Differential Higgs Boson Pair Production at Next-to-Next-to-Leading Order in QCD

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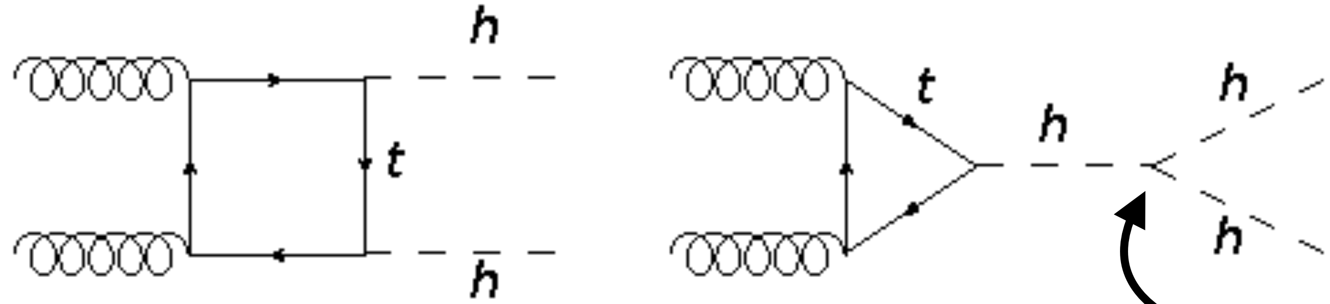
work in collaboration with:
Daniel de Florian, Massimiliano Grazzini, Catalin Hanga, Stefan Kallweit, Philipp Maierhöfer, Javier Mazzitelli, Dirk Rathlev

[arXiv:1606.09519, to appear in JHEP]

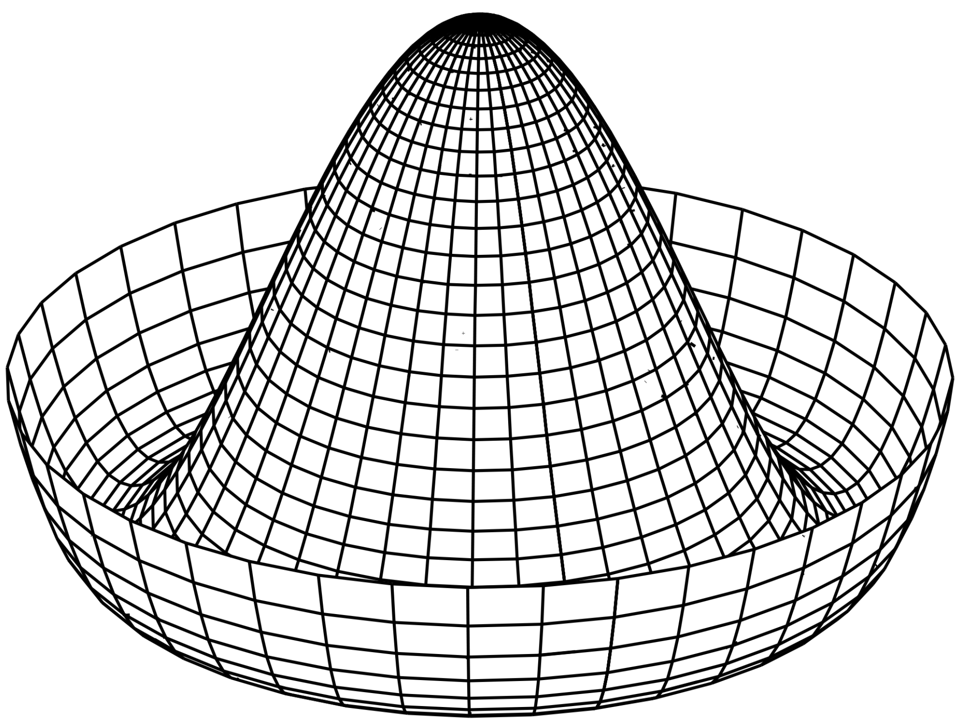
DESY Theory Workshop
DESY, Hamburg, 28th September 2016

Introduction

- pp→HH offers direct access to the trilinear Higgs coupling



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



Introduction

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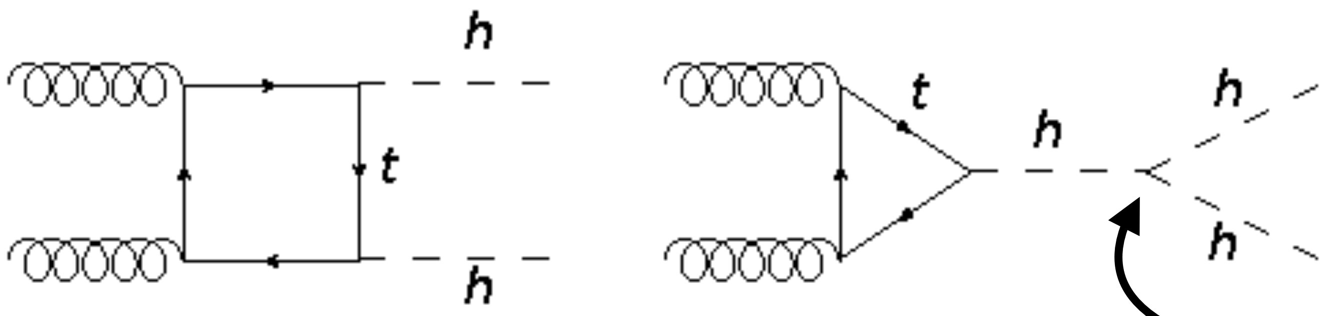
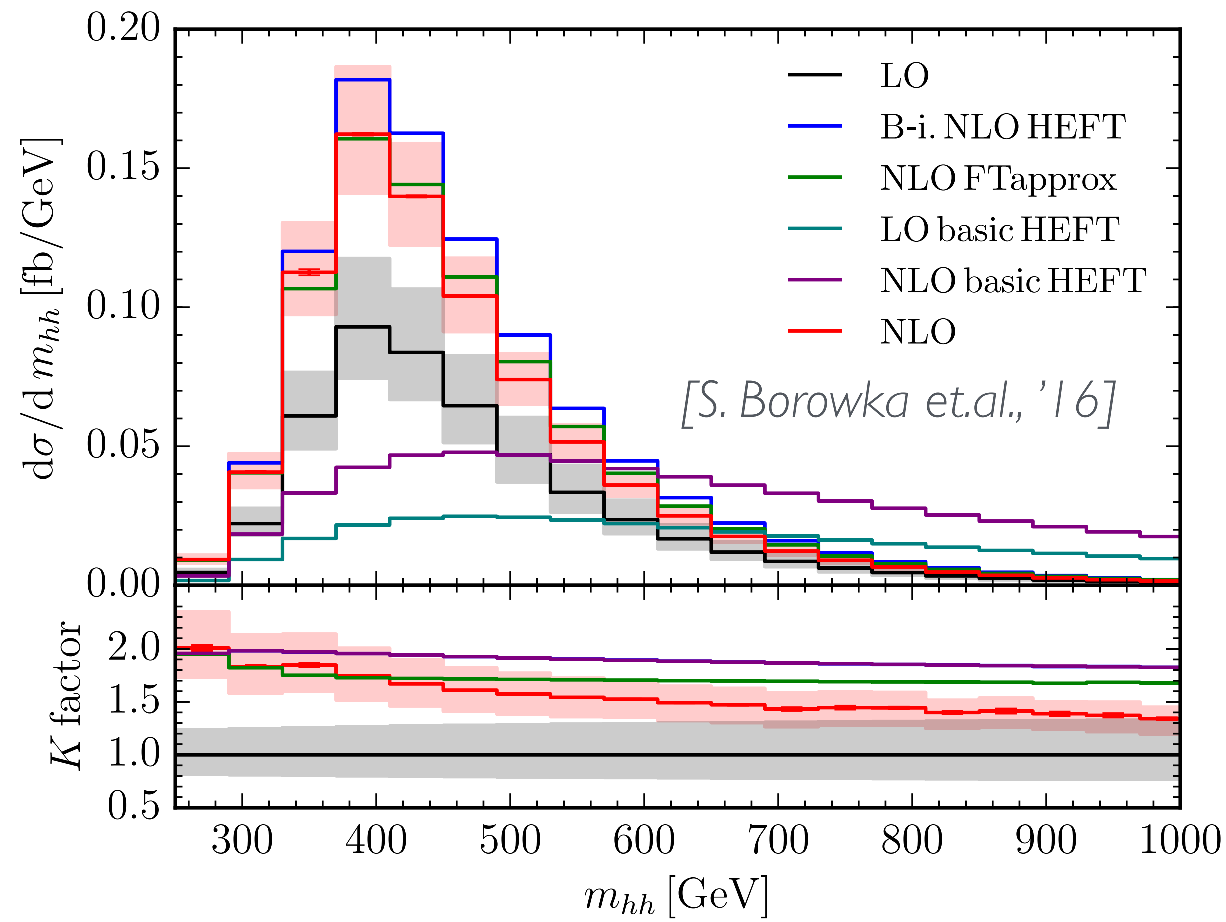
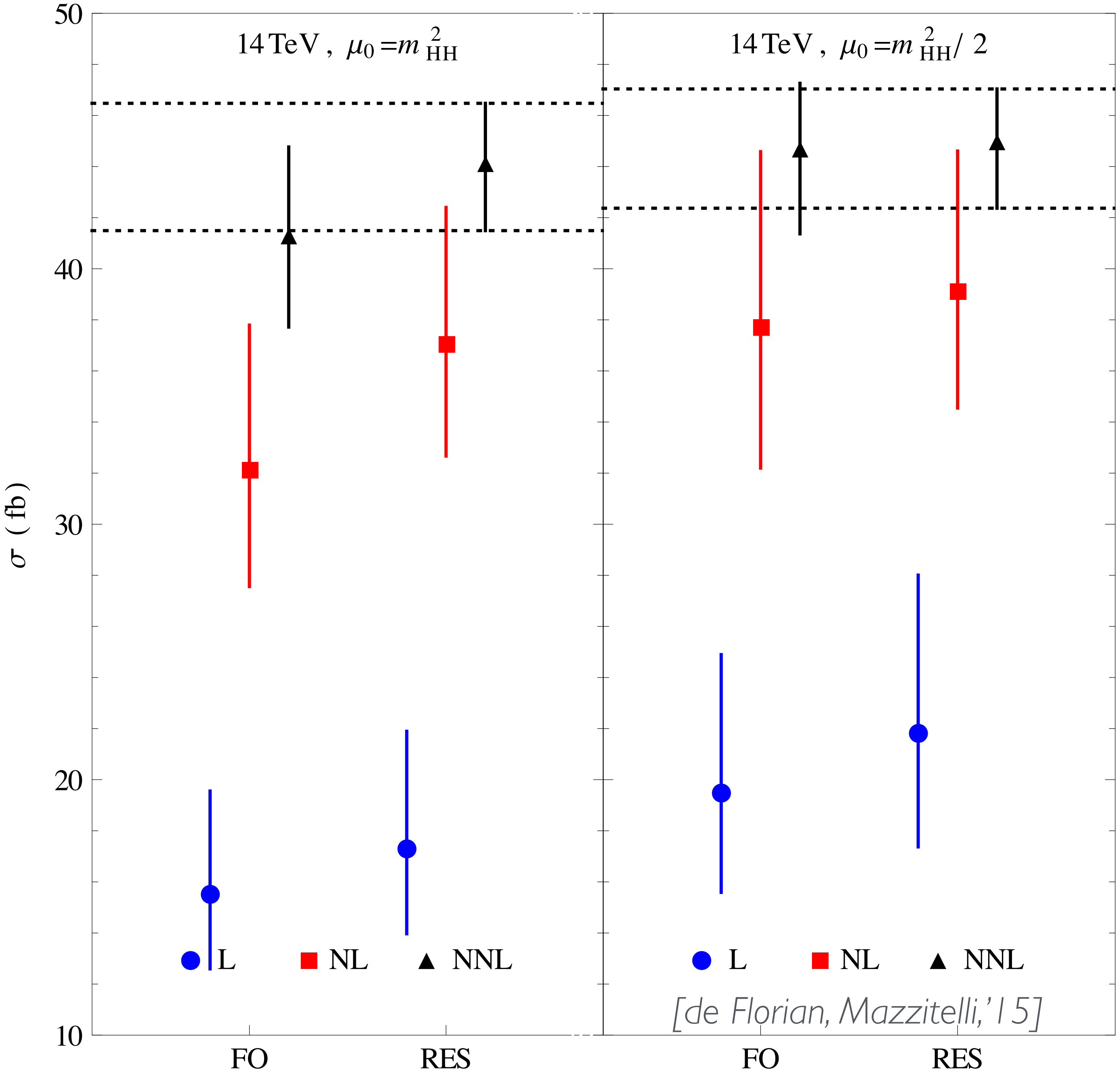


$$V(H) = \frac{1}{2}M_H^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda' H^4$$

- Loop-induced process with 4 mass scales
  → higher orders extremely complicated!
- Full NLO result available since recently
  [S. Borowka et.al., 2x '16]
- based on purely numerical evaluation of the required two-loop amplitudes
- Indicates breakdown of HEFT
  (Higgs Effective Field Theory)
- NLO corrections are huge (~90%)
  & full results beyond NLO out of scope.
  → how to go beyond NLO?



Inclusive NNLO in HEFT



- Inclusive NNLO: $\sigma^{\text{NNLO}}_{\text{HEFT}} / \sigma^{\text{NLO}}_{\text{HEFT}} \approx 20\%$
  [de Florian, Mazzitelli,'13, '13]
- $\sigma^{\text{NNLO}}_{\text{HEFT}} \approx \sigma^{\text{NNLL}}_{\text{HEFT}}$ for $\mu_0 = m_{HH}/2$
  [de Florian, Mazzitelli,'15]

→ fully differential NNLO

HH up to NNLO in HEFT

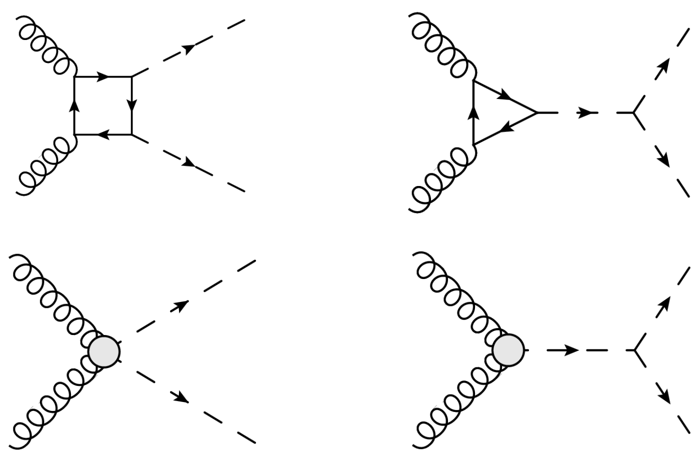
[Djouadi, Spira, Zerwas, '91; Dawson, Dittmaier, Spira, '98]

$$\mathcal{L}_{\text{HEFT}} = -\frac{1}{4} G_{\mu\nu} G^{\mu\nu} \left(C_H \frac{H}{v} - C_{HH} \frac{H^2}{v^2} \right)$$

$$C_X = -\frac{\alpha_{\text{S}}}{3\pi} \sum_{n \geq 0} C_X^{(n)} \left(\frac{\alpha_{\text{S}}}{\pi} \right)^n \;, \text{ with } X = H, HH$$

LO

LO HEFT



Integrate out tops

Matching coefficients known up to NNLO

[Grigo, Melnikov, Steinhauser, '14]

HH up to NNLO in HEFT

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Matching coefficients known up to NNLO

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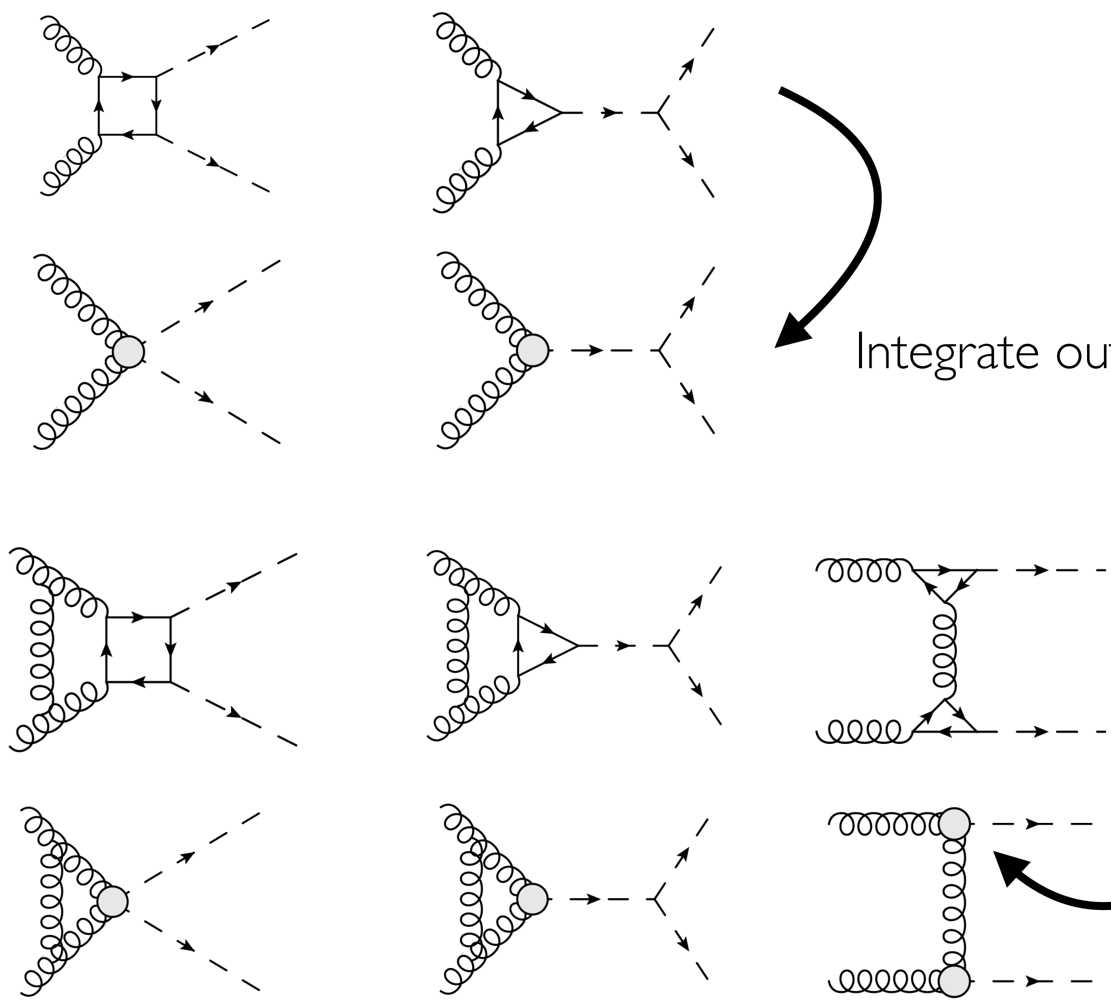
LO

LO HEFT

NLO

NLO HEFT



Integrate out tops

tree-level double operator insertion

HH up to NNLO in HEFT

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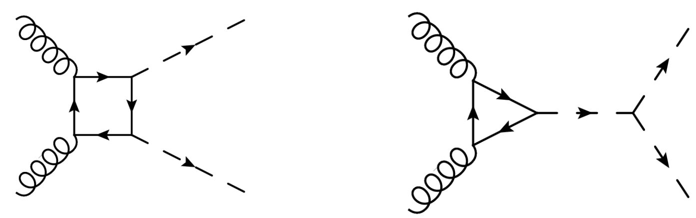
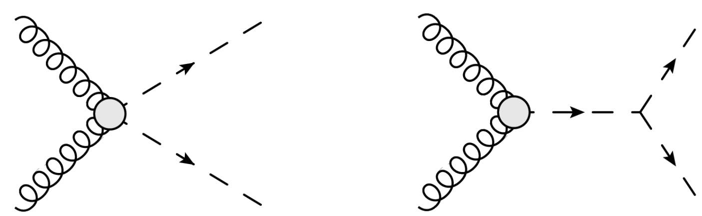
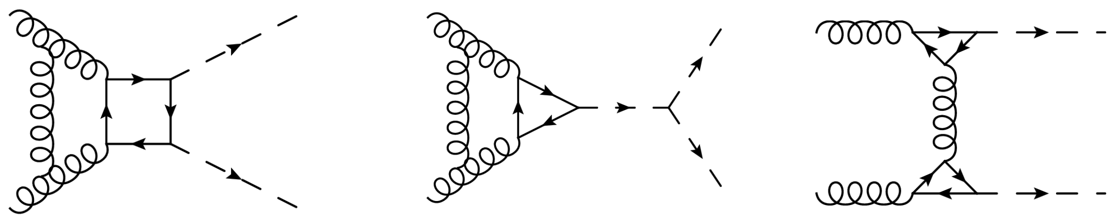


Integrate out tops

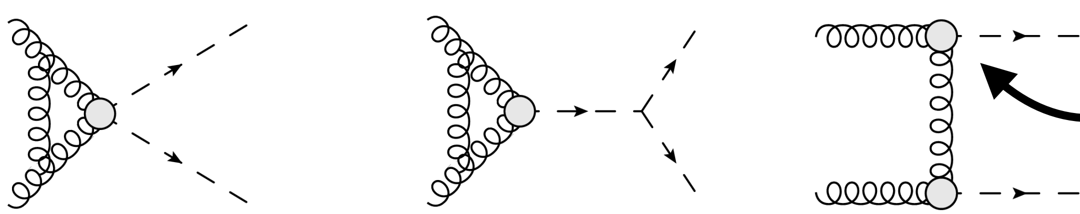
LO HEFT



NLO

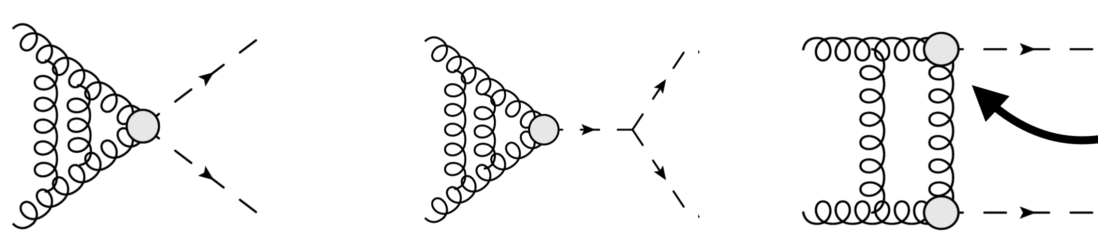


NLO HEFT



tree-level double operator insertion

NNLO HEFT



one-loop double operator insertion

HH two-loop virtual

- easily fits on one slide (finite part):

$$\frac{d\sigma^{(2)}_{\text{fin}}}{dt} = F_{\text{LO}}\left\{|C_{\text{LO}}|^2\,\mathcal{F}^{(2)} + \text{Re}(C_{\text{LO}})\,\mathcal{R}^{(2)} + \text{Im}(C_{\text{LO}})\,\mathcal{I}^{(2)} + \mathcal{V}^{(2)} + \mathcal{O}(\epsilon)\right\}$$

$$C_{LO} = \frac{6\,\lambda\,v^2}{s - M_H^2 + iM_H\Gamma_H} - 1$$

$$\mathcal{V}^{(2)} = \frac{1}{(3stu)^2}\left[M_H^8(t+u)^2 - 2M_H^4 tu(t+u)^2 + t^2u^2\left(4s^2 + (t+u)^2\right)\right],$$

$$\mathcal{I}^{(2)} = 4\pi\left(1 + \frac{2M_H^4}{s^2}\right)\log\left(\frac{(M_H^2-t)(M_H^2-u)}{t\,u}\right),$$

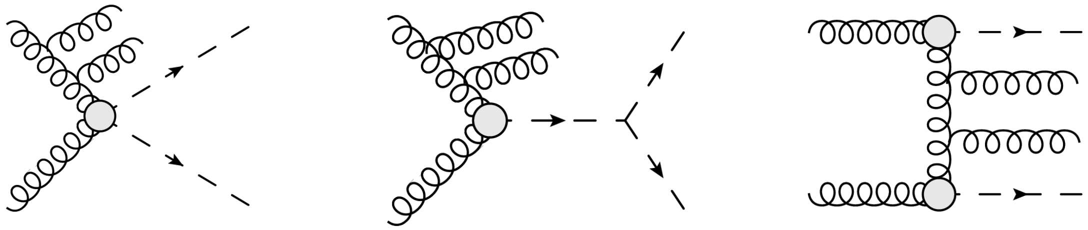
$$\mathcal{F}^{(2)} = \left(\frac{8N_f}{3} + \frac{19}{2}\right)\log\left(\frac{s}{M_t^2}\right) + N_f\left(\frac{217\zeta_2}{12} - \frac{17\zeta_3}{6} - \frac{3239}{108}\right) - \frac{11\zeta_2 N_f^2}{18} - \frac{249\zeta_2}{2} - \frac{253\zeta_3}{4} + \frac{45\zeta_4}{8} + \frac{8971}{36},$$

$$\mathcal{R}^{(2)} = -\left(1 + \frac{2M_H^4}{s^2}\right)\left\{-\frac{24}{3}\zeta_2 + 2\text{Li}_2\left(1 - \frac{M_H^4}{t\,u}\right) + 4\text{Li}_2\left(\frac{M_H^2}{t}\right) + 4\text{Li}_2\left(\frac{M_H^2}{u}\right) + 4\log\left(1 - \frac{M_H^2}{t}\right)\log\left(-\frac{M_H^2}{t}\right) + 4\log\left(1 - \frac{M_H^2}{u}\right)\log\left(-\frac{M_H^2}{u}\right) - \log^2\left(\frac{t}{u}\right)\right\} + \frac{4M_H^2}{s} + \frac{314}{9} - \frac{20}{27}N_f - \frac{33 - 2N_f}{9}\log\left(\frac{t\,u}{s^2}\right) + 8(C_H^{(2)} - C_{HH}^{(2)}).$$

[de Florian, Mazzitelli, '13]
[Grigo, Melnikov, Steinhauser, '14]

HH real-virtual and real-real

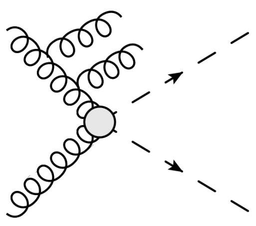
real-real

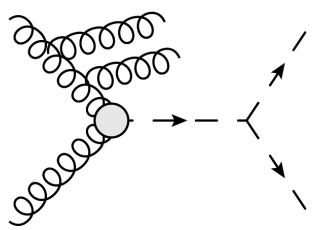


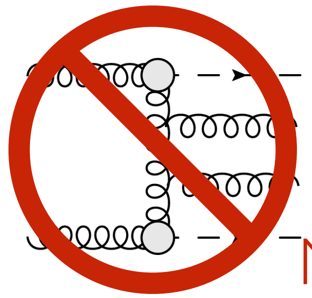
+ qg, qq channels

HH real-virtual and real-real

real-real



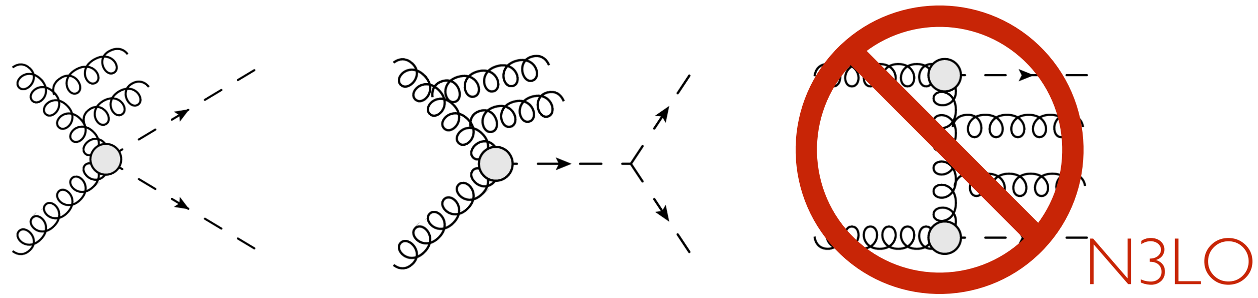




+ qg, qq channels

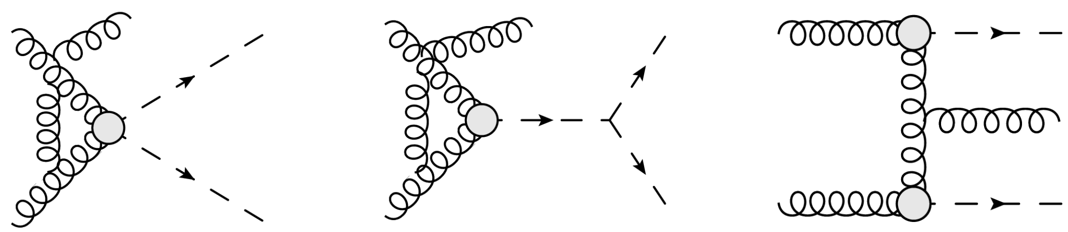
HH real-virtual and real-real

real-real



+ qg, qq channels

real-virtual



+ qg, qq channels

- obtained from **OpenLoops** *[JML, Maierhöfer, Pozzorini]*
- provides very fast and stable tree & one-loop amplitudes for

  pp → H, pp → H+j, pp → H+jj, pp → H+jjj

  pp → HH, pp → HH+j, pp → HH+jj

qT Subtraction

[Catani, Grazzini, '12]
[Catani, Cieri, de Florian, Ferrera, Grazzini, '14]
[Gehrmann, Lübbert, Yang, '14]

$$\mathrm{d}\sigma^{HH}_{\mathrm{NNLO}} = \mathcal{H}^{HH}_{\mathrm{NNLO}} \otimes \mathrm{d}\sigma^{HH}_{\mathrm{LO}} + \left[\mathrm{d}\sigma^{HH+\mathrm{jet}}_{\mathrm{NLO}} - \mathrm{d}\sigma^{\mathrm{CT}}_{\mathrm{NNLO}}\right]$$

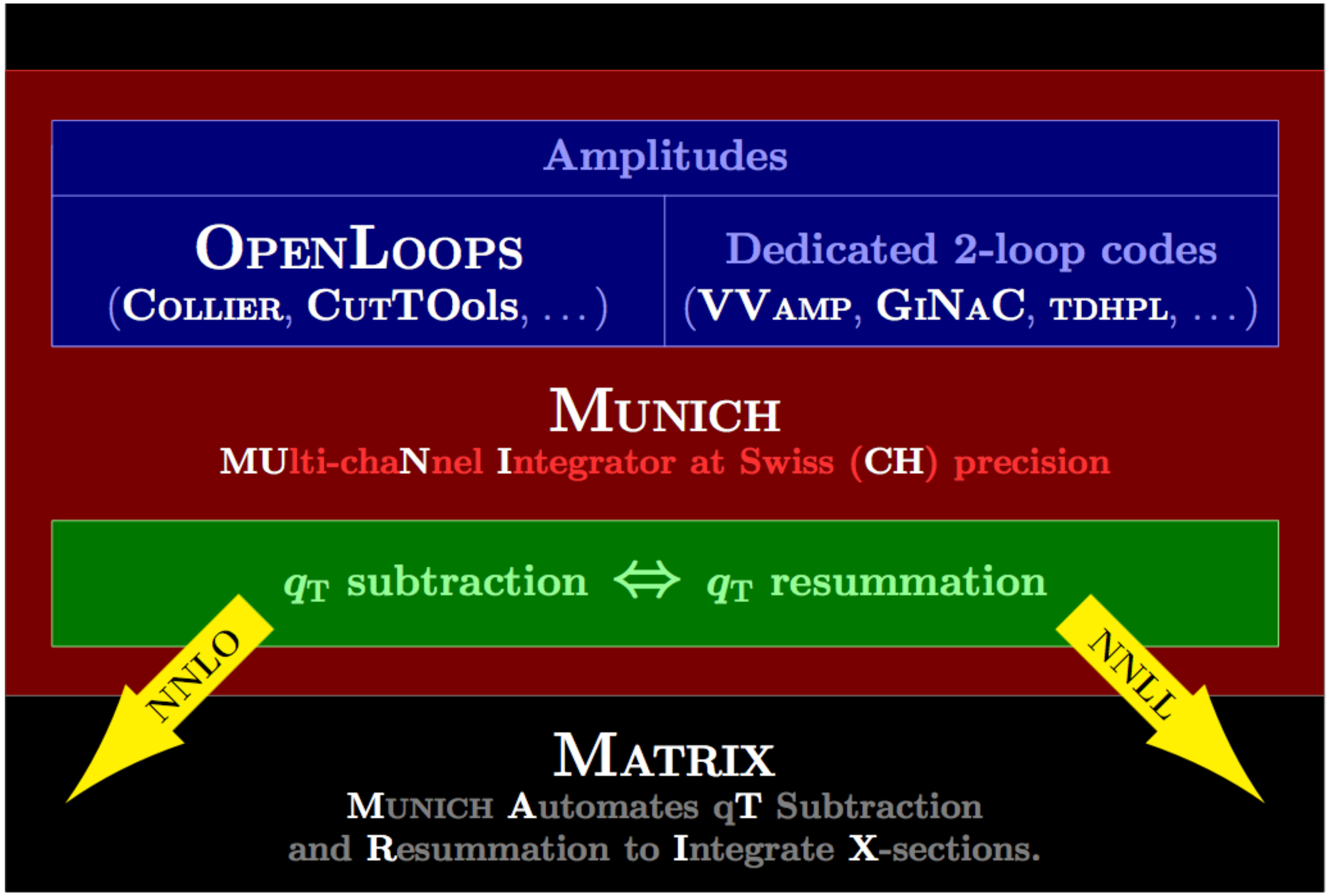
hard-collinear coefficient
includes two-loop virtual

real-virtual + real-real

process-independent counterterm

IR singular in the limit $q_{\mathrm{T},HH} \to 0$, but sum is finite!

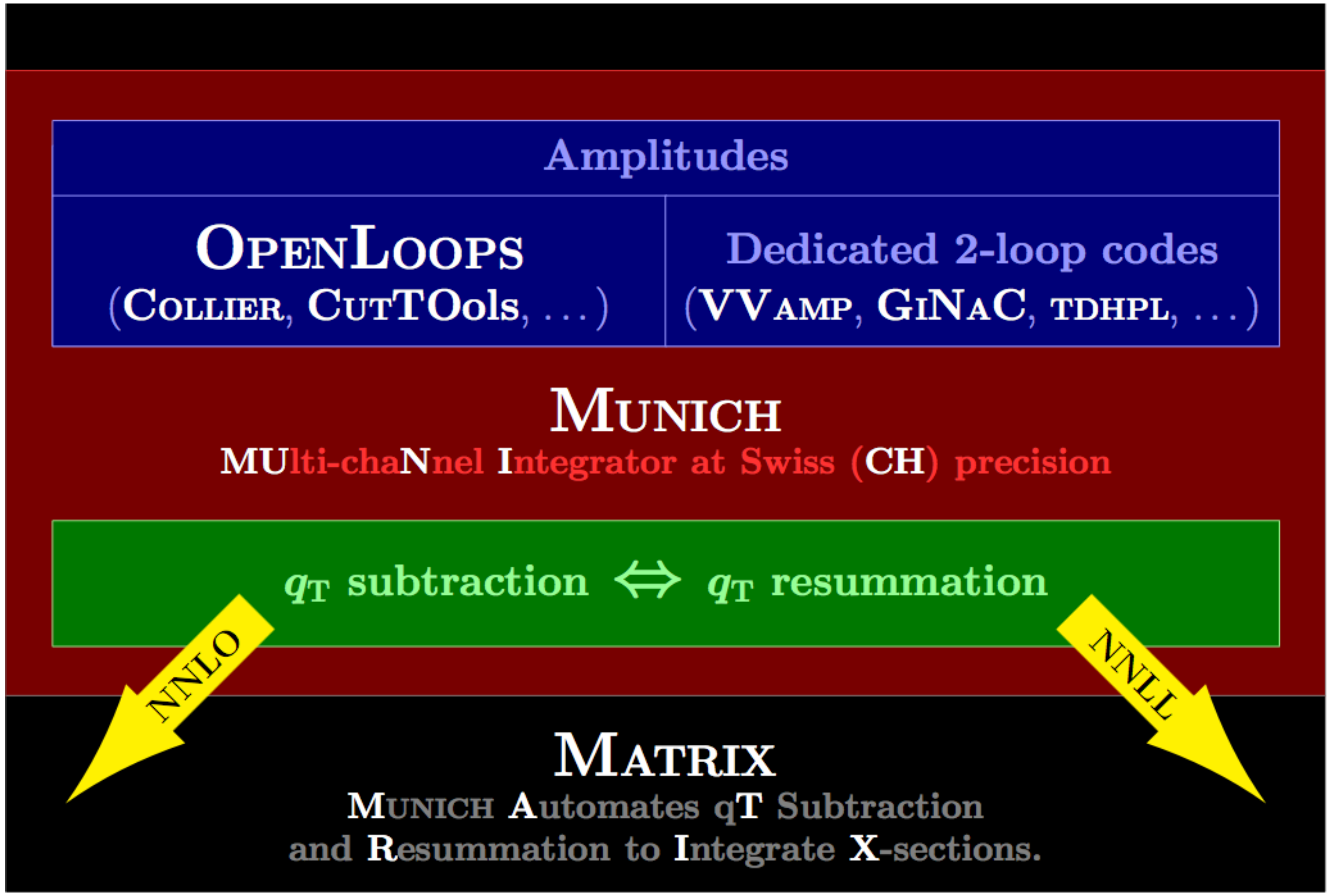
MATRIX Framework



Available processes in MATRIX @ NNLO(+NNLL) QCD:

- **pp→V**, V=W,Z and pp→ll, pp→lν
- **pp→VV'**, V=W,Zγ and pp→4l, pp→2l2ν, pp→2lγ, pp→lνγ
- **pp→H**
- **pp→HH**

MATRIX Framework



Available processes in MATRIX @ NNLO

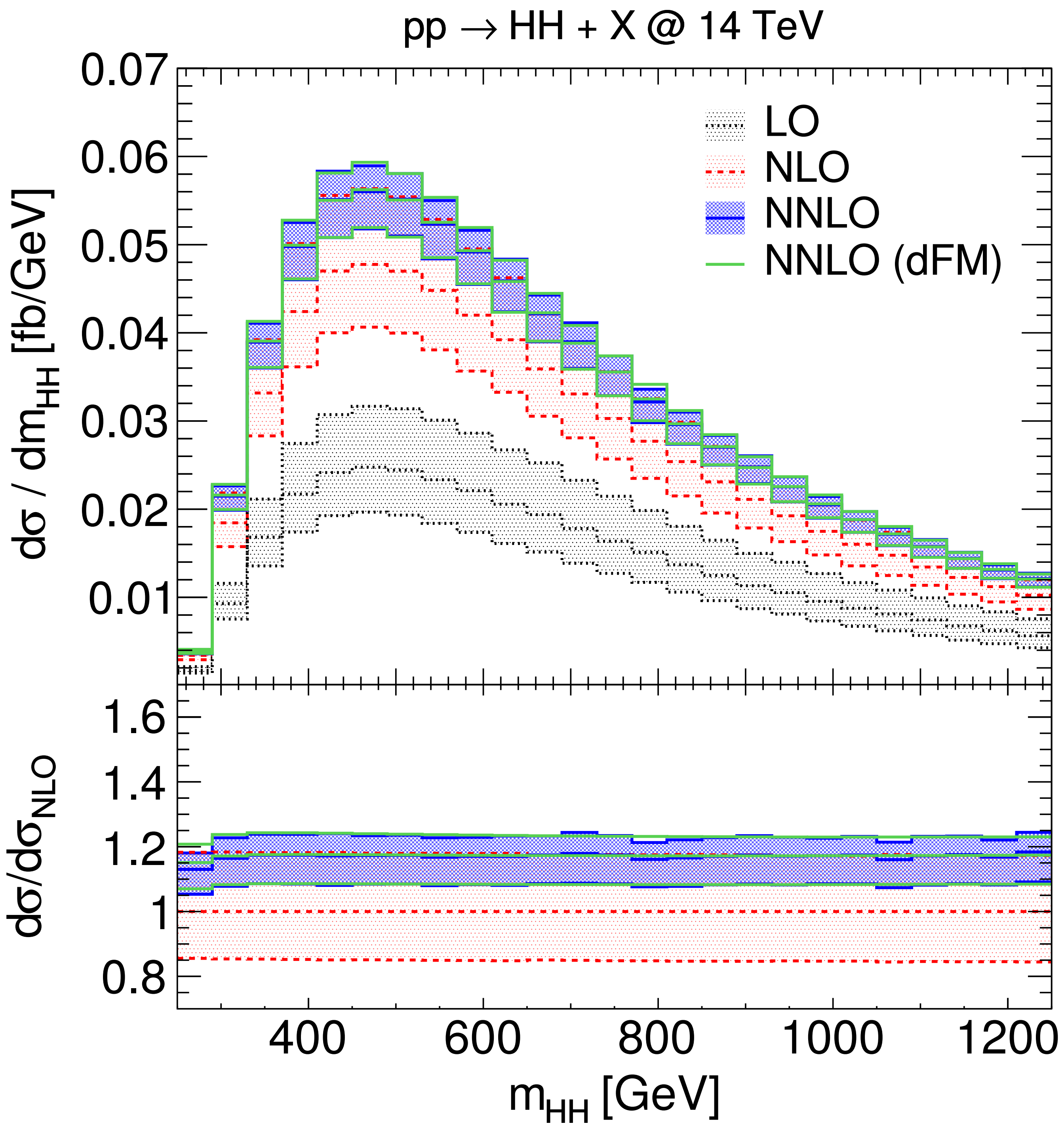
pp→V, V=W,Z and

, pp→2l2ν, pp→2l**γ**, pp→lν**γ**

pp→HH

all single- and di-boson processes of the SM (✔)

Results: LHC14 TeV



120 %

$\sqrt{s}$ [TeV]	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]	$\sigma_{\rm NNLO}$ [fb]
13	$13.8059(13)\,^{+31.5\%}_{-22.5\%}$	$25.829(3)\,^{+17.8\%}_{-15.4\%}$	$30.38(3)\,^{+5.2\%}_{-7.7\%}$
14	$17.0778(16)\,^{+30.7\%}_{-22.1\%}$	$31.934(3)\,^{+17.5\%}_{-15.1\%}$	$37.52(4)\,^{+5.2\%}_{-7.6\%}$

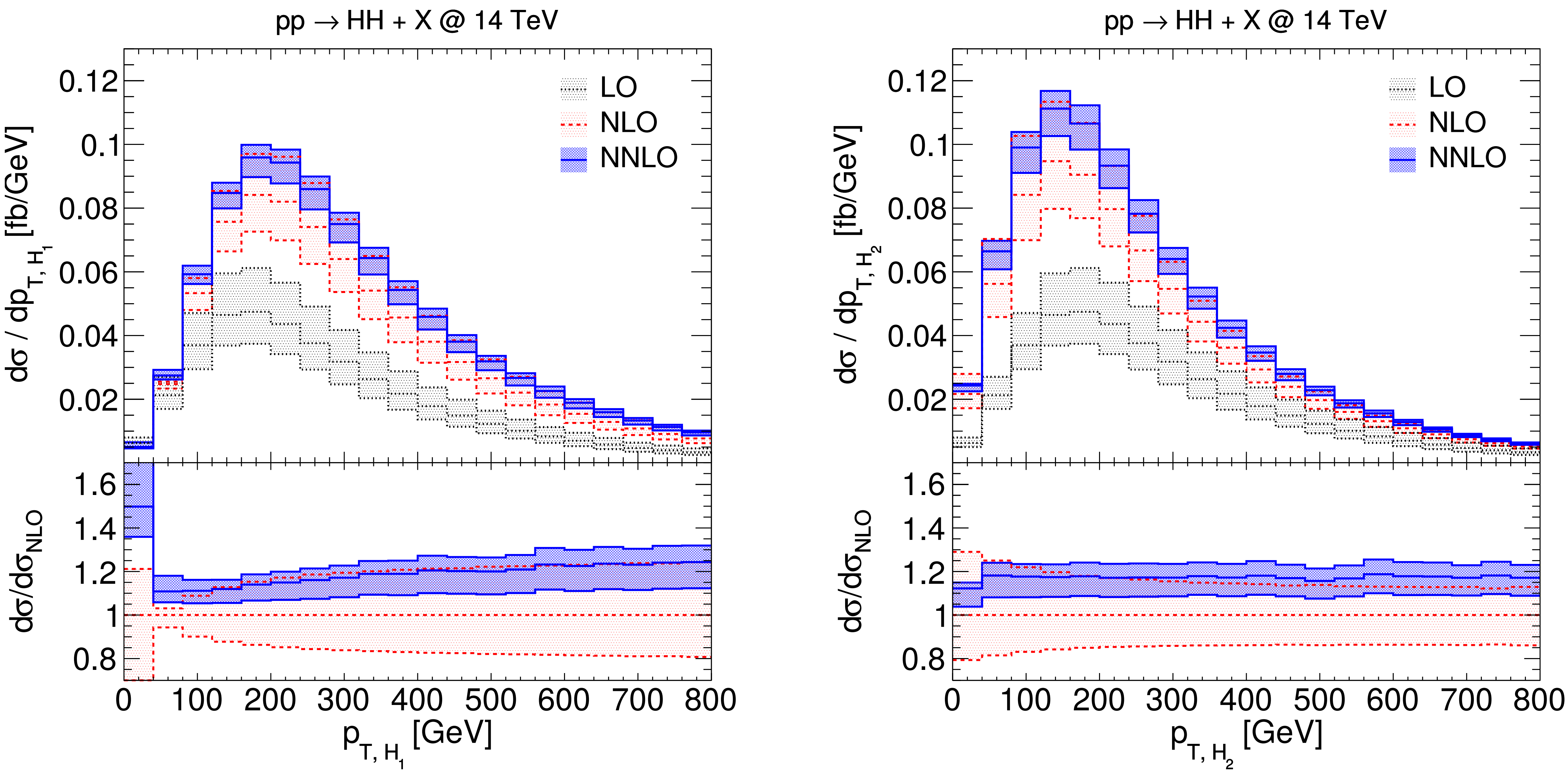
87 % 18 %

- NNLO corrections:
  - almost flat in m_{HH}
  - at the level of 18%
  - scale uncertainties at the level of 10%
  - overlap with NLO uncertainty band

- perfect agreement with analytical result of *[de Florian-Mazzitelli, '13]*

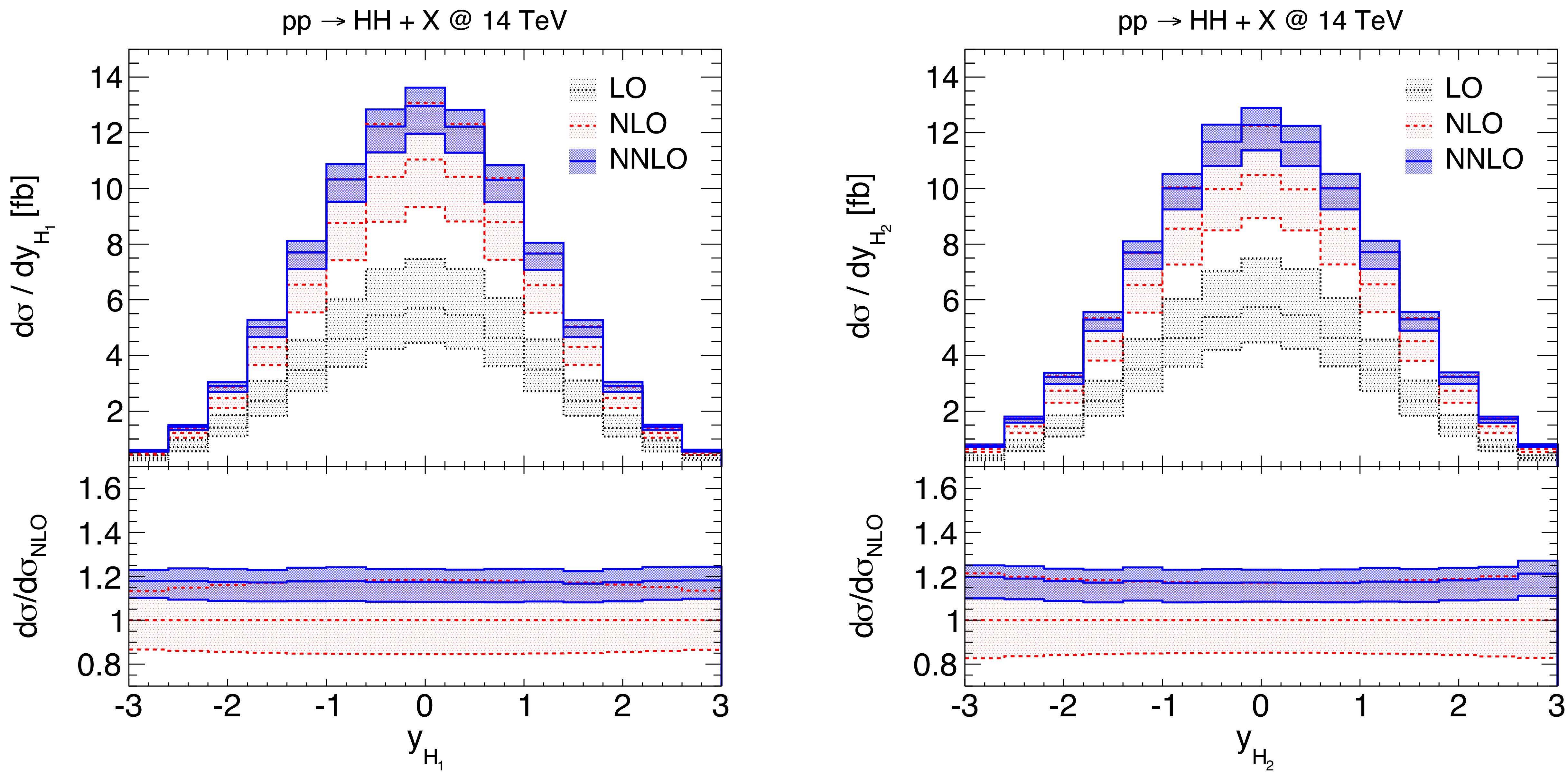
Setup: $\mu_0 = m_{HH}/2$ + 7 pt. variation, PDF4LHC_nlo for NLO & LO / PDF4LHC_nnlo for NNLO, mH = 125 GeV

Results: LHC14 TeV



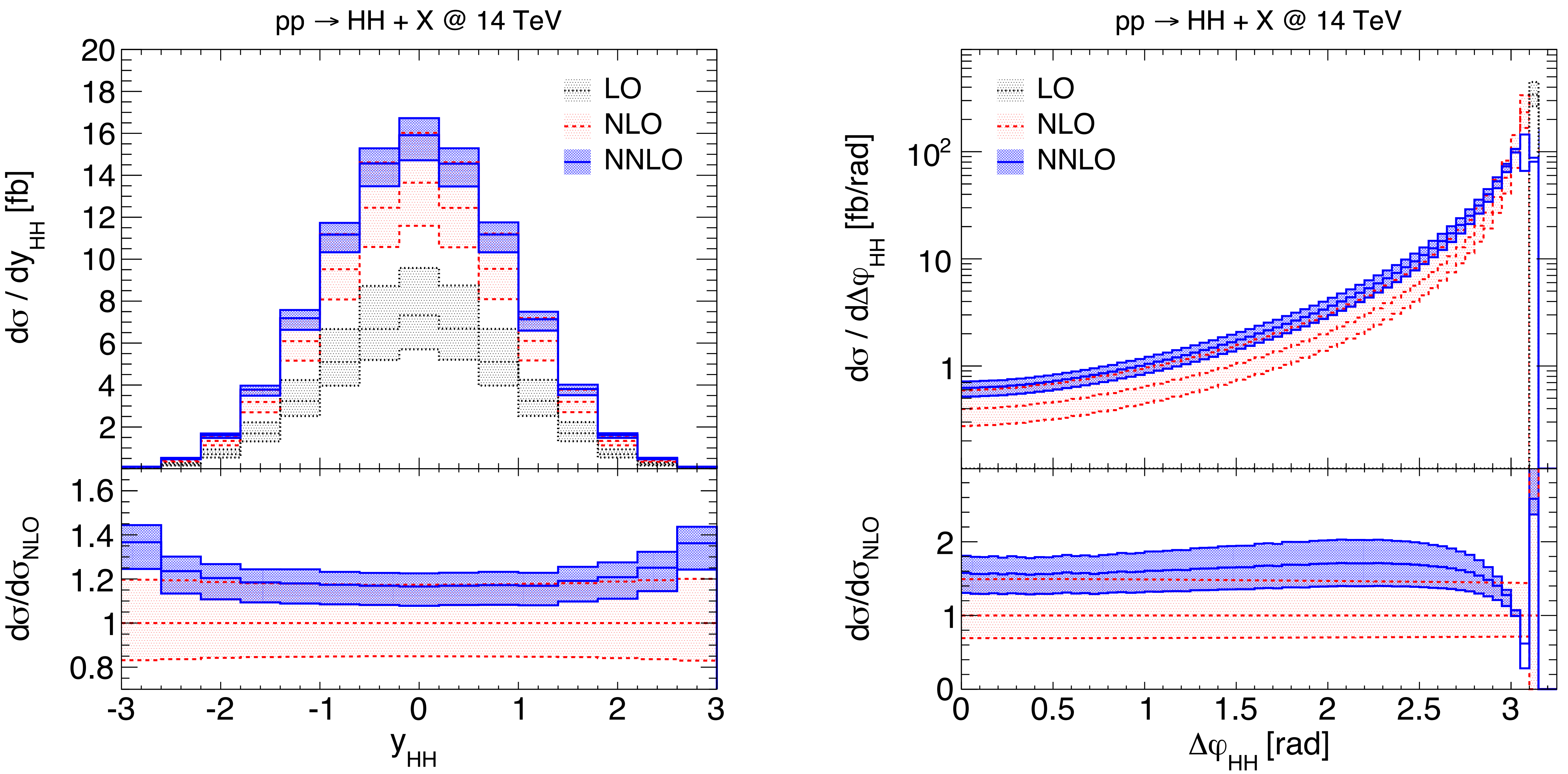
- mild increase of NNLO/NLO for large $p_{T,H1}$: 10% – 25%
- flat NNLO/NLO for large $p_{T,H2}$
- scale uncertainties 5-10%

Results: LHC14 TeV



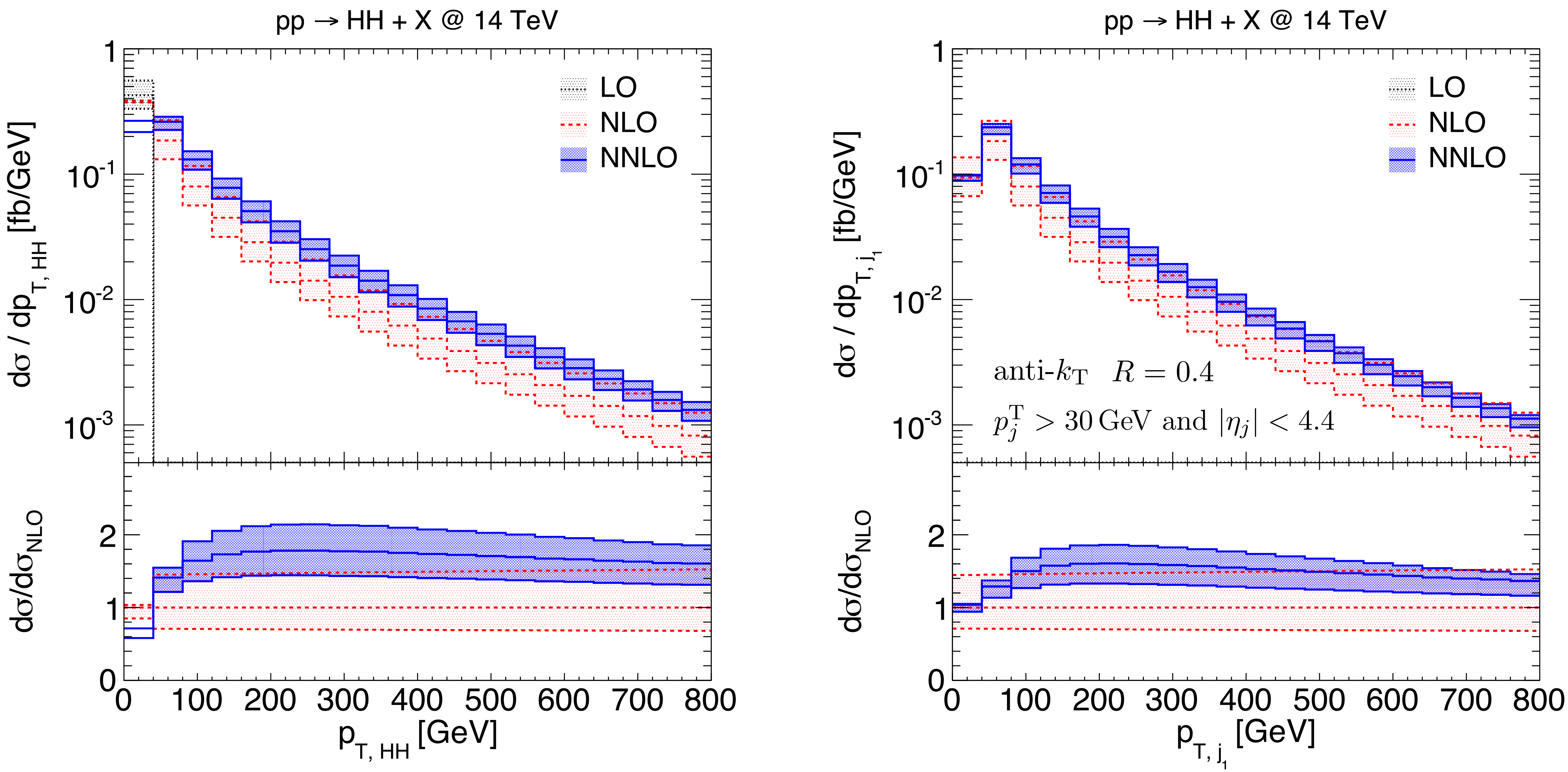
- almost flat NNLO/NLO

Results: LHC14 TeV



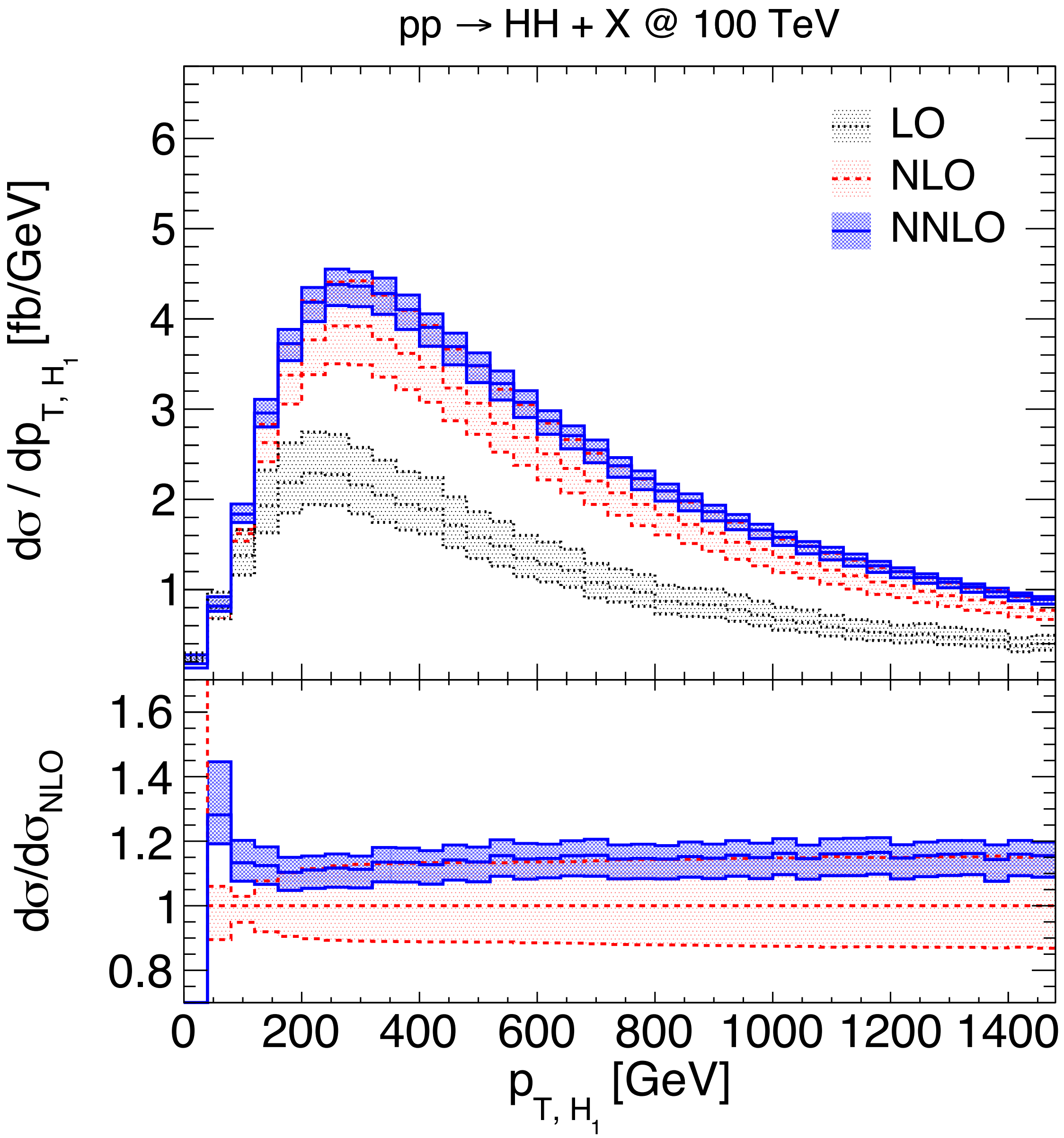
- NNLO/NLO increases to 40% for large y_{HH}
- at LO HH back-to-back → NNLO $\Delta\varphi_{HH}$ effectively NLO: 60-80% corrections

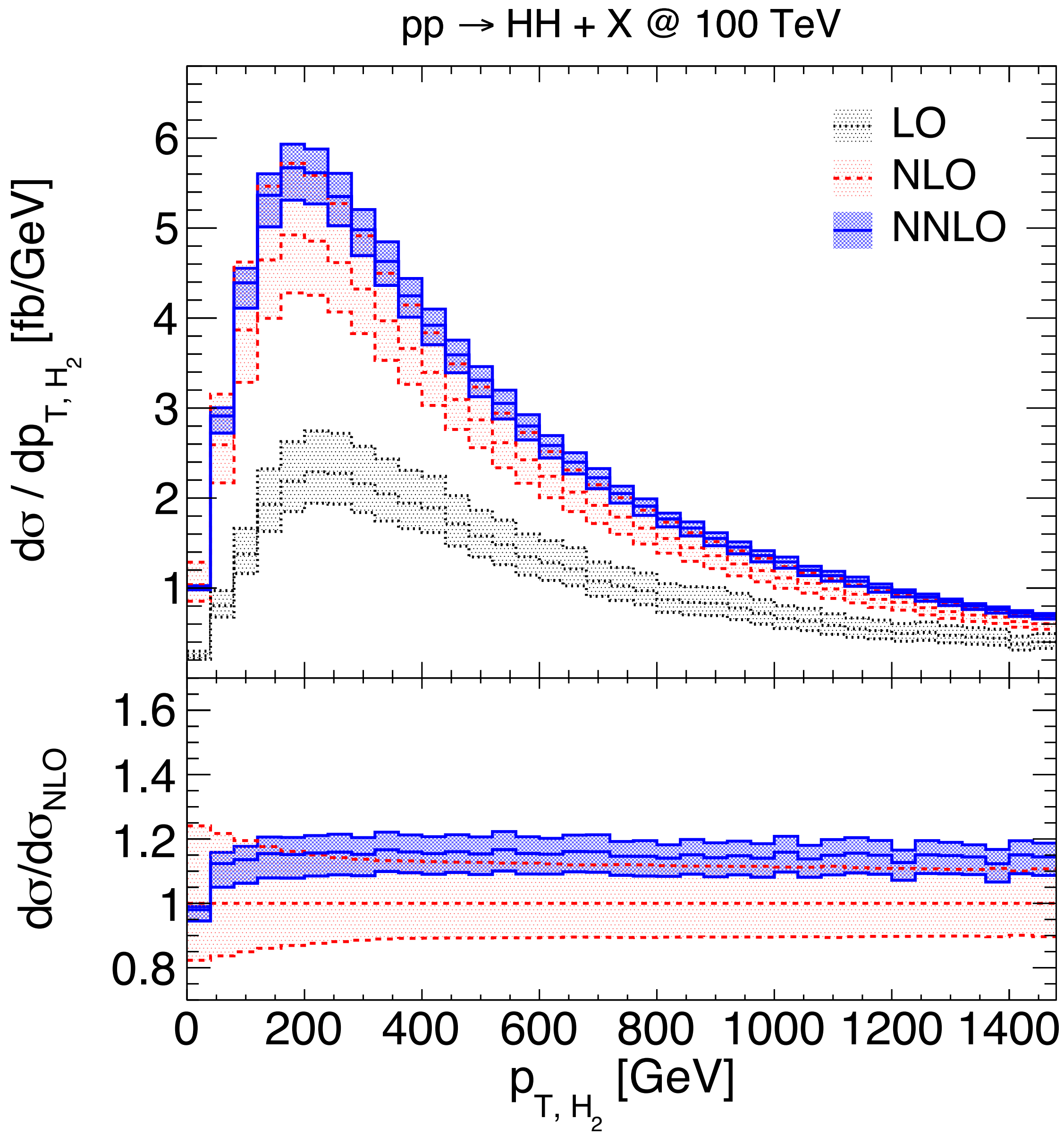
Results: LHC14 TeV



- effectively NLO: 60-80% NNLO/NLO corrections
- in the limit $p_{T,HH} \to 0$ large log terms $\log^n(p_{T,HH}/m_{HH})$ ➞ resum

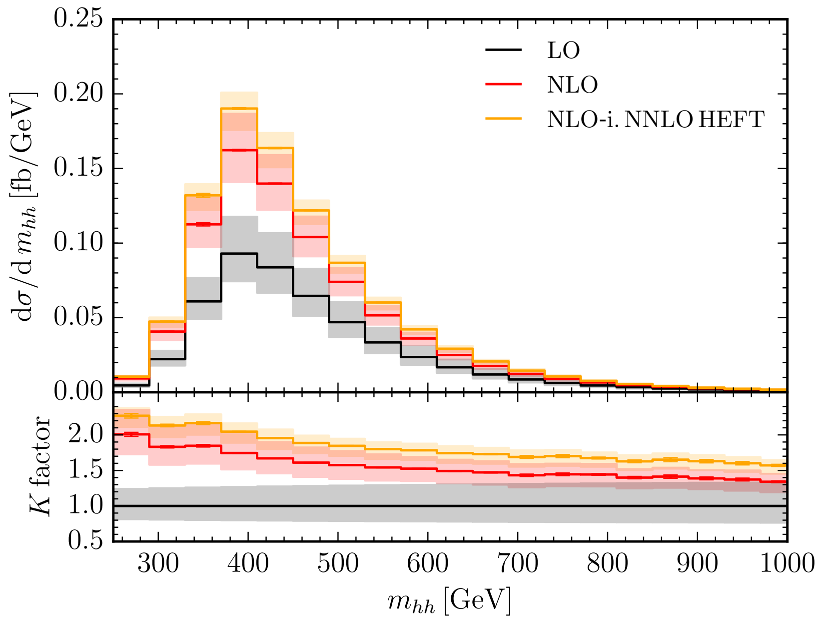
Results: FCC100 TeV



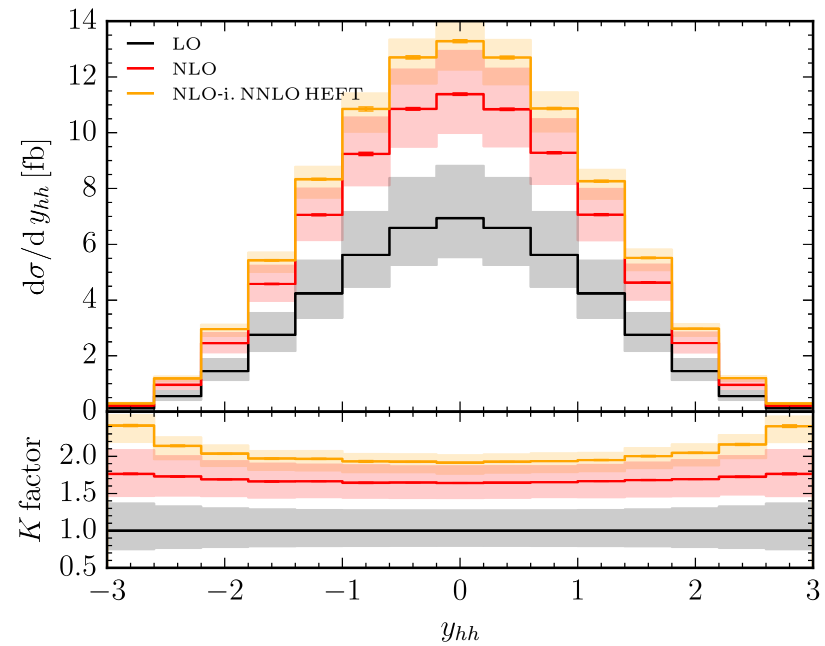


- similar behaviour of NNLO/NLO for $p_{T,H1}$ and $p_{T,H2}$ as at 14 TeV

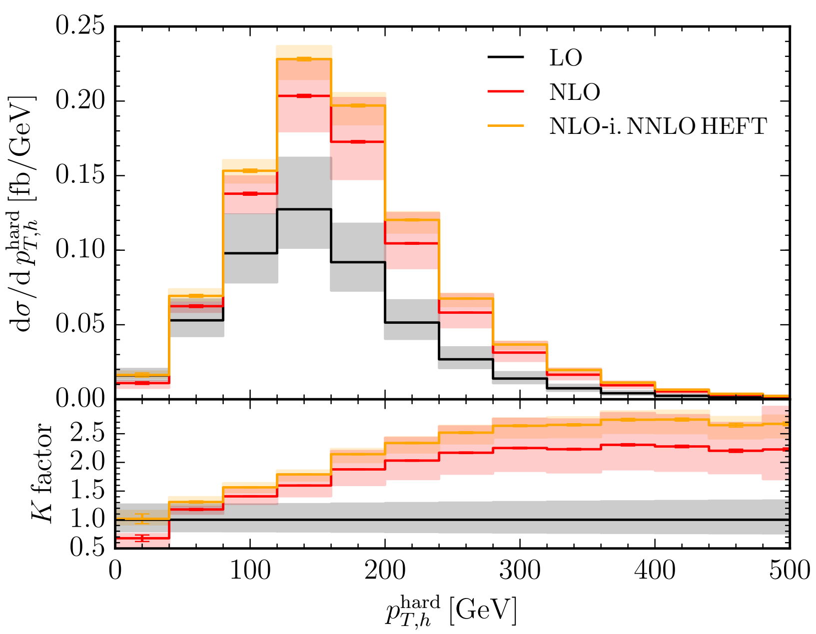
NLO-improved NNLO HEFT



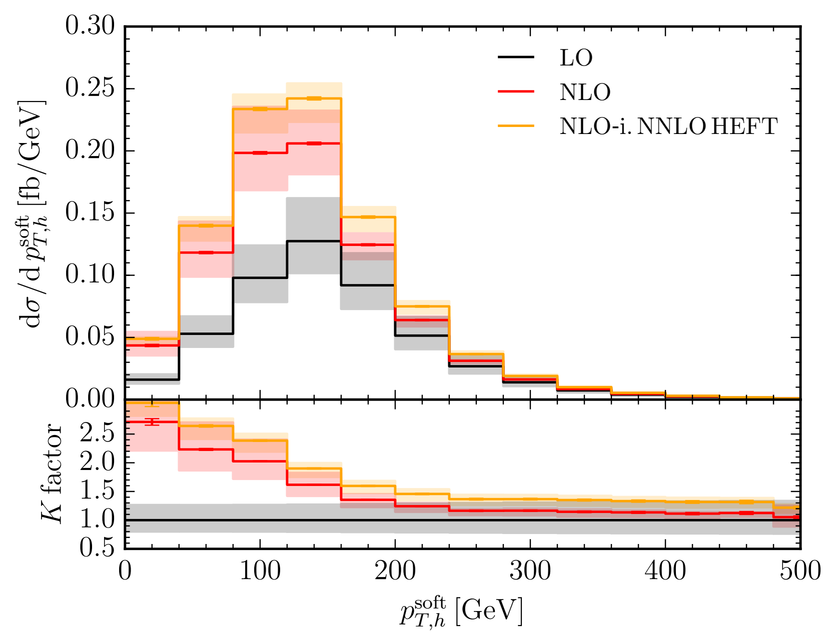
(a) 14 TeV, m_{hh}



(b) 14 TeV, y_{hh}



(c) 14 TeV, leading p_T



(d) 14 TeV, subleading p_T

[S. Borowka et.al., arXiv:1608.04798]

First steps combining full NLO and NNLO HEFT have been presented recently in
[S. Borowka et.al., arXiv:1608.04798]

Idea: apply differential NNLO/NLO K-factor to full NLO calculation

$$\mathrm{d}\sigma^{\text{NLO-i. NNLO HEFT}} = \mathrm{d}\sigma^{\text{NLO}}\frac{\mathrm{d}\sigma^{\text{NNLO basic HEFT}}}{\mathrm{d}\sigma^{\text{NLO basic HEFT}}}$$

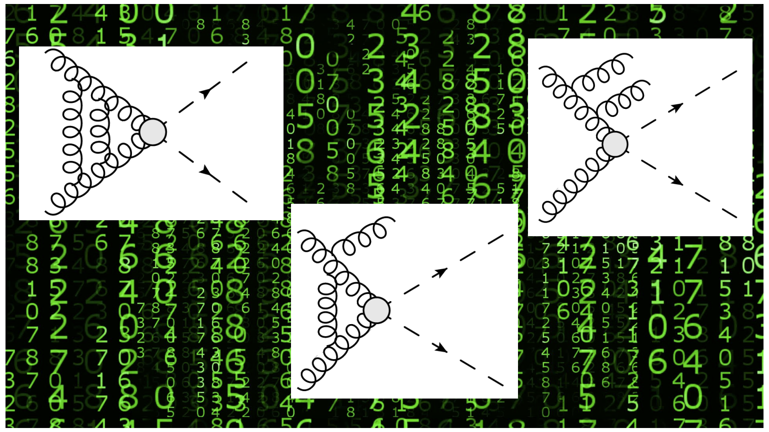
$$\sigma^{\text{NLO-i. NNLO HEFT}} = 38.67^{+5.2\%}_{-7.6\%}\ \text{fb @ 14 TeV}$$

$$\sigma^{\text{B-i. NLO HEFT}} = 38.32^{18.1\%}_{14.9\%}\ \text{fb @ 14 TeV}$$

Further refinements possible:

- fully-differential: projection to Born phase-space,…
- ….

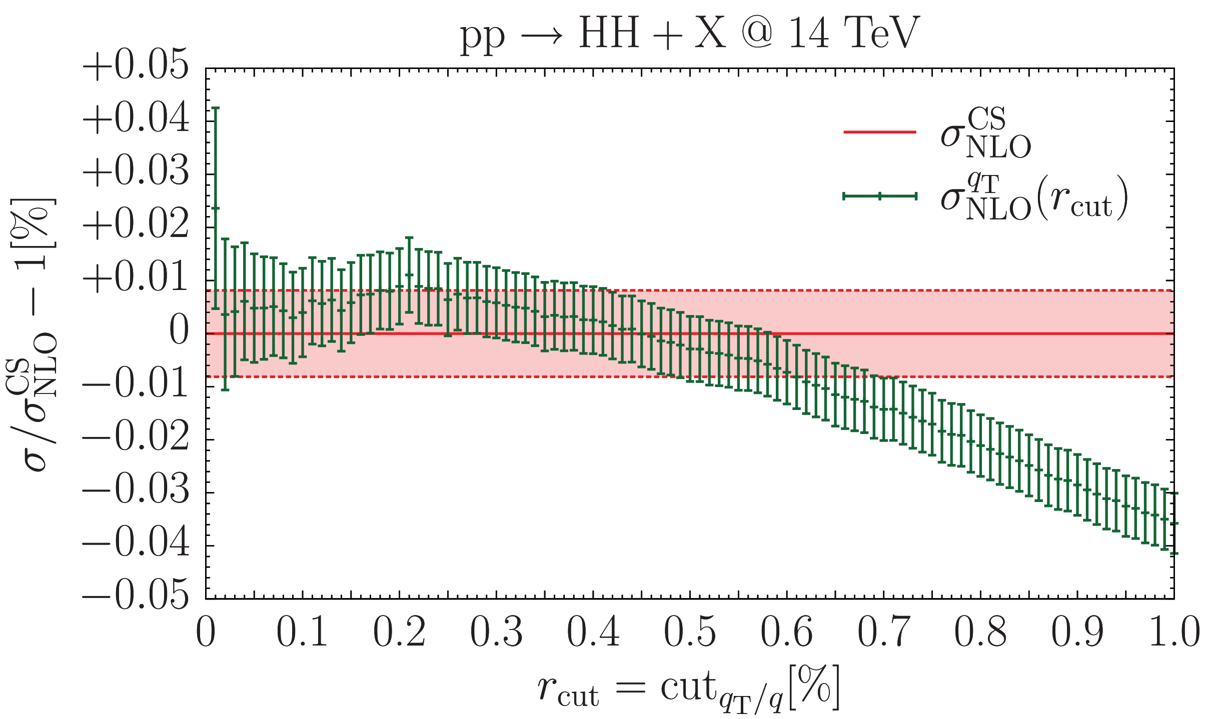
Conclusions

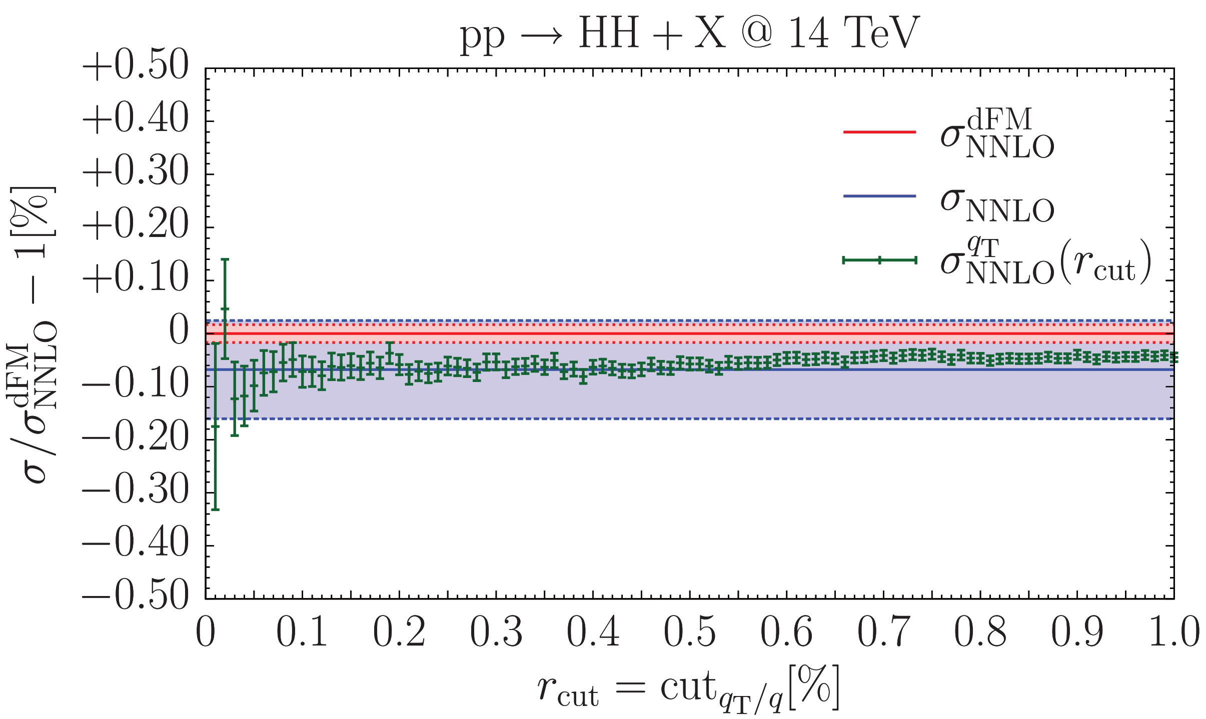


- HH @ NNLO in HEFT available in the MATRIX
- mild phase space dependence of NNLO corrections
- NNLO/NLO at the level of 10-25%
- scale uncertainties at NNLO at the level of 5-15%
- mostly overlapping uncertainty bands between NNLO and NLO
- Outlook:
  - Higgs decays
  - NNLO+NNLL
  - Refine combination with full NLO

Backup slides

Validation & Stability





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