Higgs pair production cross section: theoretical status

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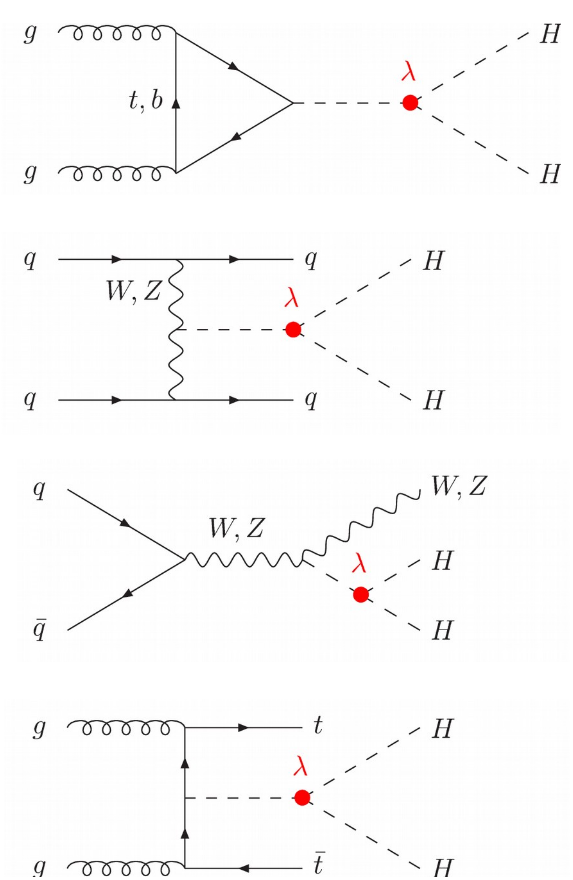
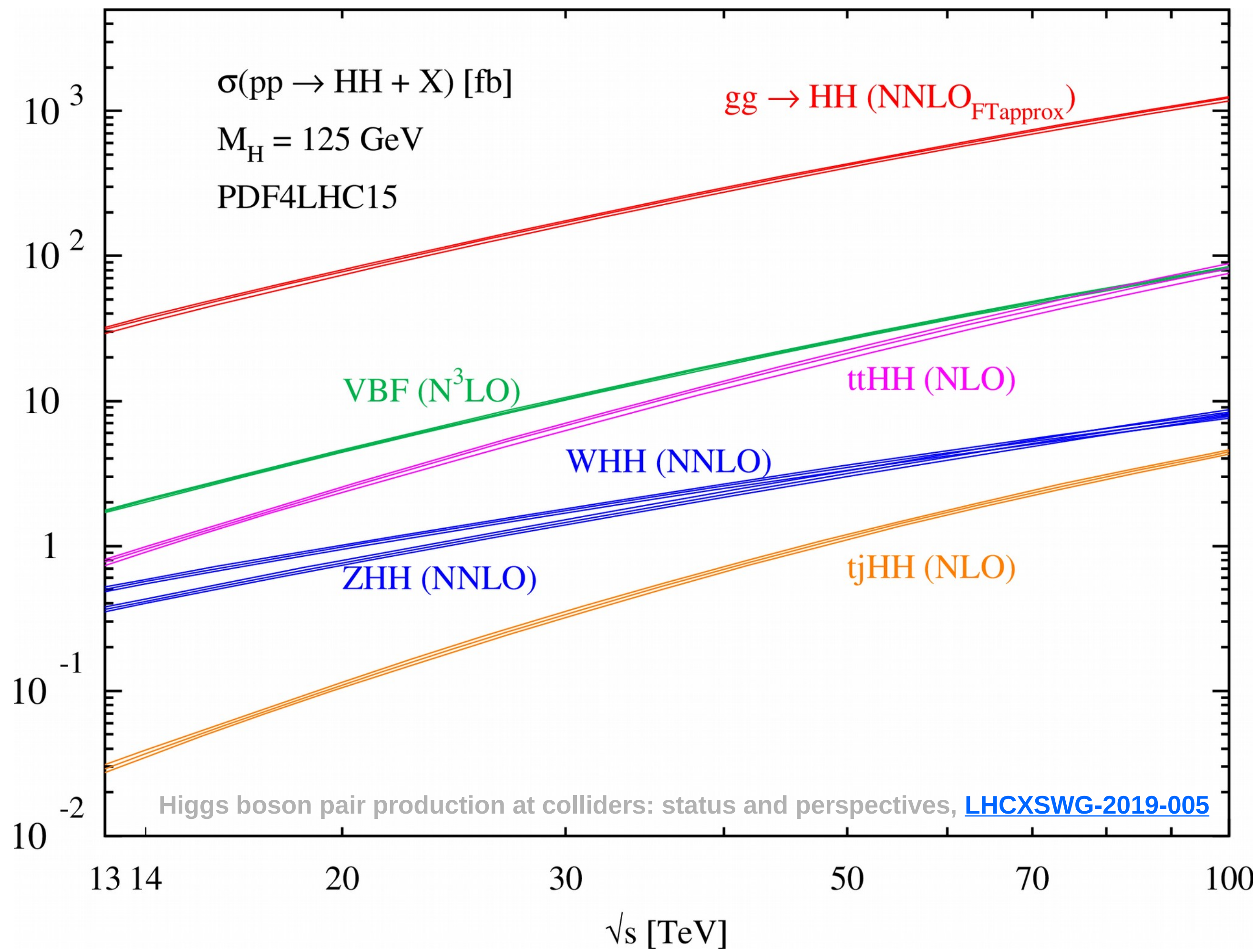
Outline

- Overview of production modes
- Top-quark mass scheme and scale uncertainties
- Cross sections for modified self-coupling
- Other recent developments





Overview of production modes

- The cross sections for all the production modes have been updated to the most accurate available predictions in the hh twiki page
- Results available for different collider energies and Higgs boson masses

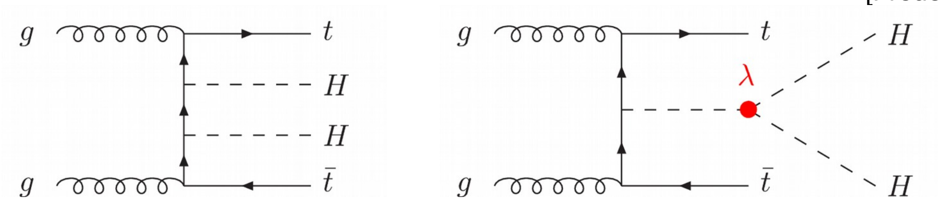
$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
ggF HH	$31.05^{+2.2\%}_{-5.0\%} \pm 3.0\%$	$36.69^{+2.1\%}_{-4.9\%} \pm 3.0\%$	$139.9^{+1.3\%}_{-3.9\%} \pm 2.5\%$	$1224^{+0.9\%}_{-3.2\%} \pm 2.4\%$
VBF HH	$1.73^{+0.03\%}_{-0.04\%} \pm 2.1\%$	$2.05^{+0.03\%}_{-0.04\%} \pm 2.1\%$	$8.40^{+0.11\%}_{-0.04\%} \pm 2.1\%$	$82.8^{+0.13\%}_{-0.04\%} \pm 2.1\%$
ZHH	$0.363^{+3.4\%}_{-2.7\%} \pm 1.9\%$	$0.415^{+3.5\%}_{-2.7\%} \pm 1.8\%$	$1.23^{+4.1\%}_{-3.3\%} \pm 1.5\%$	$8.23^{+5.9\%}_{-4.6\%} \pm 1.7\%$
W^+HH	$0.329^{+0.32\%}_{-0.41\%} \pm 2.2\%$	$0.369^{+0.33\%}_{-0.39\%} \pm 2.1\%$	$0.941^{+0.52\%}_{-0.53\%} \pm 1.8\%$	$4.70^{+0.90\%}_{-0.96\%} \pm 1.8\%$
W^-HH	$0.173^{+1.2\%}_{-1.3\%} \pm 2.8\%$	$0.198^{+1.2\%}_{-1.3\%} \pm 2.7\%$	$0.568^{+1.9\%}_{-2.0\%} \pm 2.1\%$	$3.30^{+3.5\%}_{-4.3\%} \pm 1.9\%$
$t\bar{t}HH$	$0.775^{+1.5\%}_{-4.3\%} \pm 3.2\%$	$0.949^{+1.7\%}_{-3.1\%} \pm 3.1\%$	$5.24^{+2.9\%}_{-6.4\%} \pm 2.5\%$	$82.1^{+7.9\%}_{-7.4\%} \pm 1.6\%$
$tjHH$	$0.0289^{+5.5\%}_{-3.6\%} \pm 4.7\%$	$0.0367^{+4.2\%}_{-1.8\%} \pm 4.6\%$	$0.254^{+3.8\%}_{-2.8\%} \pm 3.6\%$	$4.44^{+2.2\%}_{-2.8\%} \pm 2.4\%$

Higgs boson pair production at colliders: status and perspectives, LHCXSWG-2019-005

Sub-leading channels

- **HH** associated production with **top quarks** known at **NLO**

[Frederix et al., 1401.7340]



$$\mathrm{LO}(14\ \mathrm{TeV}):\ 1.245^{+36\%}_{-25\%}$$

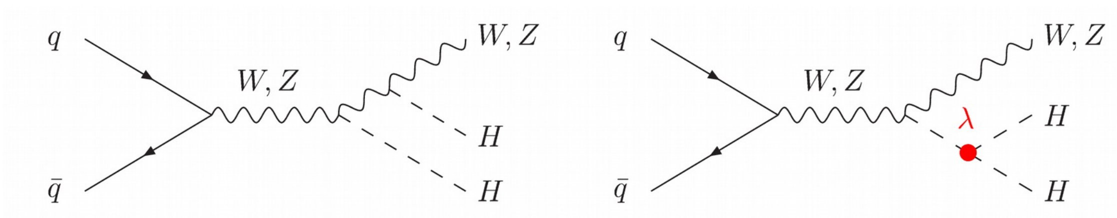
$$\mathrm{NLO}(14\ \mathrm{TeV}):\ 0.981^{+2.3\%}_{-9.0\%}$$

Obs: not the same setup as in previous table

- Negative corrections (about -20%), large reduction of scale uncertainties

- **HH** associated production with **vector bosons** known at **NNLO**

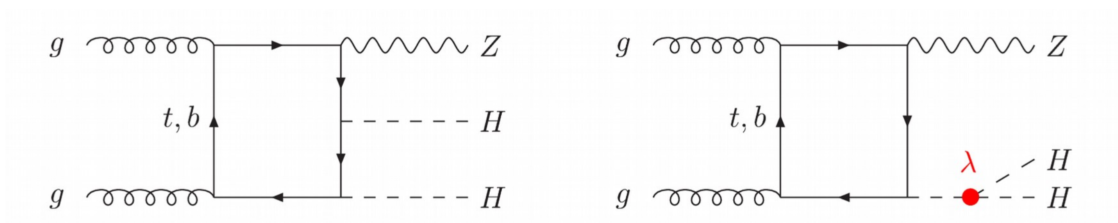
[Baglio et al., 1212.5581]; [Li et al., 1607.06382, 1710.02464]



- QCD corrections increase total cross section by about 30%

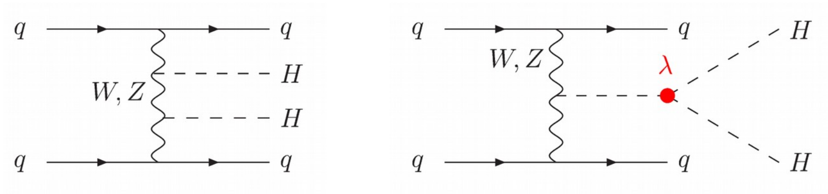
- ZHH has sizeable gluon-initiated loop-induced component, +20-30% in NNLO correction

(considerably larger than in ZH)



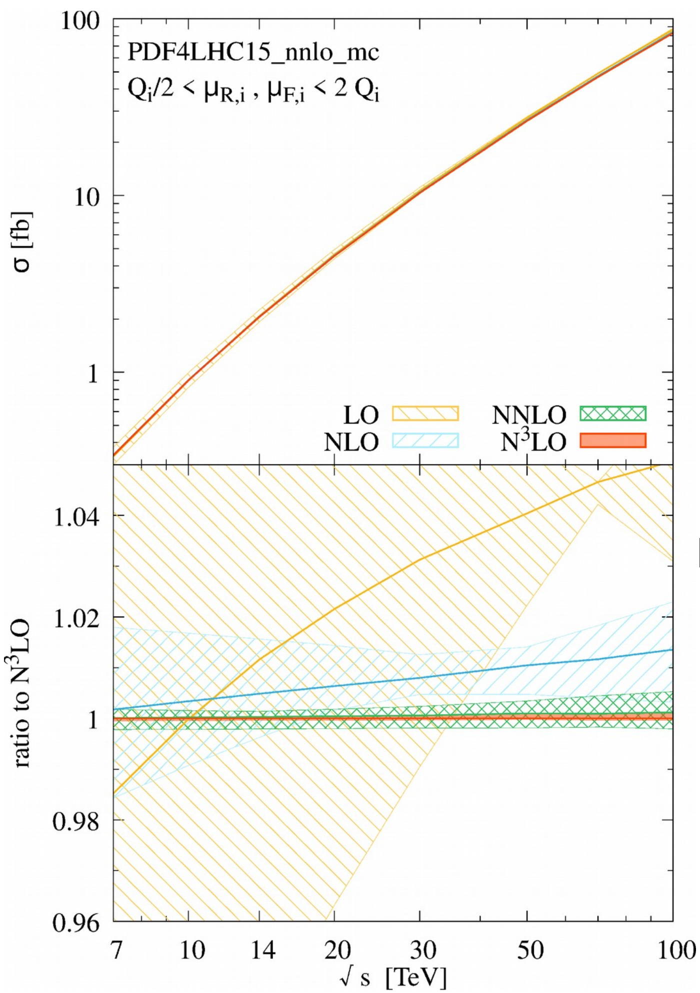
Vector boson fusion

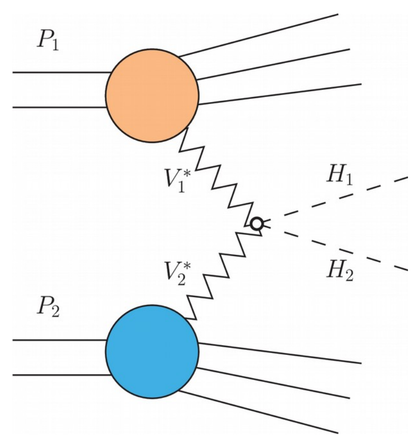
- Second-largest production mode



- Corrections known at N^{3}LO within the structure function approach, fully differential at NNLO

[Dreyer and Karlberg, 1811.07906, 1811.07918]



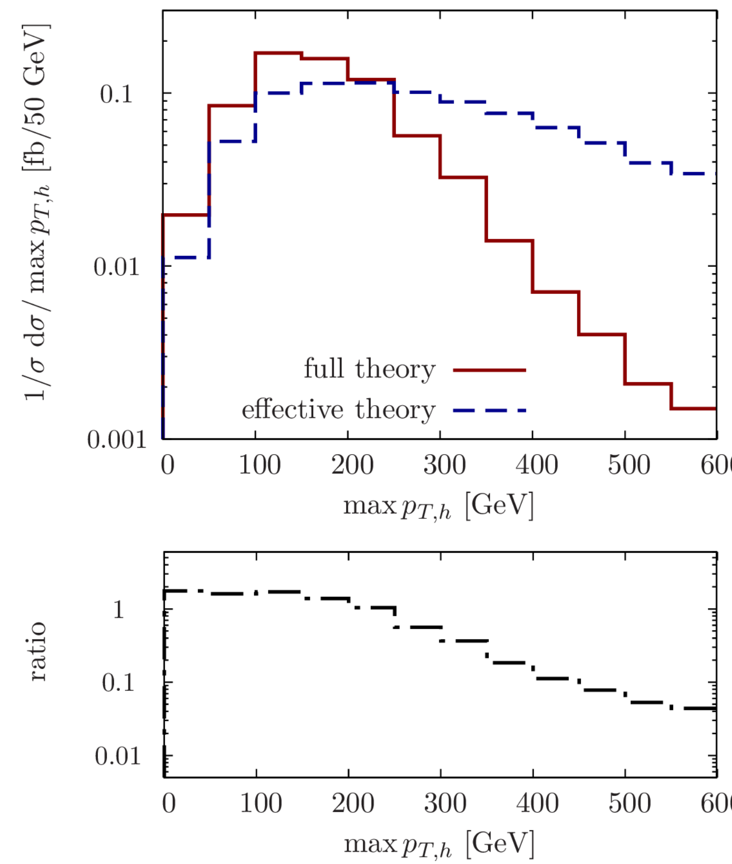


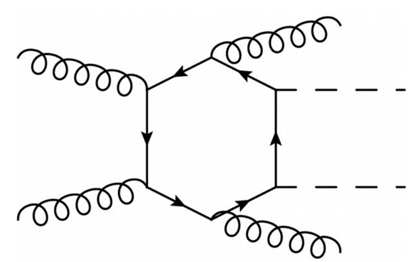
NLO corrections around 10%, while NNLO and N^{3}LO are at the percent and sub-percent level

Scale uncertainties at the per-mille level

- Gluon fusion contribution to HH+2jets is very large
- Crucial to simulate it with full top-quark dependence

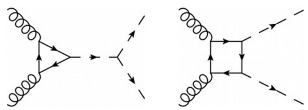
[Dolan et al., 1310.1084]





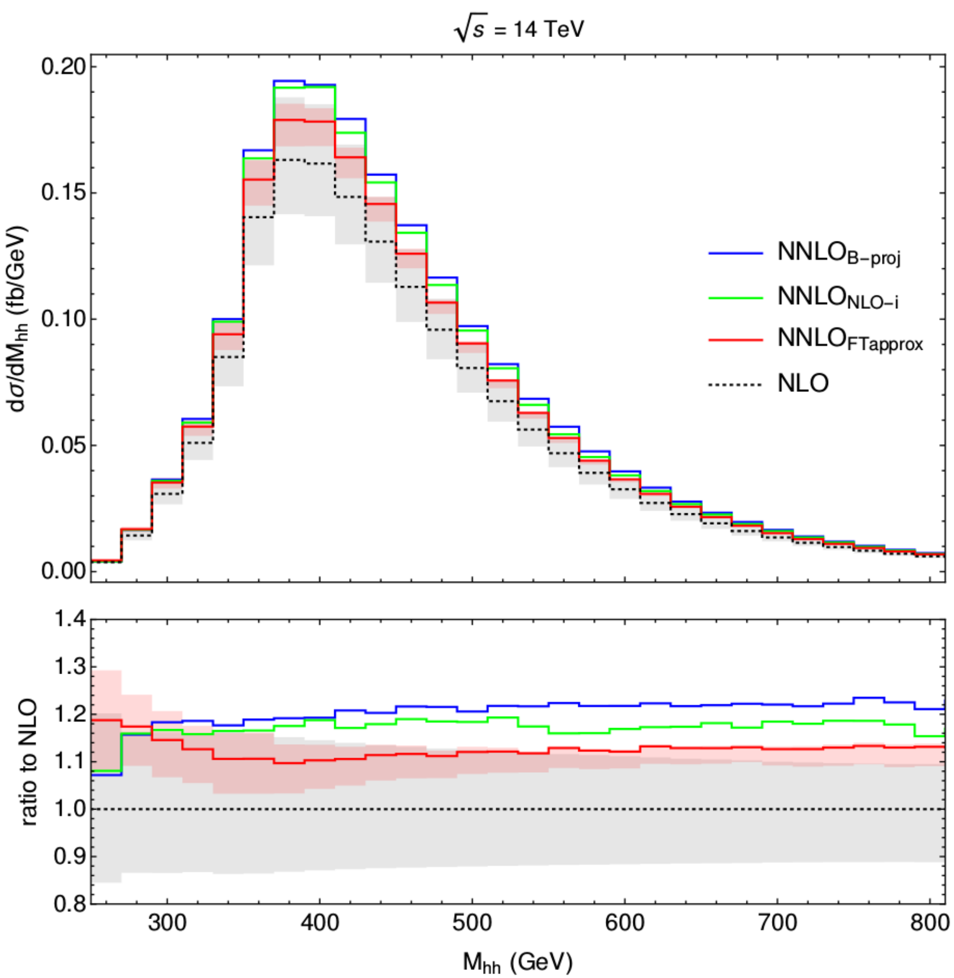
OpenLoops2+Sherpa
for LO loop-induced provided
by Jonas Lindert

Gluon fusion

- Largest production mode 
- NLO corrections known with full top-quark mass dependence
  [S. Borowka et al., 1604.06447, 1608.04798], [J. Baglio et al., 1811.05692]
- Current recommendation: $\text{NNLO}_{\text{FTapprox}}$ → full NLO + partial m_t dependence at NNLO
  [M. Grazzini, JM et al., 1803.02463]

↓ reweighting

$$\mathcal{R}(ij \to HH + X) = \frac{\mathcal{A}^{\text{Born}}_{\text{Full}}(ij \to HH + X)}{\mathcal{A}^{(0)}_{\text{HEFT}}(ij \to HH + X)}$$

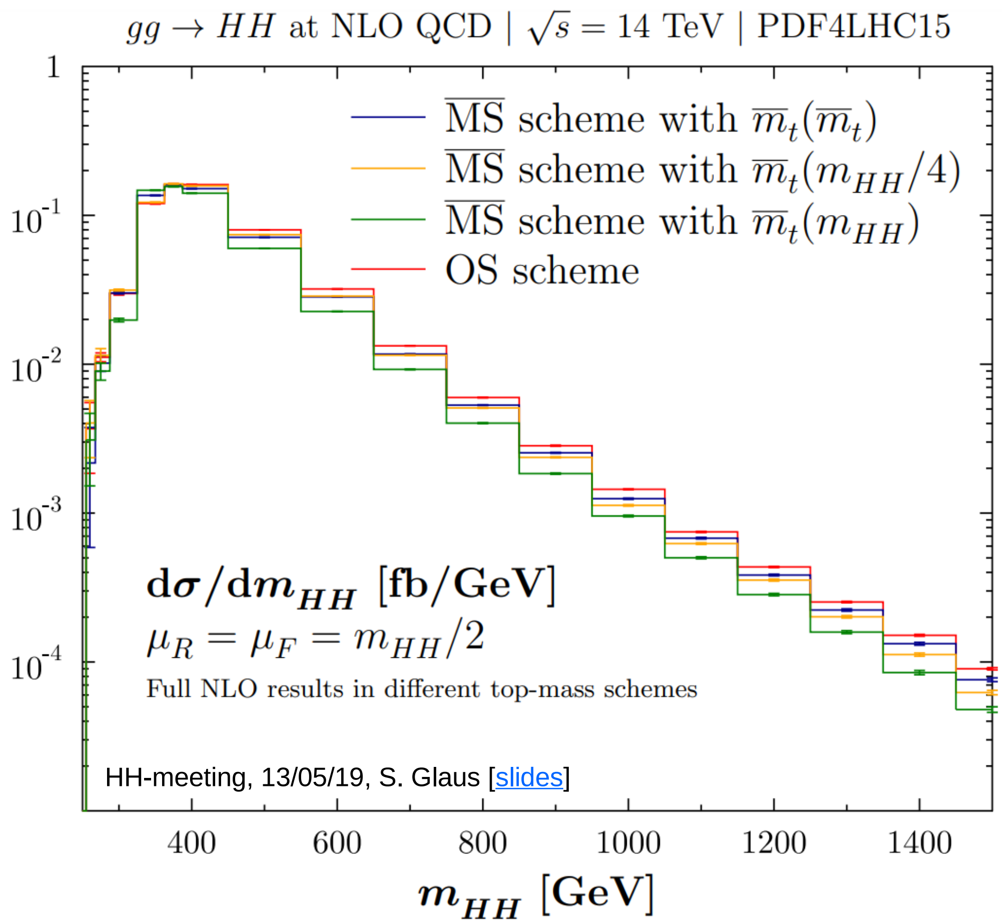


- NLO corrections: ~65% increase
  Scale uncertainties ~±13%
- NNLO (FTapprox), additional 12%
  Reduced scale uncertainty, +2%-5%
- Missing finite mt effects estimated to be at the few percent level
- Obs: here we are always considering the on-shell scheme for the top mass!

Top mass scheme uncertainty

- NLO HH cross section has also been computed in the $\overline{\text{MS}}$ scheme

[Baglio at al., 1811.05692]



$$\frac{d\sigma(gg \to HH)}{dQ}\bigg|_{Q=300\text{ GeV}} = 0.0298(7)^{+6\%}_{-34\%}\ \text{fb/GeV},$$

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

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

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

Pole mass central value

Unc. from variation $\overline{m}_t(m_{hh}) - \overline{m}_t(m_{hh}/4)$

For total cross section (preliminary)

$$\sigma(gg \to HH) = 32.78^{+4\%}_{-17\%}\ \text{fb}$$

HH-meeting, 13/05/19, S. Glaus [slides]

- Large variation also present in single Higgs *for a heavy Higgs boson*

HH-meeting, 13/05/19, S. Glaus [slides]

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

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

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

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

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

$$\sigma(gg \to H)\big|_{m_H=1200\text{ GeV}} = 0.402^{+0.0\%}_{-26.0\%}\ \text{pb}$$

Top mass scheme uncertainty

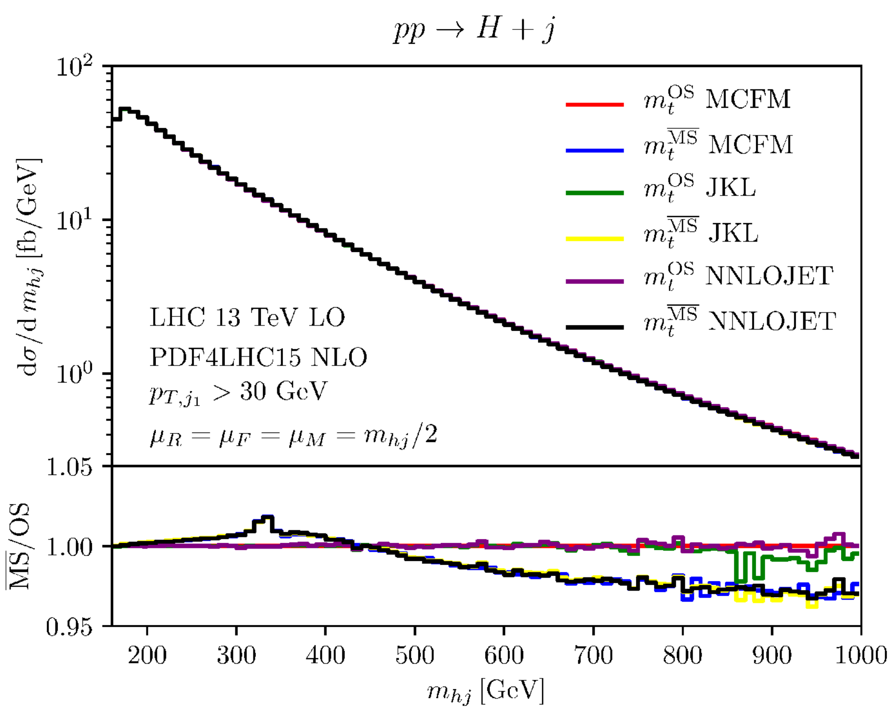
- Reduction of these scheme and scale uncertainties is unclear

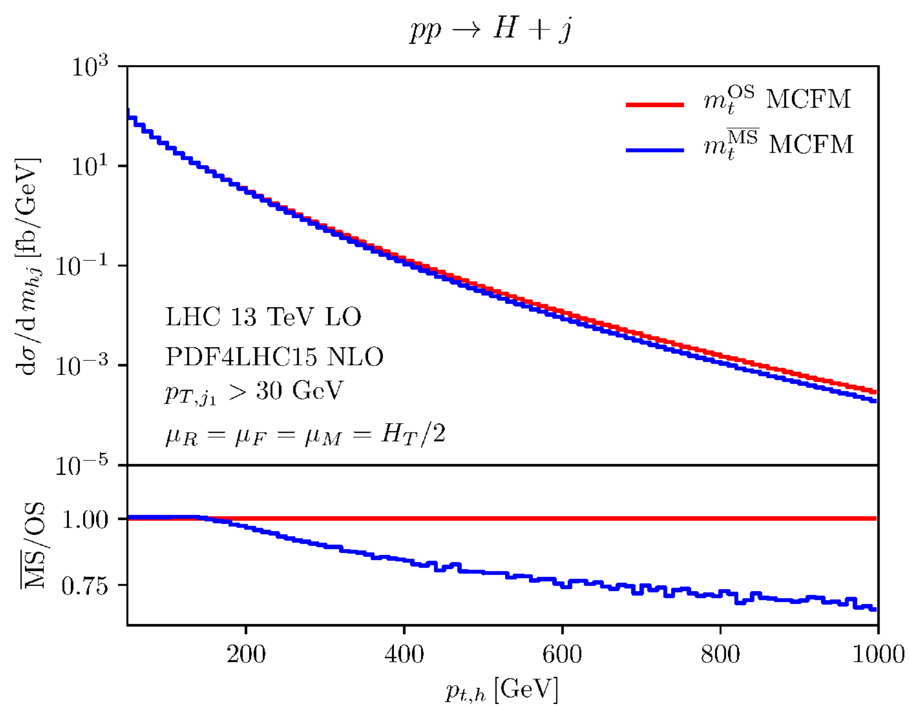
HH-meeting, 17/06/19, M. Spira [slides]

- Study of top mass scheme uncertainties in HH, HJ, ggHZ (vs ggZZ), H* started at LH

[LH twiki: mass scheme uncertainties, S. Jones, M. Spira, ...]

  - How are these various processes affected by the mass scheme uncertainty?
  - To what extent is this problem coming from “Triangle-type” topologies vs “Box-type” topologies? (See for example expanded result of Steinhauser et al.)
  - Can we say anything about what is a sensible (or not sensible) choice of scheme?
  - Should we be treating masses running in the loops differently from those entering the Yukawa couplings?
  - How much of this behaviour is due to the mass dependence of the Yukawa vs. top quarks in loop?
  - How large is this uncertainty in the context of the onshell/ofshell Higgs measurements?





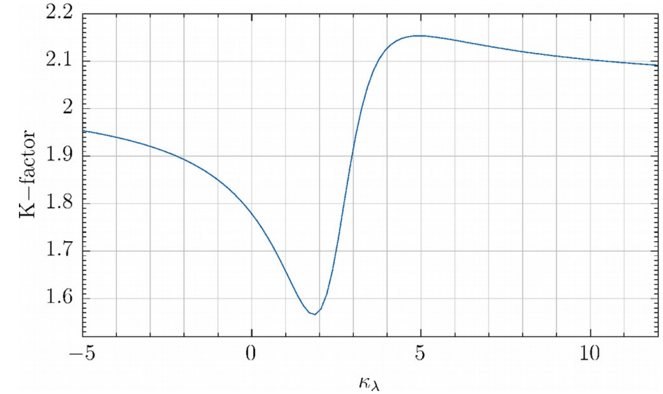
[Plots from S. Jones]

Cross section vs λ_{hhh}

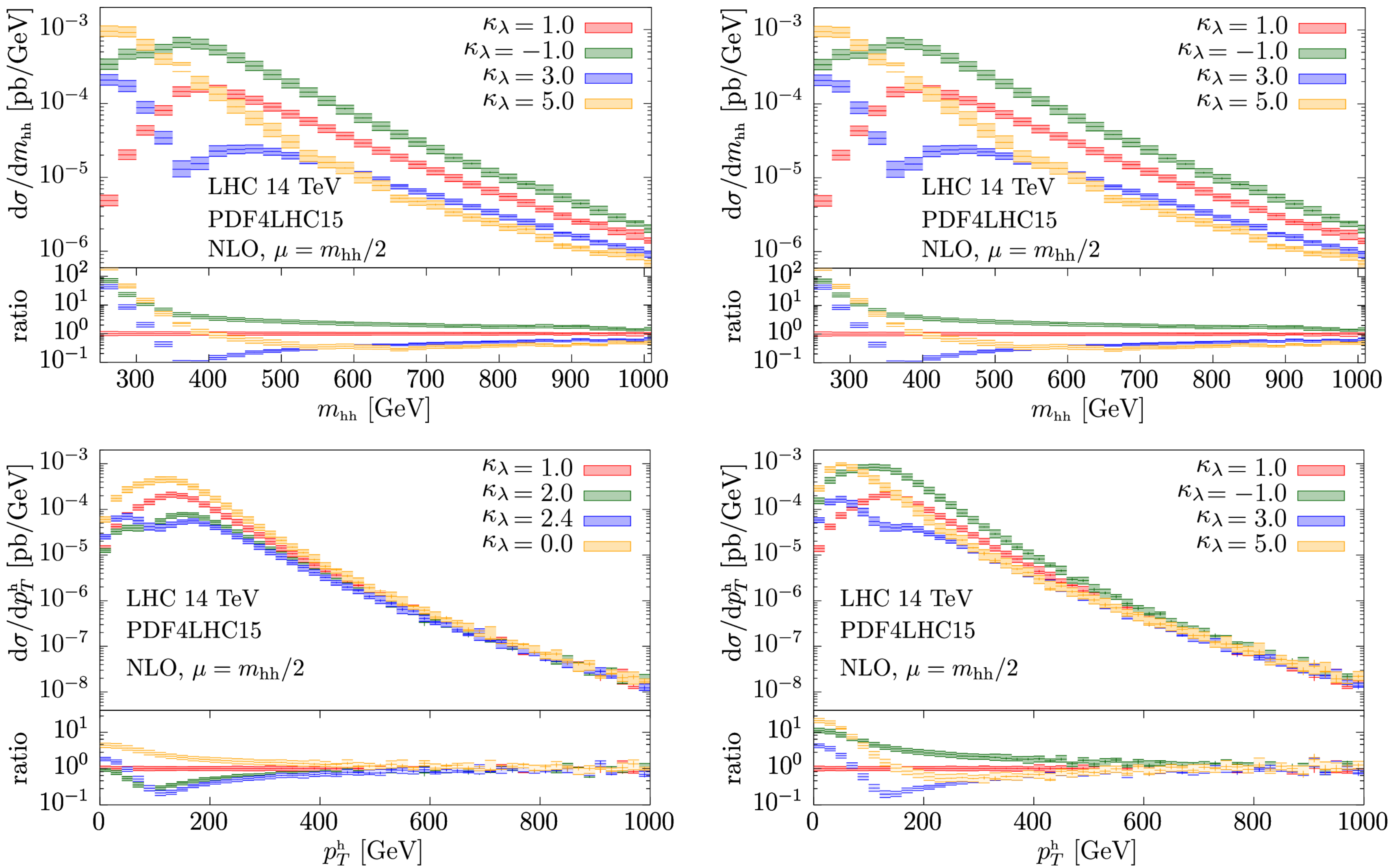
- NLO generator including λ variations now available:

[G. Heinrich et al., 1903.08137]

http://powhegbox.mib.infn.it/
in User-Processes-V2/ggHH/



- Fully differential predictions can be obtained:



- These results still need to be matched to the higher SM precision ($NNLO_{FTapprox}$)

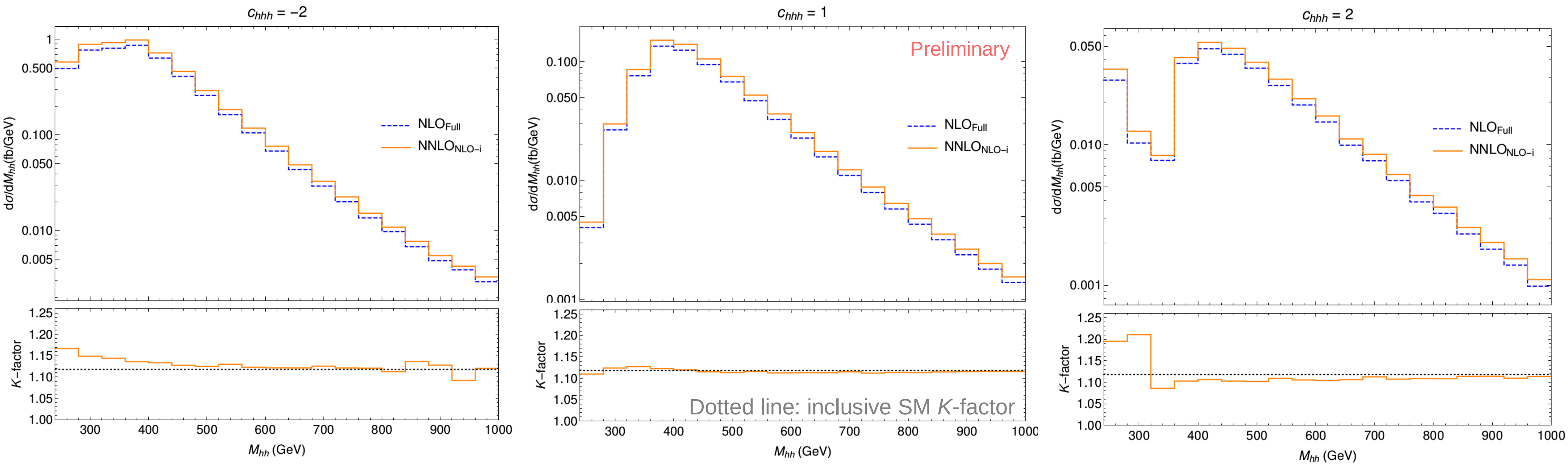
Cross section vs λ_{hhh}

- Simplest approach: multiply NLO prediction by SM ratio: $NNLO_{FTapprox}/NLO$

Not optimal: what about scale uncertainties? And differential distributions?

- More advanced combination of full NLO and (improved-)HTL NNLO started at Les Houches

[G. Heinrich et al., 1903.08137] [D. de Florian, JM, I. Fabre, 1704.05700]



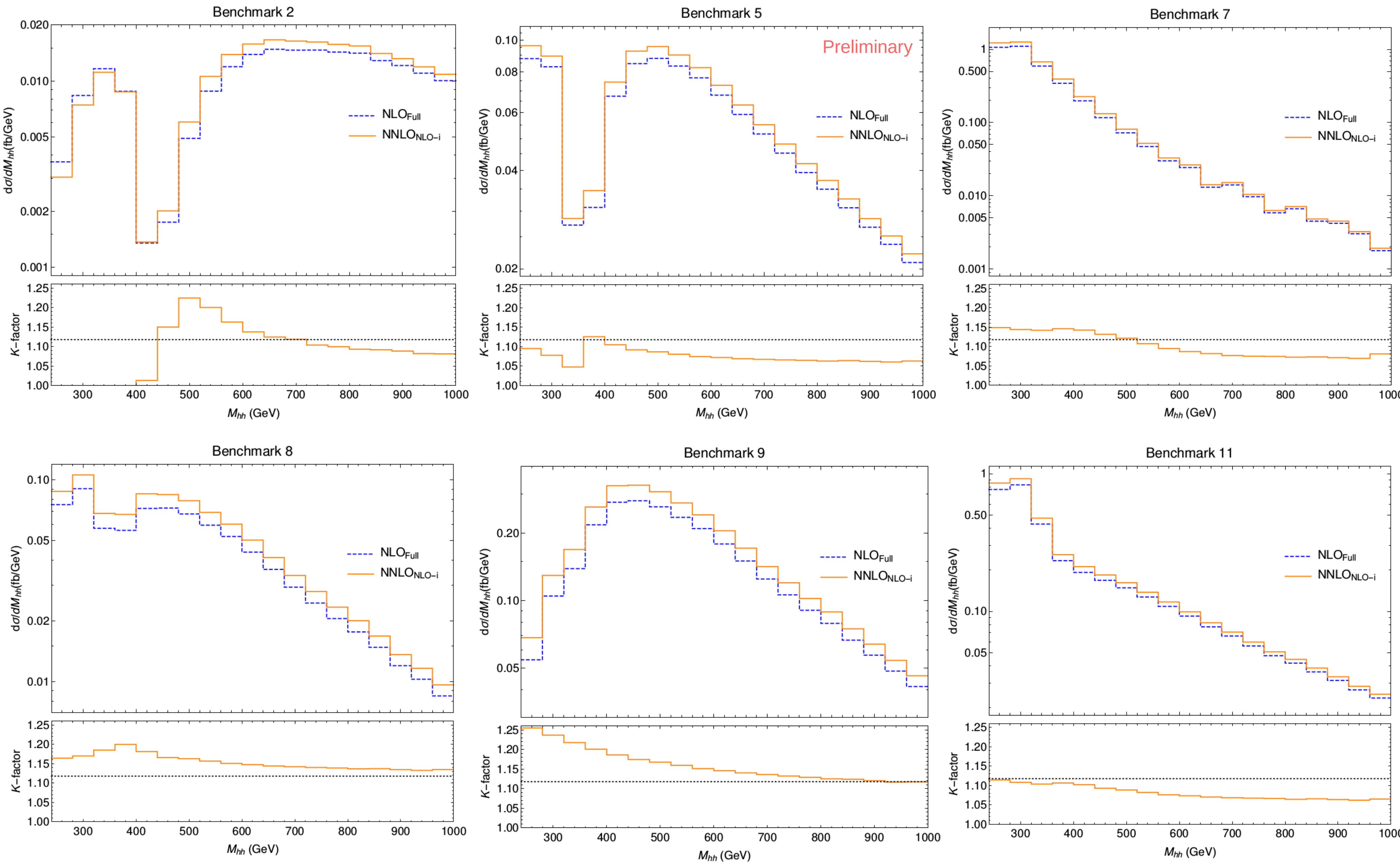
- Rescaling by the SM inclusive *K*-factor seems to be a good approximation in many cases

- In some cases we can have non-uniform *K*-factors, different to the SM one

- This combination will allow to have a proper evaluation of NNLO scale uncertainties for $c_{hhh}\neq 1$

- The previous combination can also be extended to include EFT dimension 6 operators

[Benchmarks from 1806.05162]

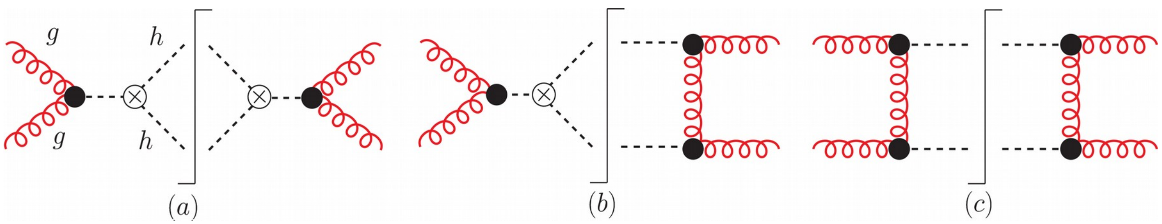


- NNLO K-factors have a much larger variation compared to only self-coupling modifications

Gluon fusion: N^3LO in the HTL

[L. Chen et al., 1909.06808]

- One can profit from single-H results, analogously to what was done at previous orders

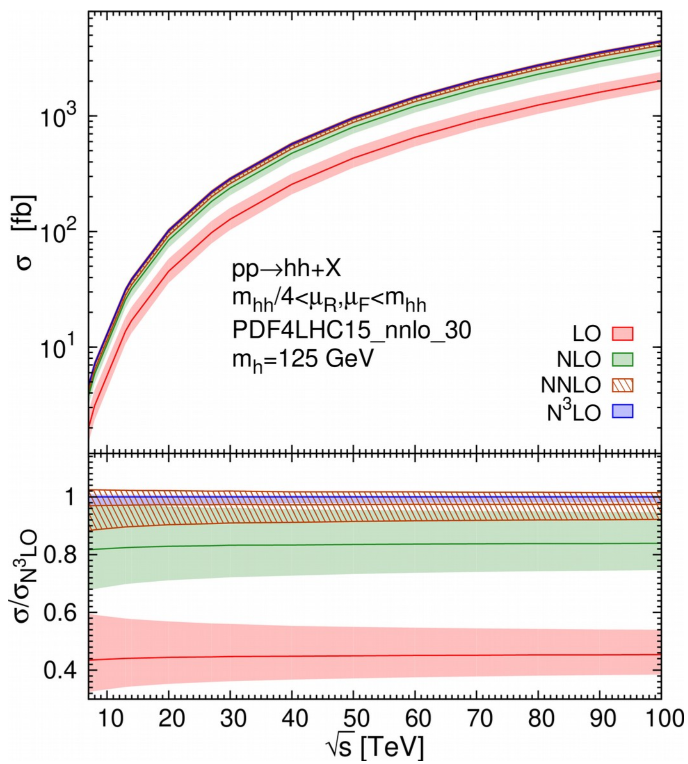


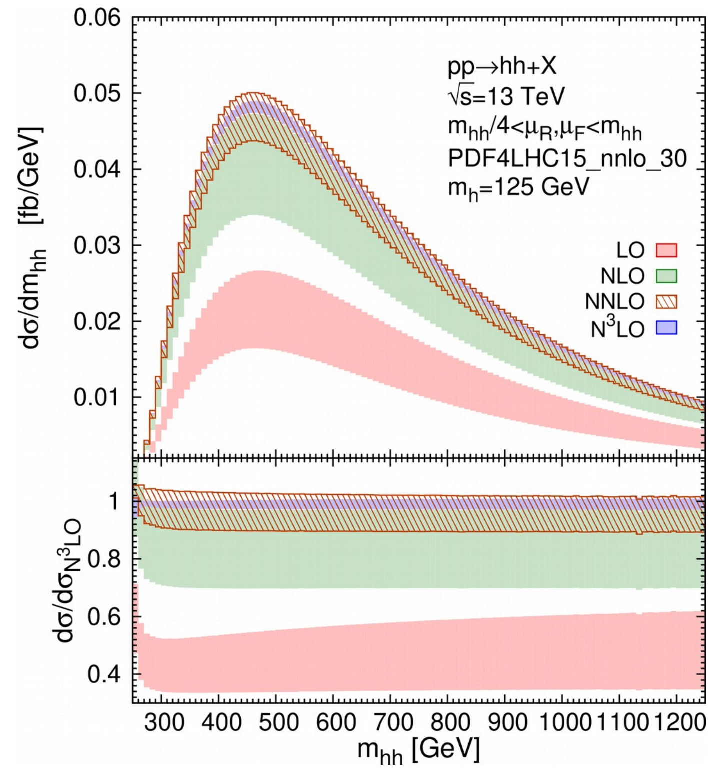
Group contributions according to number of effective ggH vertices

For HH at N3LO, is needed:
(a) at N3LO, (b) at NNLO, (c) at NLO

Increase of about 3% at the LHC w.r.t. the NNLO prediction

Further reduction of the scale uncertainties, around +0.7%-2.8%





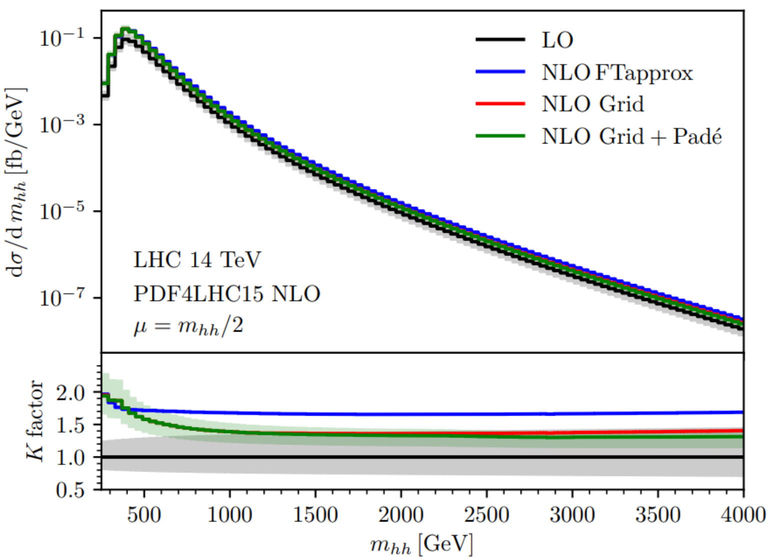
- The phenomenological application of these results remains to be seen, since finite top mass effects need to be taken into account

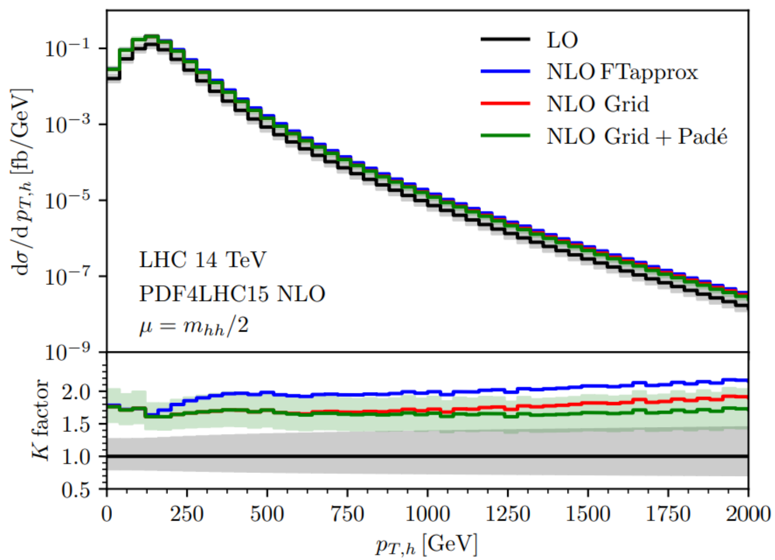
More on finite m_t effects

- Full NLO known numerically, but other approaches based on analytical expansions have been developed in the last years

$1/m_t$ expansion [J. Davies et al., 1909.01361, ...] →	Valid below $2m_t$ threshold
High-energy limit [J. Davies et al., 1811.05489] →	Valid above ~700-800GeV
Small Higgs pT [R. Bonciani et al., 1806.11564] →	Valid below ~750GeV
Large-mt and threshold expansions + conformal mapping and Pade approx. [R. Gröber et al., 1709.07799] →	Valid below ~700GeV

- They might provide a way to improve the knowledge of finite m_t effects beyond NLO
  - Recent application to top mass dependence of Higgs form factor at three loops [J. Davies et al., 1906.00982]
- They could also help to understand the m_t scheme uncertainties in different m_{hh} regions
- Also some practical applications, for instance: improved grid for NLO virtual corrections [J. Davies et al., 1907.06408]



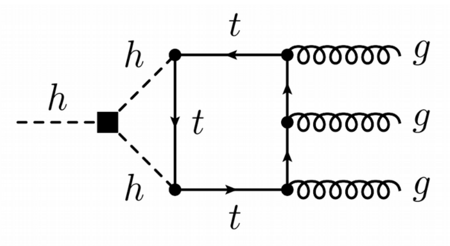


Improved description of the large m_{hh} and $p_{T,h}$ regions

Even more relevant at higher collider energies

Self-coupling from single-H measurements

- Higgs self-coupling can also be constrained via loop effects in single-H production
  [See sec. 2.3.2 of LHCXSWG-2019-005 for a review]
- Differential information very important to improve the limits
- Effect of λ on Higgs transverse momentum spectrum limited by complexity of calculation
- Relevant amplitudes recently computed in large m_t expansion
  [M. Gorbahn and U. Haisch, 1902.05480]

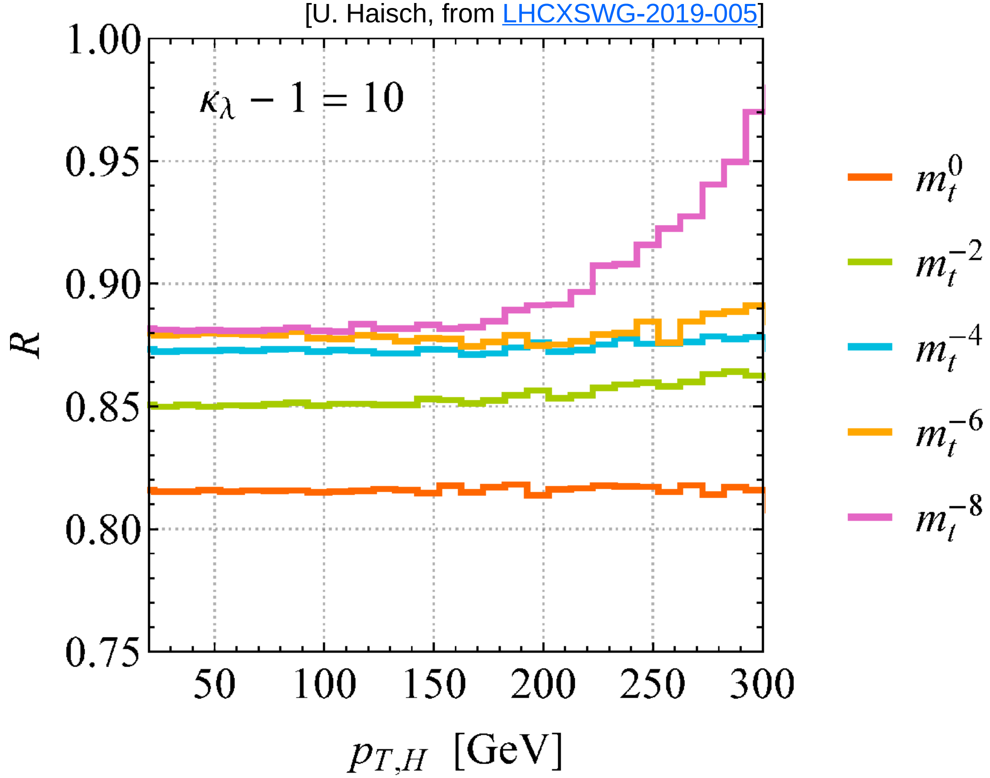


R = Ratio between k_λ - 1 = 10 and SM

Large m_t expansion converges well in the region of validity, $p_{T,H}$<m_t

These results will allow to study the λ effect in low and moderate $p_{T,H}$

[U. Haisch, from LHCXSWG-2019-005]



Summary and outlook

- The precision of the theory predictions for HH production has improved significantly in the last years
- Also subleading channels known to a very high accuracy
- There is still more work to do: top scheme uncertainties, lambda variations at NNLO, further improvements of finite m_t effects beyond NLO…
- Stay tuned! Mailing list: lhc-higgs-hh@cern.ch

HH-review, **Higgs boson pair production at colliders: status and perspectives**,
now available in CDS: LHCXSWG-2019-005

Please send your comments!