PARTON-SHOWER AND FIXED-ORDER QCD EFFECTS IN WEAK-BOSON FUSION AND $H \to b\bar{b}$ DECAY

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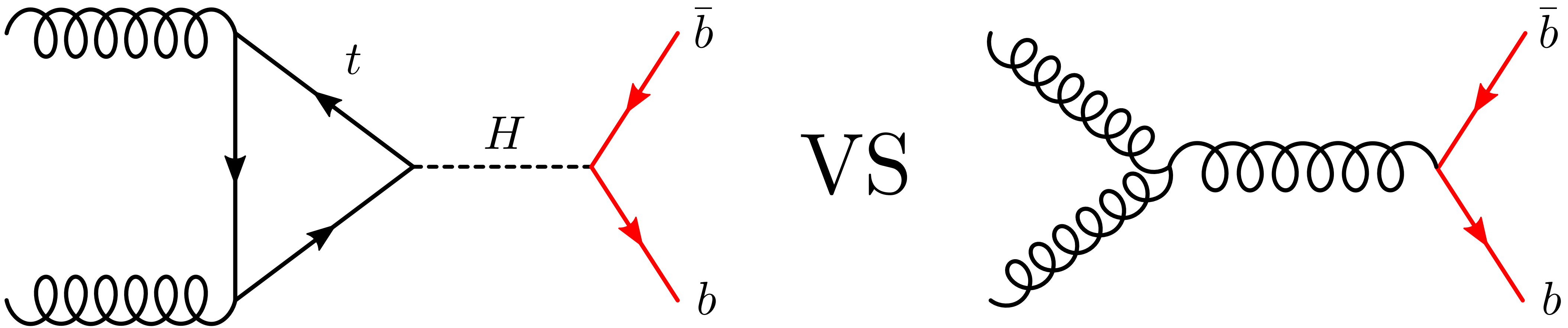
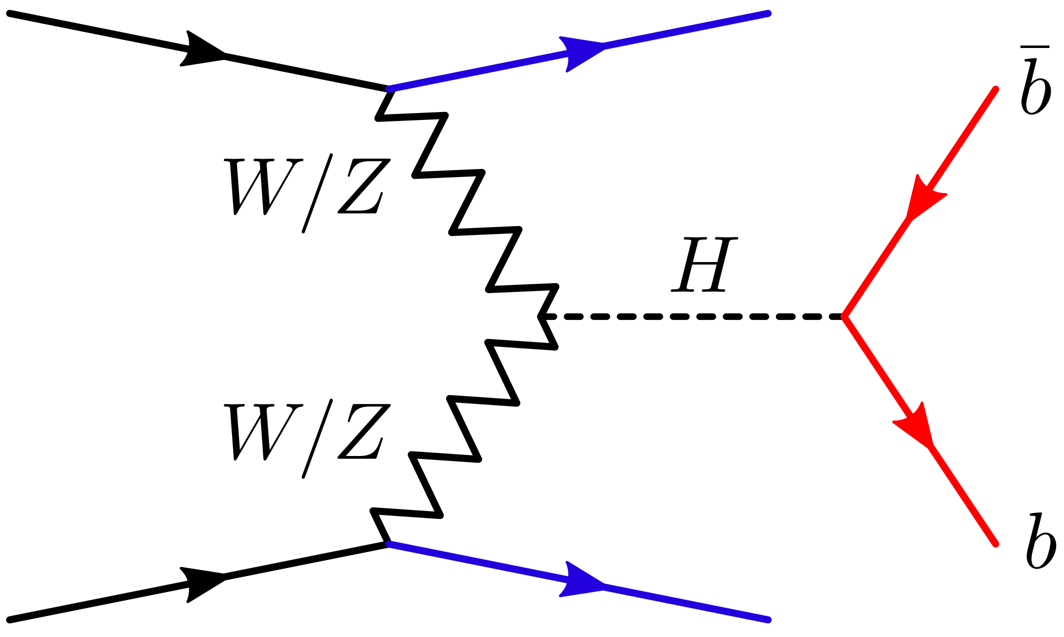
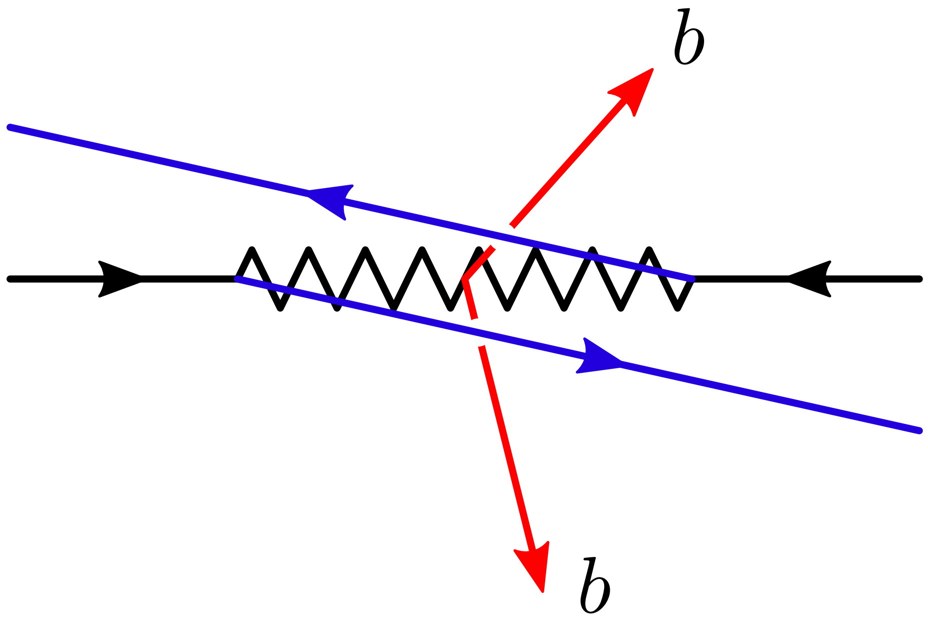
based on arXiv:2507.01448

DESY Theory Workshop “Synergies Towards The Future Standard Model” 2025-09-24



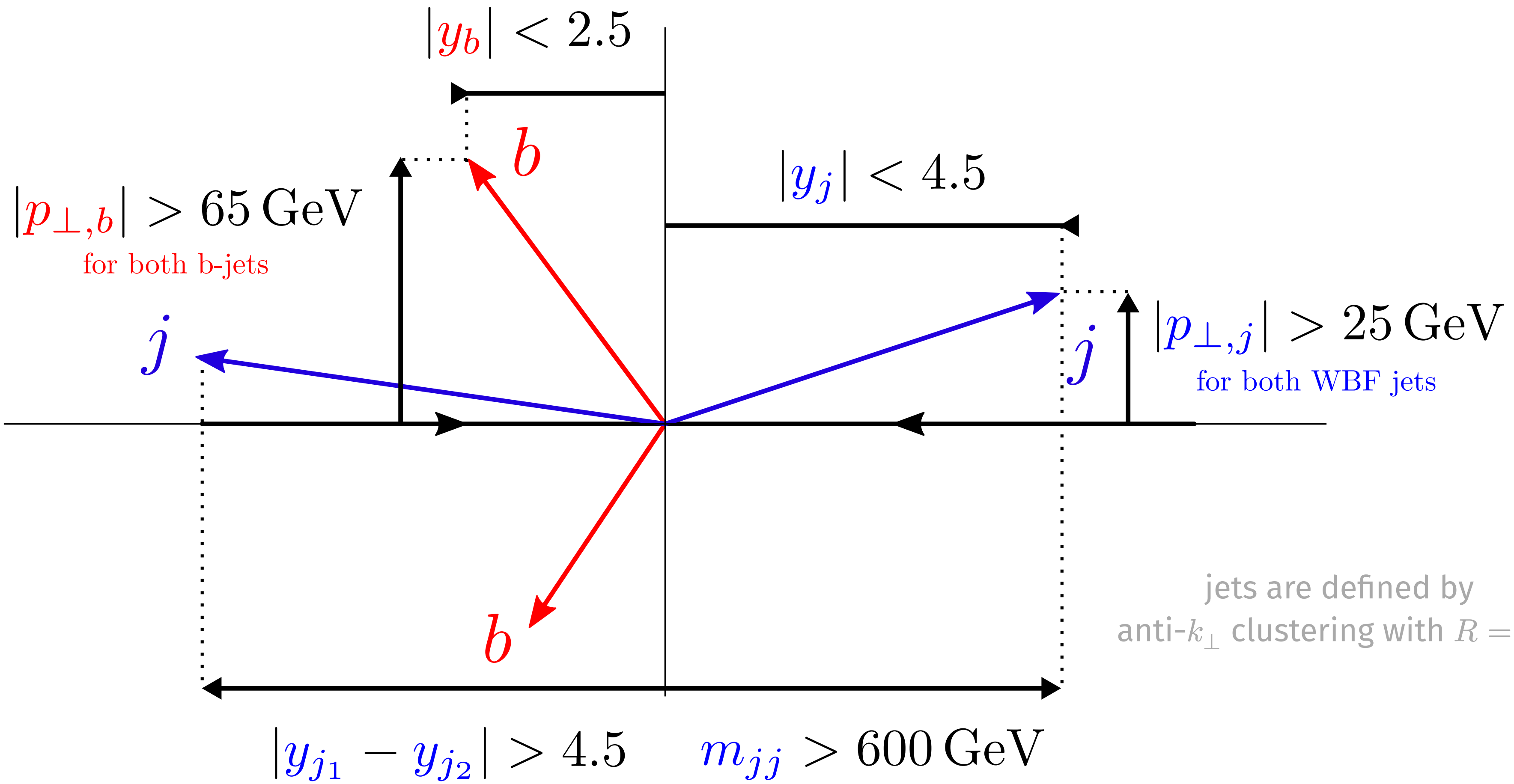
The $H \to b\bar{b}$ decay is difficult to measure
due to large number of b-jets from QCD background





On the other hand, Higgs-boson production in weak-boson fusion (WBF)
can be separated from QCD backgrounds by
its distinct signature of two back-to-back jets

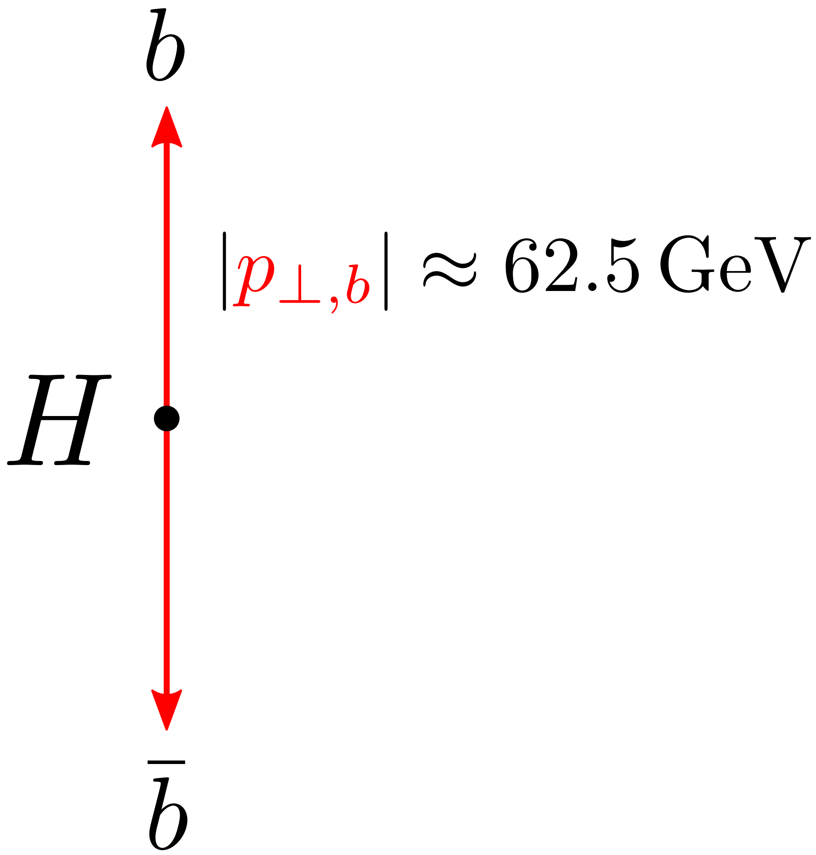
event selection is based on analysis of [ATLAS, Eur.Phys.J.C 81 (2021) 6, 537]



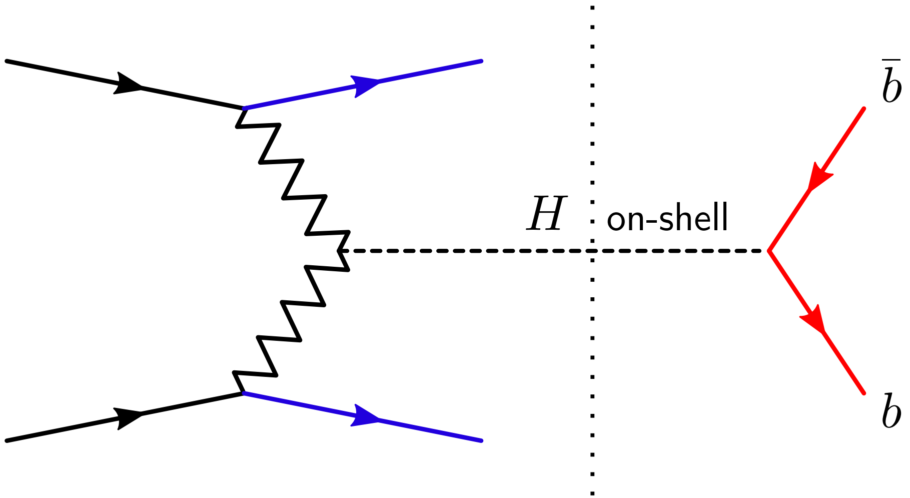
jets are defined by
anti-$k_\perp$ clustering with $R = 0.4$

We look for events with two light nearly-back-to-back jets with a high invariant mass and two b-tagged jets

$$|p_{\perp,b}| > 65\,\mathrm{GeV} > \frac{m_H}{2}$$



These event selection criteria are rather strict:
only events with a sufficiently boosted Higgs boson are accepted



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

$$\mathrm{Br}_{H\to b\bar{b}} = \frac{\Gamma_{H\to b\bar{b}}}{\Gamma_{H\to \mathrm{anything}}}$$

$$\int_{\mathrm{inclusive}} \mathrm{d}\sigma_{\mathrm{WBF}} \mathrm{d}\Gamma_{H\to b\bar{b}} = \int_{\mathrm{inclusive}} \mathrm{d}\sigma_{\mathrm{WBF}} \times \int_{\mathrm{inclusive}} \mathrm{d}\Gamma_{H\to b\bar{b}}$$

$$\int_{\mathrm{fiducial}} \mathrm{d}\sigma_{\mathrm{WBF}} \mathrm{d}\Gamma_{H\to b\bar{b}} \neq \int_{\mathrm{fiducial}} \mathrm{d}\sigma_{\mathrm{WBF}} \times \int_{\mathrm{fiducial}} \mathrm{d}\Gamma_{H\to b\bar{b}}$$

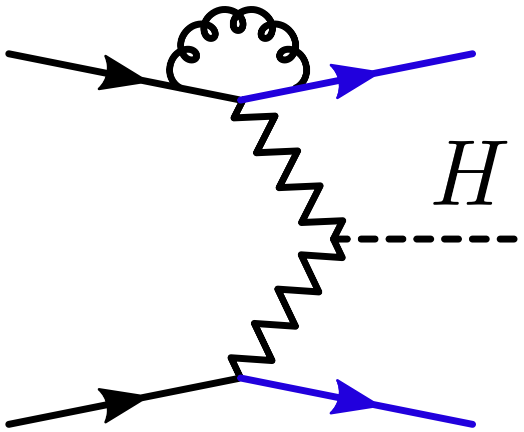
The production and decay subprocesses are factorized in the narrow-width approximation, but the event selection criteria introduce correlations

Fixed-order corrections to weak-boson fusion

- Weak-boson fusion in double-DIS approximation up to NNLO QCD

  [Cacciari, Dreyer, Karlberg, Salam, Zanderighi (2015)] [Cruz-Martinez, Gehrmann, Glover, Huss (2018)] [Asteriadis, Caola, Melnikov, Röntsch (2022)]

$$\sigma^{\mathrm{WBF}}_{\mathrm{fiducial}}/\mathrm{fb} \approx \underset{\mathrm{LO}}{971} \quad \underset{\substack{\Delta\mathrm{NLO}\\(\text{-}8\%)}}{-\,81} \quad \underset{\substack{\Delta\mathrm{NNLO}\\(\text{-}3\%)}}{-\,31} + \ldots$$



- Electroweak corrections and interference effects up to NLO EW ($\sim -5\%$)

  [Ciccolini, Denner, Dittmaier (2007)]

- Nonfactorizable corrections at NNLO QCD ($\sim -0.3\%$)

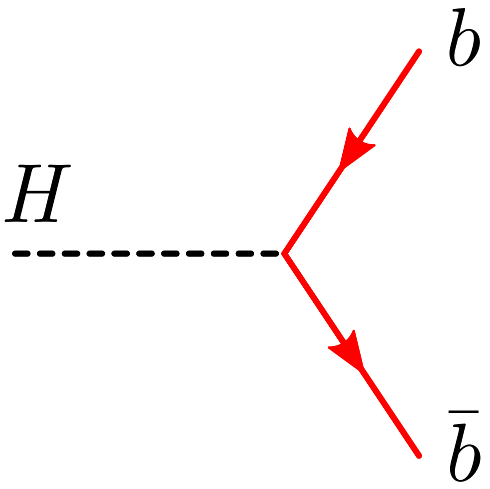
  [Liu, Melnikov, Penin (2019)] [Asteriadis, Brønnum-Hansen, Melnikov (2023)]

QCD corrections to weak-boson fusion are of order $\sim -11\%$

- $H \to b\bar{b}$ with massless b quarks up to N³LO [Mondini, Schiavi, Williams (2019)]
- $H \to b\bar{b}$ with massive b quarks up to NNLO

  [Behring, Bizoń (2020)] [Bernreuther, Chen, Si (2018)]

$$\underset{(\mu = m_H)}{\Gamma_{H\to b\bar{b}}}/\mathrm{MeV} \approx \underset{\mathrm{LO}}{1.926} + \underset{\substack{\Delta\mathrm{NLO}\\(+21\%)}}{0.400} + \underset{\substack{\Delta\mathrm{NNLO}\\(+6\%)}}{0.106} + \dots$$

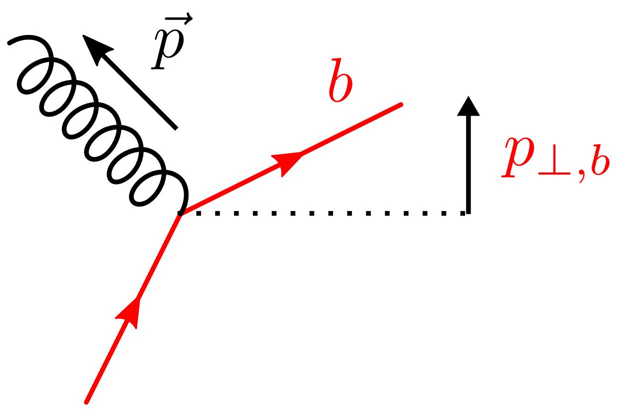


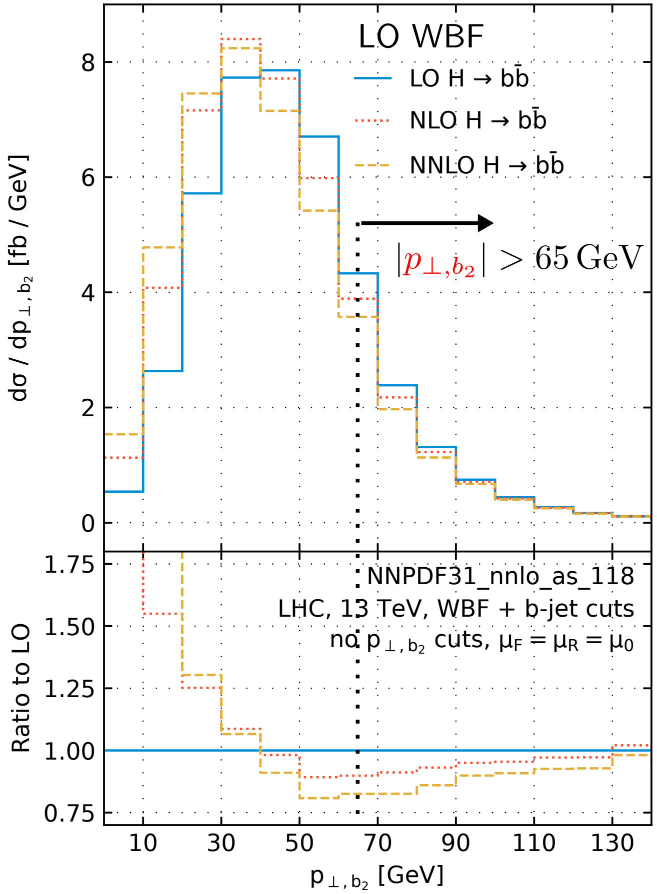
QCD corrections to $H \to b\bar{b}$ decay are of order ~ $+27\%$

[Asteriadis, Behring, Melnikov, Novikov, Röntsch (2024)]

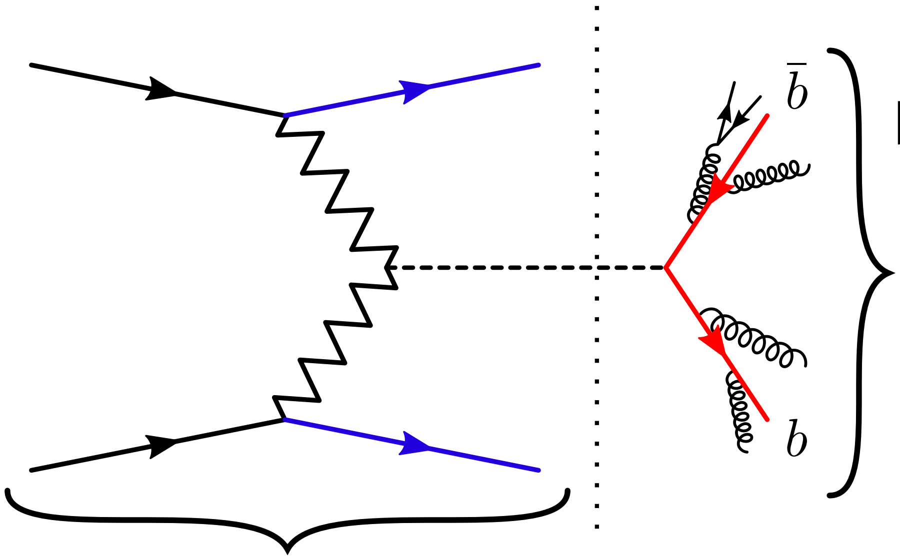
$$\sigma_{\text{fiducial}}/\text{fb} = \underset{\text{LO}}{75.6} \quad \underset{\substack{\Delta\text{NLO} \\ (\text{-}31\%)}}{-\,23.2} \quad \underset{\substack{\Delta\text{NNLO} \\ (\text{-}10\%)}}{-\,7.8} + \ldots$$

But with the used event selection criteria the corrections to the combined process $pp \to H\left(b\bar{b}\right)jj$ are large: −41% in comparison to LO!





These large corrections are due to the tendency of QCD radiation in the $H \to b\bar{b}$ decay to reduce the transverse momentum of the b-jet, thus lowering the probability that they pass the b-jet selection criteria



fixed-order

parton shower:

LO+PS — leading-order + Pythia8.3

or

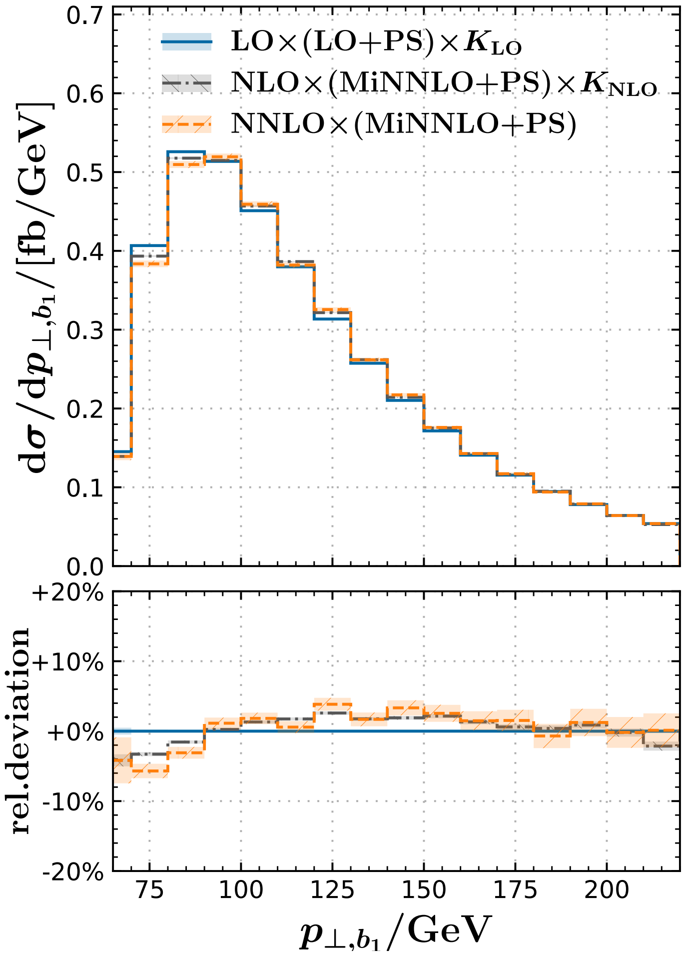
MiNNLO+PS — POWHEG + MiNLO + Pythia8.3
NNLO-accurate

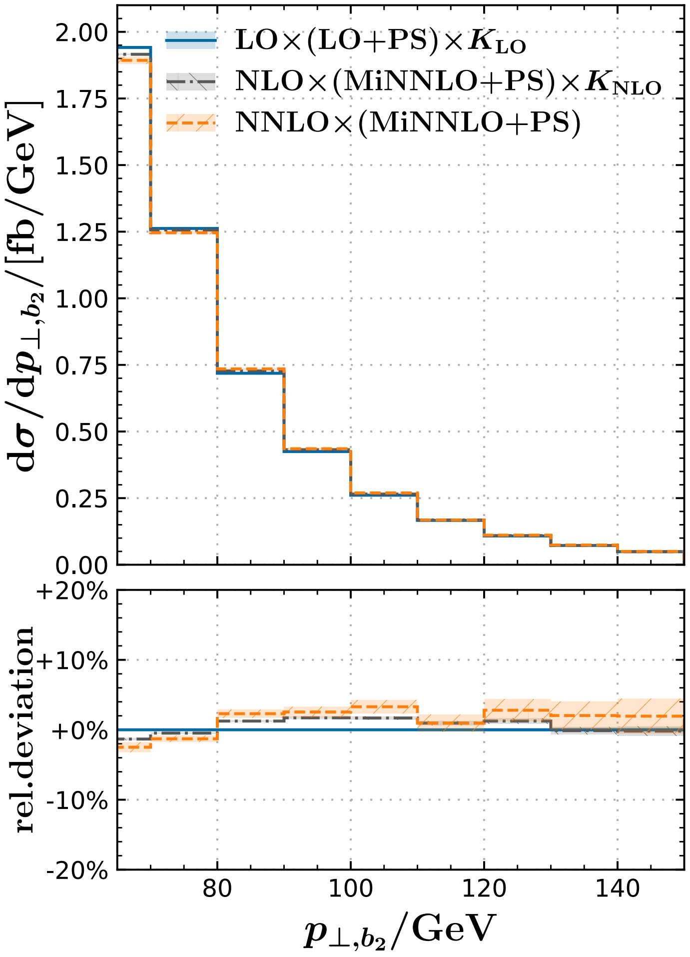
To investigate this further, in this study we combine
$H \to b\bar{b}$ decay events with a parton shower and fixed-order WBF

σ/fb	fixed order	LO+PS	MiNNLO+PS
LO	75.6	46.6	45.2
NLO	52.4	43.6(1)	42.3
NNLO	44.6(1)	43.1(1)	41.4(1)

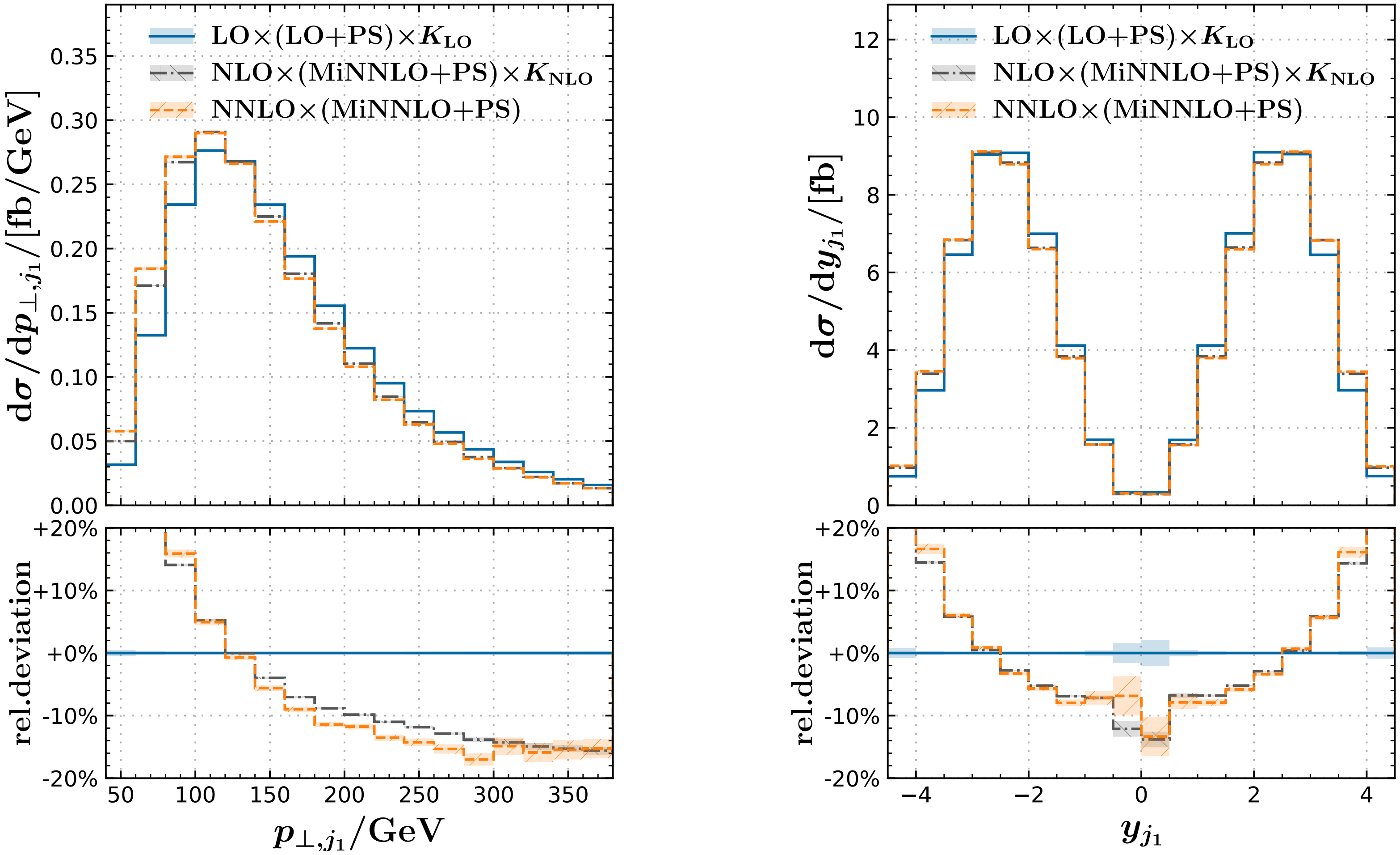
(number in parenthesis indicates Monte-Carlo uncertainty)

Parton shower in the decay subprocess resums most of the large corrections and dramatically improves stability across different orders

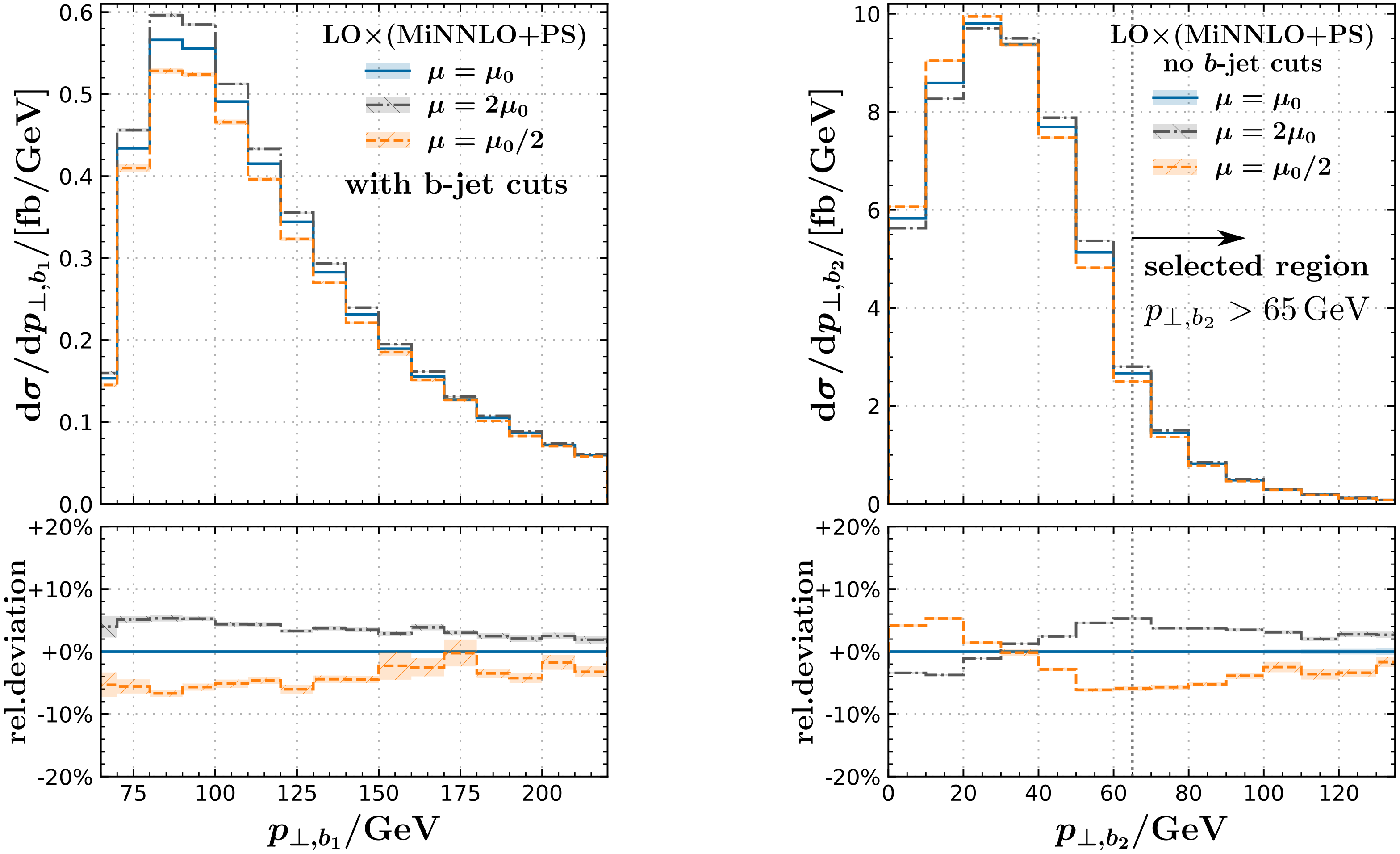




Even the simplest approximation, — LO+PS times an overall K-factor, — captures the shape of the b-jet distributions up to a few percent



On the other hand, fixed-order corrections to WBF are important for distributions of light WBF-tagging jets



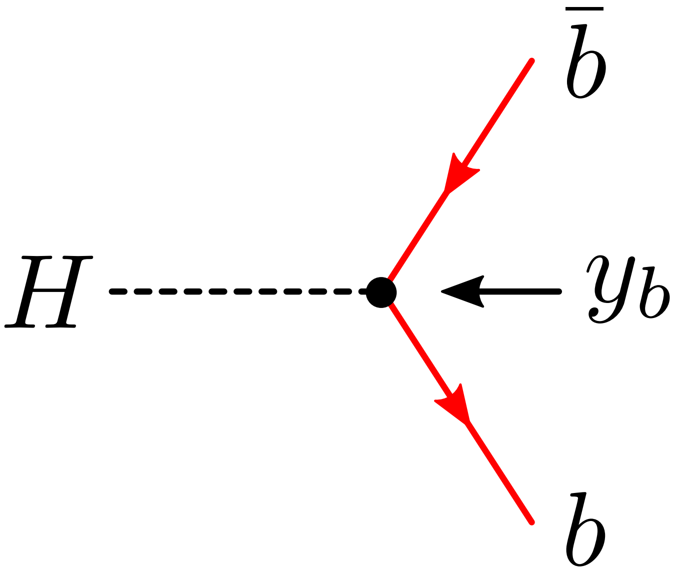
The b-jet distributions are sensitive to the renormalization scale used in the decay subprocess, indicating perturbative uncertainty of order ~ 5%

Conclusions

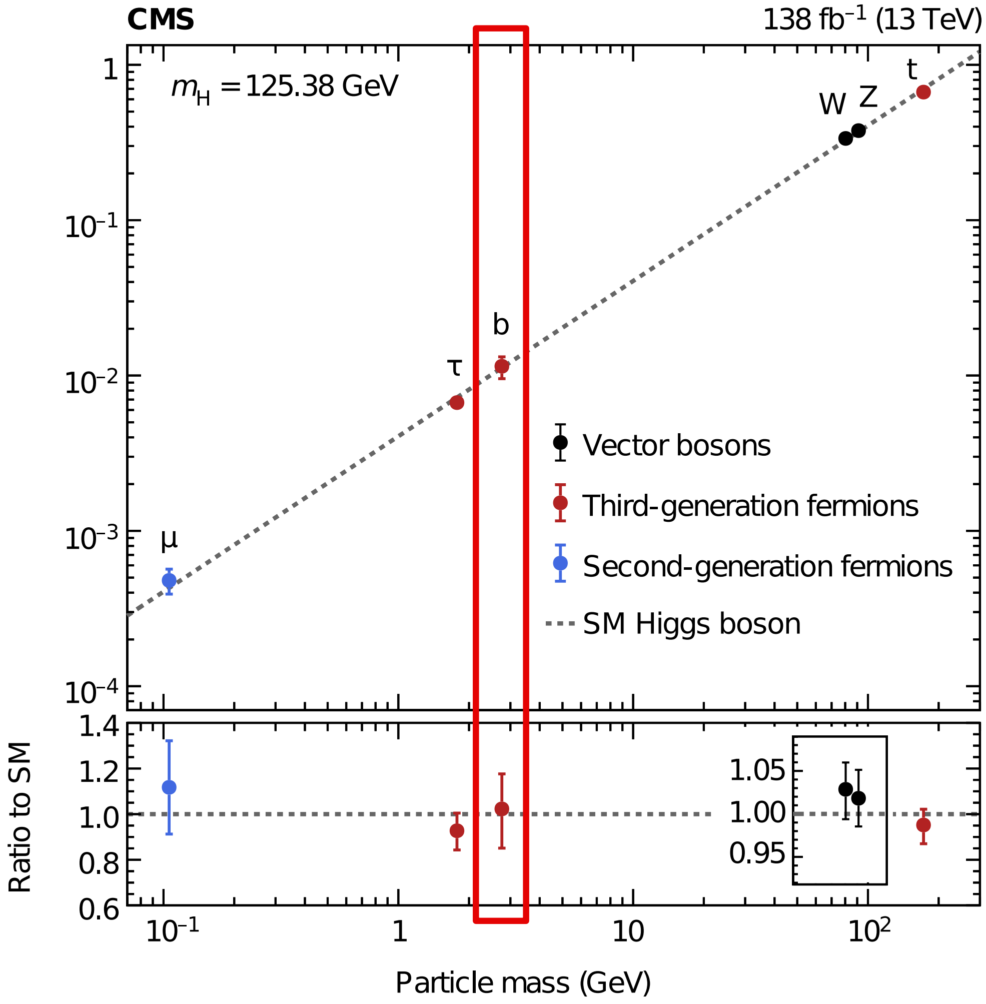
- The strict event selection criteria used for the combined process $pp \to H\left(b\bar{b}\right)jj$ introduce sensitivity to soft and collinear radiation in the decay subprocess, and lead to large fixed-order corrections (-40%).
- Using a parton shower for the decay subprocess effectively resums these large corrections and restores perturbative convergence.
- A similar interplay between event selection criteria and fixed-order and parton-shower simulations was found for double Higgs production. [Braun, Fontes, Heinrich (2025)]
- Electroweak and interference corrections are in principle known and are expected to further reduce the cross-section by ~ 5%.
- The remaining uncertainty is of order ~ 5%, the dominant source of uncertainty is in the differential modelling of the $H \to b\bar{b}$ decay subprocess.

Thank you for the attention!

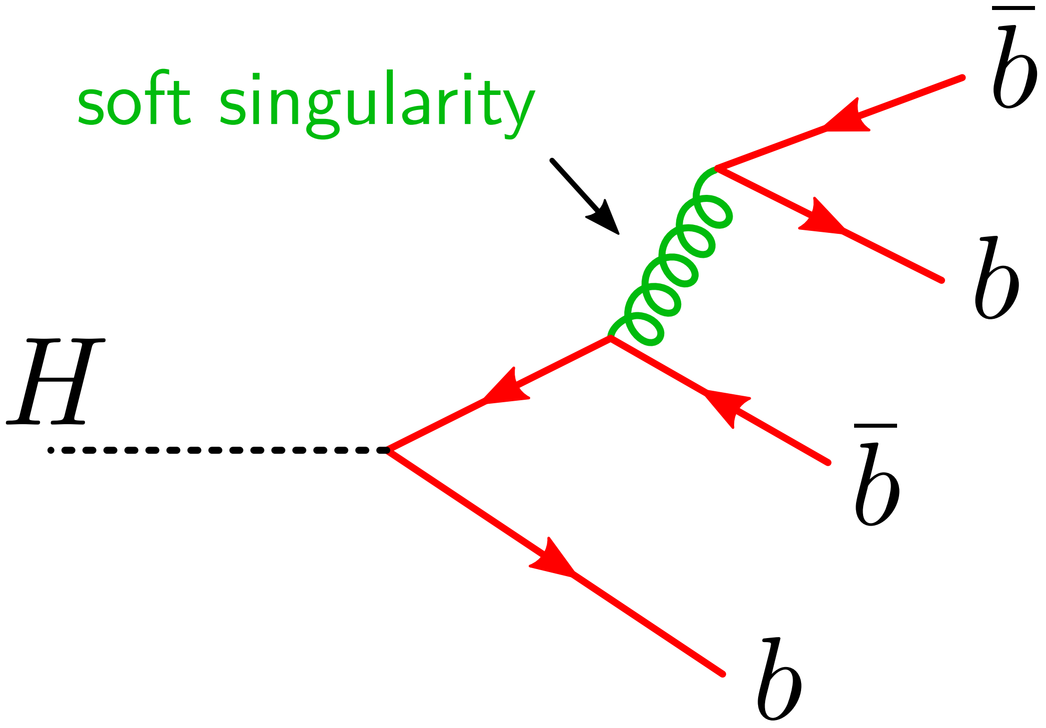
Backup



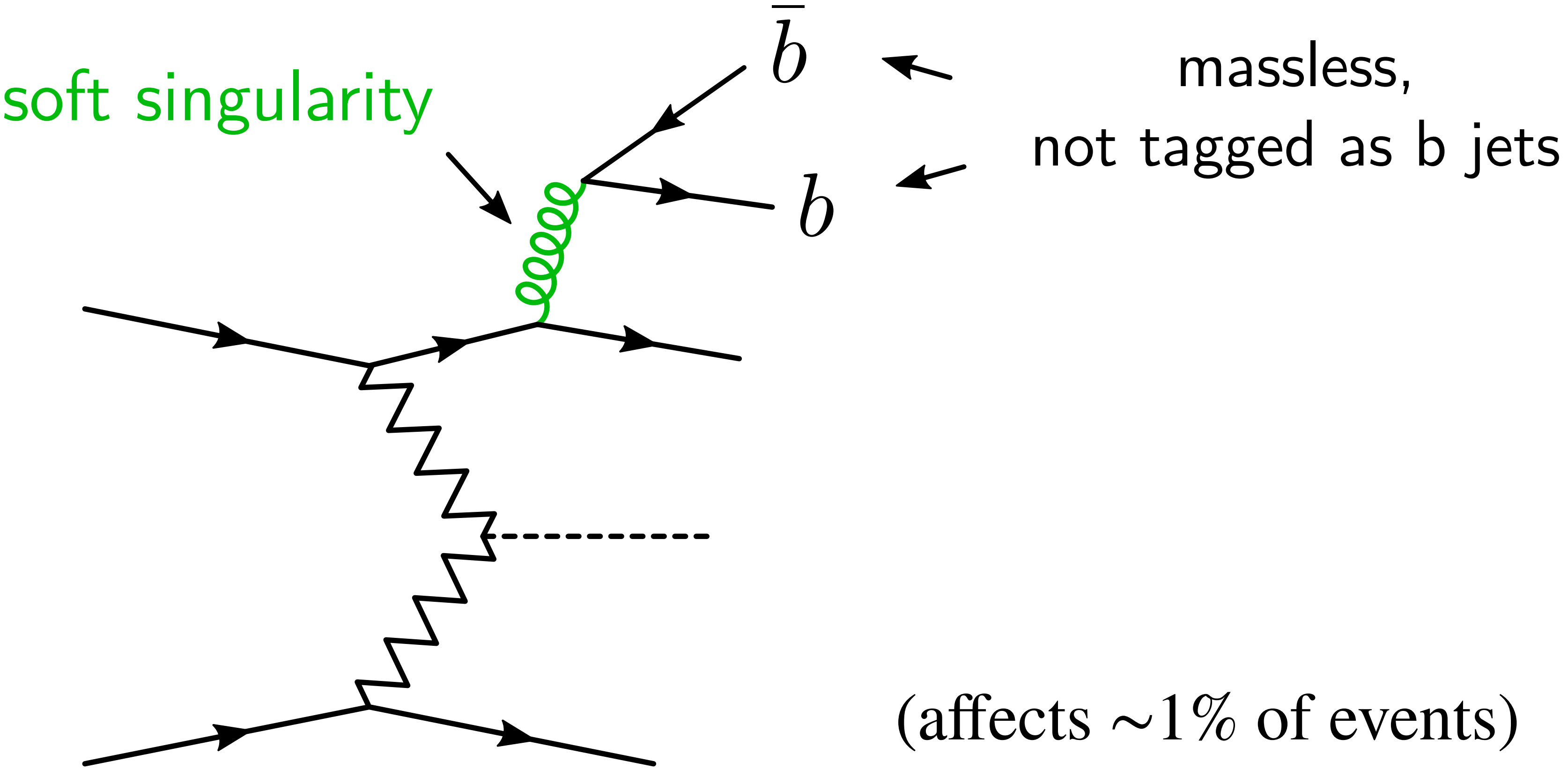
[CMS Collaboration, Nature 607, 60–68 (2022)]



The b-quark Yukawa coupling y_b can be measured in $H \to b\bar{b}$ decay.



With *massless* b quarks b-jet tagging is potentially IRC-unsafe, because a soft gluon can split into a $b\bar{b}$ pair, which end up in different jets and change their flavor. In the $H \to b\bar{b}$ calculation this soft singularity is regulated by a finite b-quark mass.



The available weak-boson-fusion calculations neglect the b-quark mass.
To ensure IRC-safety, we do not tag b jets originating from WBF.
As a result, we can use the standard anti-$k_\perp$ jet clustering algorithm.

Corrections with LO decay

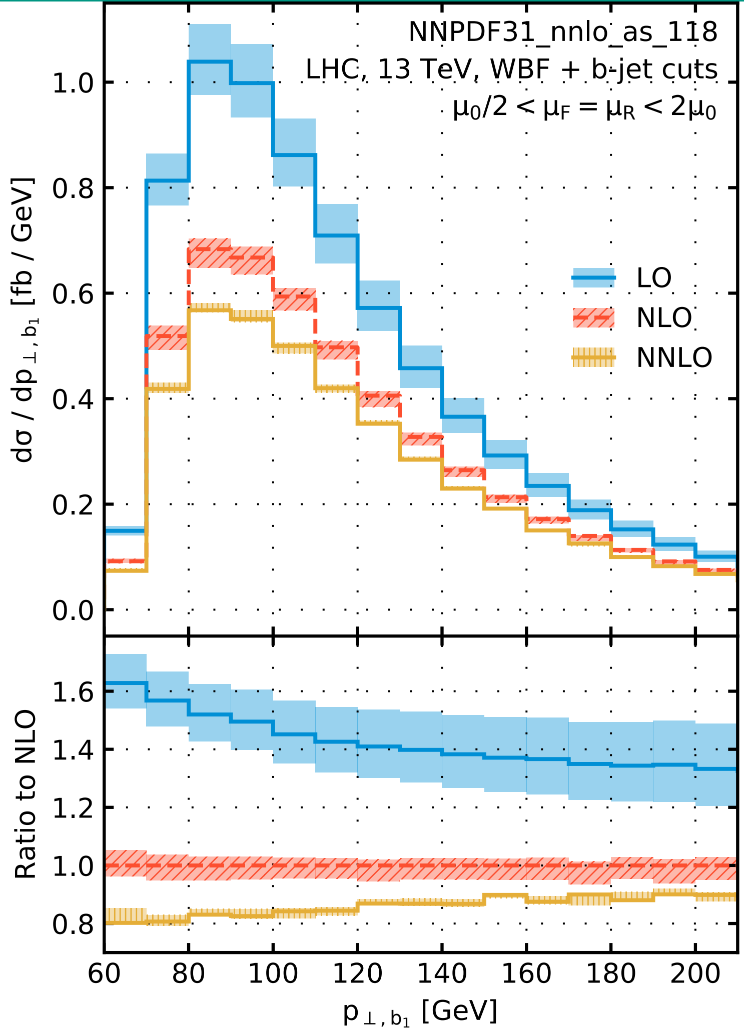
$$\sigma_{\text{fiducial}}/\text{fb} = \underset{\text{LO}}{75.9} \quad \underset{\substack{\Delta\text{NLO} \\ \text{(-7\%)}}}{-\;\;5.0} \quad \underset{\substack{\Delta\text{NNLO} \\ \text{(-2\%)}}}{-\,1.5} + \ldots$$

With leading-order decay, the production corrections to $pp \to H(\to b\bar{b})jj$ are relatively small [Asteriadis, Caola, Melnikov, Röntsch (2022)] scale variation $^{2\mu_0}_{\mu_0/2}$ in WBF

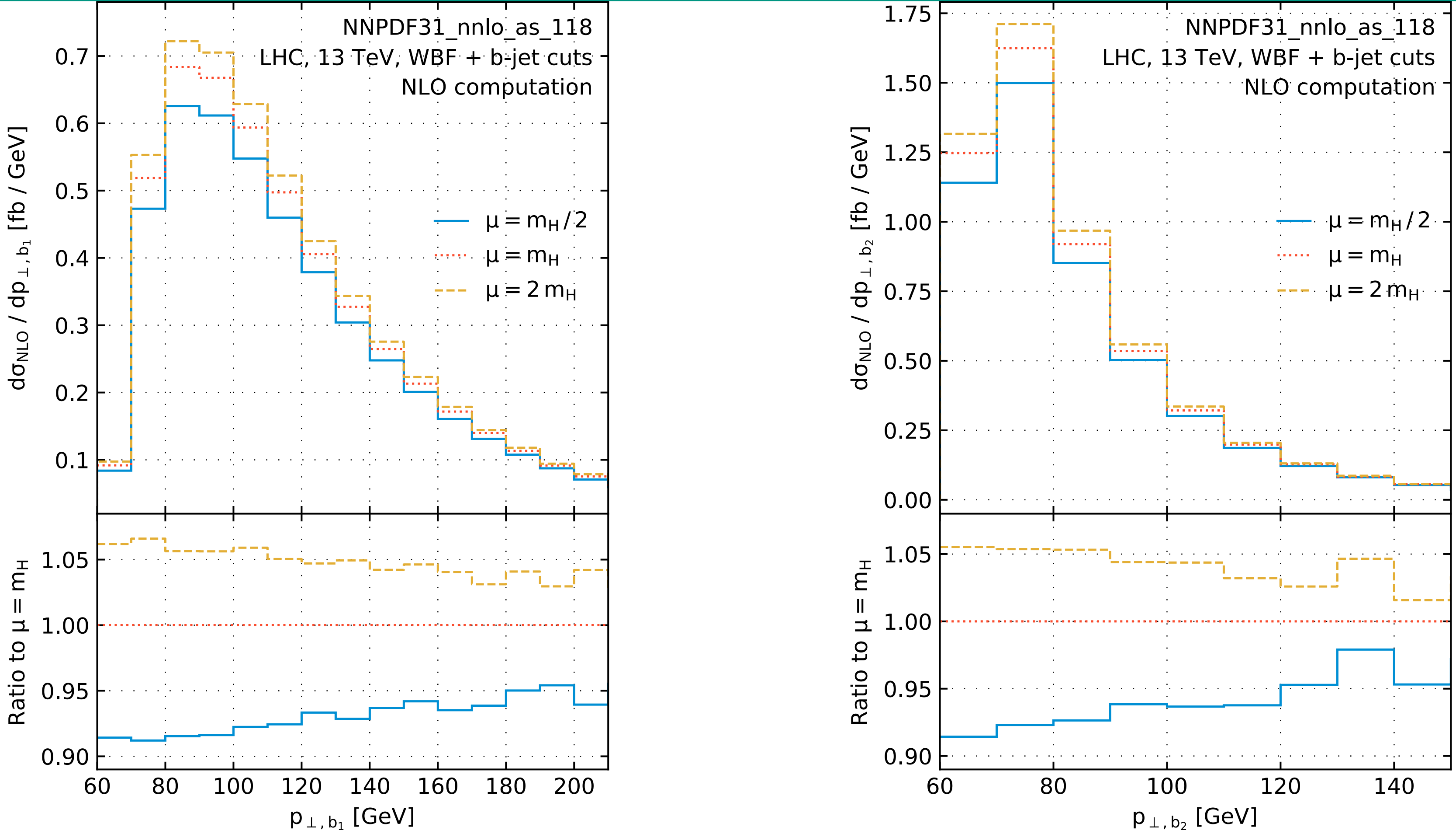
$$\sigma^{\mathrm{LO}} = 75.6^{-5.6}_{+6.5}\ \mathrm{fb} \qquad (\pm 9\%)$$

$$\sigma^{\mathrm{NLO}} = 52.4^{+1.5}_{-2.6}\ \mathrm{fb}\ (\text{-}31\% \pm 3\%)$$

$$\sigma^{\mathrm{NNLO}} = 44.6^{+0.9}_{-0.6}\ \mathrm{fb}\ (\text{-}10\% \pm 1\%)$$



Production-scale variations do not cover the observed large corrections



The impact of scale variation in the decay $H \to b\bar{b}$ is comparable to that in the WBF production, and does not capture the observed large corrections either

Fixed-order decay corrections

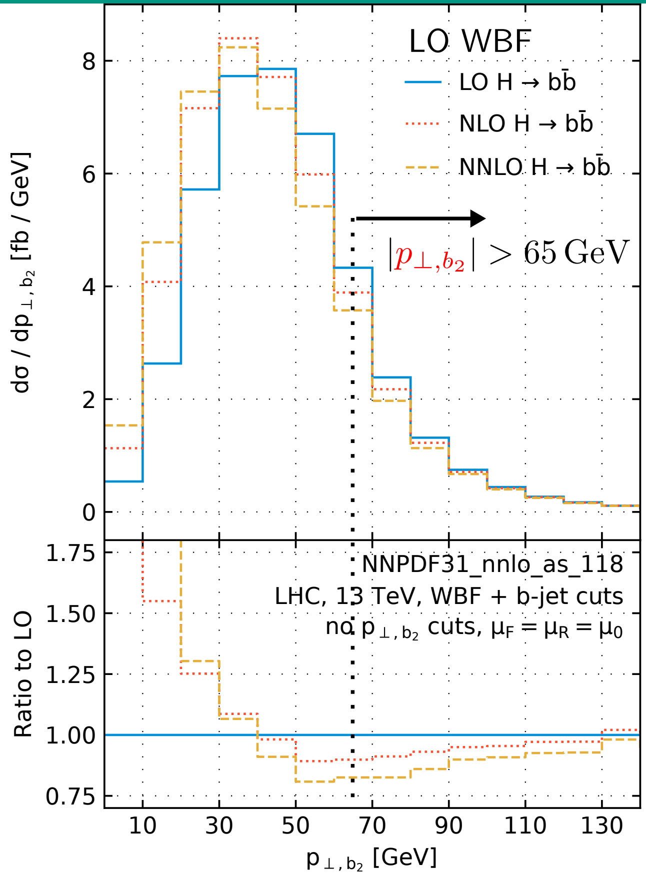
$$\mathrm{d}\sigma = \mathrm{Br}_{H\to b\bar{b}}\, \mathrm{d}\sigma_{\mathrm{WBF}} \frac{\mathrm{d}\Gamma_{H\to b\bar{b}}}{\Gamma_{H\to b\bar{b}}}$$

$$\sigma_{\text{fiducial}}/\text{fb} = \underset{\text{LO}}{75.6} \; \underset{\substack{\Delta\text{NLO}\\ \text{decay}\\ \text{(-7\%)}}}{-\,5.3} \; \underset{\substack{\Delta\text{NNLO}\\ \text{decay}\\ \text{(-7\%)}}}{-\,5.0} \; + \ldots$$

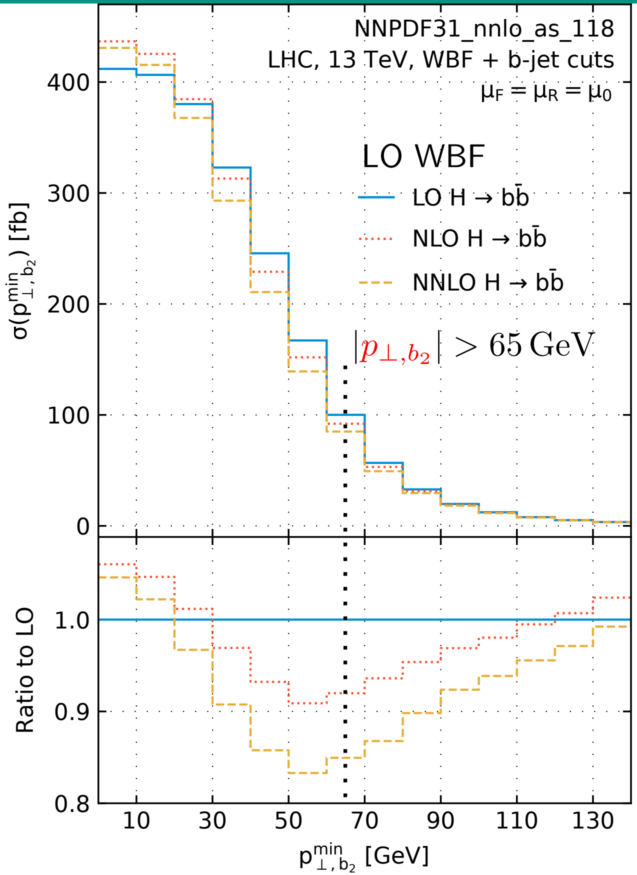
$$\underset{(\mu = m_H)}{\Gamma_{H\to b\bar{b}}}/\text{MeV} = \underset{\text{LO}}{1.926} + \underset{\substack{\Delta\text{NLO}\\ (+21\%)}}{0.400} + \underset{\substack{\Delta\text{NNLO}\\ (+6\%)}}{0.106} + \ldots$$

Corrections to the total $H \to b\bar{b}$ decay width $\Gamma_{H\to b\bar{b}}$ are *positive*,
but they are large and *negative* with the used event selection criteria

$p_{\perp,b_2}$ threshold in the fixed-order calculation

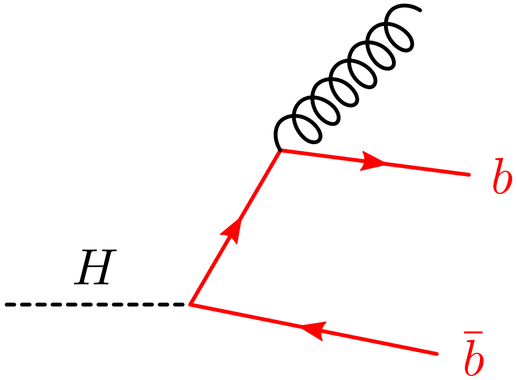


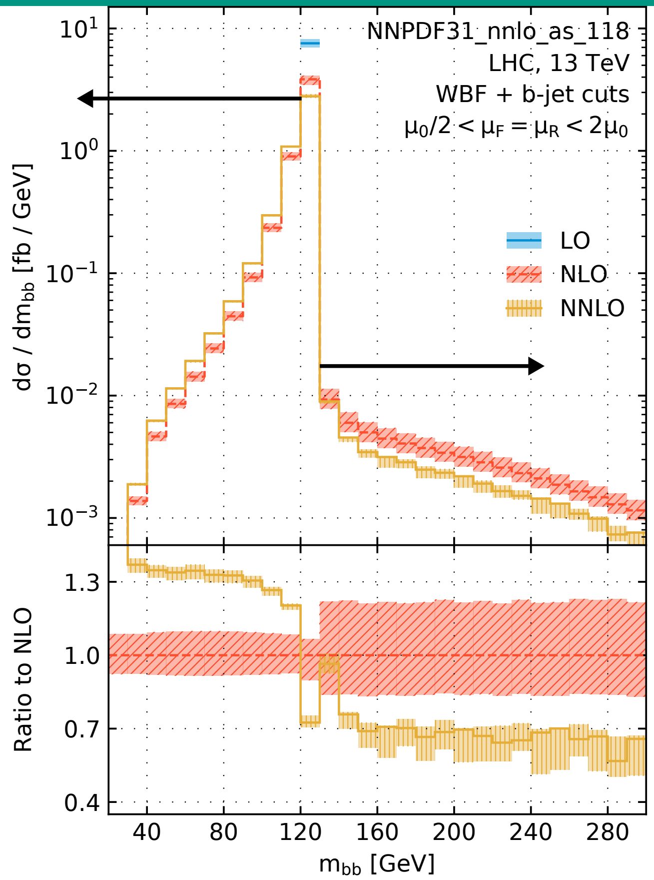
cumulative →

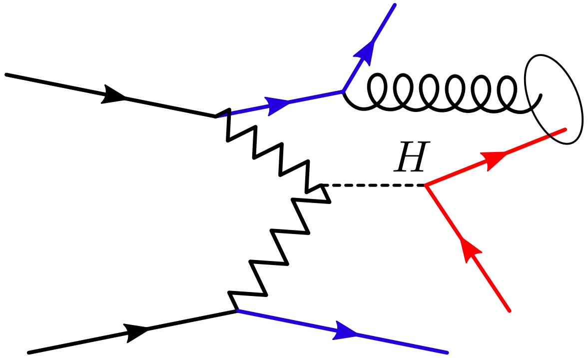


With the chosen $p_{\perp,b_2}$ threshold the decay corrections do not seem to converge. The convergence improves with more inclusive event selection, but experimentally this is not feasible.

$m_{b\bar{b}}$ distribution in the fixed-order calculation







(b jets originating in WBF are not included)

QCD radiation in the $H \to b\bar{b}$ decay reduces the invariant mass $m_{b\bar{b}}$ of the reconstructed Higgs boson. Rarely, QCD radiation from weak-boson fusion can increase this invariant mass.