



Fully differential Higgs boson production in VBF at NNLO with Higgs decays

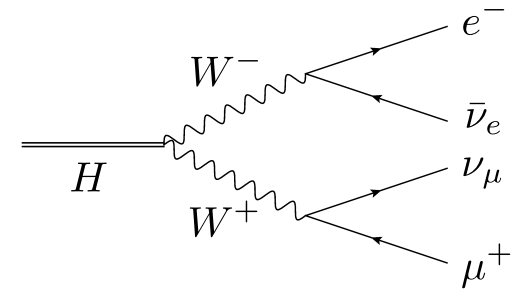
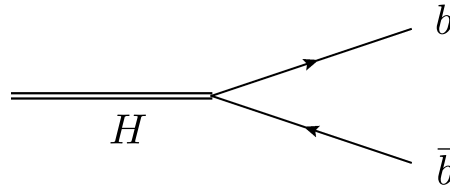
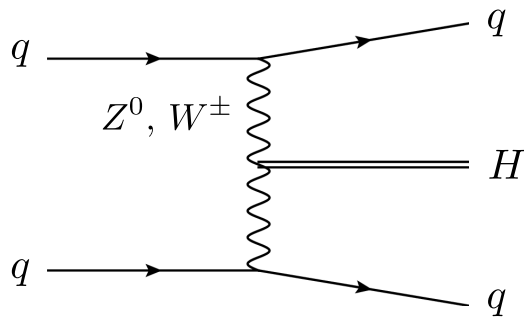
In collaboration with Fabrizio Caola, Kirill Melnikov and Raoul Röntsch

Details in arXiv:2110.02818

Konstantin Asteriadis | October 18, 2021

Higgs 2021 – Stony Brook University

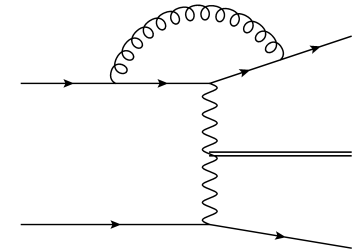
Higgs boson production in vector boson fusion



- Second highest Higgs production mode at the LHC
- **All existing results beyond NLO for stable Higgs production \rightarrow effects of decay not yet studied at high precision!**

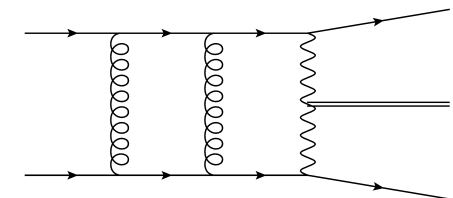
- **Factorizable** contributions well studied:

- Effectively deep inelastic scattering of two protons
- **Fully differential** computed up to **NNLO QCD** corrections
[Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15; Cruz-Martinez, Glover, Gehrmann, Huss '18]
- **Inclusive** computed up to **N³LO QCD** corrections
[Dreyer, Karlberg '16]

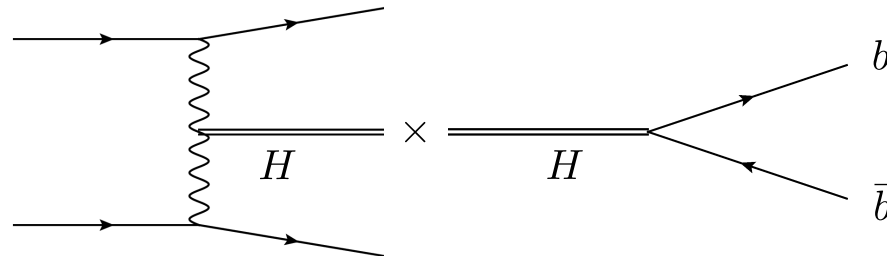


- **Non-factorizable** contributions (*not considered in the following*)

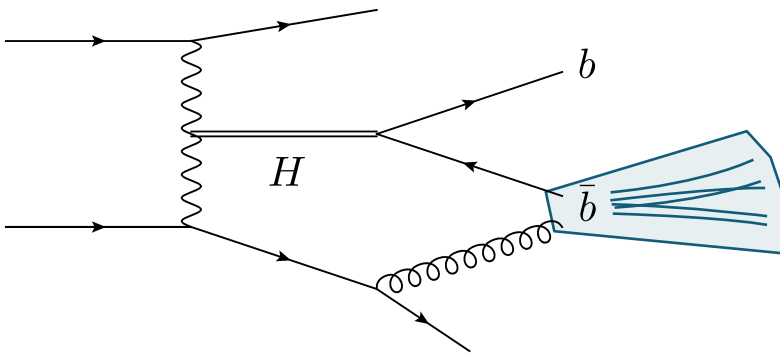
- Expected to be small but relevant at a precision of a few percent
- First studies appeared only recently
[Liu, Melnikov, Penin '19; Dreyer, Karlberg, Tancredi '20; Chen, Figy, Plätzer '21]



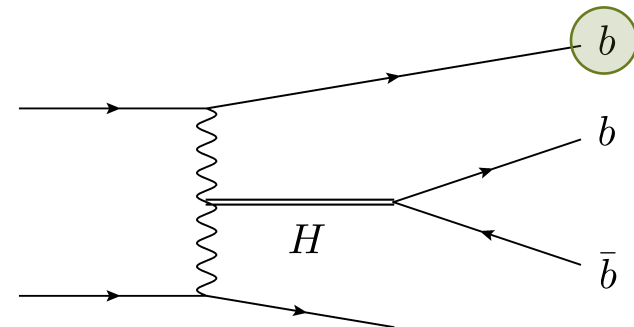
VBF + H \rightarrow $b\bar{b}$ decay



- Narrow width approximation \rightarrow factorization of on-shell Higgs production and on-shell Higgs decay
- In this study: H \rightarrow $b\bar{b}$ decay at LO QCD with massless b quarks



Jet-clustering breaks factorization



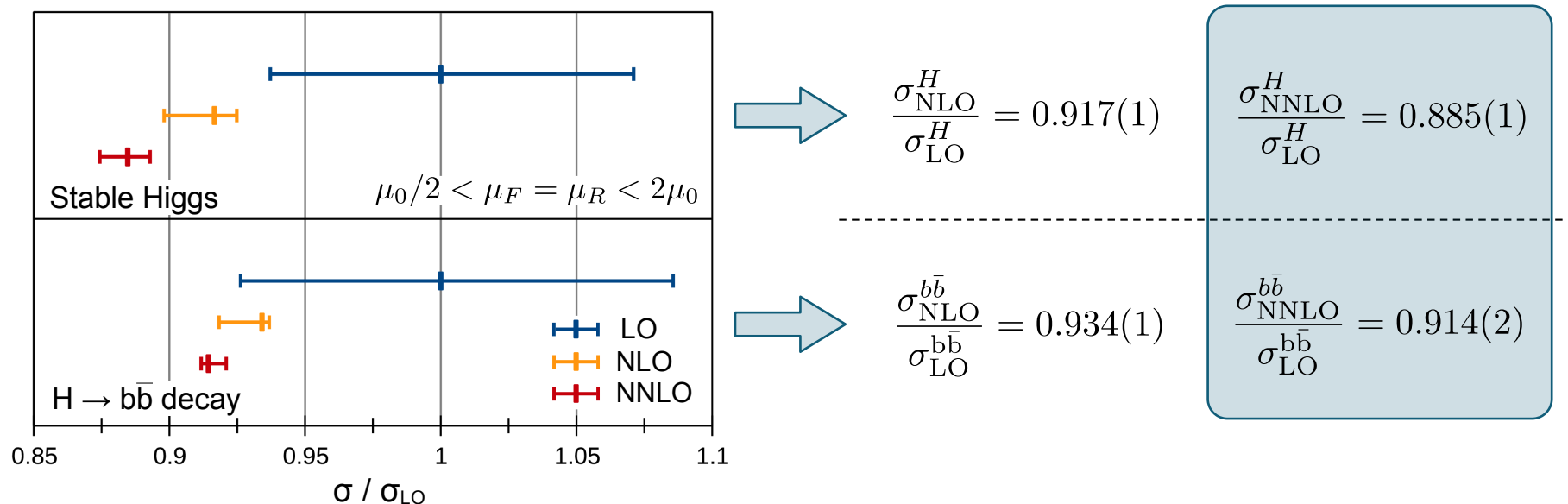
B-tagging breaks factorization

- Expected to be small effects, but higher order corrections are small too
- Cross section for b-jets from production process tiny \rightarrow no flavour tagging in Higgs production process
- In addition: cuts on b-jets may change fiducial VBF region

Fiducial cross section

- Cuts on b-jets; loosely following latest ATLAS measurement: 2 resolved b-jets, $p_{\perp, j_b} > 65 \text{ GeV}$, $|y_{j_b}| < 2.5$ [Eur. Phys. J. C 81, 537 (2021)]
- Sizable fiducial cross section, $O(100000)$ events with HL-LHC

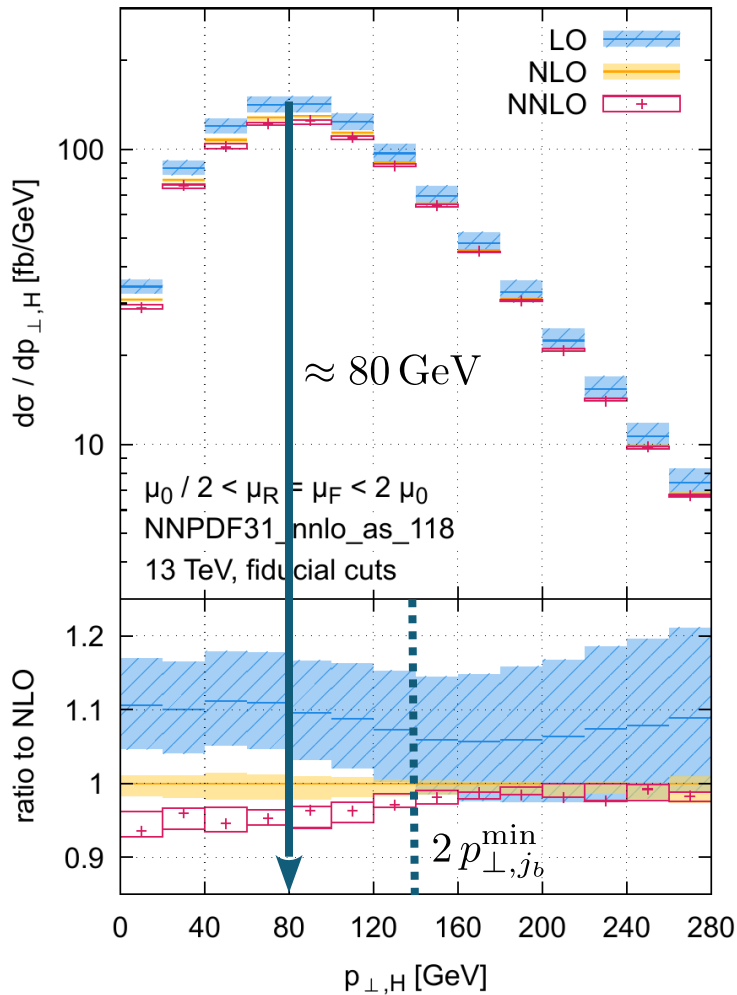
$$\sigma_{\text{LO}}^{b\bar{b}} = 75.9_{-6.5}^{-5.6} \text{ fb}, \quad \sigma_{\text{NLO}}^{b\bar{b}} = 70.9_{-1.2}^{+0.2} \text{ fb}, \quad \sigma_{\text{NNLO}}^{b\bar{b}} = 69.4_{-0.2}^{+0.5} \text{ fb}$$



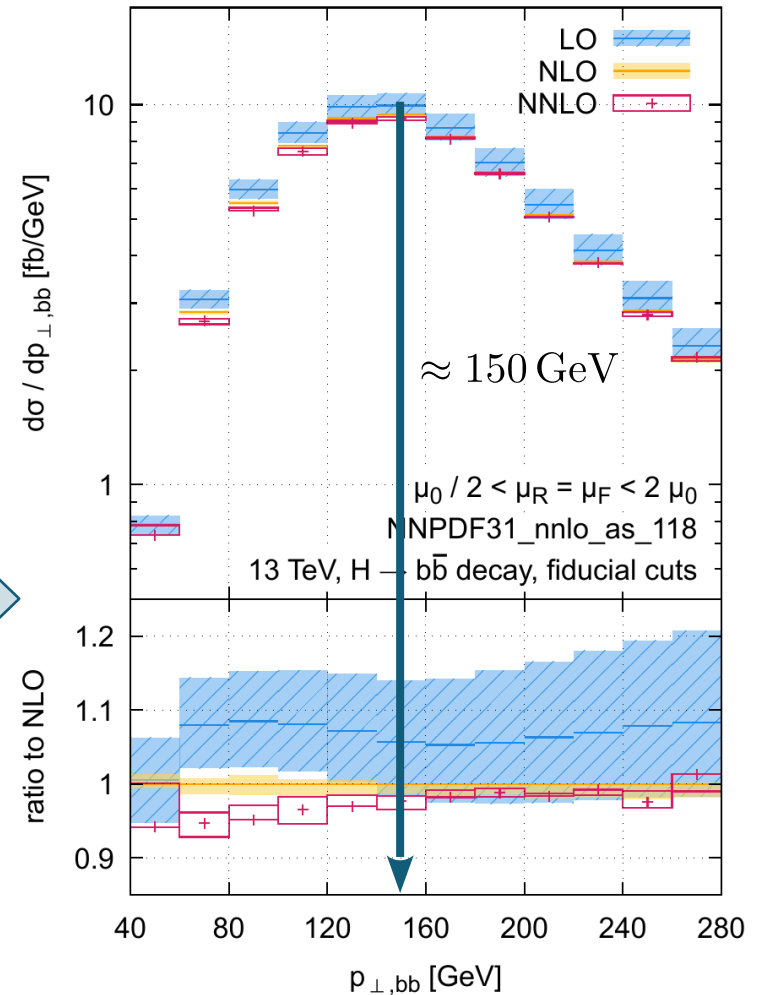
- Noteworthy features: smaller residual scale uncertainty and better perturbative convergence compared to stable Higgs production

Overall: effect of H \rightarrow $b\bar{b}$ decay of same order as NNLO corrections themselves!

- Simple reason: pt cuts on b-jets ($p_{\perp, j_b} > 65 \text{ GeV}$) preferentially selects events with high Higgs pt



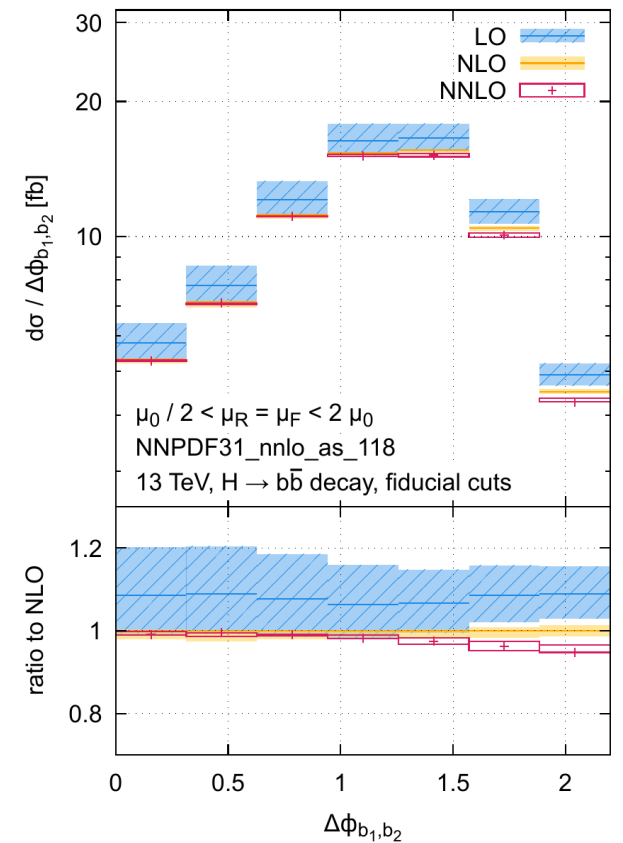
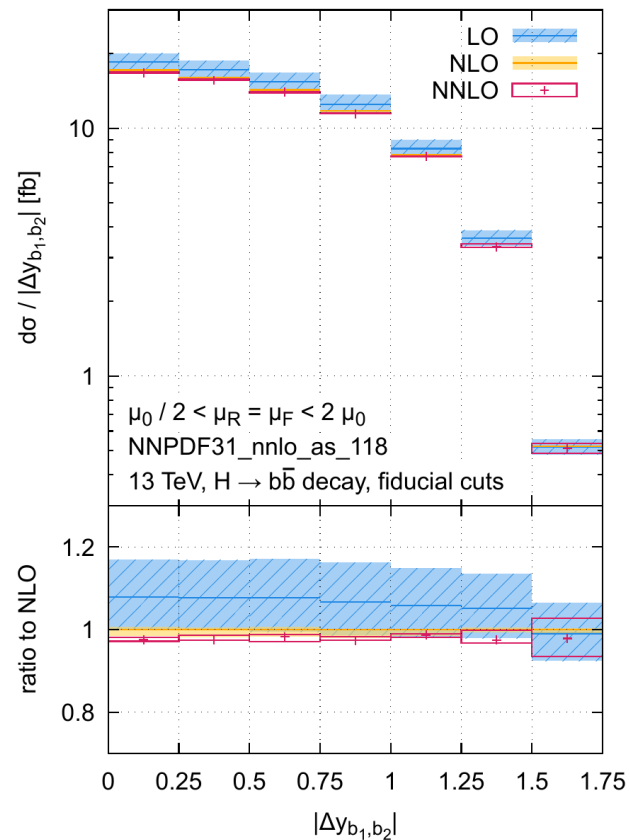
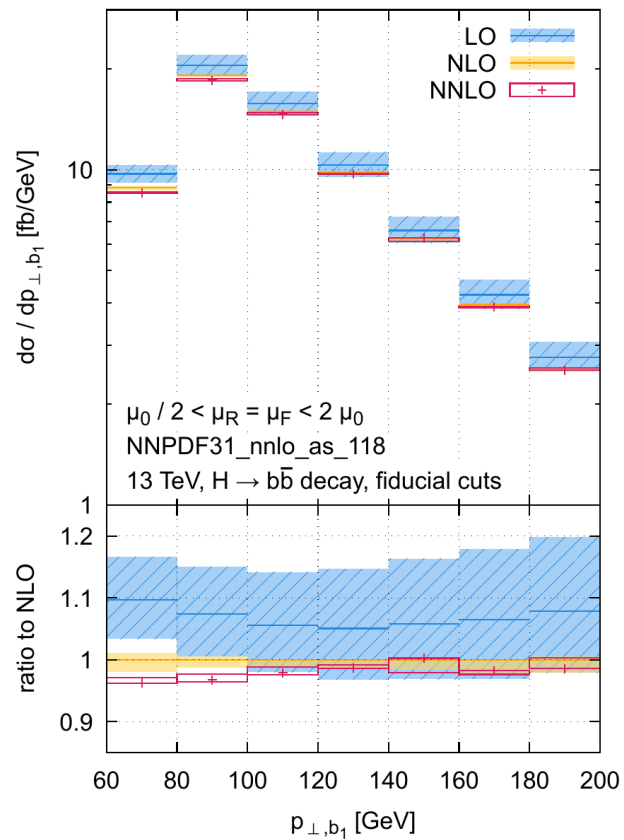
including decay



- For $p_t > 130 \text{ GeV}$ NNLO corrections are smaller and within residual scale uncertainty band
- Stable Higgs production with additional p_t cut $p_{\perp,H} > 150 \text{ GeV}$

$$\frac{\sigma_{\text{NNLO}}^H}{\sigma_{\text{LO}}^H} = 0.89 \quad \xrightarrow{\text{Higgs } p_t \text{ cut}} \quad \frac{\sigma_{\text{NNLO}}^H}{\sigma_{\text{LO}}^H} = 0.91 \quad \xrightarrow{\text{including decay}} \quad \frac{\sigma_{\text{NNLO}}^{b\bar{b}}}{\sigma_{\text{LO}}^{b\bar{b}}} = 0.914(2)$$

Differential cross sections



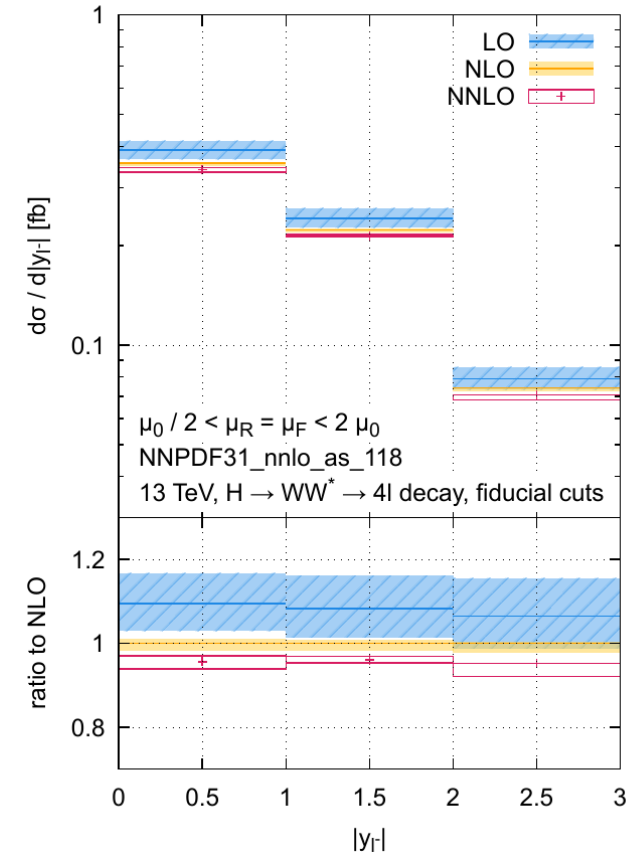
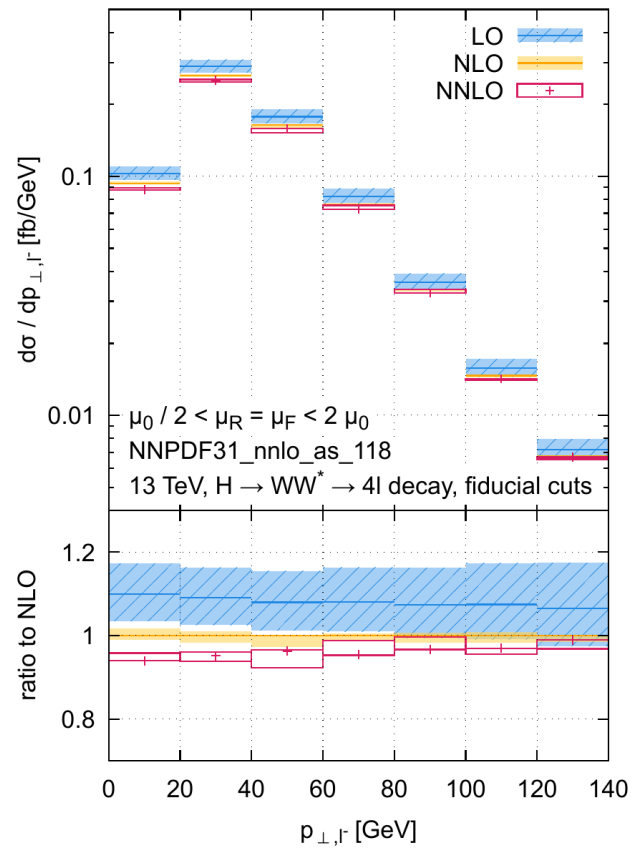
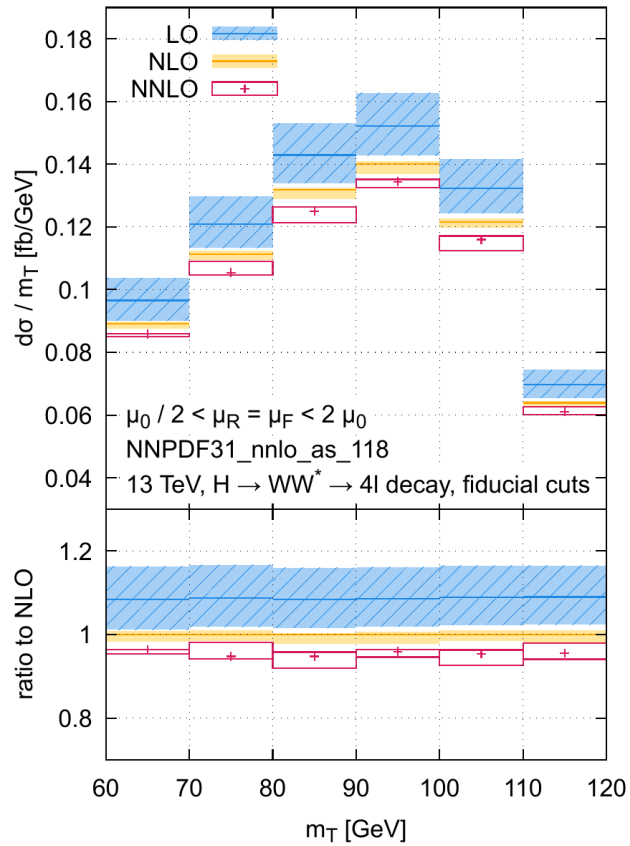
- Shapes of NLO distributions **not affected** by NNLO corrections
- Simple reweighting possible as long as NNLO/NLO K-factor is computed with a proper cut on the p_t of the stable Higgs boson

VBF + H → WW* → 2l 2ν

- Cuts loosely following latest CMS measurement [Phys. Lett. B 791, 96 (2019)]
 - Leading lepton $p_{\perp, l_1} > 25 \text{ GeV}$ / Subleading lepton $p_{\perp, l_2} > 13 \text{ GeV}$
 - Rapidity of leptons between rapidity of VBF tagged jets
 - Transverse mass: $60 \text{ GeV} < m_T \equiv \sqrt{2p_T^{l_1 l_2} p_T^{\text{miss}} (1 - \cos \Delta\phi_{l_1 l_2, \vec{p}_T^{\text{miss}}})} < 125 \text{ GeV}$
 - Lepton system: $p_{\perp, l_1 l_2} > 30 \text{ GeV}$ $m_{l_1 l_2} > 12 \text{ GeV}$
 - Missing pt: $p_T^{\text{miss}} > 20 \text{ GeV}$
- Mild cuts on Higgs decay products
- **Similar corrections as in case of stable Higgs expected and found**

$\sigma_{\text{NNLO}}^{l^- \bar{\nu} l^+ \nu}$	$=$	$\underbrace{0.719 \text{ fb}}_{\text{LO}}$	$+$	$\underbrace{(-0.057) \text{ fb}}_{\Delta\text{NLO}}$	$+$	$\underbrace{(-0.03) \text{ fb}}_{\Delta\text{NNLO}}$
				-7.9%		-4.2%
		<hr/>				
		(stable Higgs)		-8.3%		-3.2%

VBF + H \rightarrow WW* \rightarrow 2l 2 ν



- Differential K-factors rather flat
- NNLO/NLO K-factor computed with stable Higgs is a good approximation within O(1%) precision

Conclusion and Outlook

- First NNLO QCD study of Higgs boson production in vector boson fusion that includes the decay of the Higgs boson
- **VBF including $H \rightarrow b\bar{b}$ decay**
 - Non-trivial interplay from jets in production and decay processes
 - Changes in higher order corrections due to cuts on b-jets are comparable to NNLO corrections
 - Smaller residual scale uncertainty / better perturbative convergence
 - **Future work:** Include decay $H \rightarrow b\bar{b}$ massive @ NNLO
[\[Bernreuther, Chen, Si '18; Behring, Bizoń '19\]](#)
- **VBF including $H \rightarrow WW^* \rightarrow 2l 2\nu$ decay**
 - Effects of decay well captured by simple reweighting