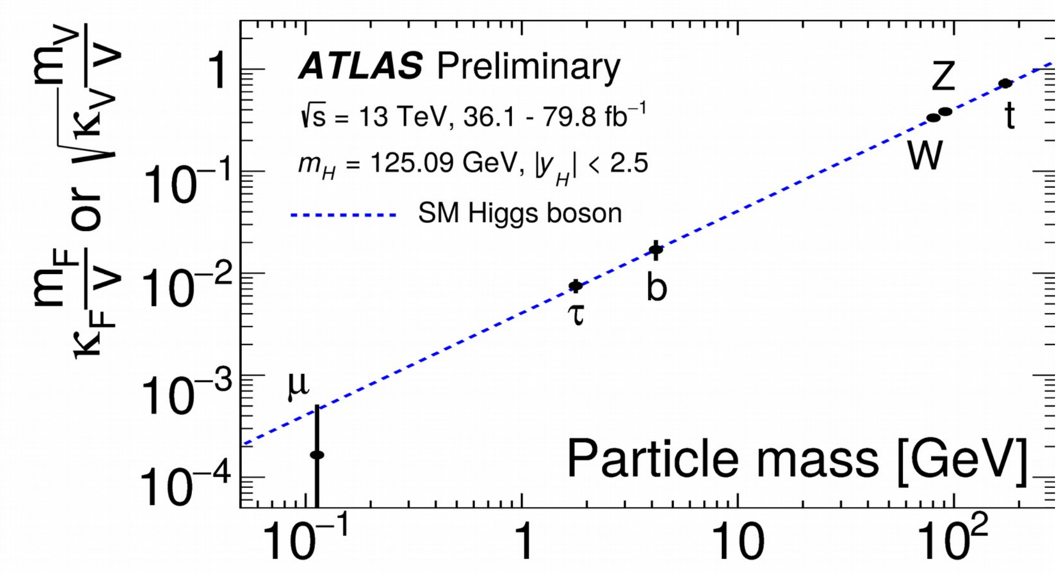
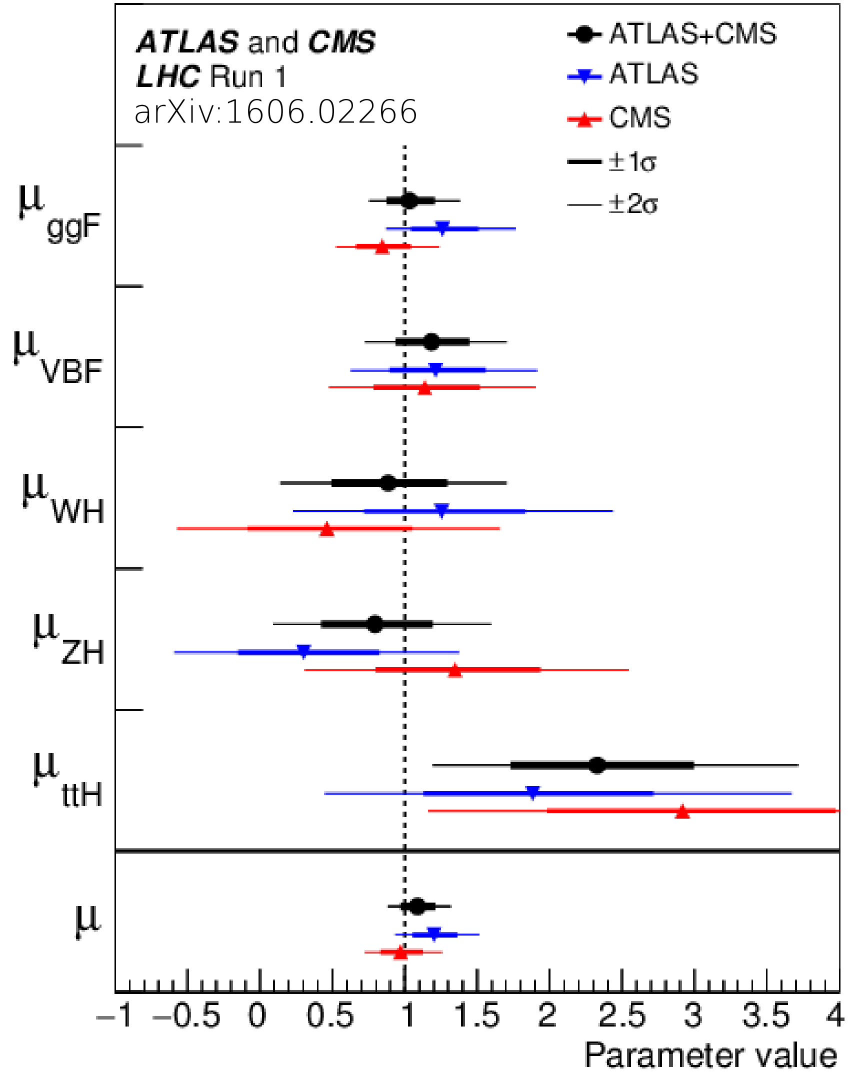
Higgs boson pair production

Javier Mazzitelli

Universität Zürich UZH

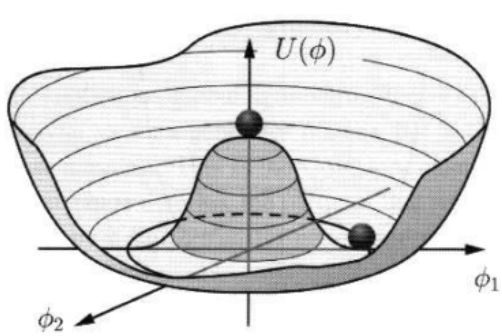
Multi-Higgs production





- Higgs couplings to fermions and gauge bosons so far compatible with SM

- What happens for the Higgs self-couplings?
  Are they relevant?
  How can we measure them?



- Self-couplings determined by the Higgs potential

$$V(H) = \frac{1}{2}M_H^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda' H^4$$

In the SM: $\lambda = \lambda' = M_H^2/(2v^2)$

- Crucial to understand EWSB

Multi-Higgs production → Direct access to Higgs self-couplings

Produce an off-shell
Higgs boson that decays into:

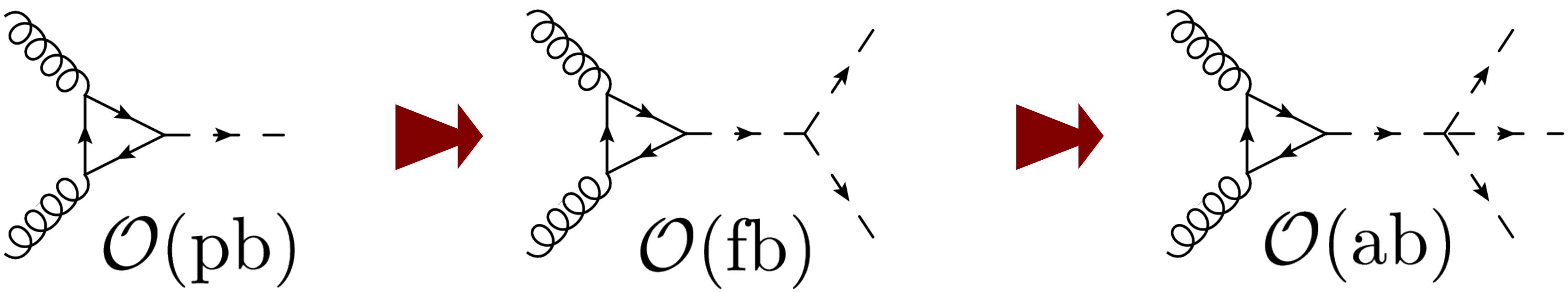
Trilinear coupling

$$H^* \to HH$$

Quartic coupling

$$H^* \to HHH$$

Experimentally very challenging!

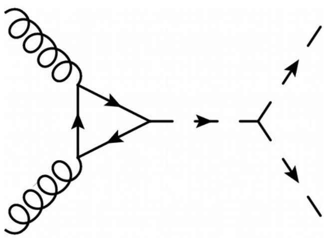


At the LHC:

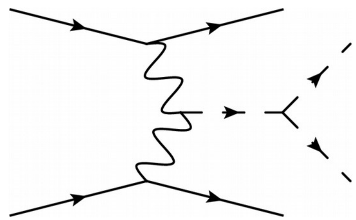
Double Higgs production:
challenging

Triple Higgs production:
impossible

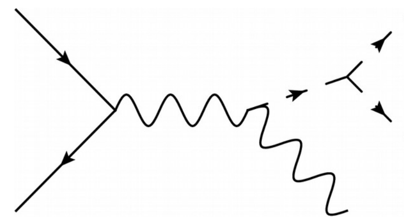
Double Higgs production mechanisms



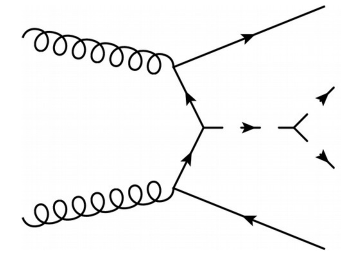
Gluon fusion



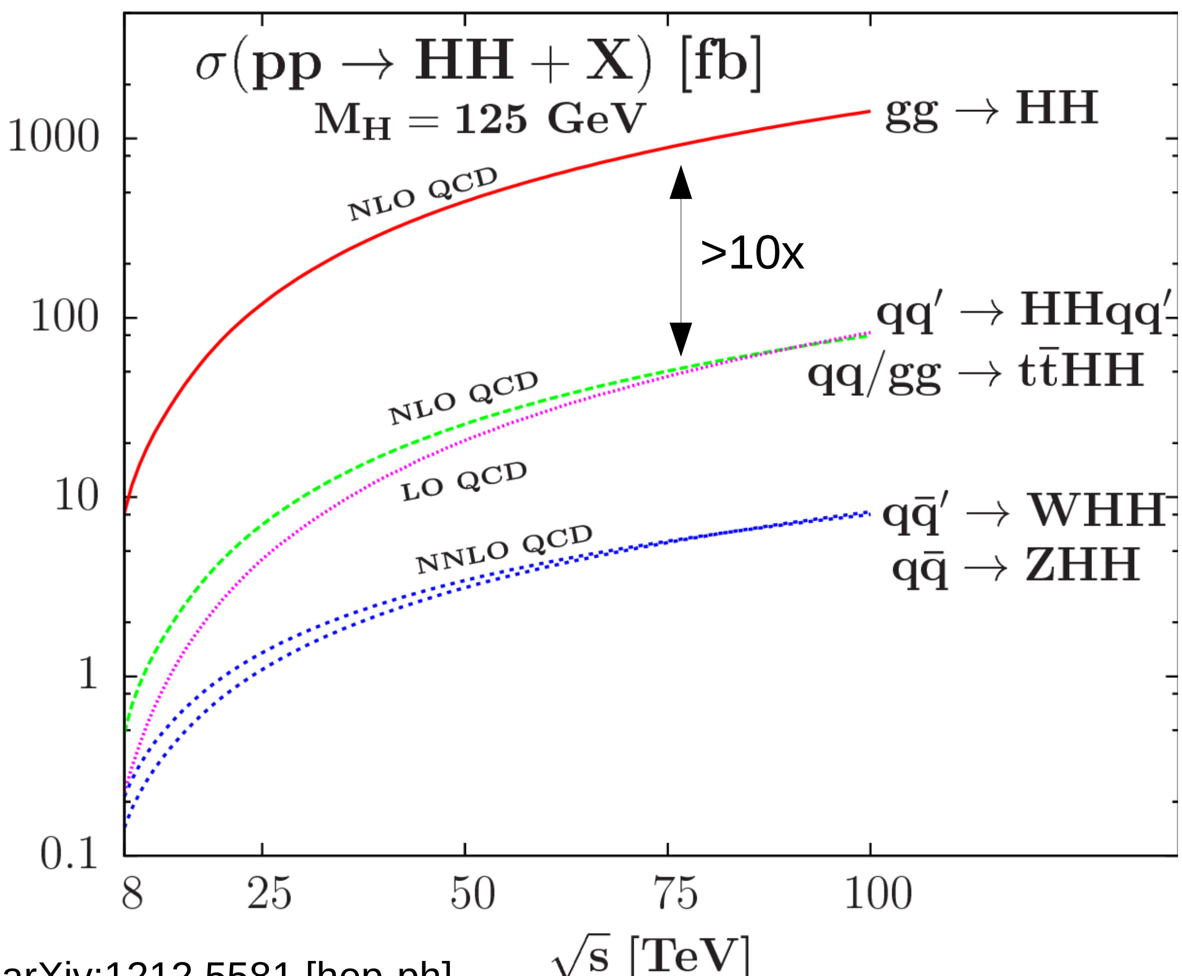
Vector boson fusion



Higgs–strahlung



ttHH



From arXiv:1212.5581 [hep-ph]

Gluon fusion

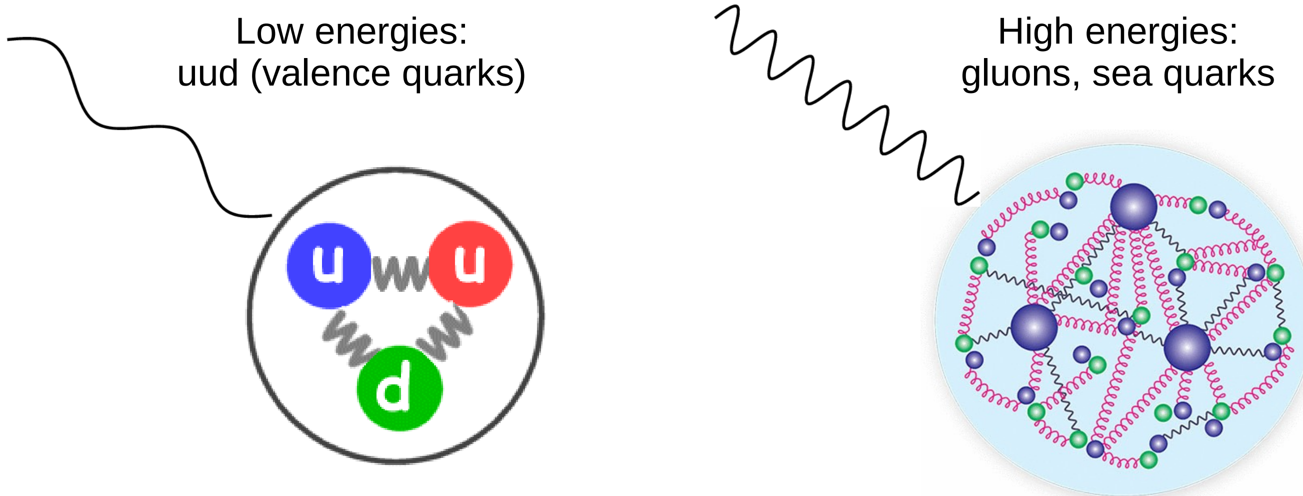
↓

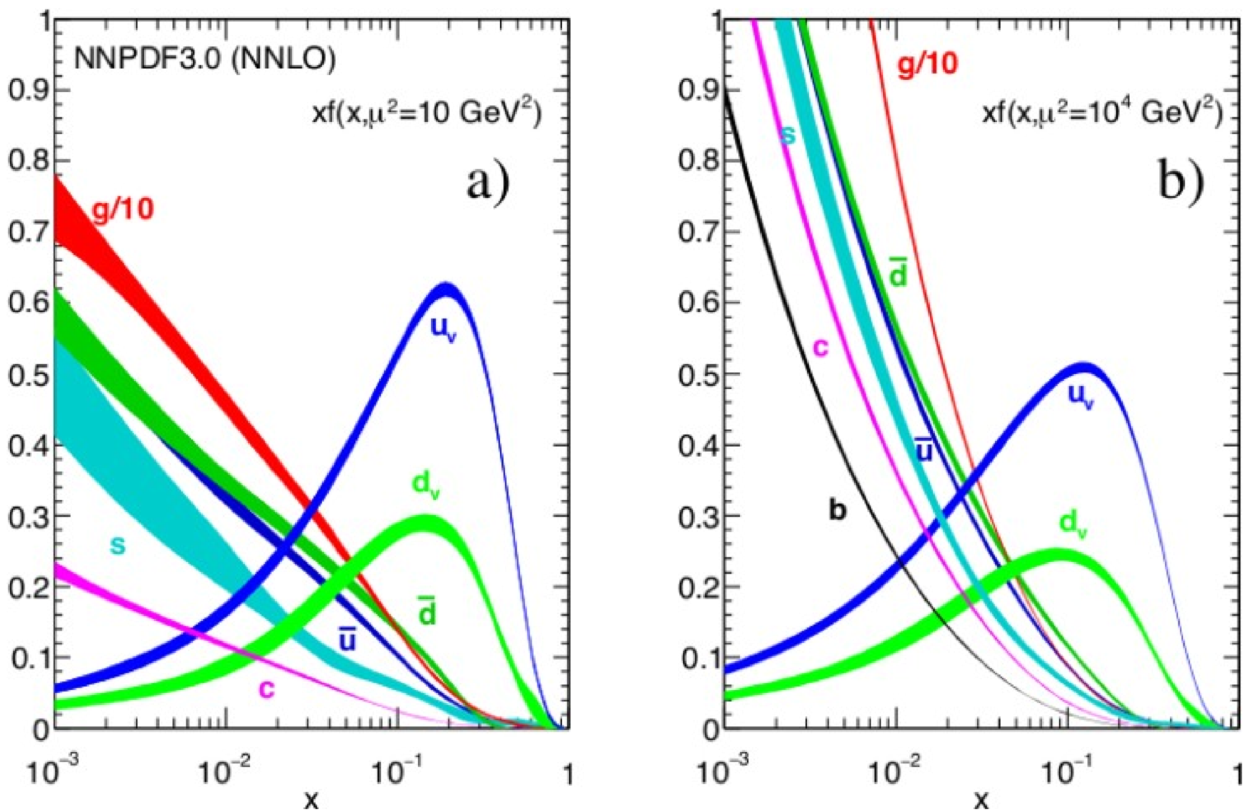
Main production channel

~1000 times smaller than single Higgs XS

Measurement of subleading channels is very difficult

Parton distrubution functions

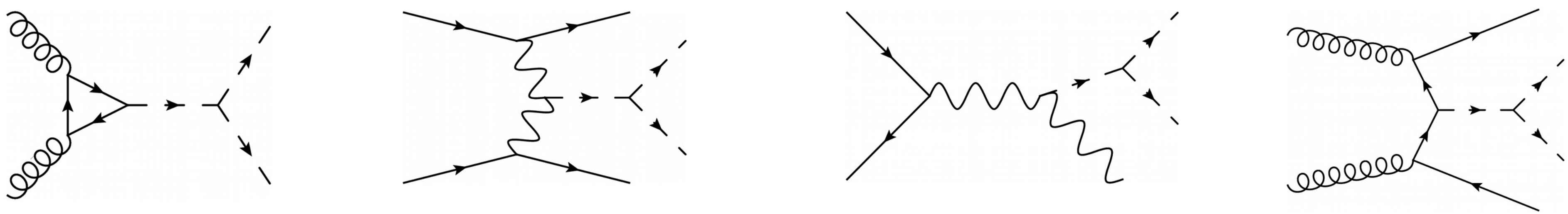




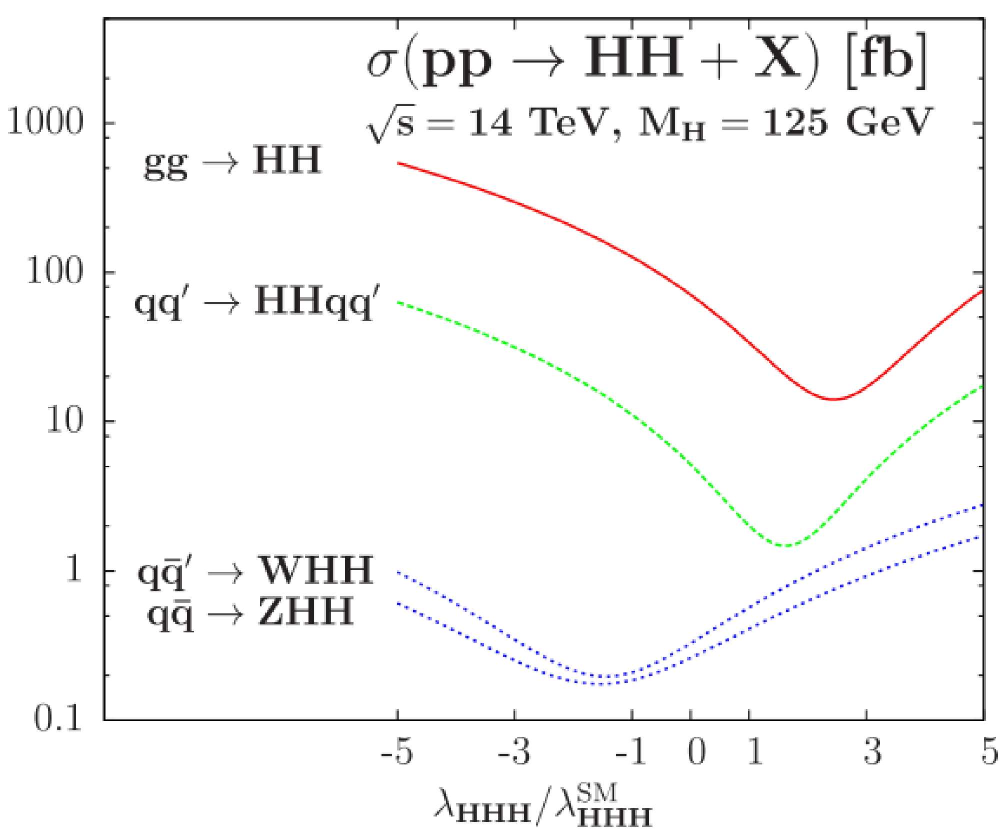
- For the production of a Higgs boson at the LHC, mean value about x~0.01
- Mainly gluons in the initial state!

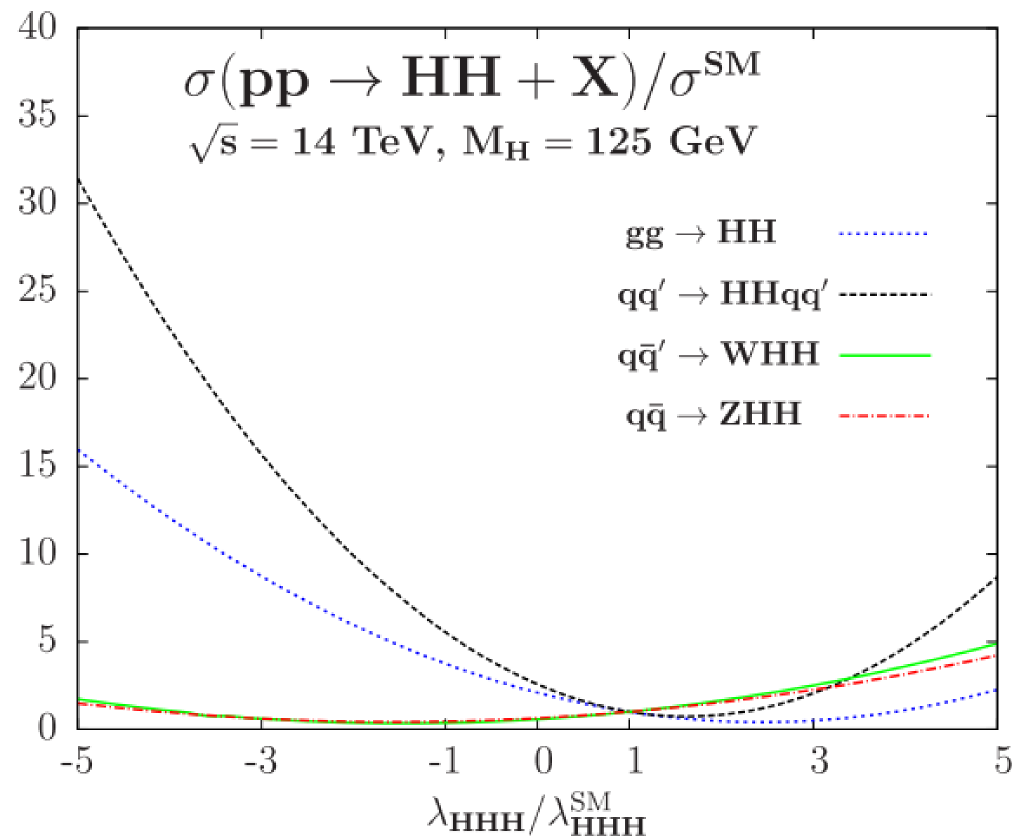
λ_{hhh} variation

Sensitivity to Higgs self-coupling for the different HH production mechanisms



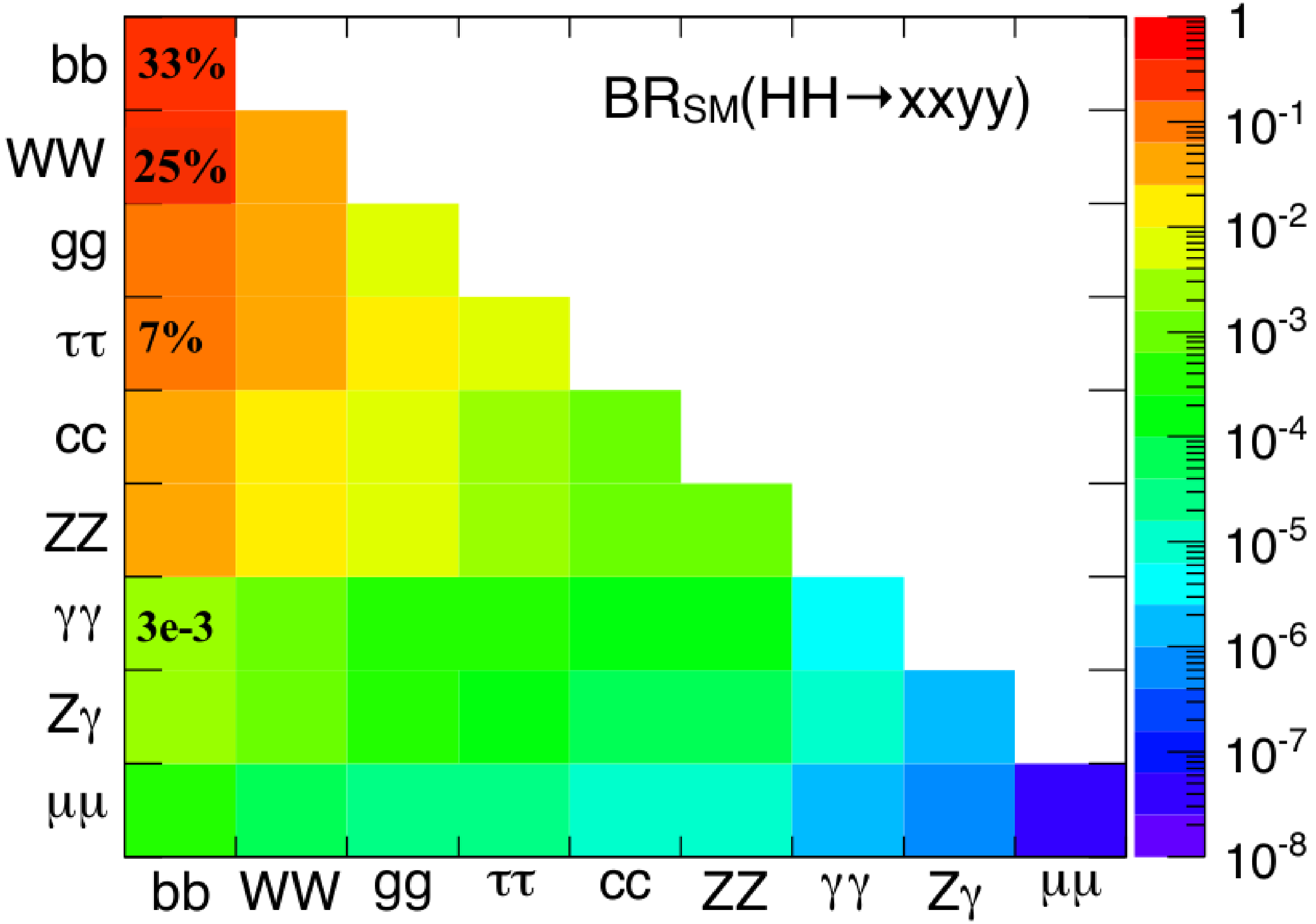
Gluon fusion | Vector boson fusion | Higgs–strahlung | ttHH





From arXiv:1212.5581 [hep-ph]

Di-Higgs decay channels



Relevant channels: in general at least one H → bb to have large BR

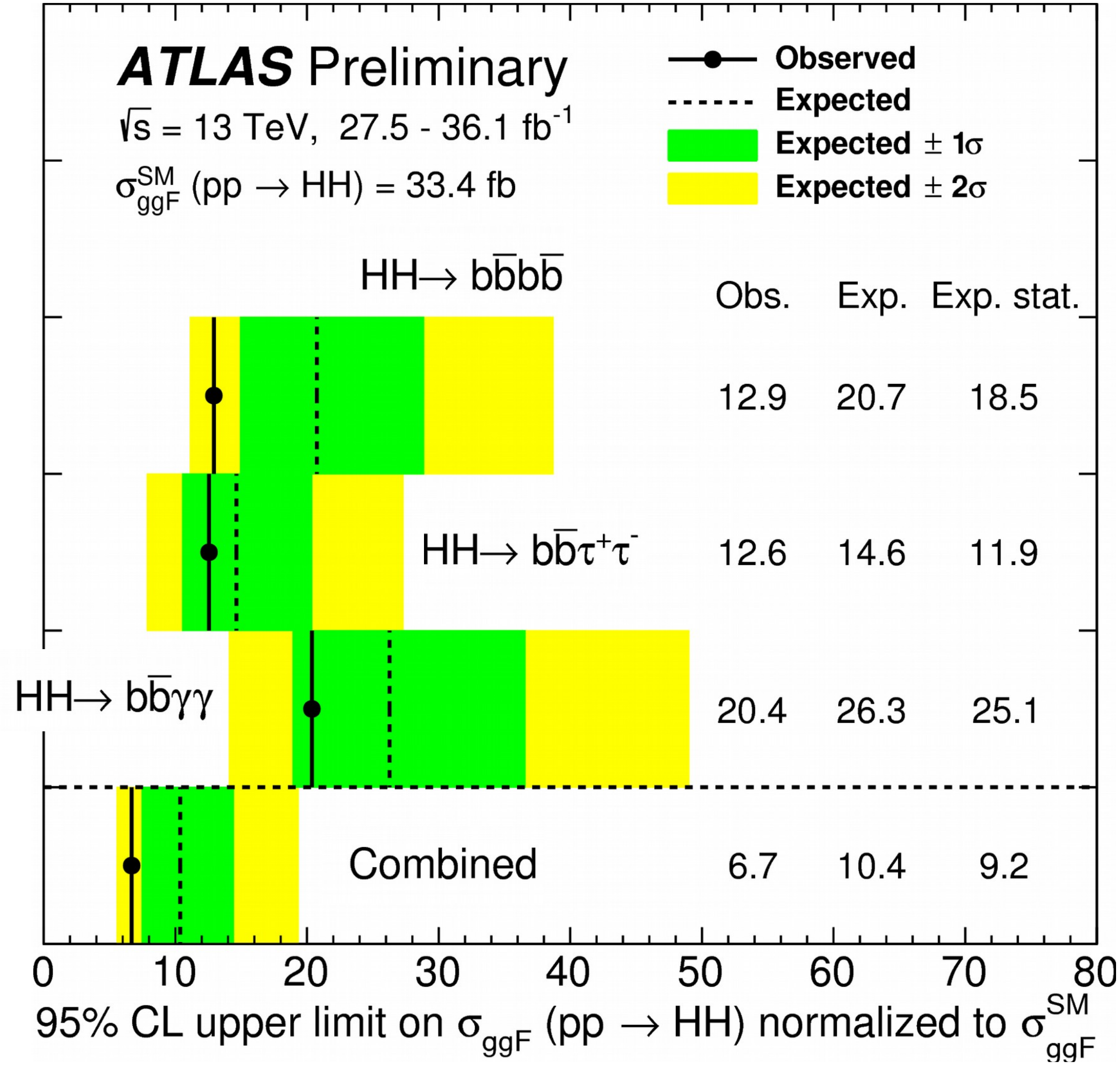
bbbb: highest BR, high QCD and tt contamination
bbWW: high BG, large irreducible tt background
bbττ: relatively low background and low BR
bbγγ: high purity, very low BR

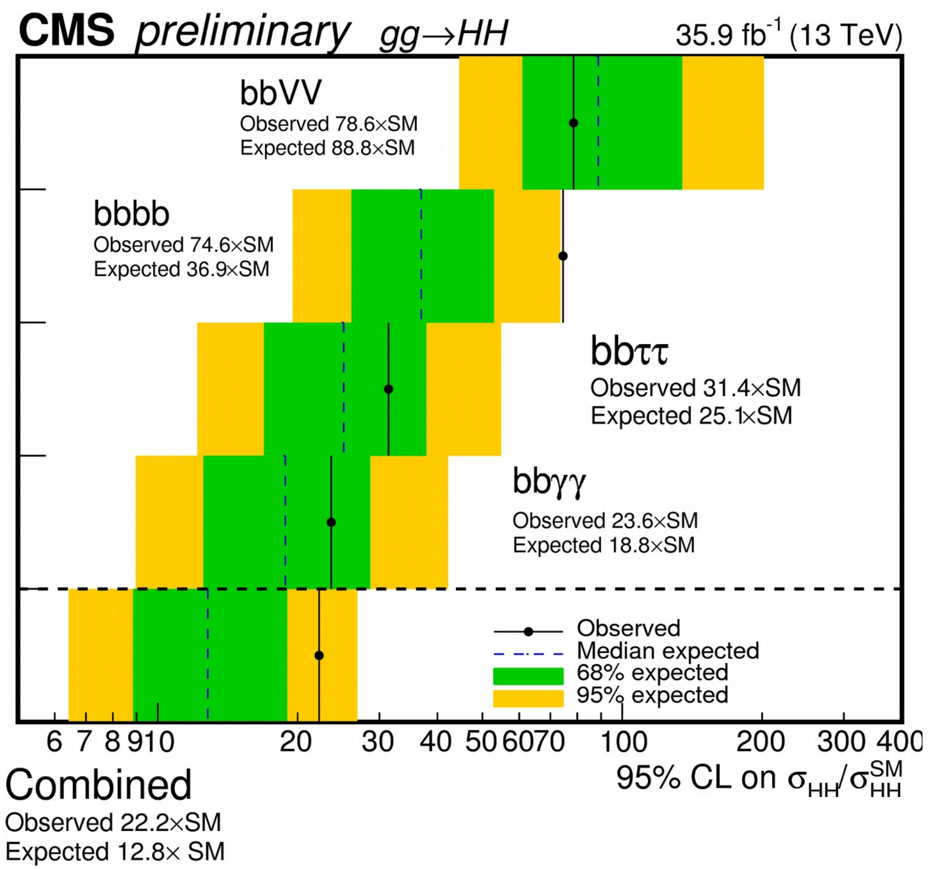
LHC results

BSM scenarios can substantially enhance the HH cross section or produce a resonance

↓

Both resonant and non-resonant searches have been performed at ATLAS and CMS





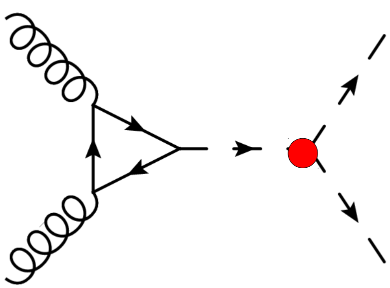
$\mathcal{O}(10)$ x SM sensitivity with 36fb^{-1} of data

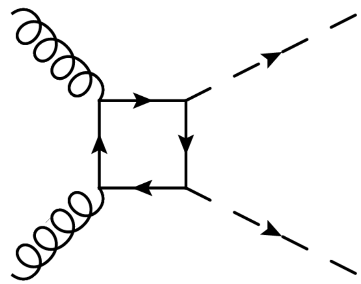
Prospects for the LHC and beyond

- Assuming a SM rate, HH production should be observed at the HL-LHC
- Expected uncertainty on the signal yield: O(50%) using bbγγ and bbττ
- Combination with other decay channels (specially 4b) will reduce this uncertainty

[ATL-PHYS-PUB-2014-019, ATL-PHYS-PUB-2015-046, CMS PAS FTR-15-002]

Higgs pair production should be observed at the HL-LHC... but we also want to measure λ

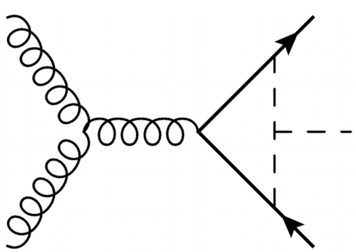




Not all the contributions are sensitive!

Assuming a SM-like scenario

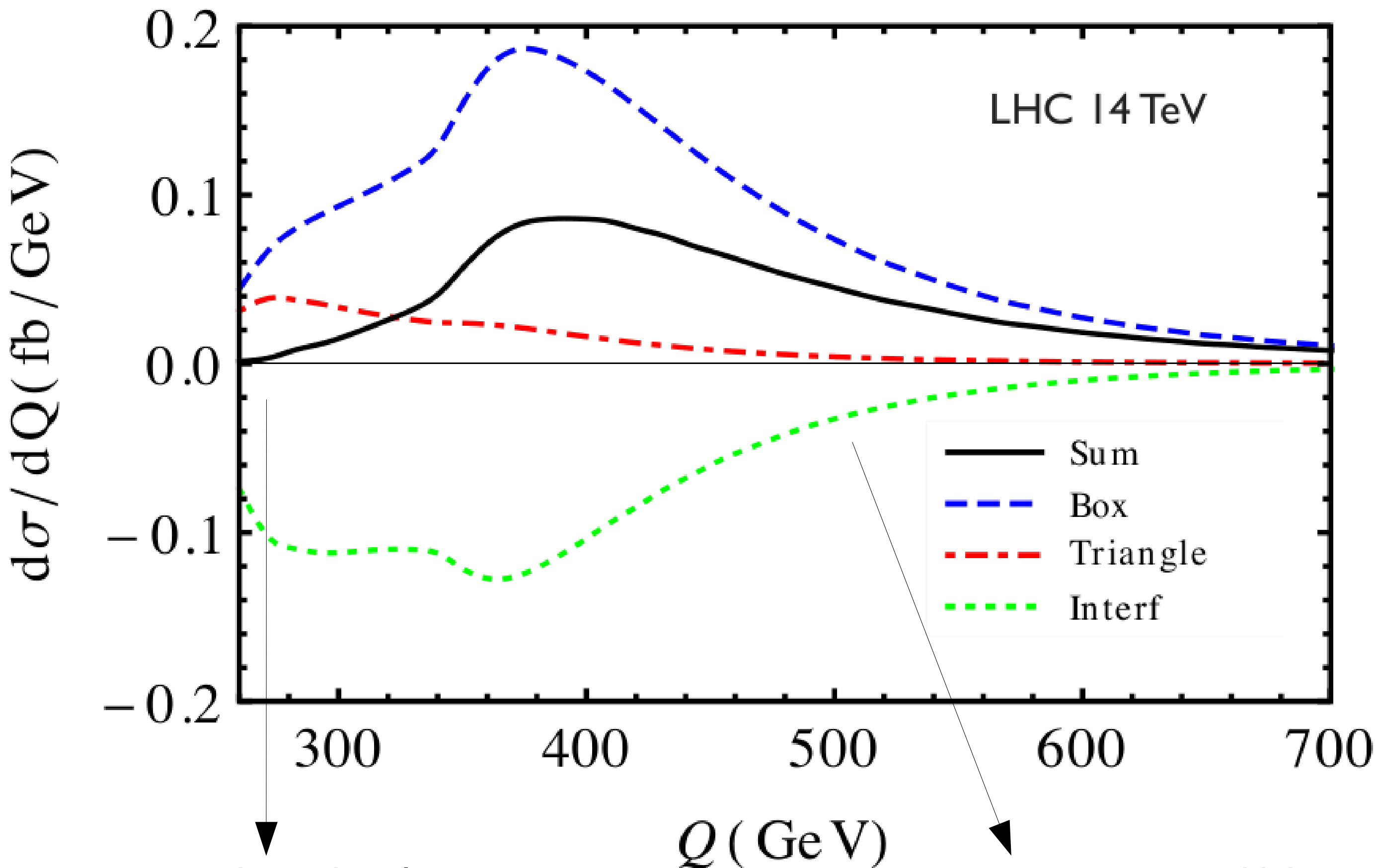
- Determination of λ will require full HL-LHC integrated luminosity and the combination of the different channels
- Even then, uncertainties on λ will be $\mathcal{O}(1)$
- Complementary information from loop effects in single Higgs and EW precision observables



- Precision determination: future colliders. HE-LHC ~30%, FCC-100 ~5%

HH production via gluon fusion

Loop induced process. At LO:



Large box-triangle cancellation at threshold

Largest sensitivity to λ from interference

The LO cross section can be written in the following way:

$$\frac{d\hat{\sigma}_{gg}}{dt} = \frac{\alpha_S^2}{2^{12}(2\pi)^3 v^4 s^2}\left(|F_1|^2 + |F_2|^2\right)$$

with

$$\begin{aligned} F_1 &= F_{1\triangle} + F_{1\Box} \\ F_2 &= F_{2\Box} \end{aligned}$$

Their explicit calculation gives the following result:

$$F_{1\triangle} = \frac{4\lambda_3 m_q^2}{s - m_H^2}\left(2 + (4m_q^2 - s)C_0(p_1, p_2)\right) \tag{3.258}$$

where $\lambda_3 = 3m_H^2\chi_\lambda$ is the Higgs trilinear coupling and $\chi_\lambda = 1$ in the Standard Model. The box diagrams instead contribute to both F_1 and F_2

$$\begin{aligned} F_{1\Box} = 4m_q^2\Big[& m_q^2(8m_q^2 - s - 2m_H^2)(D_0(p_1,p_2,p_3) + (1 \leftrightarrow 2) + (2 \leftrightarrow 3)) \\ & + p_T^2(4m_q^2 - m_H^2)D_0(p_1,p_2,p_3) + 2 + 4m_q^2 C_0(p_1,p_2) \\ & + \frac{2}{s}(m_H^2 - 4m_q^2)\left((t - m_H^2)C_0(p_1,p_3) + (u - m_H^2)C_0(p_2,p_3)\right)\Big] \end{aligned} \tag{3.259}$$

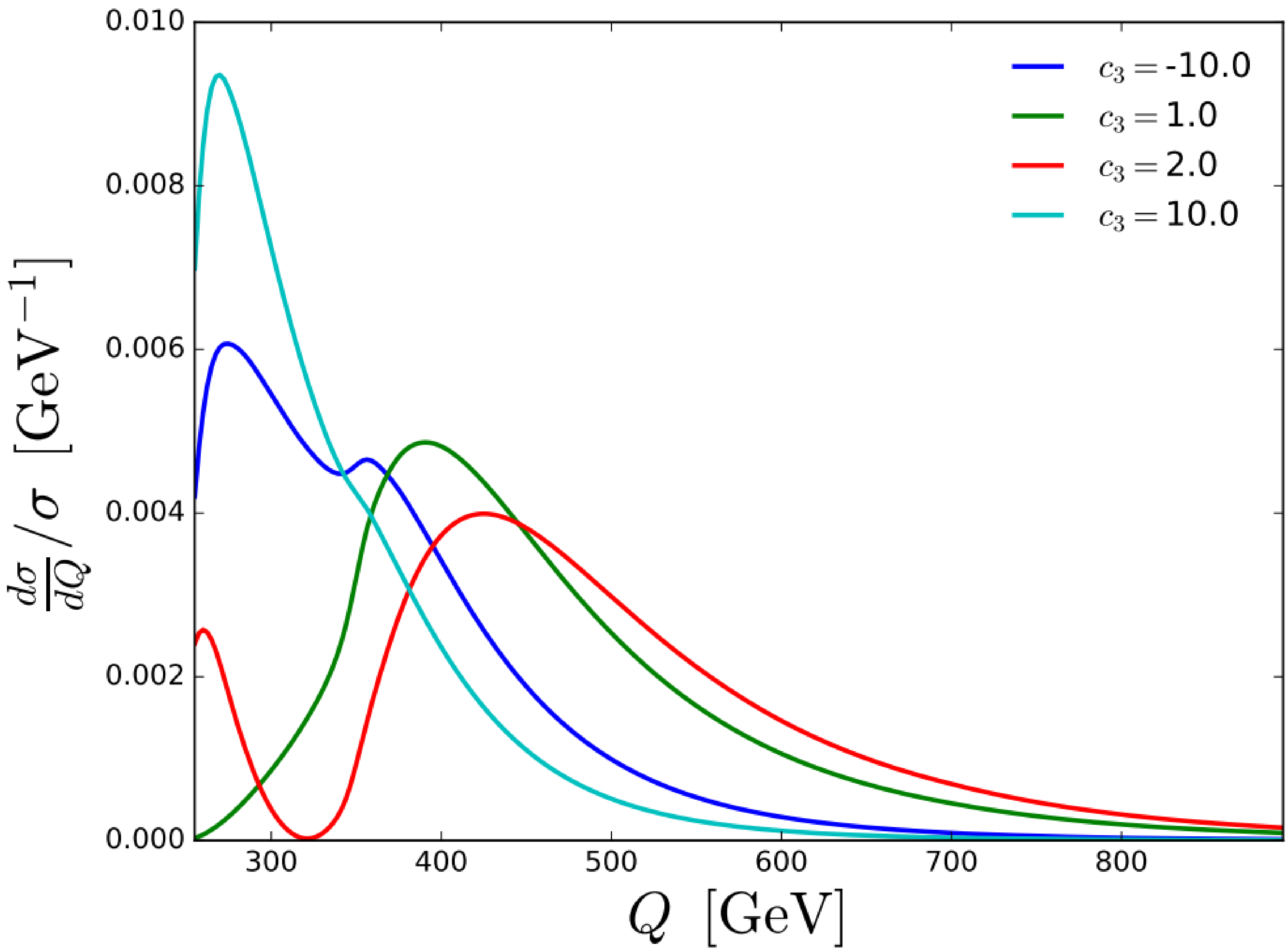
$$\begin{aligned} F_{2\Box} = 2m_q^2\Bigg[& 2(8m_q^2 + s - 2m_H^2)\Big(m_q^2(D_0(p_1,p_2,p_3) + (1 \leftrightarrow 2) + (2 \leftrightarrow 3)) \\ & - C_0(p_3,p_4)\Big) - 2\left(sC_0(p_1,p_2) + (t - m_H^2)C_0(p_1,p_3) + (u - m_H^2)C_0(p_2,p_3)\right) \\ & + \frac{1}{sp_T^2}\Big((us(8um_q^2 - u^2 - m_H^4)D_0(p_1,p_2,p_3) + st(8tm_q^2 - t^2 - m_H^4)D_0(p_2,p_1,p_3) \\ & + (8m_q^2 + s - 2m_H^2)\Big(s(s - 2m_H^2)C_0(p_1,p_2) + s(s - 4m_H^2)C_0(p_3,p_4) \\ & + 2t(m_H^2 - t)C_0(p_1,p_3) + 2u(m_H^2 - u)C_0(p_2,p_3)\Big)\Big)\Bigg] \end{aligned} \tag{3.260}$$

These results are expressed in terms of basic triangle and box scalar integrals:

$$C_0(p_1,p_2) = \int \frac{d^4k}{i\pi^2}\frac{1}{(k^2 - m_q^2)((k+p_1)^2 - m_q^2)((k+p_{12})^2 - m_q^2)} \tag{3.261}$$

$$D_0(p_1,p_2,p_3) = \int \frac{d^4k}{i\pi^2}\frac{1}{(k^2 - m_q^2)((k+p_1)^2 - m_q^2)((k+p_{12})^2 - m_q^2)((k+p_{123})^2 - m_q^2)} \tag{3.262}$$

Sensitivity to λ_{hhh} in the M_{hh} distribution

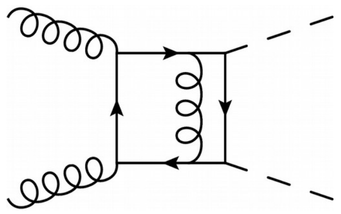


NLO corrections

- Calculation of QCD corrections is really difficult: exact NLO only became available in 2016

Borowka et al. arXiv:1604.06447

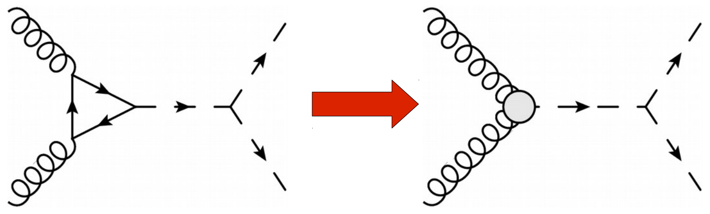
- Two-loop virtual corrections computed numerically using sector decomposition

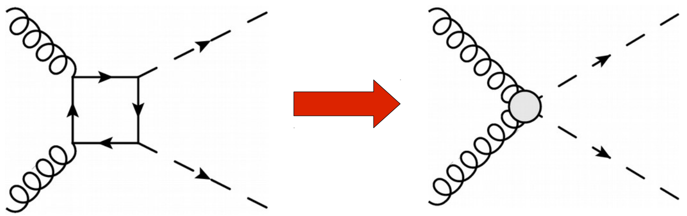


- NLO corrections are huge: about 70% increase for the total cross section at 14TeV

- Beyond NLO: not possible to compute the full corrections with the current technology

- We can use an approximation: heavy top quark mass limit (HTL, also called HEFT)





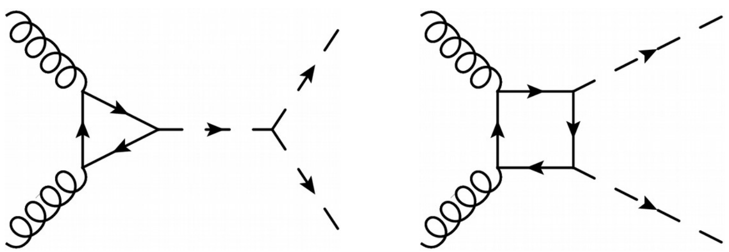
- Effective gluon-Higgs coupling: the process is tree-level in the effective theory

QCD corrections in the HTL

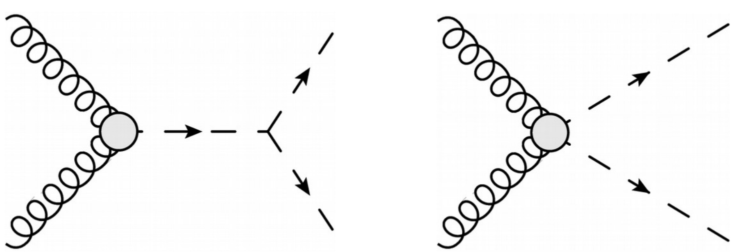
D. de Florian and JM, 1309.6594
Grigo et al., 1408.2422

E.g.: virtual corrections

Leading Order (1-loop)



Full theory



Eff. theory

- The effective vertices have the same structure!

$$\mathcal{L}_{ggH} \propto G_{\mu\nu} G^{\mu\nu} H/v$$

$$\mathcal{L}_{ggHH} \propto G_{\mu\nu} G^{\mu\nu} (H/v)^2$$

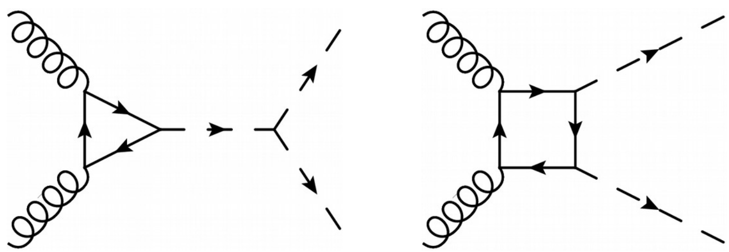
- Profit from the single Higgs production results!

QCD corrections in the HTL

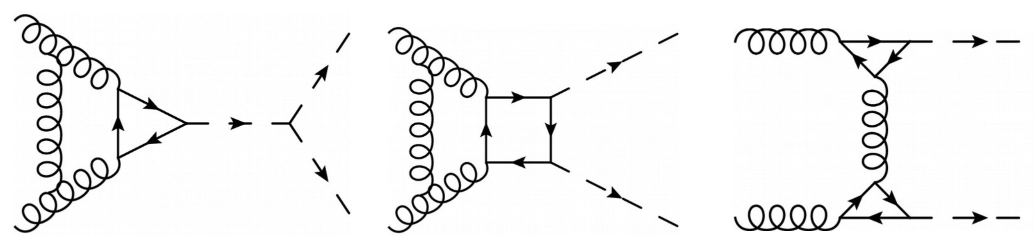
D. de Florian and JM, 1309.6594
Grigo et al., 1408.2422

E.g.: virtual corrections

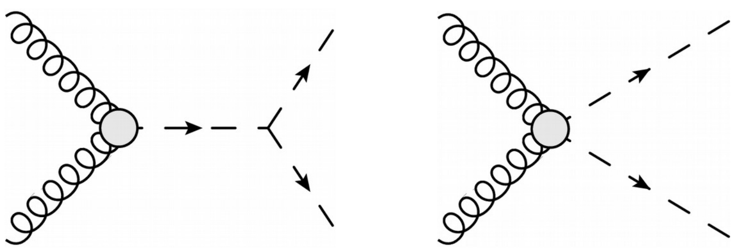
Leading Order (1-loop)

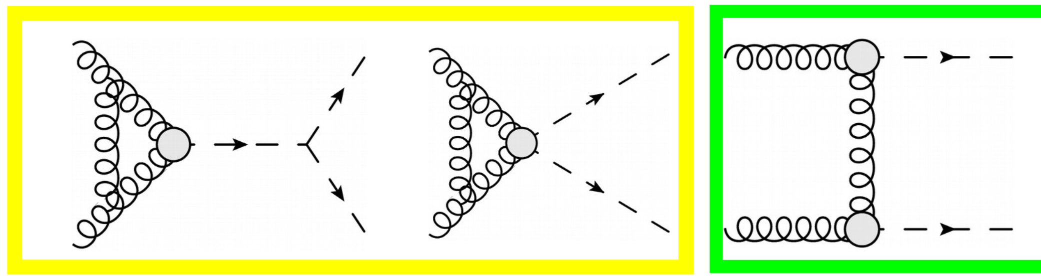


Next-to-Leading Order (2-loop)



Full theory





Eff. theory

- The effective vertices have the same structure!

$$\mathcal{L}_{ggH} \propto G_{\mu\nu}G^{\mu\nu}\, H/v$$

$$\mathcal{L}_{ggHH} \propto G_{\mu\nu}G^{\mu\nu}\, (H/v)^2$$

- Profit from the single Higgs production results!

- We can split the calculation

$$Q^2 \frac{d\hat{\sigma}}{dQ^2} = \hat{\sigma}^a + \hat{\sigma}^b$$

Single-Higgs like

Starts at NLO

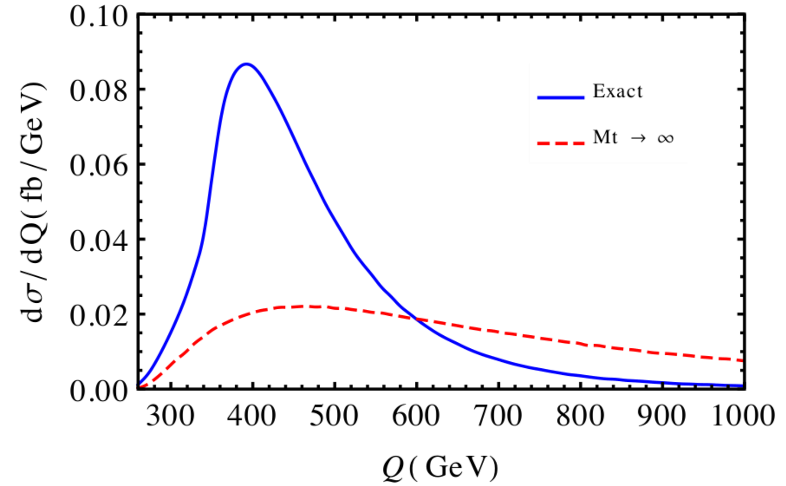
New topologies with two effective vertices

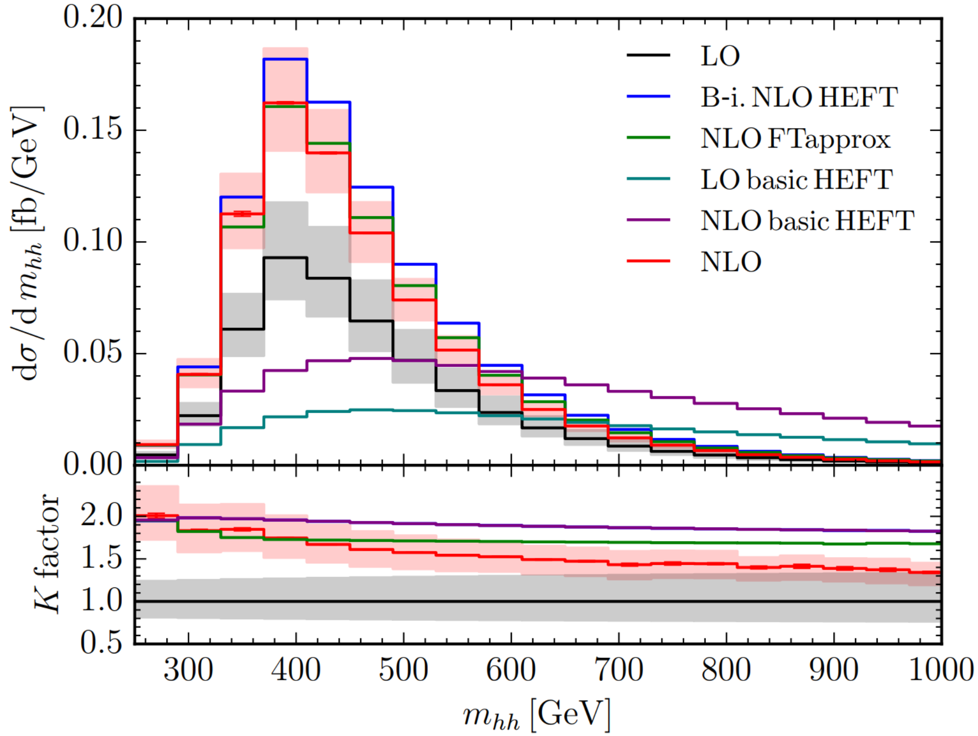
- Same idea extended at NNLO

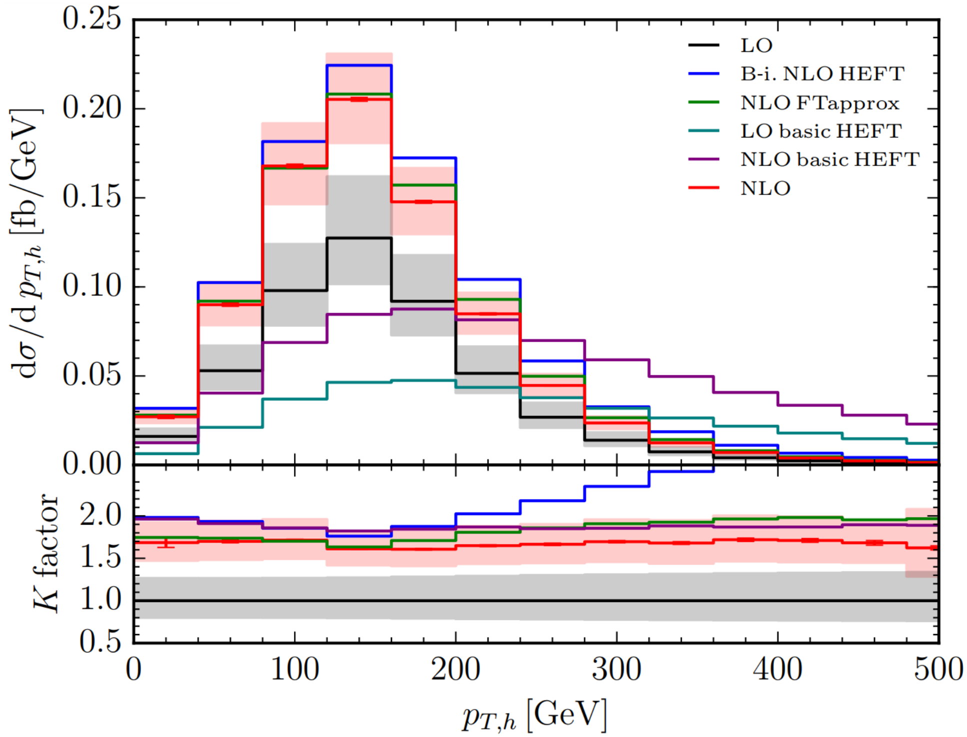
HTL vs full theory

- Large Mt limit → Much worse than for single Higgs due to the larger invariant mass of the system

- Huge improvement if we normalize the NLO corrections by the exact LO (Born-improved HTL)





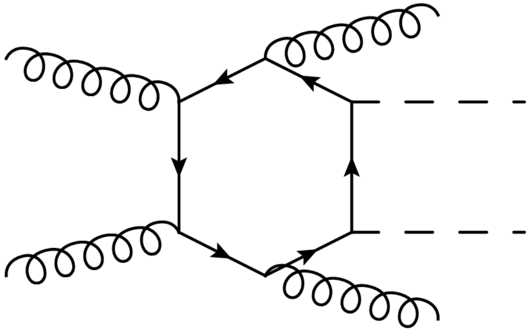


- Born improved overestimates the NLO total XS by a 15%
- Still poor description of the tail of some distributions (associated with hard radiation)
- Better approximation needed for accurate NNLO results

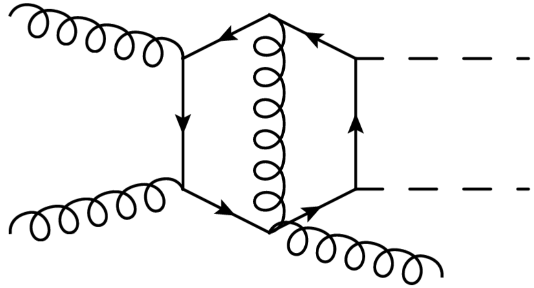
HH at NNLO with M_t effects

Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, JM [arXiv:1803.02463]

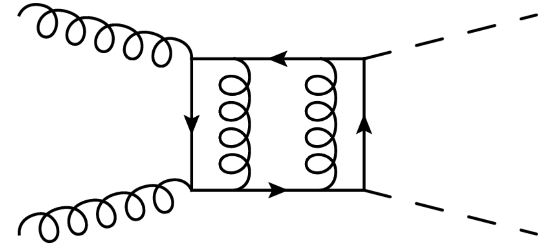
- Type of corrections in the NNLO exact calculation:



Double real (1-loop)



Real-virtual (2-loop)



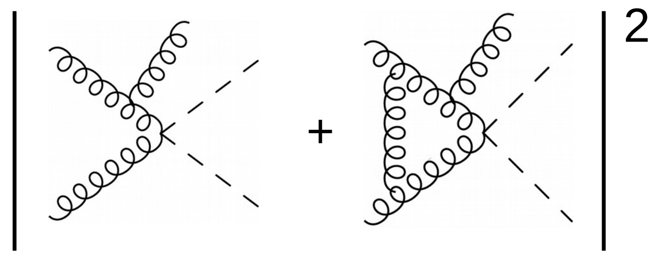
Double virtual (3-loop)

Computable using 1-loop amplitude generators

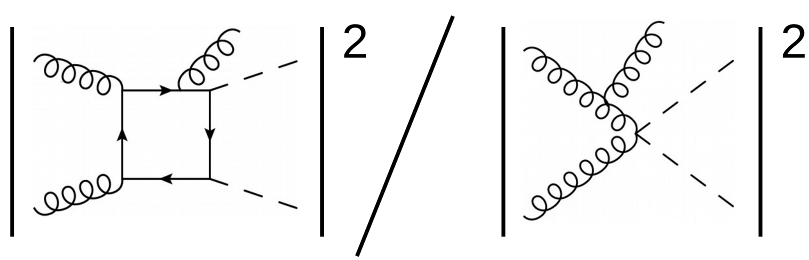
Out of reach for the moment

- Idea: construct an approximation that treats the double real corrections in an exact way

E.g. the squared amplitude:

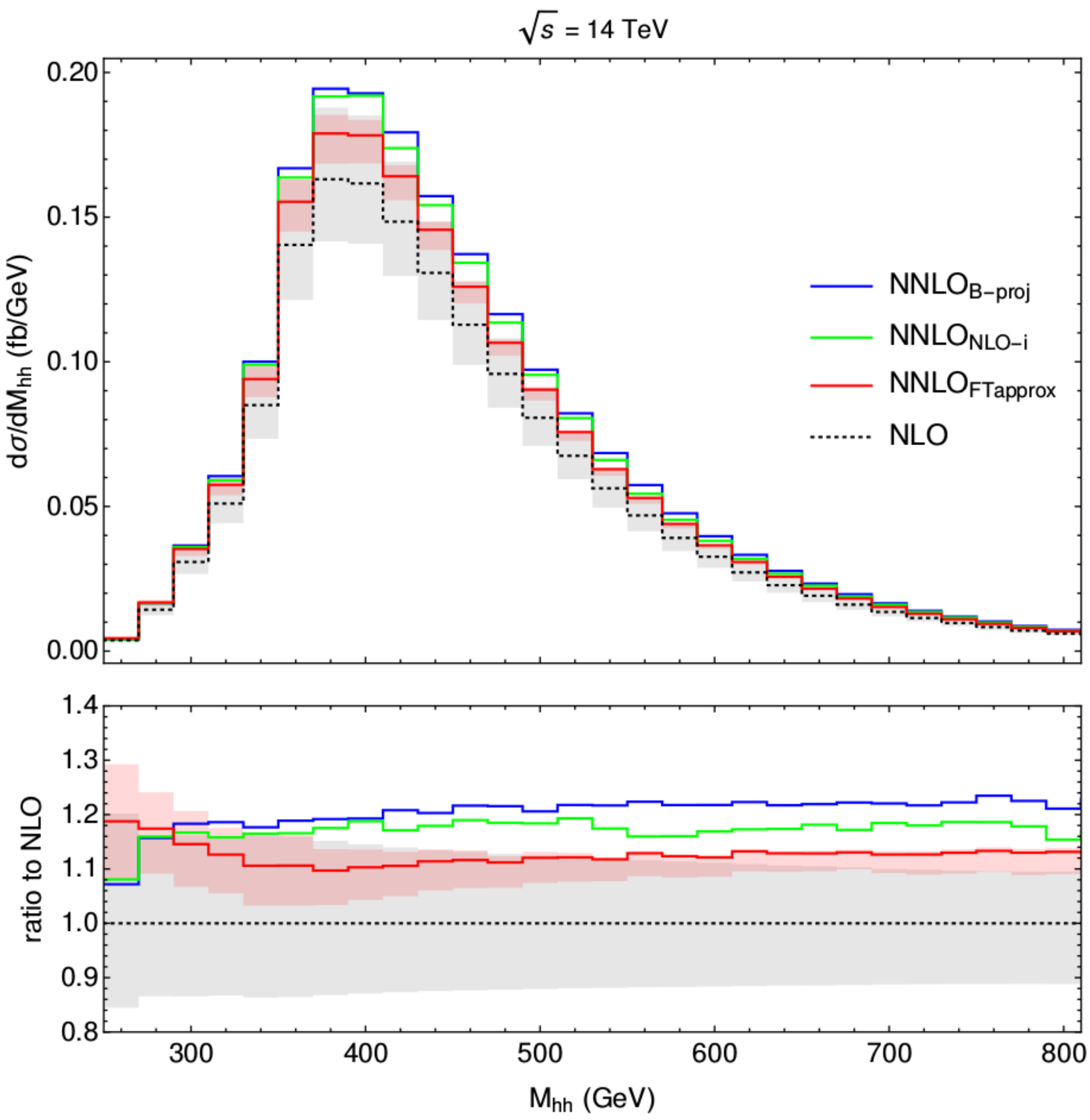


is reweighted by:



- Most advanced prediction available for this process

HH at NNLO with M_t effects



- Big reduction of the uncertainties related to the truncation of the perturbative expansion
- Overlap with the NLO band, showing signs of convergence
- Corrections of the order of a 12% for the total XS
- Uncertainties related to the approximation estimated at the few percent level