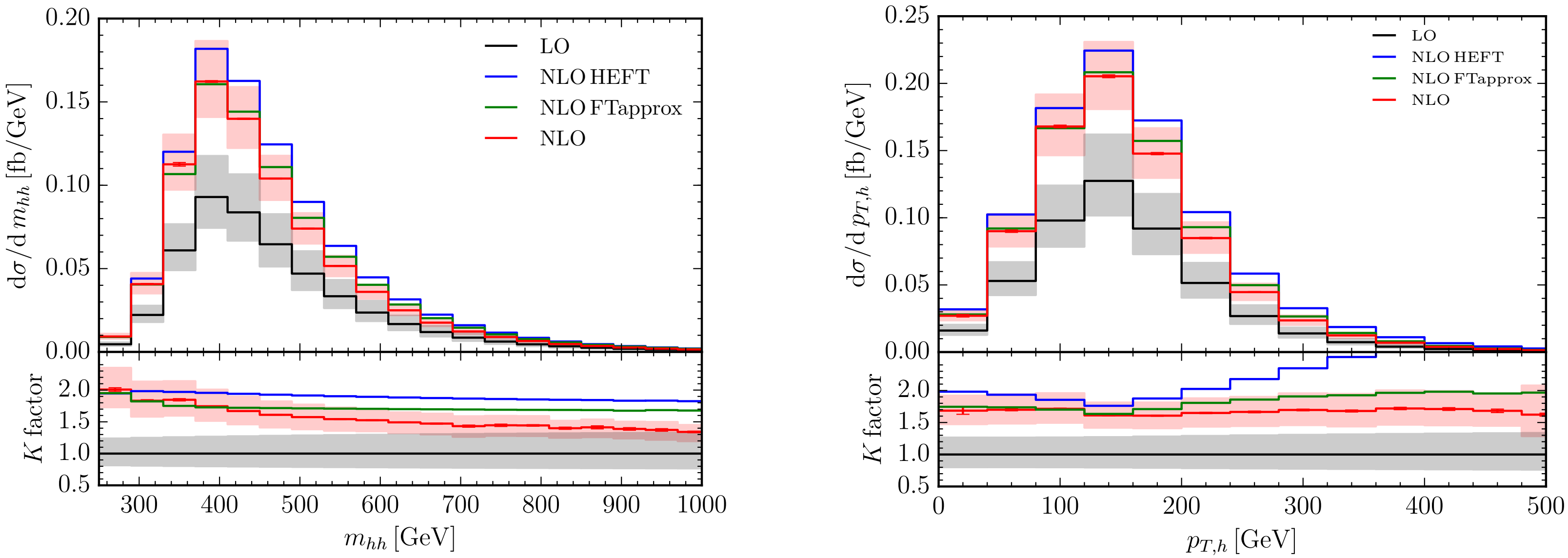
  [Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, Mazzitelli, JHEP 1805 (2018) 059]

Full NLO QCD corrections to $gg \to HH$

[**J.B.**, Campanario, Glaus, Mühlleitner, Spira, Streicher, arXiv:1811.05692]

NLO QCD in 2016

Distributions at 14 TeV [Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke, JHEP 1610 (2016) 107]



- Reduction to master integrals, sector decomposition, contour deformation
- **Large mass effects in the tail up to $\sim -30\%$ w.r.t. HTL**
- Born-improved HTL outside full NLO scale variation for $m_{HH} > 410$ GeV, $p_{T,h} > 160$ GeV
- No quantitative statement on the top-quark scheme uncertainty

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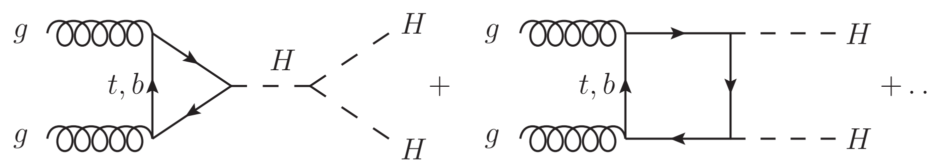
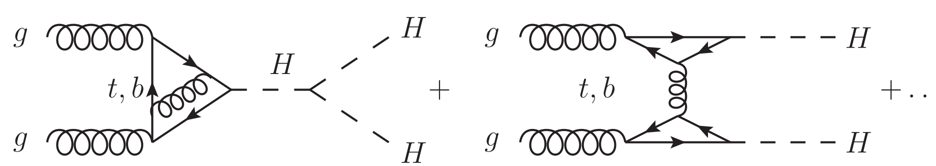
Overview of our calculation

$$\sigma_{\rm NLO}(pp\to HH+X) = \sigma_{\rm LO} + \Delta\sigma^{(1)}_{\rm virt} + \Delta\sigma^{(2)}_{\rm virt} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{q\bar{q}}$$

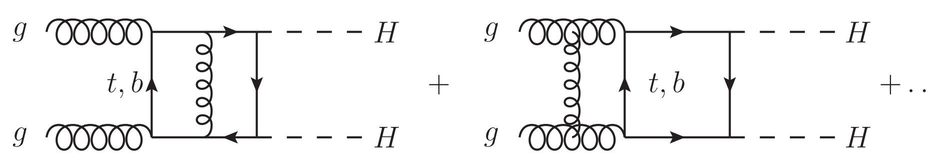
- **1-loop LO $\sigma_{\rm LO}$:**



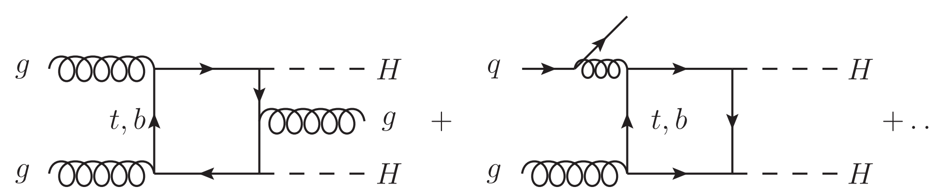
- **2-loop triangle + 1-particle reducible $\Delta\sigma^{(1)}_{\rm virt}$:**



- **2-loop box $\Delta\sigma^{(2)}_{\rm virt}$:**



- **1-loop reals $\Delta\sigma_{ij}$:**



Technical setup for the virtual corrections

- Triangle from single Higgs, 1-particle reducible analytically calculated

  [see also Degrassi, Giardino, Gröber, EPJC 76 (2016) 411]

- Classification of the **47 2-loop tensor box diagrams** into 6 topologies (+ corresponding fermion-flow reversed diagrams)

- With dimensional regularization $D = 4 - 2\epsilon$:
  calculate the **matrix-element form factors F_1 and F_2** using `FORM/Reduce/Mathematica` for $g(k_1)g(k_2) \to H(k_3)H(k_4)$,

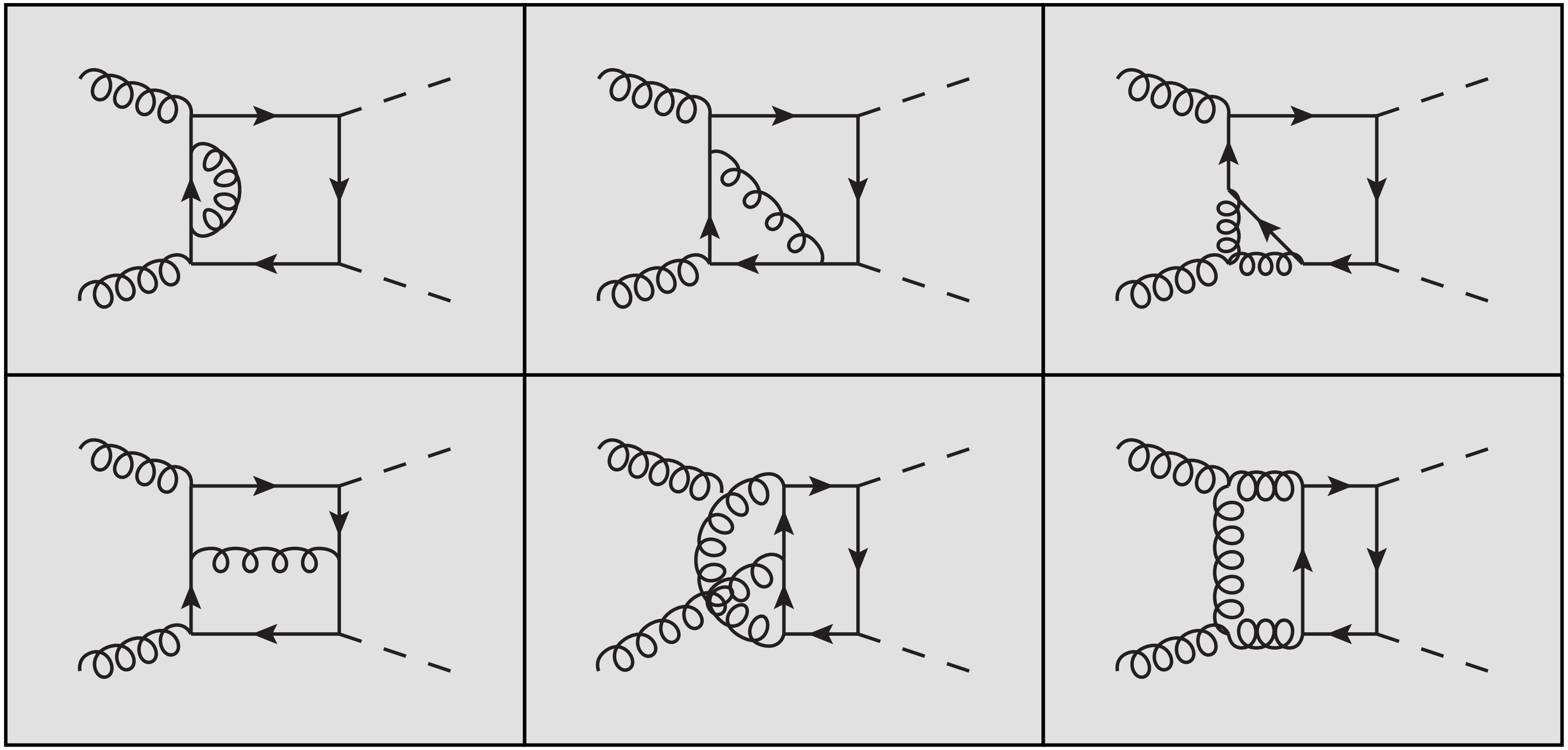
$$\mathcal{M} = \varepsilon^*_\mu(k_1)\varepsilon^*_\nu(k_2)\left(F_1 \mathbf{T}_1^{\mu\nu} + F_2 \mathbf{T}_2^{\mu\nu}\right),$$

$$\mathbf{T}_1^{\mu\nu} = g^{\mu\nu} - \frac{k_2^\mu k_1^\nu}{k_1 \cdot k_2}, \qquad p_T^2 = 2\frac{(k_2 \cdot k_3)(k_1 \cdot k_3)}{k_1 \cdot k_2} - k_3^2,$$

$$\mathbf{T}_2^{\mu\nu} = g^{\mu\nu} + \frac{k_2^\mu k_1^\nu}{(k_1 \cdot k_2)p_T^2}k_3^2 - \frac{2}{p_T^2}\left[\frac{k_2 \cdot k_3}{k_1 \cdot k_2}k_3^\mu k_1^\nu + \frac{k_1 \cdot k_3}{k_1 \cdot k_2}k_2^\mu k_3^\nu - k_3^\mu k_3^\nu\right]$$

- **Perform Feynman parametrization**
  $\to$ 6-dimensional integrals to be (numerically) evaluated

2-loop virtual box corrections



2-loop virtual box corrections

- **Extraction of ultraviolet (UV) divergences:**
  Endpoint subtraction of the Feynman integrals

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

- **Infrared (IR) divergences in the middle of the range**
  $\Rightarrow$ Subtraction of the integrand and analytical integration
  - Generic denominator $N = ar^2 + br + c$, $N_0 = br + c$
  - Feynman parameters (x, s, t) and $\rho = \dfrac{\hat{s}}{m_t^2}$
  - $a = \mathcal{O}(\rho), \quad b = 1 + \mathcal{O}(\rho), \quad c = -\rho x(1-x)(1-s)t$

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

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Handling threshold instabilities

- **Threshold at $\hat{s} = m_{HH}^2 = 4m_t^2$:**
  $\Rightarrow$ Analytical continuation in the complex plane with

$$m_t^2 \to m_t^2\,(1 - i\tilde{\epsilon})\,, \quad \tilde{\epsilon} \ll 1$$

- **Enhance stability above threshold with integration by parts** With $N = a + bx$,

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

$$\int_0^1 dx\,\frac{4b\,f(x)\log N}{N^3} = \left[-\frac{f(x)(1+2\log N)}{N^2}\right]_0^1 + \int_0^1 dx\,\frac{f'(x)(1+2\log N)}{N^2}$$

UV renormalization and IR subtraction

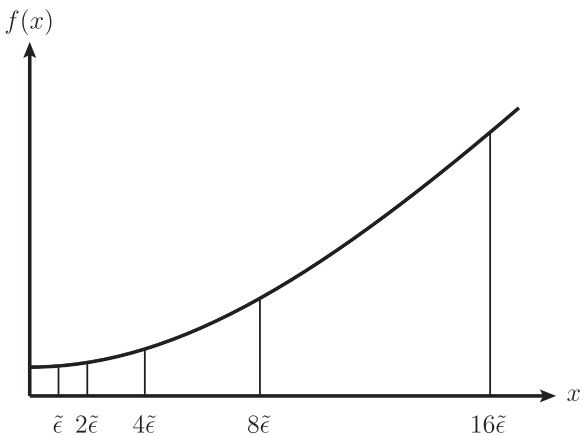
- **α_s and m_t input parameters to renormalize**
  - → $\overline{\text{MS}}$ renormalization for α_s with 5 active flavors, δ_{α_s}
  - → Top-quark contribution to the external gluon self-energies, δ_g
  - → On-shell renormalization for m_t, δ_{m_t}

- **IR subtraction, $\delta_{\rm IR}$:**

  Subtraction of Born-improved HTL virtual corrections to box diagrams ⇒ IR-safe virtual mass-effects

Richardson extrapolation

- **Goal: From $m_t^2(1 - i\tilde{\epsilon})$, obtain the limit $\tilde{\epsilon} \to 0$**
- **Solution: Richardson extrapolation of the result!**
  Assuming $f(\tilde{\epsilon}) - f(0)$ polynomial for small $\tilde{\epsilon}$, method to accelerate the convergence of $f(\tilde{\epsilon})$ to $f(0)$



$$\mathrm{RiEx}_{2,\tilde{\epsilon}} = 2f(\tilde{\epsilon}) - f(2\tilde{\epsilon}) = f(0) + \mathcal{O}(\tilde{\epsilon}^2)$$

$$\mathrm{RiEx}_{3,\tilde{\epsilon}} = \frac{1}{3}\Big[8f(\tilde{\epsilon}) - 6f(2\tilde{\epsilon}) + f(4\tilde{\epsilon})\Big] = f(0) + \mathcal{O}(\tilde{\epsilon}^3)$$

$$\mathrm{RiEx}_{4,\tilde{\epsilon}} = \frac{1}{21}\Big[64f(\tilde{\epsilon}) - 56f(2\tilde{\epsilon}) + 14f(4\tilde{\epsilon}) - f(8\tilde{\epsilon})\Big] = f(0) + \mathcal{O}(\tilde{\epsilon}^4)$$

$$\mathrm{RiEx}_{5,\tilde{\epsilon}} = \frac{1}{315}\Big[1024f(\tilde{\epsilon}) - 960f(2\tilde{\epsilon}) + 280f(4\tilde{\epsilon}) - 30f(8\tilde{\epsilon}) + f(16\tilde{\epsilon})\Big] = f(0) + \mathcal{O}(\tilde{\epsilon}^5)$$

Richardson extrapolation

- **Goal: From $m_t^2\,(1 - i\tilde{\epsilon})$, obtain the limit $\tilde{\epsilon} \to 0$**
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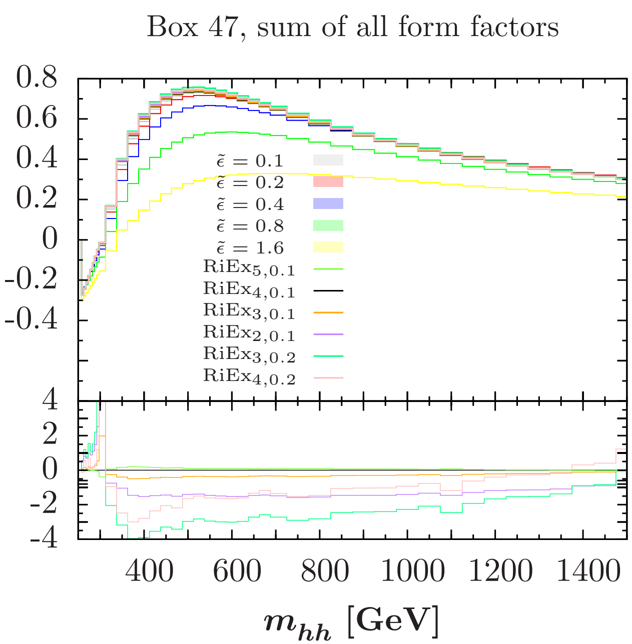
  Assuming $f(\tilde{\epsilon}) - f(0)$ polynomial for small $\tilde{\epsilon}$, method to accelerate the convergence of $f(\tilde{\epsilon})$ to $f(0)$



$$\mathrm{RiEx}_{2,\tilde{\epsilon}} = 2f(\tilde{\epsilon}) - f(2\tilde{\epsilon}) = f(0) + \mathcal{O}(\tilde{\epsilon}^2)$$

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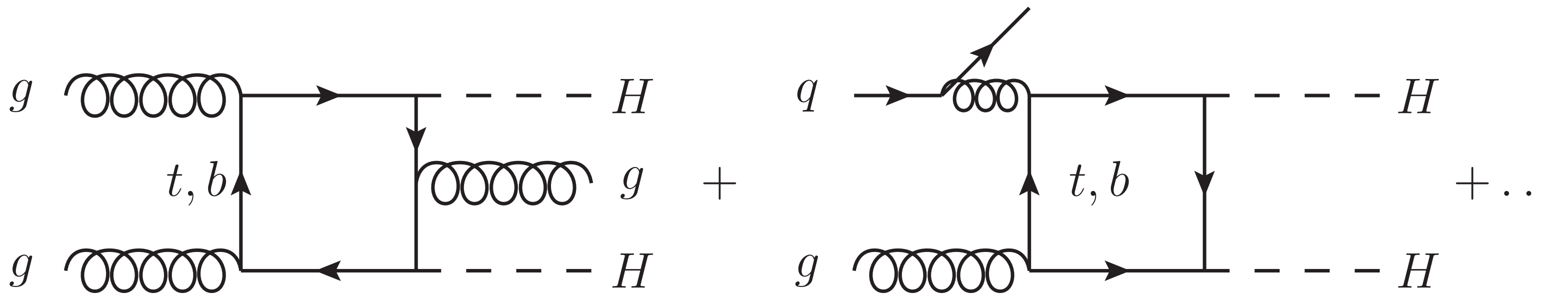
Calculation of the real corrections

Partonic sub-processes $gg \to HHg$, $gq/\bar{q} \to HHq/\bar{q}$, $q\bar{q} \to HHg$



- Full matrix elements generated with `FeynArts/FormCalc` [see Hahn, PoS ACAT2010 (2010) 078], evaluated with 1-loop library `COLLIER` [Denner, Dittmaier, Hofer, CPC 212 (2017) 220]
- Then subtracted with Born-improved HTL matrix-element squared calculated analytically
  $\Rightarrow$ **IR safe mass effects in the reals**

Putting everything together

- Numerical integration performed with VEGAS on a cluster, $\hat{t}$-integration
- **Final hadronic result:**

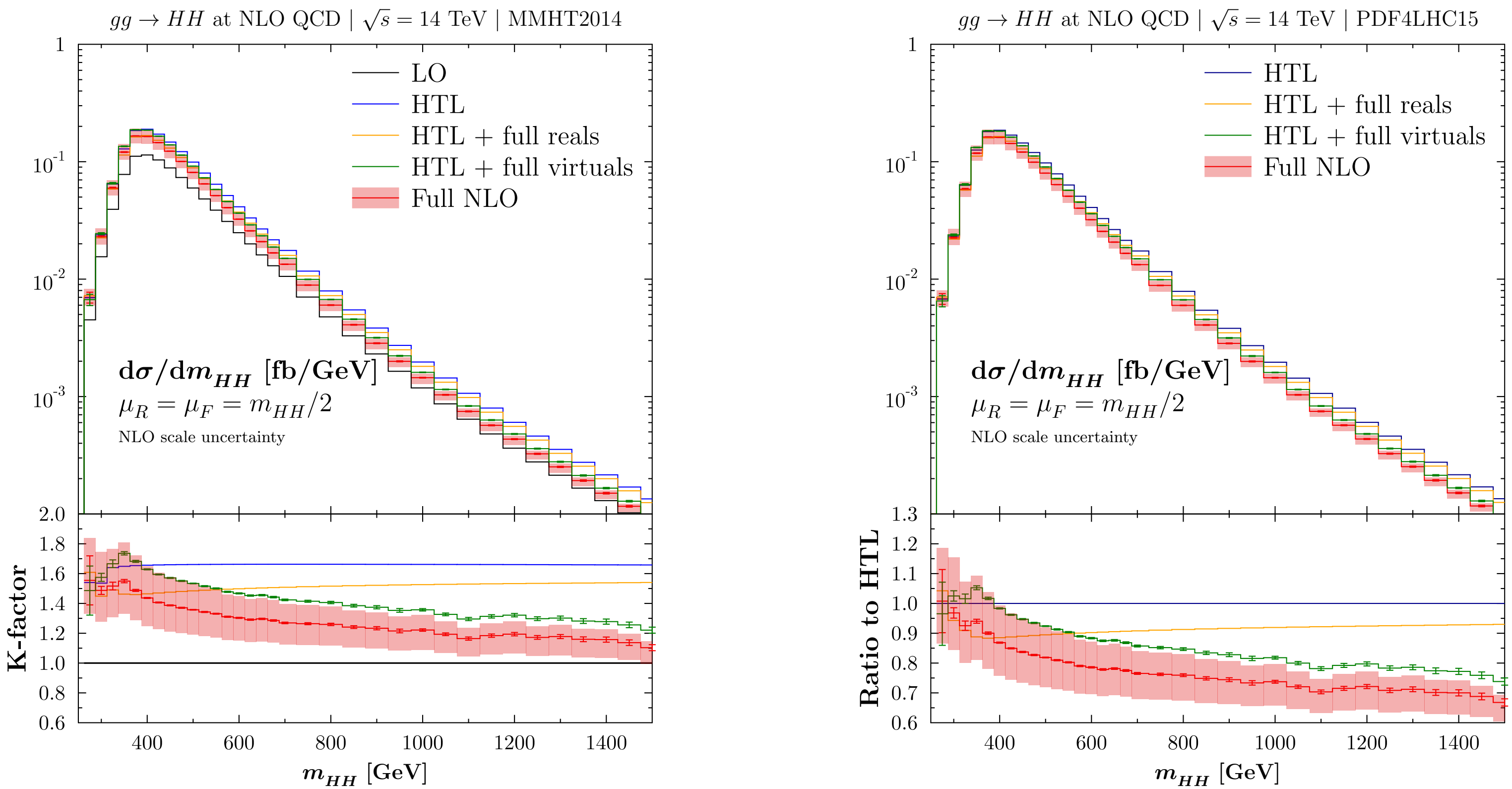
$$\Delta\hat{\sigma}_{\rm virt} = \int d\Phi_{2\to 2}\left[(\delta_{\alpha_s} + \delta_g + \delta_{m_t} + \delta_{\rm IR} + \mathcal{M}^{\square}_{\rm virt})(\mathcal{M}_{\rm LO})^*\right] + \Delta\hat{\sigma}^{\triangle}_{\rm virt} + \Delta\hat{\sigma}^{\rm 1PR}_{\rm virt}$$

$$m^2_{HH}\frac{d\sigma_{\rm NLO}}{dm^2_{HH}} = m^2_{HH}\frac{d\sigma_{\tt HPAIR}}{dm^2_{HH}} + m^2_{HH}\frac{d\Delta\sigma_{\rm virt}}{dm^2_{HH}} + m^2_{HH}\frac{d\Delta\sigma_{\rm reals}}{dm^2_{HH}}$$

HTL hadronic result calculated with HPAIR [Spira, 1996]

- **Input parameters:** **can be freely chosen!** PDG values for M_W and M_Z, $M_H = 125$ GeV, $m_t = 172.5$ GeV, $G_F = 1.1663787\times 10^{-5}$ GeV^{-2}, $\sqrt{s} = 14$ TeV

Final results



- Mass effects in the real corrections $\sim -10\%$ as in [Maltoni, Vryonidou, Zaro, JHEP 1411 (2014) 079]
- **Mass effects in the virtual corrections $\sim -25\%$ at $m_{HH} = 1$ TeV**
- **First independent cross-check** of the results in the literature: $\sigma^{\rm NLO}_{\rm PDF4LHC} = 32.78(7)^{+13.5\%}_{-12.5\%}$ fb vs $\sigma^{\rm literature}_{\rm PDF4LHC} = 32.91(11)^{+13.5\%}_{-12.5\%}$ fb

Focus on the top-quark mass uncertainty

Top-quark scheme uncertainty easily calculable!

Switch to $\overline{\text{MS}}$ scheme and calculate xs for $m_t = \overline{m}_t(\overline{m}_t)$, $m_t = \overline{m}_t(m_{HH}/4)$, $m_t = \overline{m}_t(m_{HH}/2)$, $m_t = \overline{m}_t(m_{HH})$

- Recalculate HPAIR xs and the real corrections $\rightarrow$ fast!
- Recalculate 2-loop corrections $\rightarrow$ OK!
- Switch the mass counterterm from OS to $\overline{\text{MS}}$ scheme

$$\frac{\delta m_t}{m_t} = \frac{\alpha_s}{\pi}\Gamma(1+\epsilon)\left(\frac{4\pi\mu_R^2}{m_t^2}\right)^{\epsilon}\left(\frac{1}{\epsilon} - \log\left(\frac{\mu_{R,t}^2}{m_t^2}\right)\right)$$

- **Results:** $\left.\frac{d\sigma}{dQ}\right|_{Q=300\text{GeV}} = ^{+10\%}_{-22\%}$, $\left.\frac{d\sigma}{dQ}\right|_{Q=400\text{GeV}} = ^{+7\%}_{-7\%}$, $\left.\frac{d\sigma}{dQ}\right|_{Q=600\text{GeV}} = ^{+0\%}_{-26\%}$, $\left.\frac{d\sigma}{dQ}\right|_{Q=1200\text{GeV}} = ^{+0\%}_{-30\%}$ $(Q = M_{HH})$

$\Rightarrow \sigma^{\text{tot}}_{NLO} = 32.78(7)^{+2\%}_{-25\%}$ **(very preliminary interpolation!!)**

Conclusion and outlook

$gg \to HH$ @ NLO in 2019: Two independent calculations finally exist on the market!

- **First independent cross-check since 2016 for the full 2-loop NLO QCD corrections in gluon fusion!**
  $\to$ Complete different method compared to the 2016 calculation [IBP, Richardson extrapolation, etc]
  $\to$ Code flexible: m_t, M_H **not fixed a priori, can be changed at will**
  $\to$ results compatible with 2016 study
- **Allows for the first evaluation of the top-quark scheme uncertainty, that is found to be large!**
- **Outlook: Extension to BSM physics and in particular EFT and 2HDM models**

Backup slides

Details for the renormalization

- **UV renormalization: δ_{α_s}, δ_g, δ_{m_t}**

  → $\overline{\text{MS}}$ renormalization for α_s with 5 active flavors $N_F = 5$

$$\frac{\delta\alpha_s}{\alpha_s} = \frac{\alpha_s}{\pi}\Gamma(1+\epsilon)\,(4\pi)^{\epsilon}\left[-\frac{33-2(N_F+1)}{12\epsilon}+\frac{1}{6}\log\left(\frac{\mu_R^2}{m_t^2}\right)\right], \quad \delta_{\alpha_s} = \frac{\delta\alpha_s}{\alpha_s}\mathcal{M}_{\text{LO}}$$

  → Top-quark contribution to the external gluons self-energies

$$\delta_g = \frac{\alpha_s}{\pi}\Gamma(1+\epsilon)\left(\frac{4\pi\mu_R^2}{m_t^2}\right)^{\epsilon}\left(-\frac{1}{6\epsilon}\right)\mathcal{M}_{\text{LO}}$$

  → On-shell renormalization for m_t

$$\frac{\delta m_t}{m_t} = \frac{\alpha_s}{\pi}\Gamma(1+\epsilon)\left(\frac{4\pi\mu_R^2}{m_t^2}\right)^{\epsilon}\left(\frac{1}{\epsilon}+\frac{4}{3}\right), \quad \delta_{m_t} = -2\frac{\delta m_t}{m_t}m_t^2\frac{\partial\mathcal{M}_{\text{LO}}}{\partial m_t^2}$$

- **IR subtraction:**

$$\delta_{\text{IR}} = \frac{\alpha_s}{\pi}\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\left(\frac{4\pi\mu_R^2}{-m_{HH}^2}\right)^{\epsilon}\left[\frac{3}{2\epsilon^2}+\frac{33-2N_F}{12\epsilon}\left(\frac{\mu_R^2}{-m_{HH}^2}\right)^{-\epsilon}-\frac{11}{4}+\frac{\pi^2}{4}\right]\mathcal{M}_{\text{LO}}$$

Details for the renormalization

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$$\delta_{\rm IR} = \frac{\alpha_s}{\pi}\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\left(\frac{4\pi\mu_R^2}{-m_{HH}^2}\right)^\epsilon\left[\frac{3}{2\epsilon^2} + \frac{33-2N_F}{12\epsilon}\left(\frac{\mu_R^2}{-m_{HH}^2}\right)^{-\epsilon} - \frac{11}{4} + \frac{\pi^2}{4}\right]\mathcal{M}_{\rm LO}$$

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Calculation of the real corrections

Building the local IR counterterm:

$$d\Delta\hat{\sigma}_{ij}^{\rm mass} = d\Delta\hat{\sigma}_{ij} - d\hat{\sigma}_{\rm LO}\,\frac{d\Delta\hat{\sigma}_{ij}^{\rm HTL}}{d\hat{\sigma}_{\rm LO}^{\rm HTL}}$$

Local IR counterterm with a projected on-shell LO $2 \to 2$ kinematics to rescale the $2 \to 3$ HTL

$2 \to 2$ OS LO from [Catani, Seymour, NPB 485 (1997) 291] with initial-state emitter, initial-state spectator

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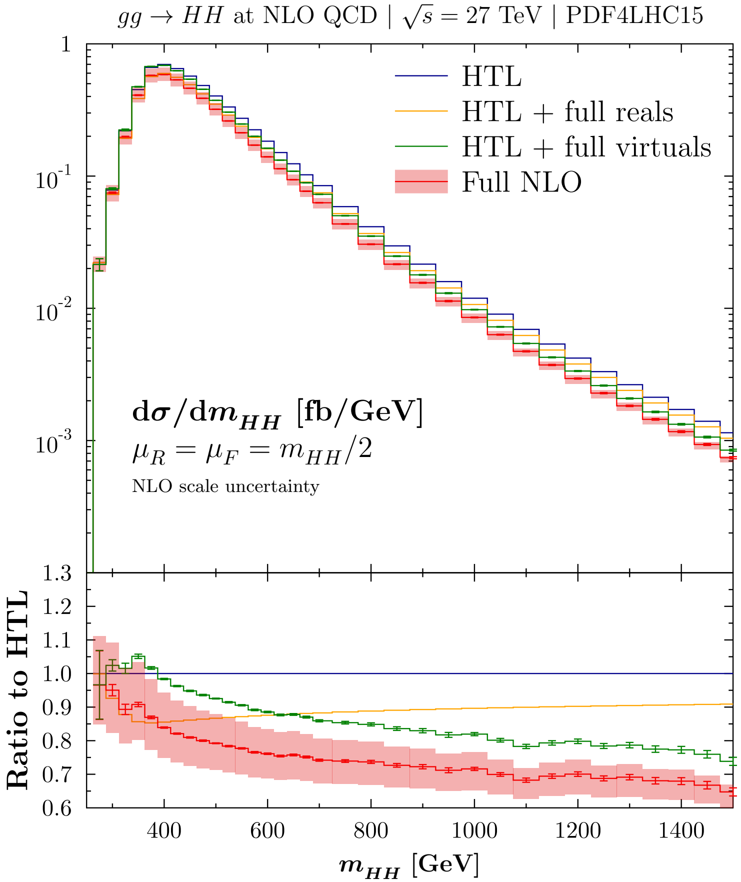
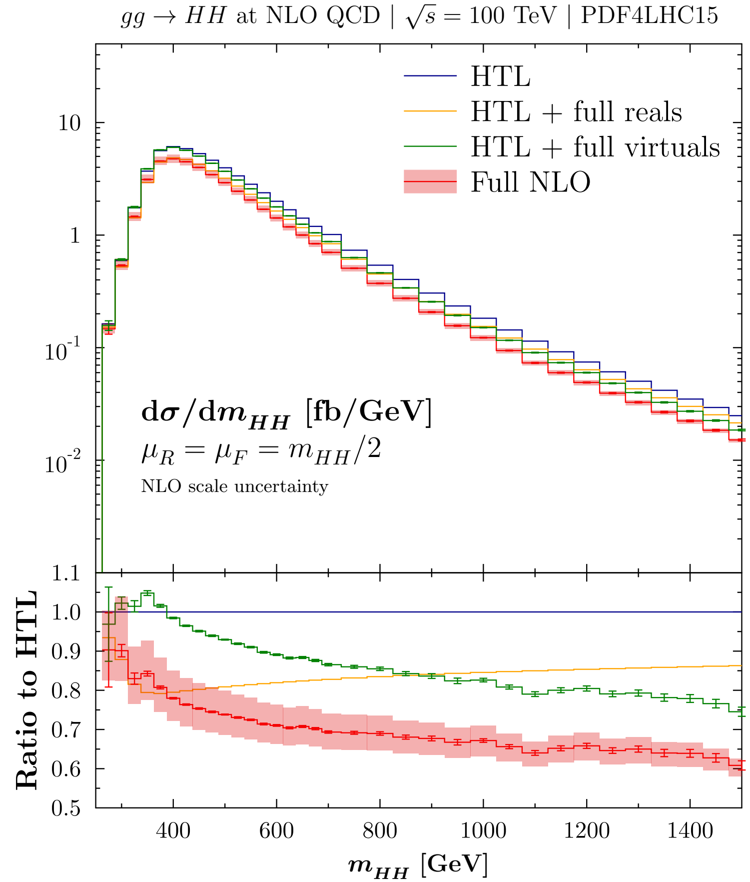
$2 \to 2$ OS LO from [Catani, Seymour, NPB 485 (1997) 291] with initial-state emitter, initial-state spectator

$\Rightarrow$ Mass effects IR safe in the real corrections

Distributions at higher center-of-mass energies

Still preliminary results!!





$\sigma_{\rm NLO}^{gg\to HH}(\sqrt{s} = 27\text{ TeV}) = 127.1(2)^{+11.5\%}_{-10.4\%}$ fb

$\sigma_{\rm NLO}^{gg\to HH}(\sqrt{s} = 100\text{ TeV}) = 1.144(2)^{+8.5\%}_{-7.1\%}$ pb