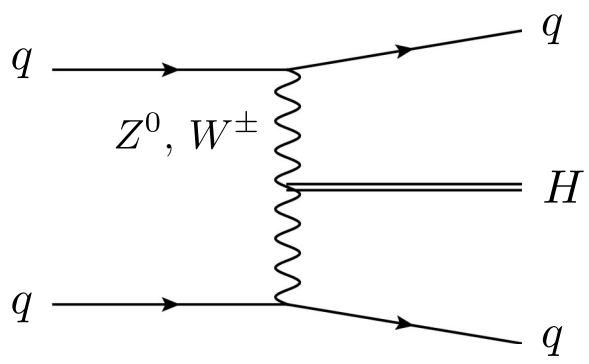
Universität Regensburg

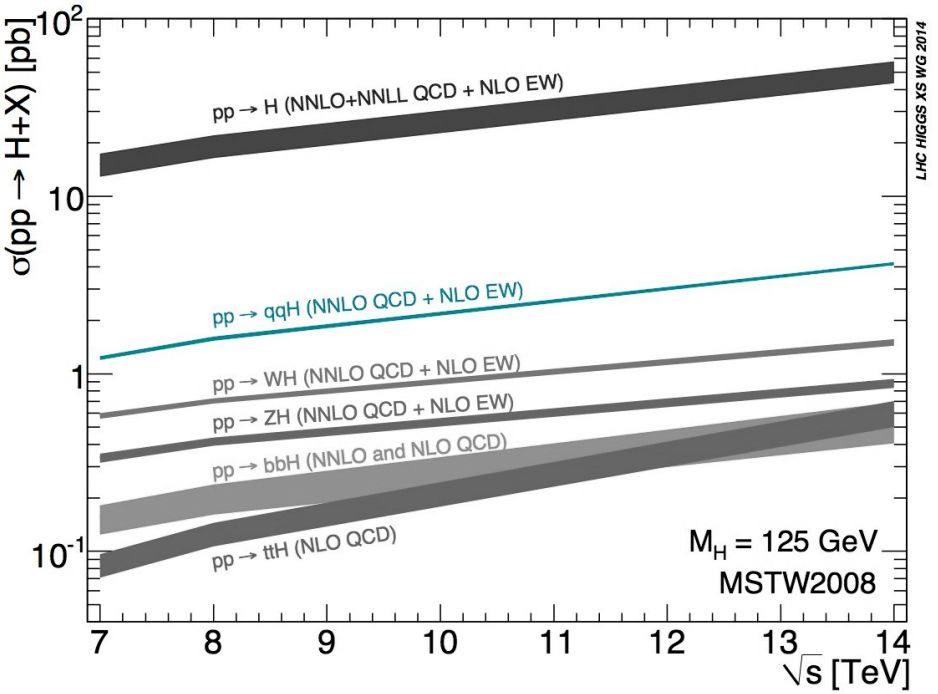
Higgs boson production in WBF with H → bb decay at NNLO

Konstantin Asteriadis | 30.07.2024

FOR2926 Summer Meeting - Regensburg

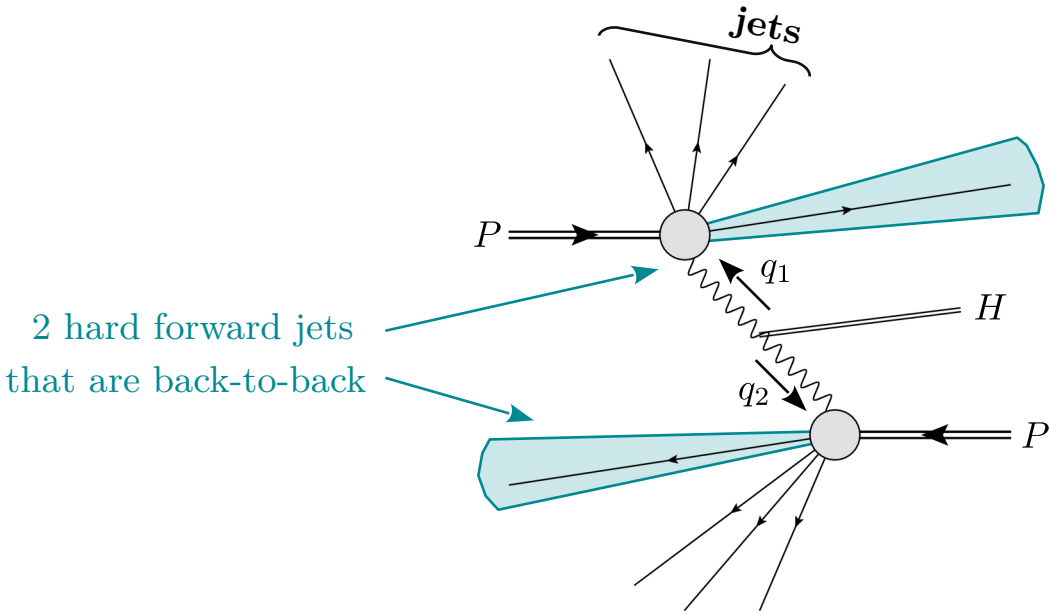
Higgs-boson production in weak boson fusion (WBF)





- Important production channel of Higgs boson @LHC (second highest cross section @14TeV)
- Probes electro-weak sector
- Very distinct signature
- ...

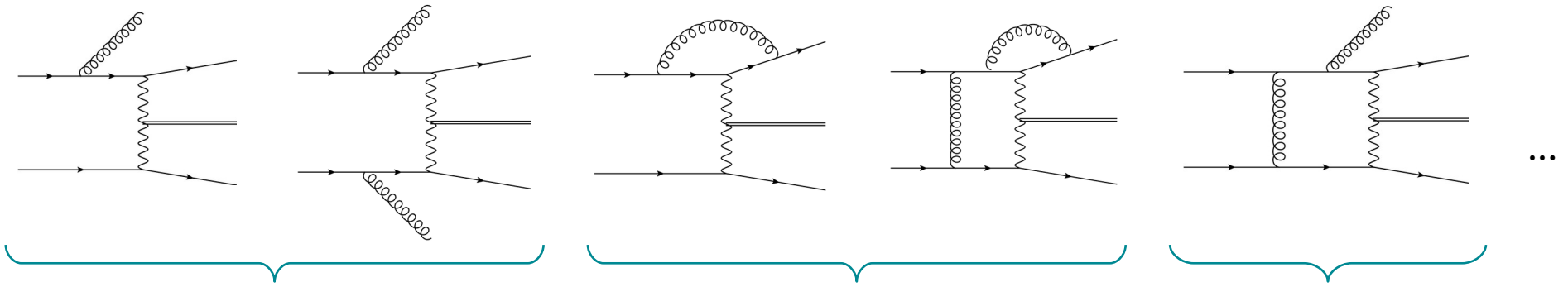
Experimental signature of WBF



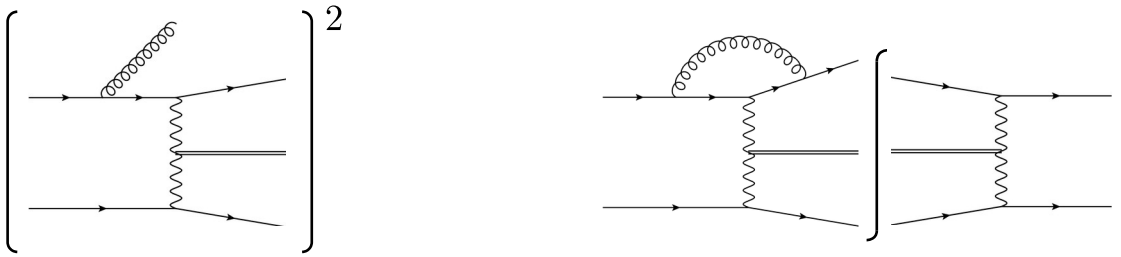
- **Typical WBF cuts:** at least 2 resolved "tag" jets with $p_{\perp,j} > 25\,\text{GeV}$ and $-4.5 < y_j < 4.5$
  - Separated in rapidity $|y_{j_1} - y_{j_2}| > 4.5$ and in different hemispheres $y_{j_1} \times y_{j_2} < 0$
  - Invariant mass $\sqrt{(p_{j_1} + p_{j_2})^2} > 600\,\text{GeV}$
  - Jets identified using anti-kt jet-algorithm with$R = 0.4$

- Experimentally measured with 10 – 20% accuracy → few percent with HL-LHC

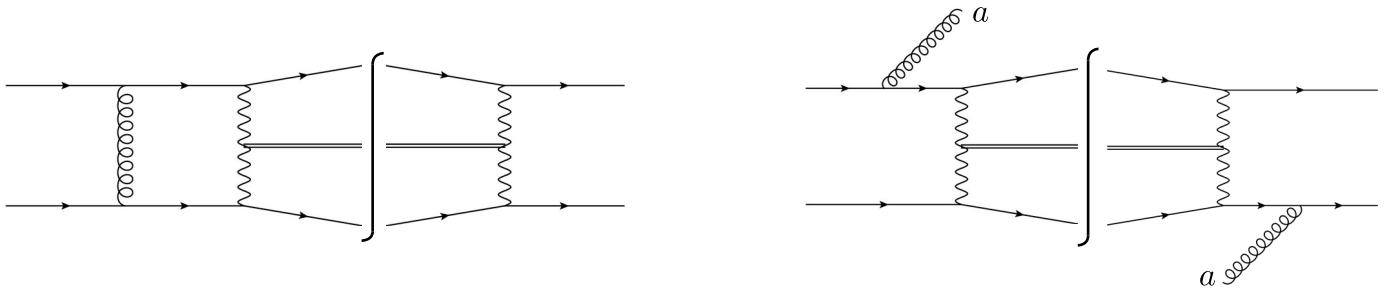
Higher order QCD correction to WBF



- 2 classes of corrections to the amplitude squared: *factorizable* and *non-factorizable*
- Examples for *factorizable* corrections

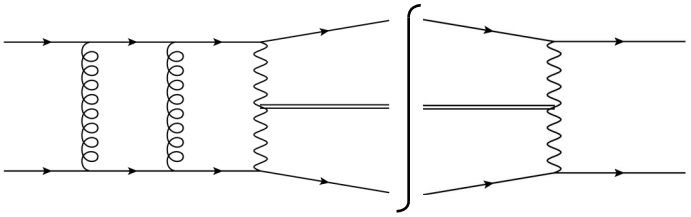


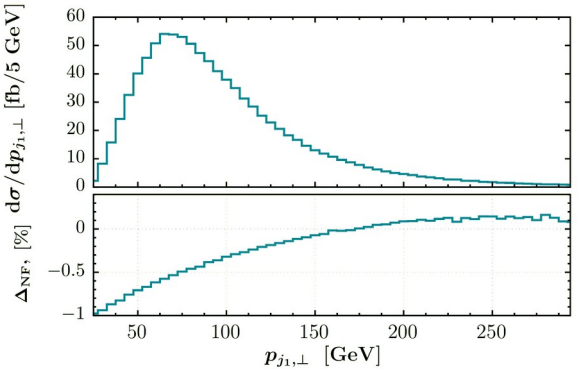
- *Non-factorizable* correction not present at NLO QCD due to colour conservation$\sim \mathrm{Tr}(T^a) = 0$



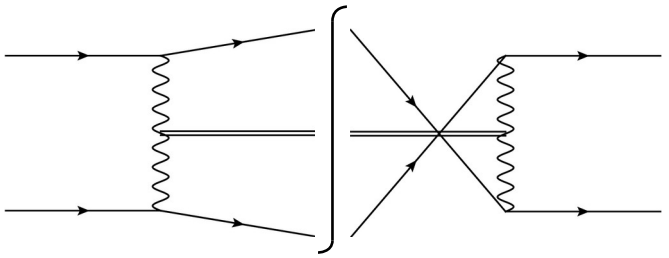
Non-factorizable corrections to WBF

- Non-factorizable two loop contributions at NNLO are colour suppressed $\sim \frac{1}{N_c^2} \approx \frac{1}{10}$
  - Not feasible to compute exact (2-loop, 5-point function with 2 scales) with current loop-technology
  - *In certain regions of the phase space enhanced by* $\pi^2 \approx 10$ *(Glauber phase)* [Liu, Melnikov, Penin '19]
  - First estimates [Dreyer, Karlberg, Tancredi '20; Chen, Figy, Plätzer '21]

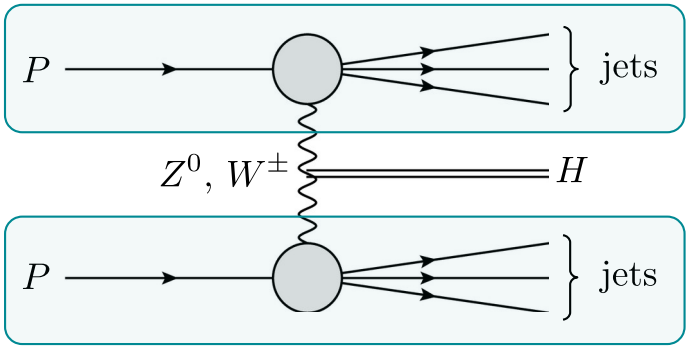




- Include contributions at least in enhanced (forward) regions of the phase space [KA, Brønnum-Hansen, Melnikov '23; Long, Melnikov, Quarroz '23, Brønnum-Hansen, Long, Melnikov '23]
- More exotic contributions in case of identical flavours are not only colour suppressed but also suppressed by large momentum transfer in the weak-boson propagators [Bolzoni et al. '11]



Factorizable corrections to WBF and state of the art of QCD analysis

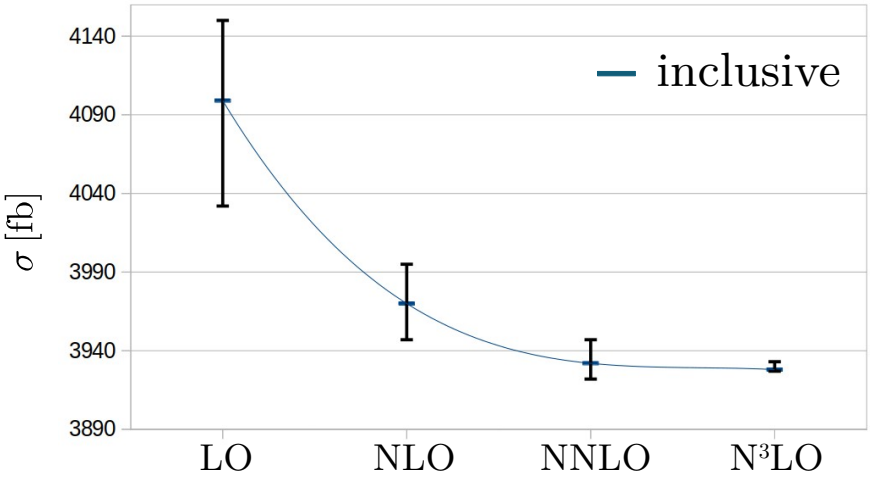


(Deep inelastic scattering)²

- Standard model with two identical but non-interacting QCD
  - Effectively DIS scattering of two protons
  - DIS well studied → possibility to use existing results

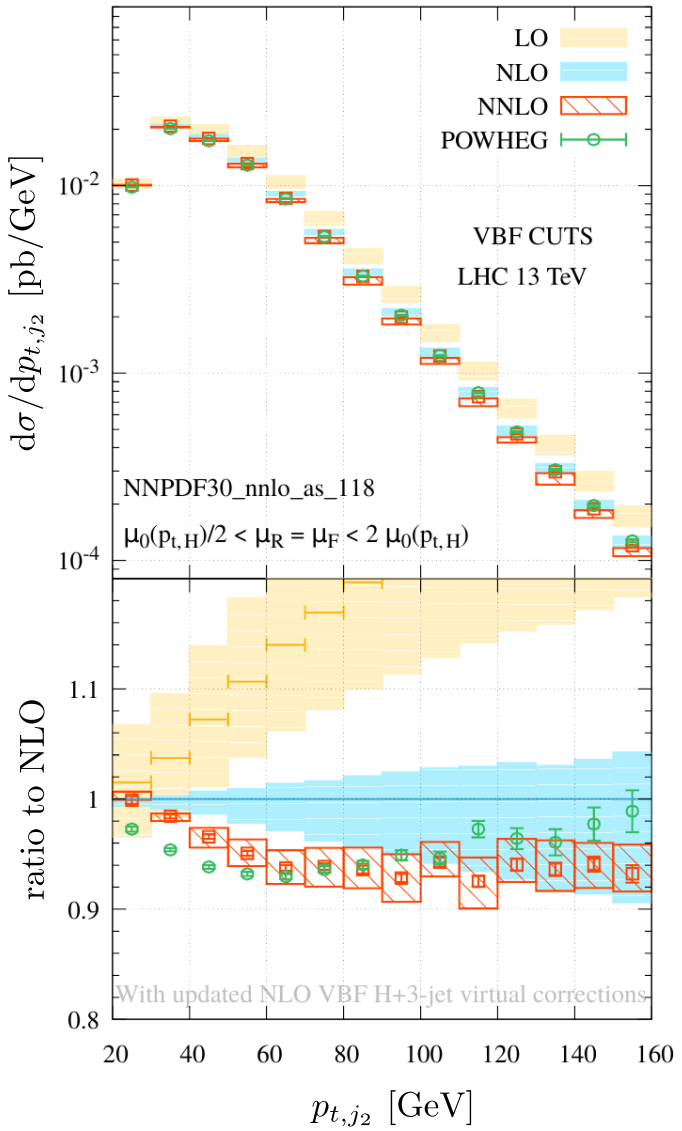
    → Factorizable corrections well studied?

- **Inclusive known till N³LO**
  [Dreyer, Karlberg '16]
  - Nicely converging, N³LO within residual scale uncertainties
- **Fully differential known till NNLO**
  [Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15]
  [Cruz-Martinez, Glover, Gehrmann, Huss '18]
  - **Fiducial cuts:** NNLO corrections outside of residual NLO scale uncertainties

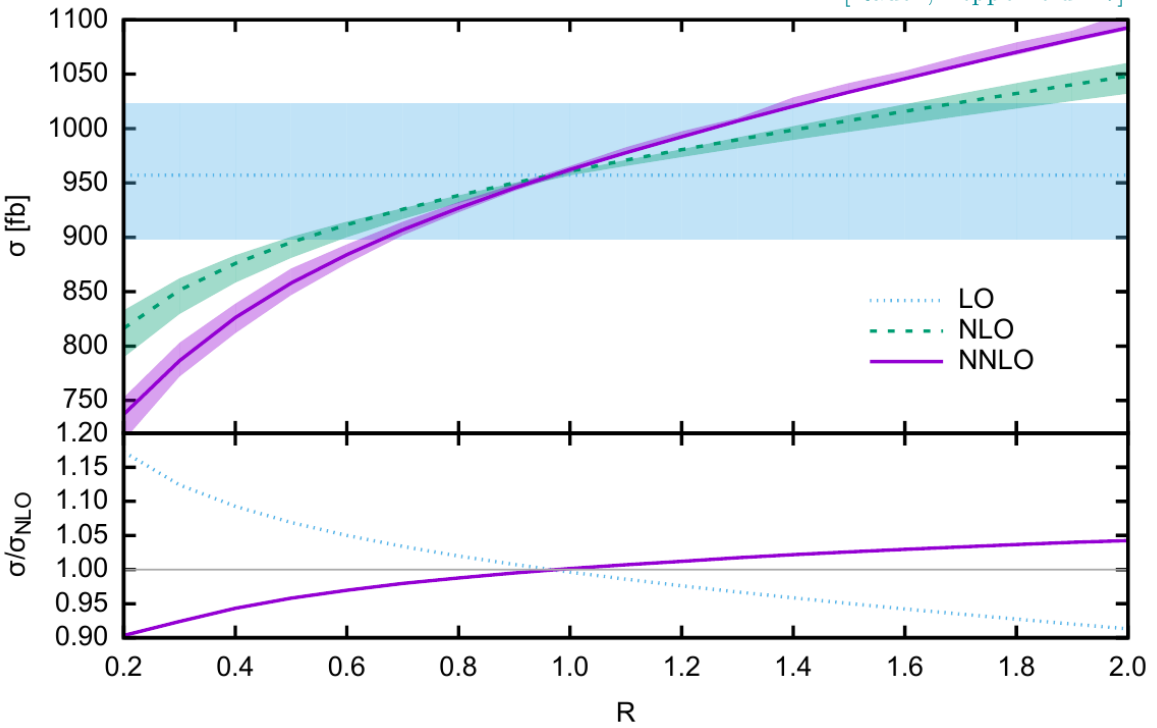


State of the art of QCD analysis

[Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15]

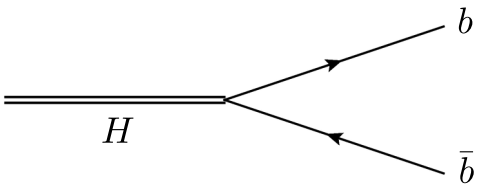


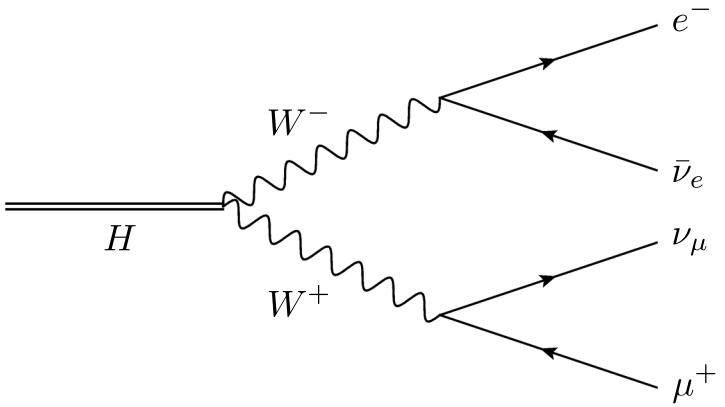
[Rauch, Zeppenfeld '17]

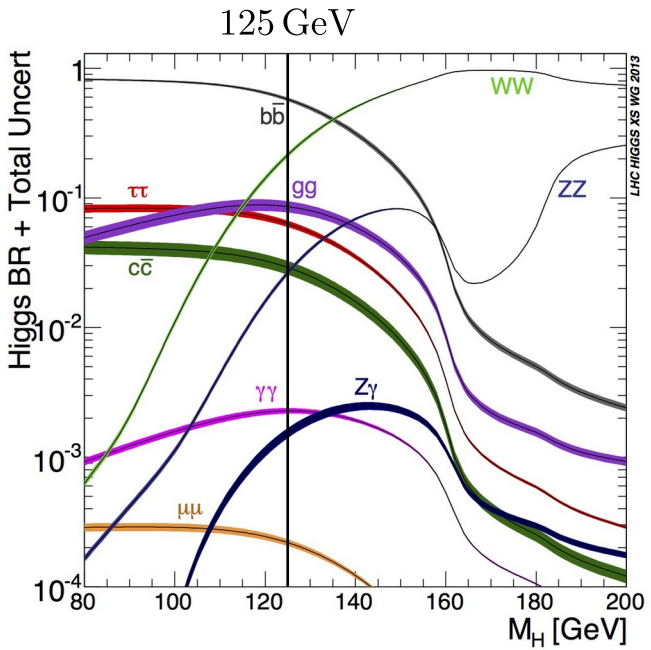


- Non-trivial jet dynamics in WBF Higgs boson poduction
- All current computations are for stable Higgs boson production → Effects of additional jets from Higgs decay?

Realistic final states [KA, Fabrizio Caola, Kirill Melnikov, Raoul Röntsch JHEP 02 (2022) 046]



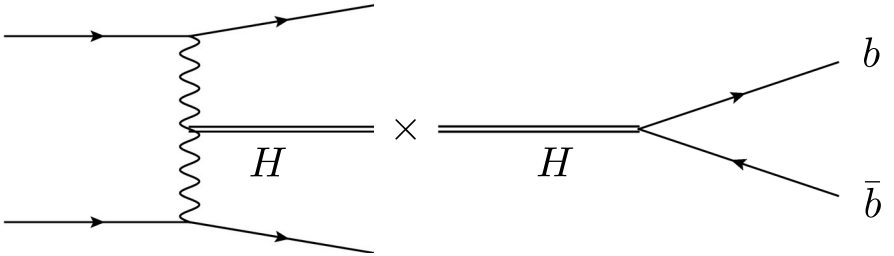


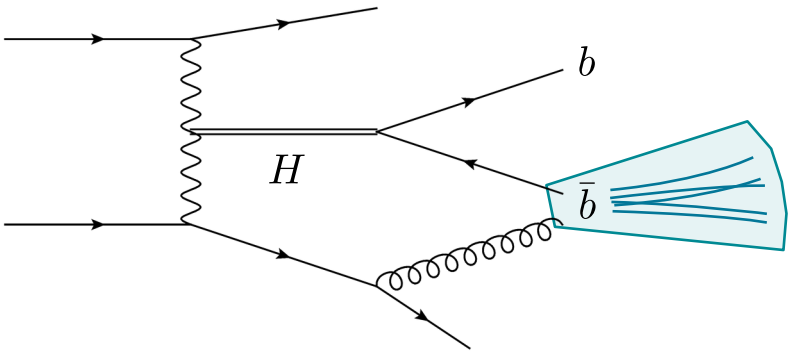


- $\mathbf{H \to b\bar{b}}$ and $\mathbf{H \to WW^* \to 2l\,2\nu}$
- Highest branching ratios
- Both studied by ATLAS and CMS
  [e.g. Eur. Phys. J. C 81, 537 (2021); Phys. Lett. B 791, 96 (2019)]
- Doing this at NNLO QCD naively simple, in practice very complicated
  - non-trivial interplay between partonic jets from production and decay when fiducial cuts are applied
  - up to 21 dimensional phase space integration that is numerically very challenging
- **In what follows: focus on $\mathbf{H \to b\bar{b}}$ decay channel**

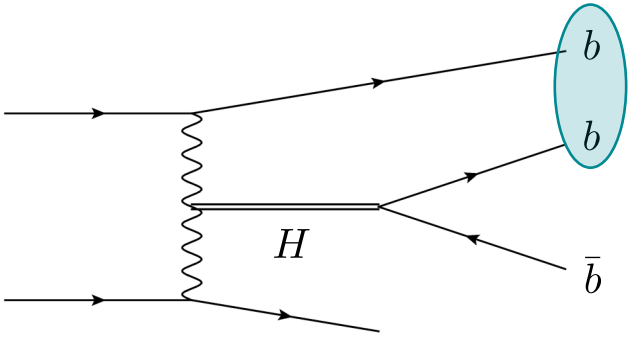
WBF + H → $b\bar{b}$ decay

- Narrow width approximation → factorization of on-shell Higgs production and on-shell Higgs decay
- Several effects break factorization of production and decay process. For example





Jet-clustering breaks factorization



B-tagging breaks factorization

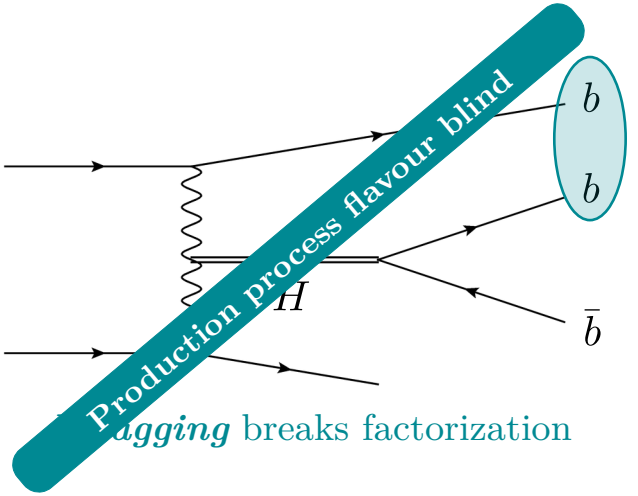
- Impact of decay on NNLO corrections is non-trivial → effects might not be captured by a simple reweighing
- We don't expect this effects to be very large but it is important to quantify their size
- Finally: cuts on b-jets may change fiducial WBF region

Physical setup

- Only *factorizable* contributions
- 13 TeV center-of-mass energy / NNPDF31-nnlo-as-118
- Scale choice [Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15; Cruz-Martinez, Glover, Gehrmann, Huss '18]

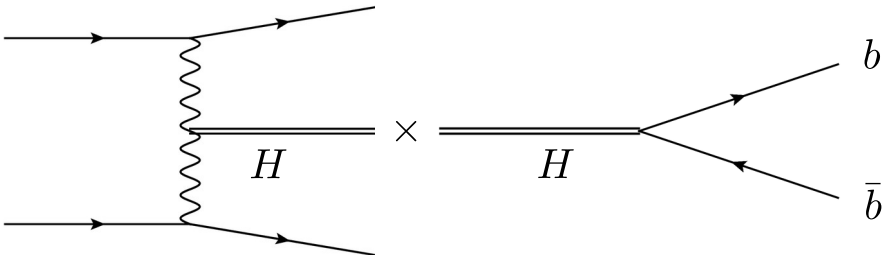
$$\mu_0 = \sqrt{\frac{m_h}{2}\sqrt{\frac{m_H^2}{4} + p_{\perp,H}^2}}$$

- Cuts on b-jets; loosely following latest ATLAS measurement [Eur. Phys. J. C 81, 537 (2021)]
  - 2 resolved b-jets
  - $p_{\perp,jb} > 65$ GeV
  - $|y_{jb}| < 2.5$
- Production process is flavour "blind"
  - At higher orders 1% of the cross section contains production b-jets in the final state
  - ... and in only 6% of the events b-jets are clustered with production jets



agging breaks factorization

WBF + H → bb



First step: Study QCD corrections to the production process but decay process is kept at LO QCD

[KA, Fabrizio Caola, Kirill Melnikov, Raoul Röntsch JHEP 02 (2022) 046]

Second step: Also include QCD corrections to the decay process

[KA, Arnd Behring, Kirill Melnikov, Ivan Novikov, Raoul Röntsch 2407.09363]

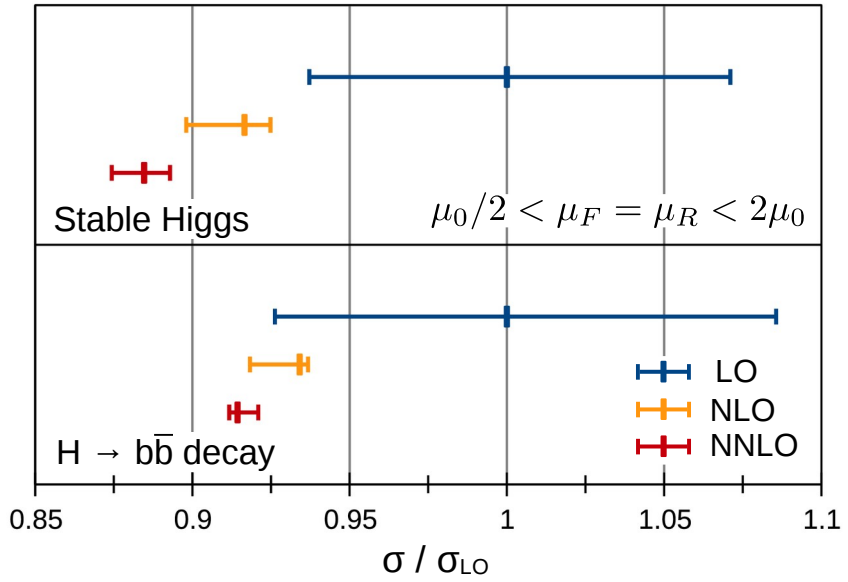
First step: WBF @NNLO + H → bb @LO

[KA, Fabrizio Caola, Kirill Melnikov, Raoul Röntsch JHEP 02 (2022) 046]

- Sizable fiducial cross section, O(100 000) events with HL-LHC

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

- Comparison to stable Higgs results



$$\frac{\sigma^{H}_{\mathrm{NLO}}}{\sigma^{H}_{\mathrm{LO}}} = 0.917(1) \quad \xrightarrow{-3.2\%} \quad \frac{\sigma^{H}_{\mathrm{NNLO}}}{\sigma^{H}_{\mathrm{LO}}} = 0.885(1)$$

$$\downarrow +1.7\% \qquad\qquad \downarrow +2.9\%$$

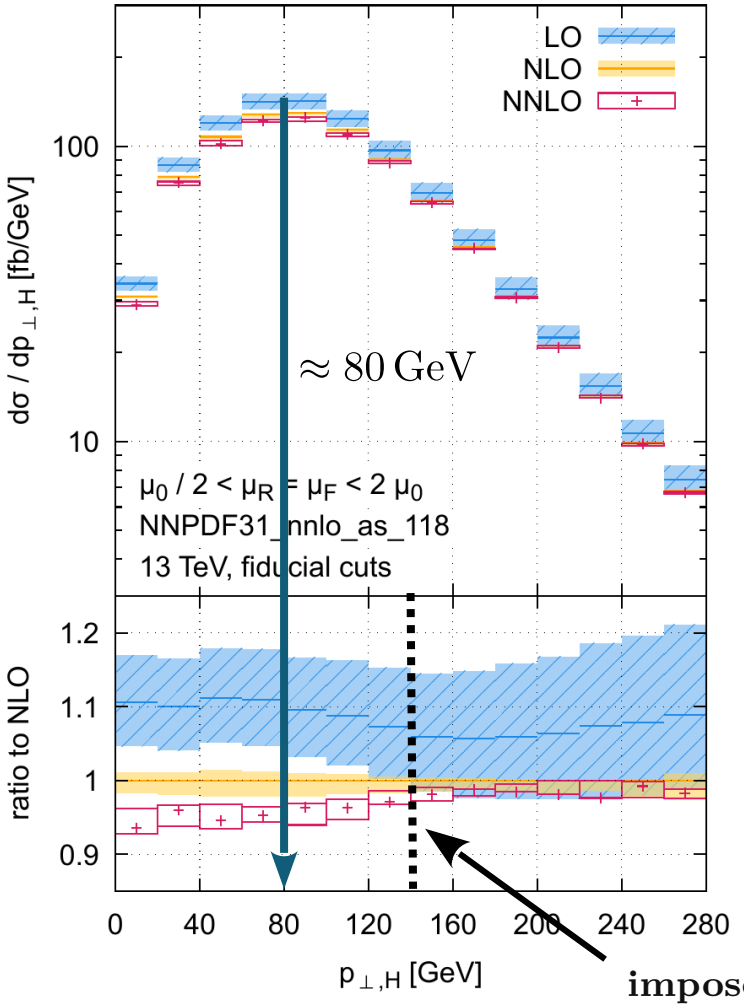
$$\frac{\sigma^{b\bar{b}}_{\mathrm{NLO}}}{\sigma^{b\bar{b}}_{\mathrm{LO}}} = 0.934(1) \qquad\qquad \frac{\sigma^{b\bar{b}}_{\mathrm{NNLO}}}{\sigma^{b\bar{b}}_{\mathrm{LO}}} = 0.914(2)$$

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

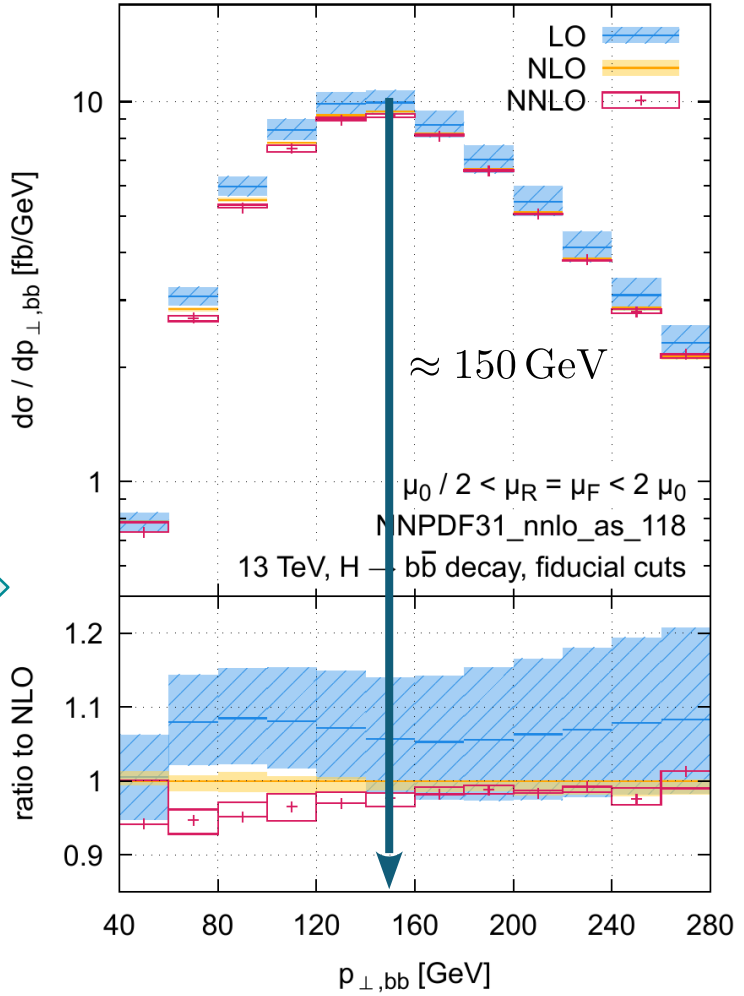
- **Overall: effect of H → bb decay of same order as NNLO corrections themselves!**

Results: fiducial cross section

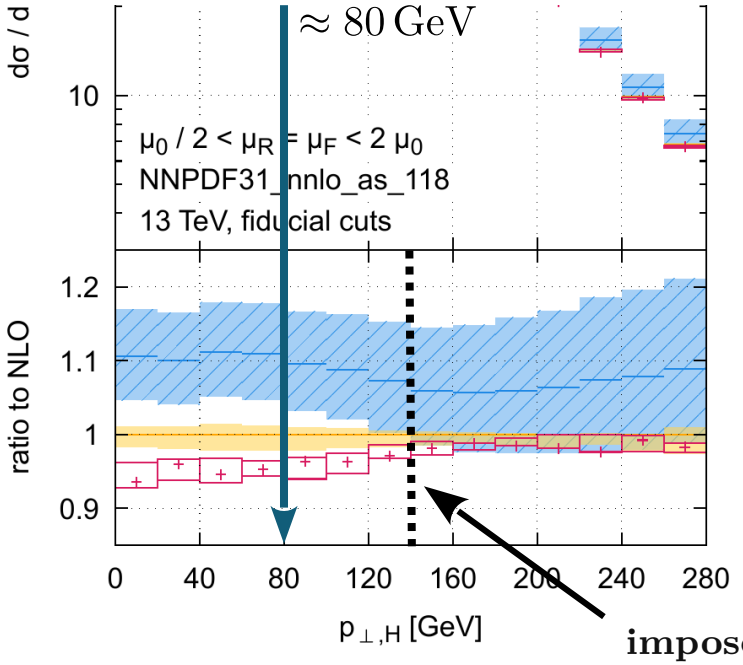
- Simple reason: pt cuts on b-jets ($p_{\perp,j_b} > 65\,\text{GeV}$) preferentially selects events with high Higgs transverse momentum



including decay



imposed "soft" pt cu2 $p_{\perp,j_b}^{\min} = 130\,\text{GeV}$



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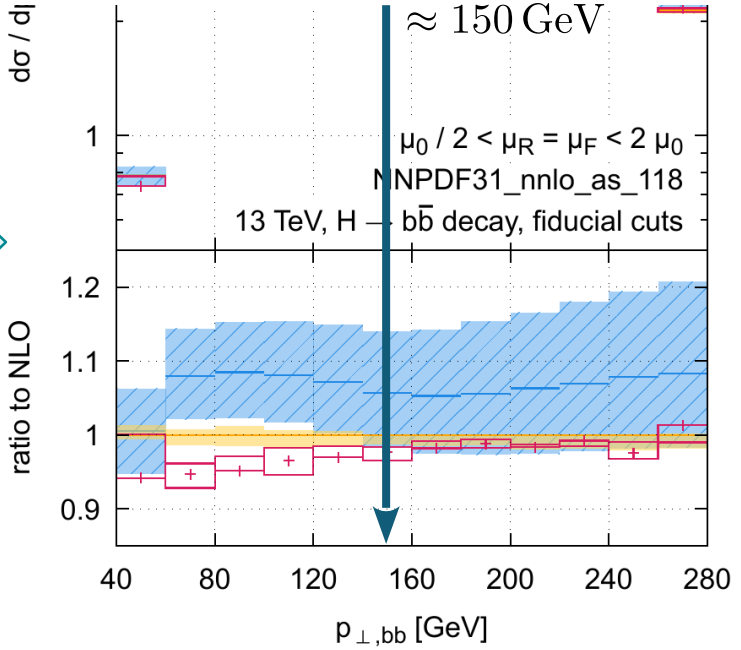
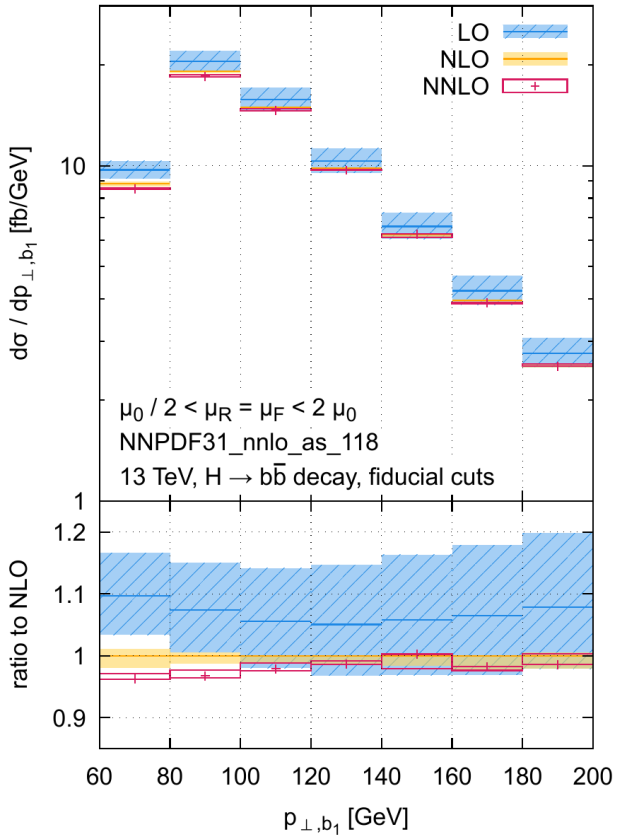


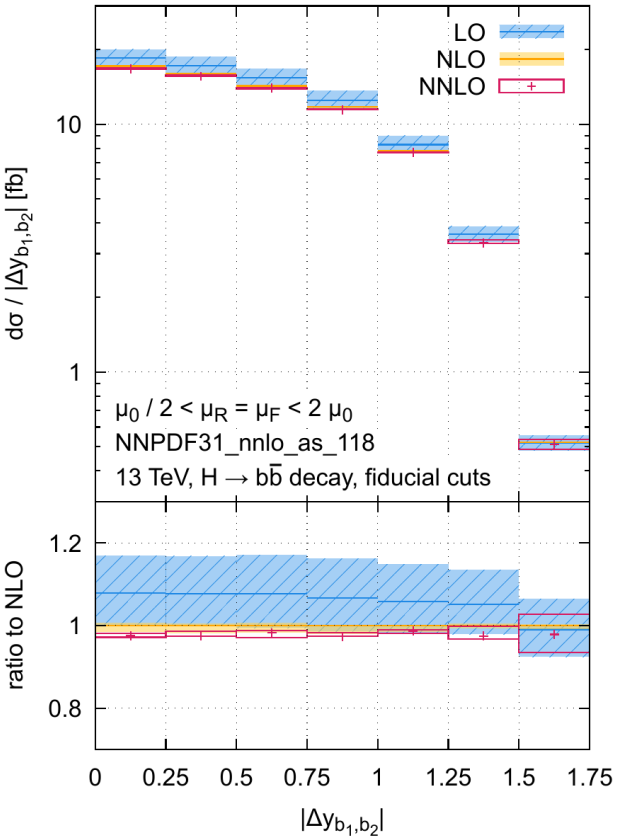
imposed "soft" pt cut $2\,p_{\perp,j_b}^{\min} = 130\,\text{GeV}$

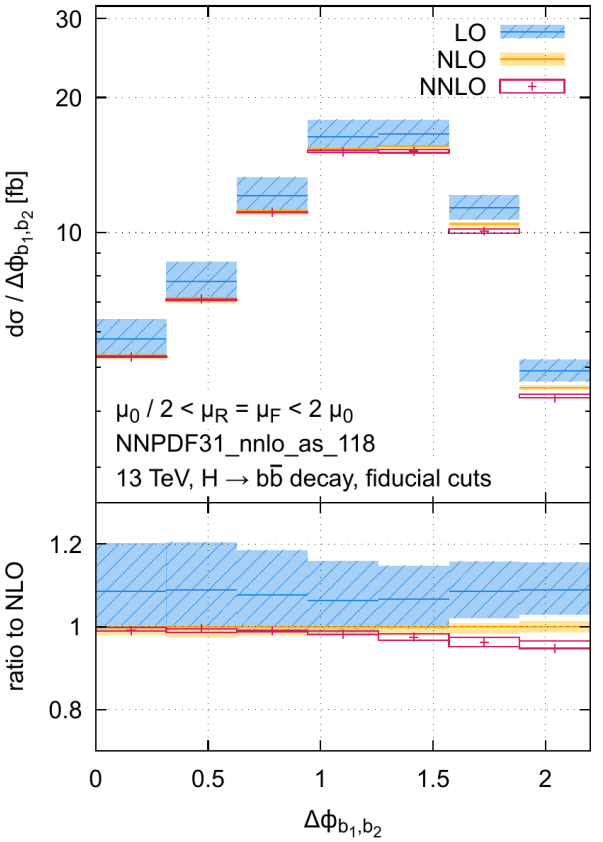
- NLO corrections are rather flat → moderate effect
- For pt > 130 GeV NNLO corrections are smaller and within residual scale uncertainty band
- Check: Stable Higgs production with additional pt cut $p_{\perp,H} > 150\,\text{GeV}$

$$\frac{\sigma^H_{\text{NNLO}}}{\sigma^H_{\text{LO}}} = 0.89 \quad \text{Higgs pt cut} \quad \frac{\sigma^H_{\text{NNLO}}}{\sigma^H_{\text{LO}}} = 0.91 \quad \text{including decay} \quad \frac{\sigma^{b\bar{b}}_{\text{NNLO}}}{\sigma^{b\bar{b}}_{\text{LO}}} = 0.914(2)$$

Results: differential cross sections





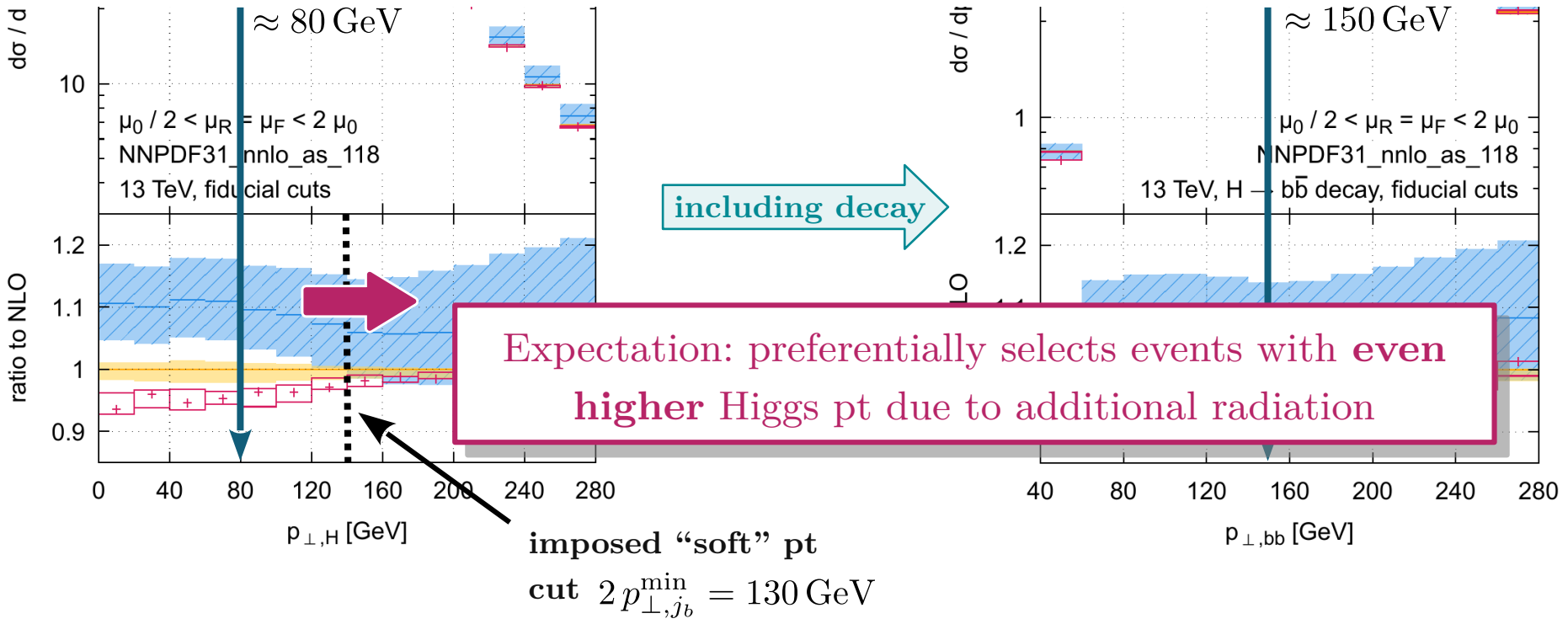


- Shapes of NLO distributions **not affected** by NNLO corrections
- Simple reweighting possible as long as NNLO/NLO K-factor is computed with a proper cut on the pt of the stable Higgs boson

Second step: WBF @NNLO + H → bb @NNLO

[KA, Arnd Behring, Kirill Melnikov, Ivan Novikov, Raoul Röntsch 2407.09363]

- Include QCD corrections to the decay process (used implementation includes massive b-quarks)
  [Bernreuther, Chen, Si '2018; Behring, Bizoń '19]
- Same physical setup and still no flavour tagging in the production process



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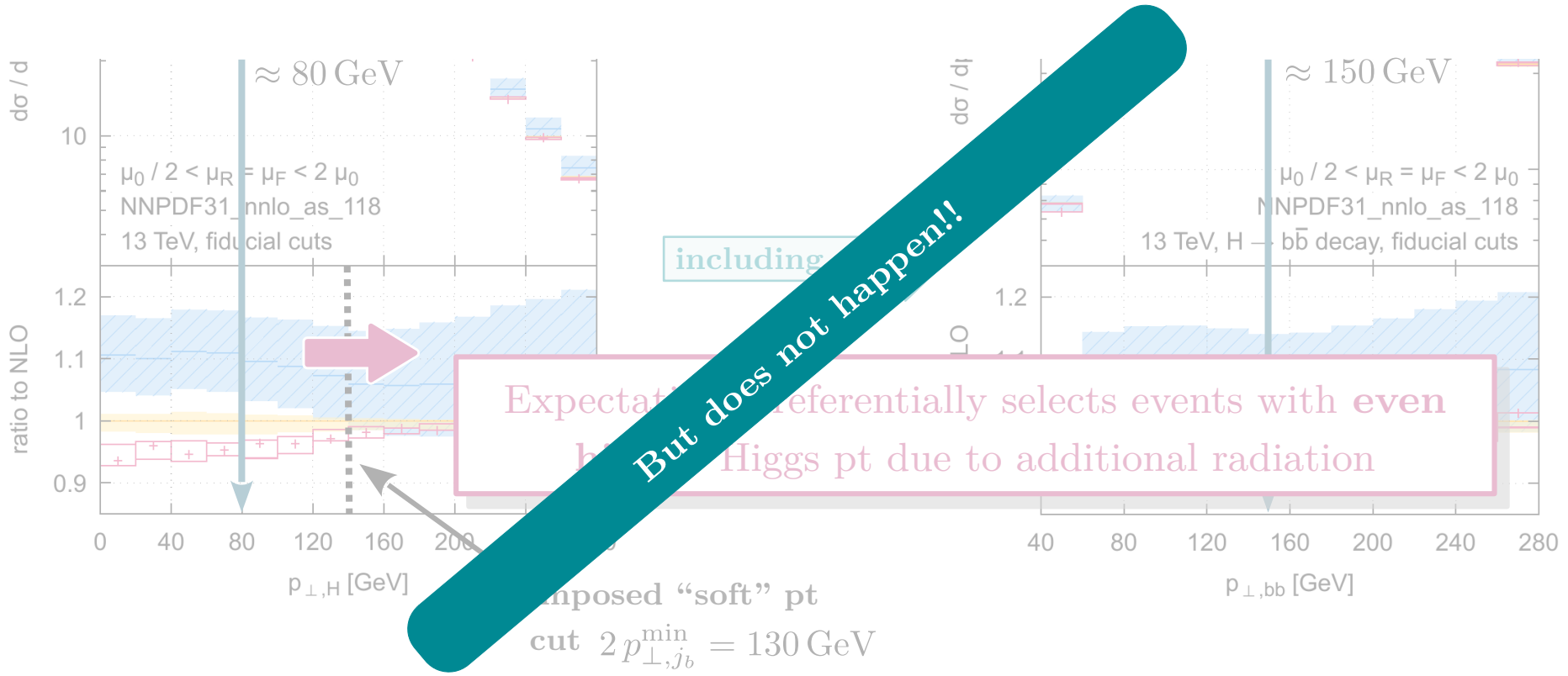


Results: fiducial cross section

- Corrections to the decay width at $\mu = m_H$

$$\Gamma^{b\bar{b}}_{\rm LO} = 1.926\ {\rm MeV}\,, \qquad \Gamma^{b\bar{b}}_{\rm NLO} = 2.327\ {\rm MeV}\,, \qquad \Gamma^{b\bar{b}}_{\rm NNLO} = 2.432\ {\rm MeV}$$

21 % **5 %**

- We keep the branching ratio fix and only expand differential shape of the decay process

$$d\sigma = {\rm Br}_{H\to b\bar{b}}\ d\sigma_{\rm WBF}\ \frac{d\Gamma_{H\to b\bar{b}}}{\Gamma_{H\to b\bar{b}}}$$

expand shape

kept fix @NNLO

- Corrections to the fiducial cross section (again with $\mu = m_H$ in the decay process)

$$\sigma^{b\bar{b}}_{\rm LO} = 75.6^{-5.6}_{+6.5}\ {\rm fb}\,, \qquad \sigma^{b\bar{b}}_{\rm NLO} = 52.4^{+1.5}_{-2.6}\ {\rm fb}\,, \qquad \sigma^{b\bar{b}}_{\rm NNLO} = 44.6^{+0.9}_{-0.6}\ {\rm fb}$$

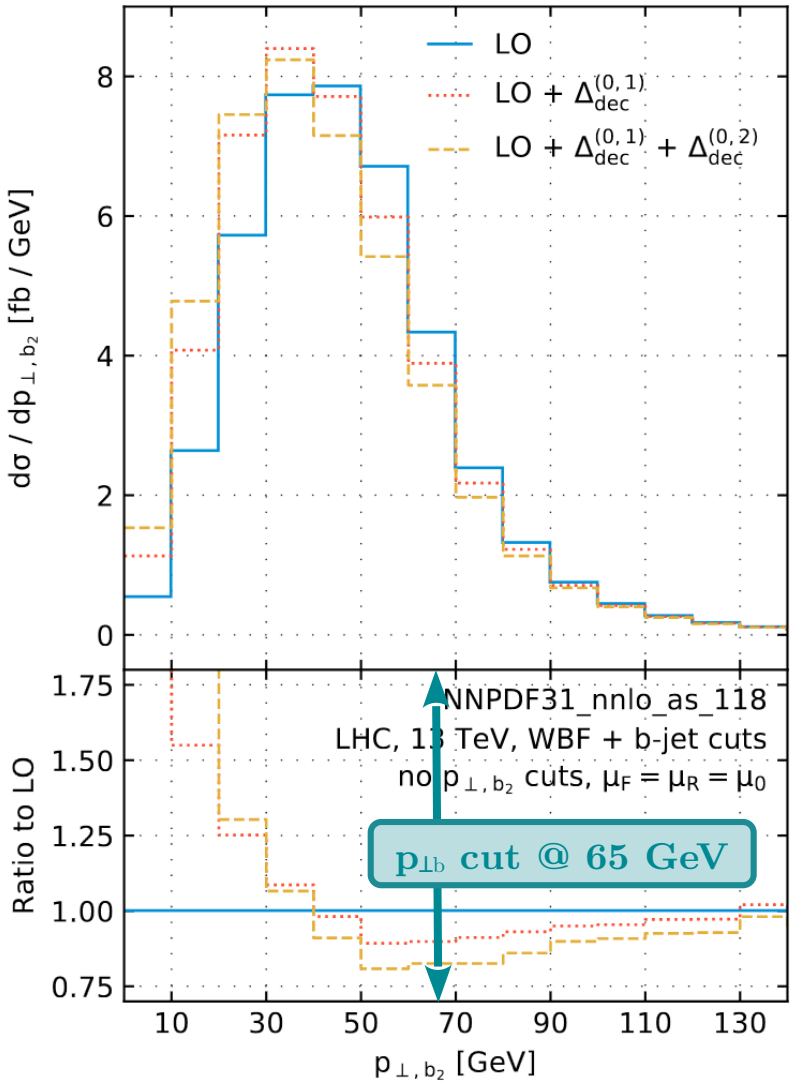
30 % **15 %**

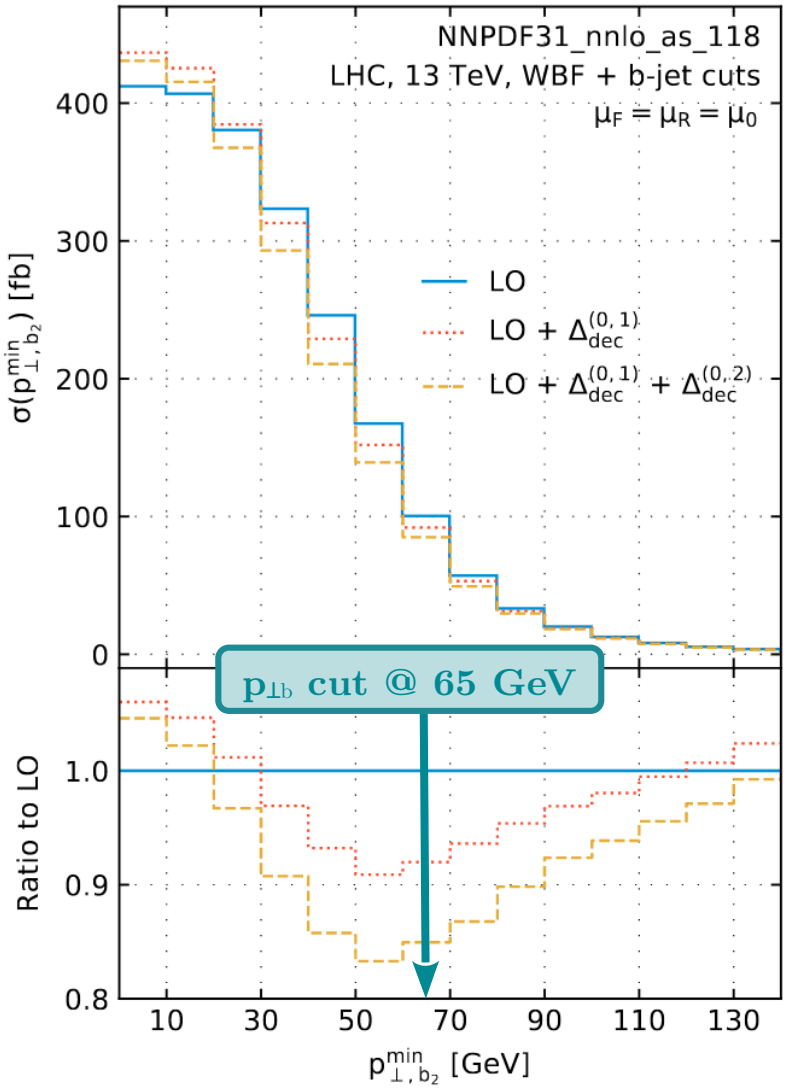
Compared to result with H → bb @LO:

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

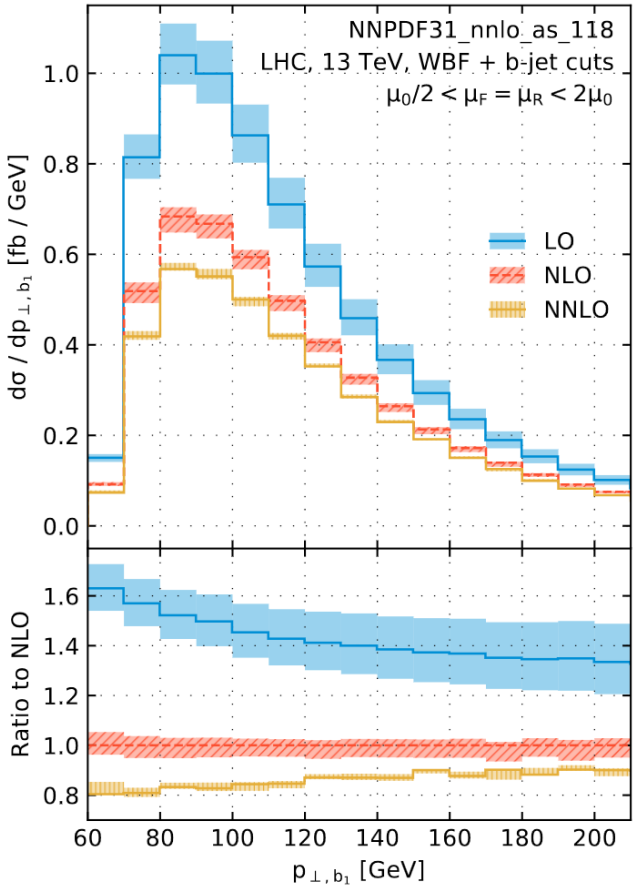
- **The reason for the large corrections are fiducial cuts on b-jets**

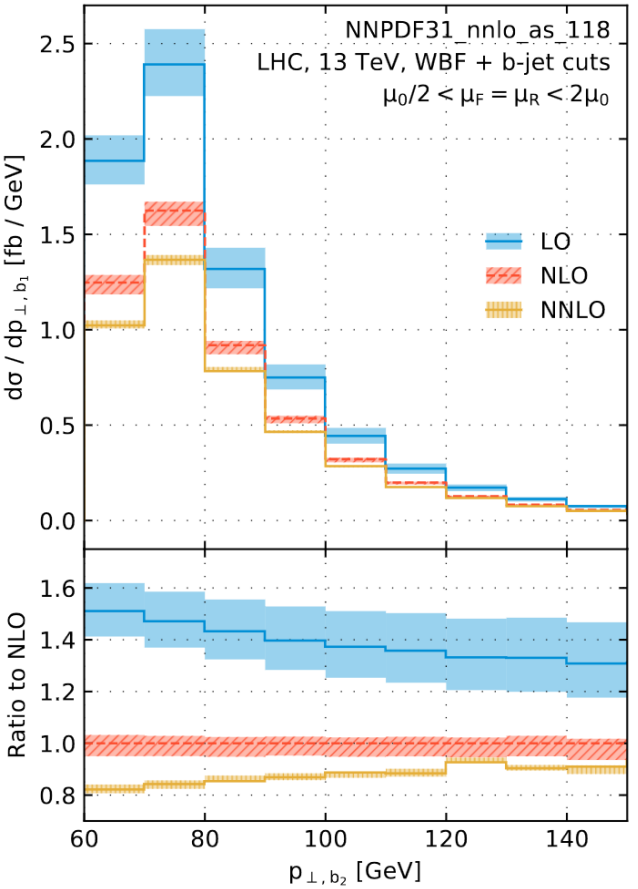
Results: fiducial cross section

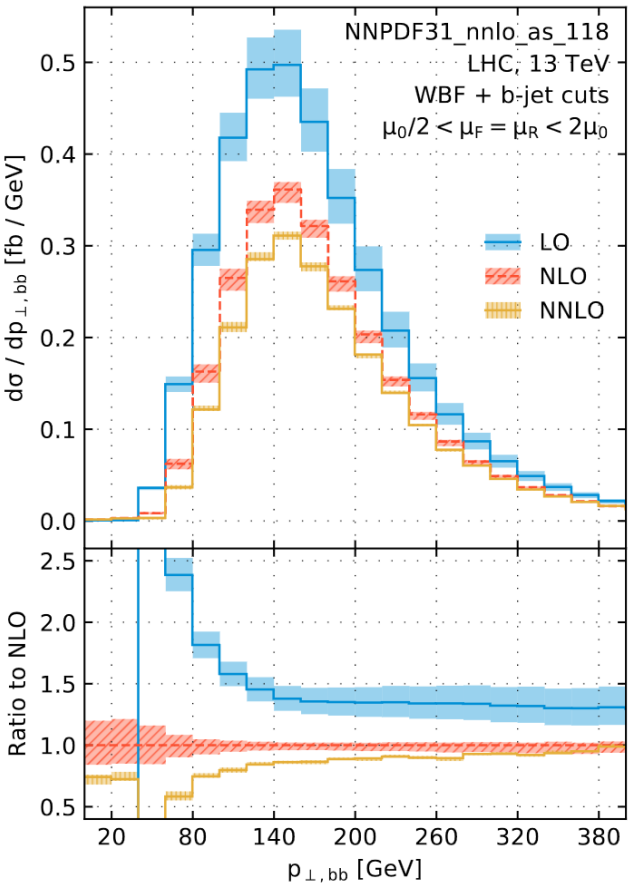




Same results in differential cross sections

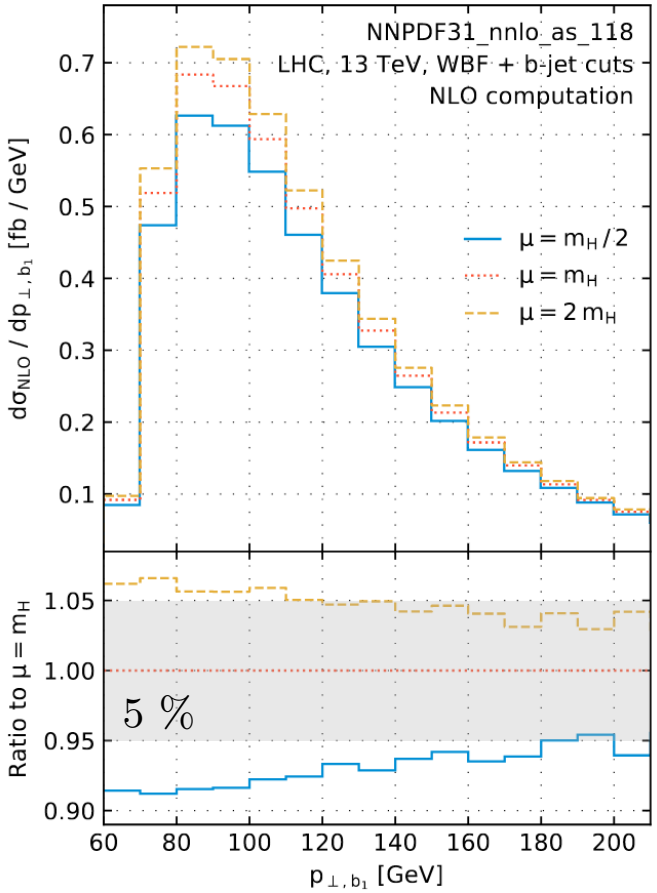


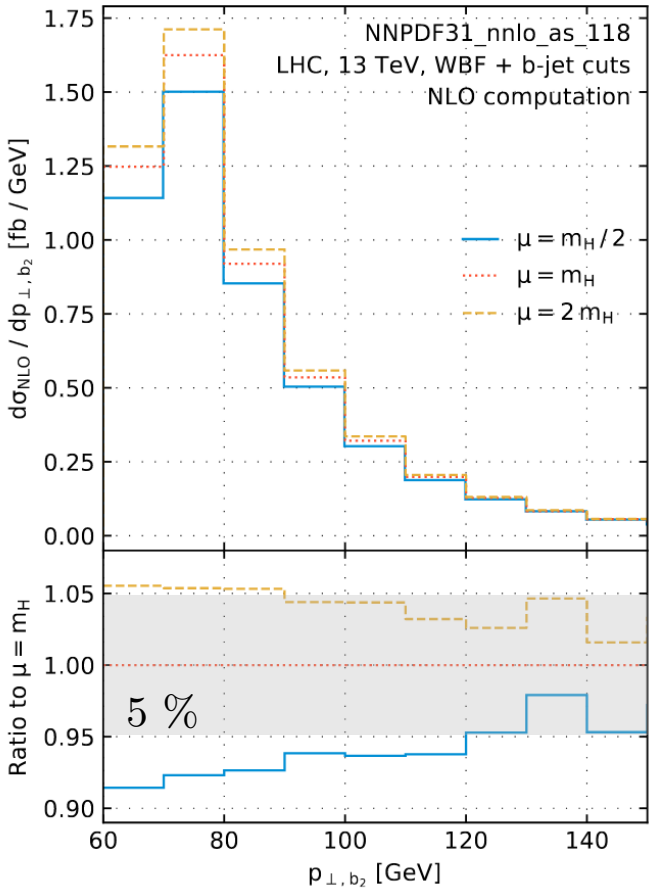




- Shapes of NLO distributions **not affected** by NNLO corrections
- Simple reweighting possible as long as NNLO/NLO K-factor is computed with a proper cut on the pt of the stable Higgs boson
- No overlap of residual scale uncertainty bands (no scale variation in the decay process)

Same results in differential cross sections





- Perturbative expansion of H → bb observed to converge somewhat faster for $\mu = m_H/2$ [Behring, Bizoń '19]
- … but with WBF, scale variation in the decay similar to production ~ 5 - 10 %

Conclusion and Outlook

- Non-trivial interplay from jets in production and decay processes

- **WBF + H → bb @ LO**
  - Changes in higher order corrections due to cuts on b-jets are comparable to NNLO corrections
  - Smaller residual scale uncertainty / better perturbative convergence

- **WBF + H → bb @ NNLO**
  - Non-trivial transverse momentum distributions of b-jets

- With current fiducial cuts no perturbative control of this process
- … but lowering the ptb cut substantially might not be possible due to experimental constraints

- To formally complete computation we need to tag b-jets in the WBF production process