Higgs-boson production in weak-boson fusion and $H \to b\bar{b}$ decay at NNLO with realistic event selection criteria

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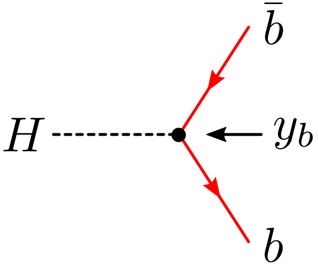
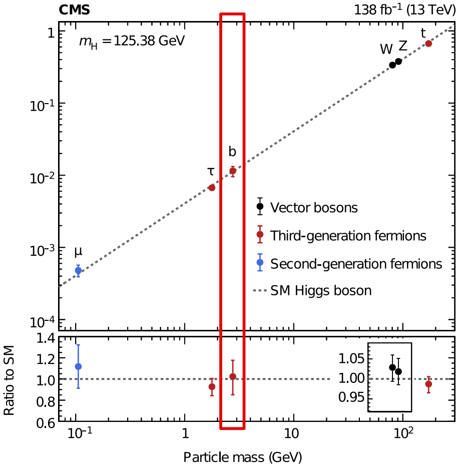
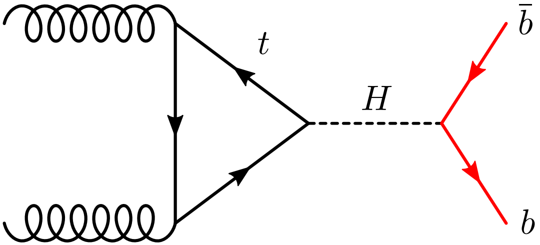
b-quark Yukawa coupling y_b



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



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



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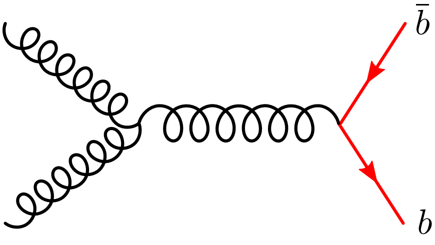
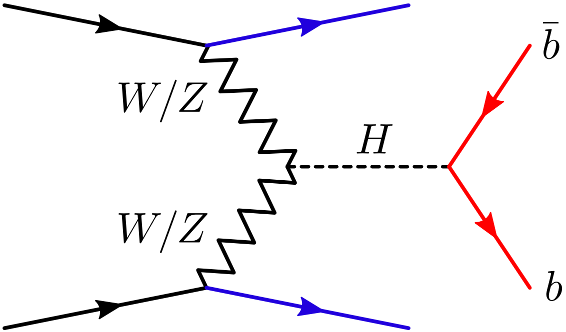
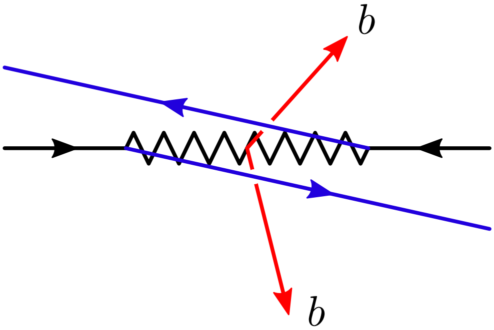


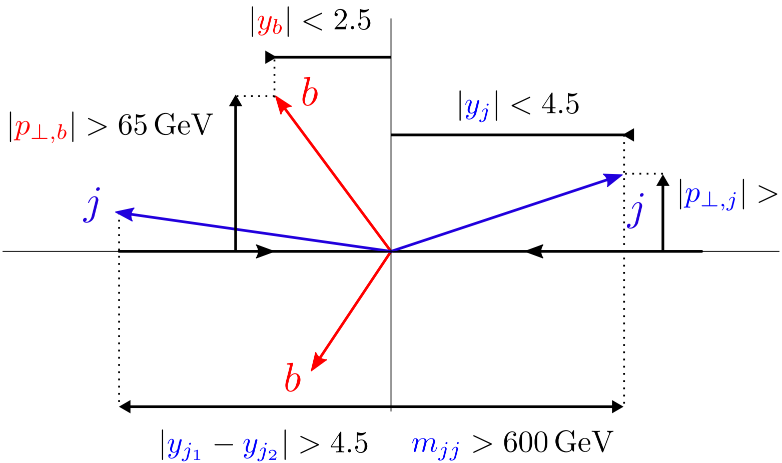
The $H \to b\bar{b}$ decay is difficult to measure
due to large number of b-jets from QCD backgrounds

Weak-boson fusion





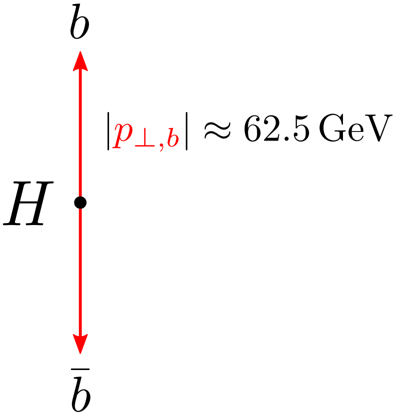
On the other hand, Higgs-boson production in weak-boson fusion (WBF) can be separated from QCD backgrounds by its distinct signature of two back-to-back jets.



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

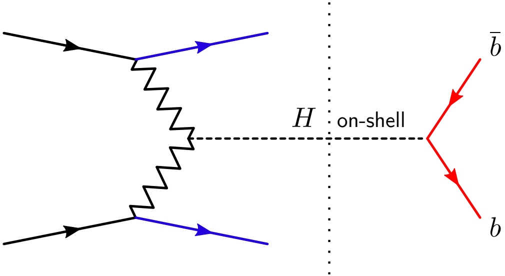
Event selection criteria

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



These event selection criteria are rather strict and require production of a boosted Higgs boson

Narrow-width approximation



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

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

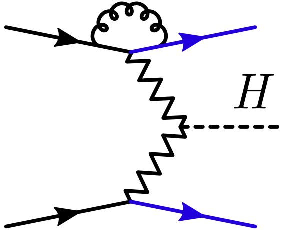
$$\int_{\mathrm{inclusive}} \mathrm{d}\sigma_{\mathrm{WBF}}\mathrm{d}\Gamma_{H\to b\bar{b}} = \int_{\mathrm{inclusive}} \mathrm{d}\sigma_{\mathrm{WBF}} \times \int_{\mathrm{inclusive}} \mathrm{d}\Gamma_{H\to b\bar{b}}$$

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

The event selection criteria introduce a correlation between the production and the decay subprocesses, even in the narrow-width approximation.

- Weak-boson fusion $pp \to Hjj$ up to NNLO QCD
  [Cacciari, Dreyer, Karlberg, Salam, Zanderighi (2015)]
  [Cruz-Martinez, Gehrmann, Glover, Huss (2018)]

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

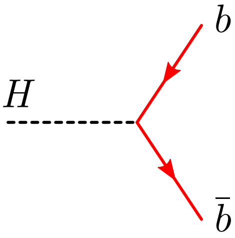


- Electroweak corrections and interference effects in WBF $pp \to Hjj$ up to NLO EW ($\sim -5\%$) [Ciccolini, Denner, Dittmaier (2007)]
- Nonfactorizable corrections to WBF $pp \to Hjj$ at NNLO QCD ($\sim -0.3\%$) [Liu, Melnikov, Penin (2019)] [Asteriadis, Brønnum-Hansen, Melnikov (2023)]

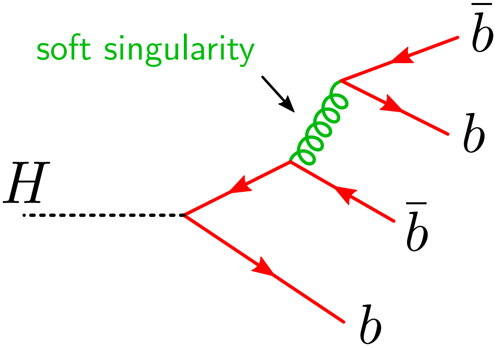
NNLO QCD corrections to weak-boson fusion are of order $\sim -3\%$

- $H \to b\bar{b}$ with massless b quarks up to $\mathrm{N^3LO}$ [Mondini, Schiavi, Williams (2019)]
- $H \to b\bar{b}$ with massive b quarks up to NNLO [Behring, Bizoń (2020)]

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



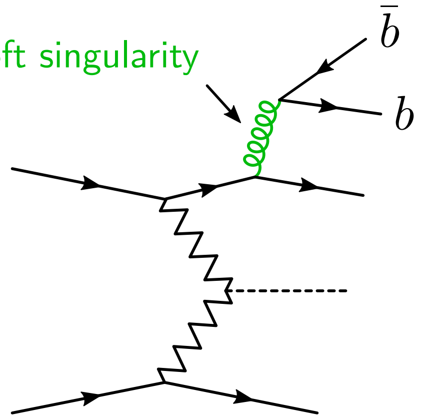
NNLO QCD corrections to $H \to b\bar{b}$ decay are of order $\sim +6\%$



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.

Flavor safety



(affects ~1% of events)

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.

Results

- Combined $pp \to H(\to b\bar{b})jj$ with NNLO production and LO decay with massless b quarks [Asteriadis, Caola, Melnikov, Röntsch (2022)]

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

- New result: $pp \to H(\to b\bar{b})jj$ with massive b quarks up to NNLO QCD

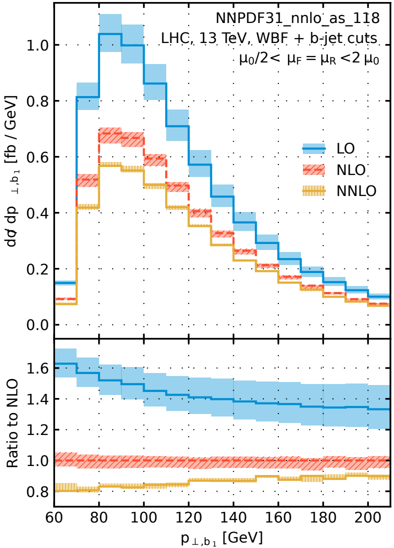
$$\sigma_{\text{fiducial}}/\text{fb} = \underset{\text{LO}}{75.6} \quad \underset{\substack{\Delta\text{NLO} \\ (\text{-}31\%)}}{-\;23.2} \quad \underset{\substack{\Delta\text{NNLO} \\ (\text{-}10\%)}}{-\;7.8} + \ldots$$

There are large negative corrections to the fiducial cross-section: -41% compared to LO!

Production-scale variations

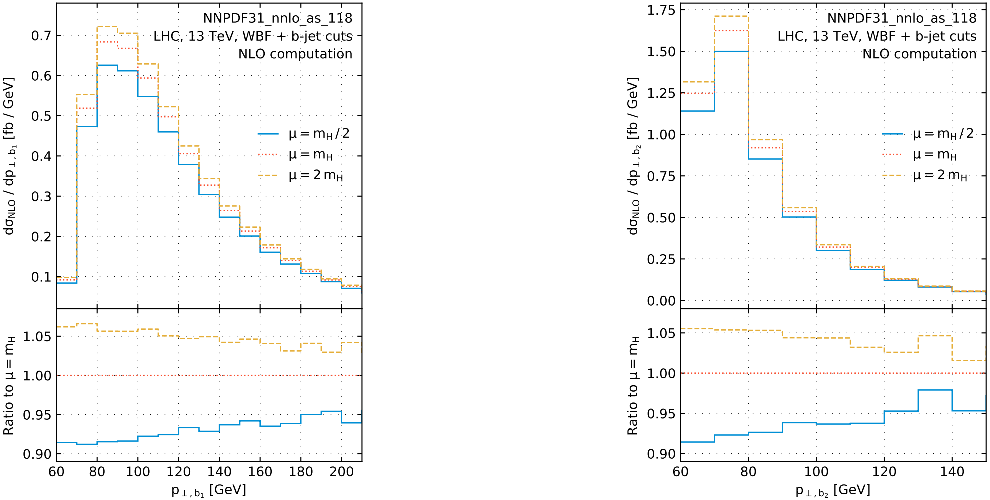
scale variation $^{2\mu_0}_{\mu_0/2}$ in WBF

$$\sigma^{\text{LO}} = 75.6^{-5.6}_{+6.5}\ \text{fb} \qquad (\pm 9\%)$$
$$\sigma^{\text{NLO}} = 52.4^{+1.5}_{-2.6}\ \text{fb}\ (\text{-}31\% \pm 3\%)$$
$$\sigma^{\text{NNLO}} = 44.6^{+0.9}_{-0.6}\ \text{fb}\ (\text{-}10\% \pm 1\%)$$



Production-scale variations do not cover the observed large corrections

Decay-scale variations



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

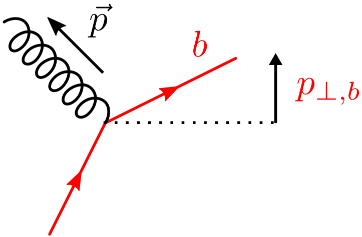
$$\mathrm{d}\sigma = \mathrm{Br}_{H\to b\bar{b}}\,\mathrm{d}\sigma_{\mathrm{WBF}}\,\frac{\mathrm{d}\Gamma_{H\to b\bar{b}}}{\Gamma_{H\to b\bar{b}}}$$

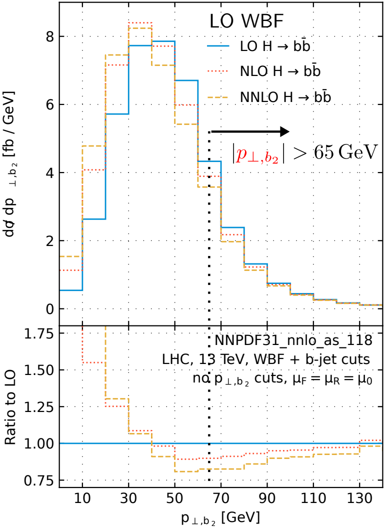
$$\sigma_{\mathrm{fiducial}}/\mathrm{fb} = \underset{\mathrm{LO}}{75.6} \; \underset{\substack{\Delta\mathrm{NLO}\\ \mathrm{decay}\\ (\text{-}7\%)}}{-\,5.3} \; \underset{\substack{\Delta\mathrm{NNLO}\\ \mathrm{decay}\\ (\text{-}7\%)}}{-\,5.0} \; + \ldots$$

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

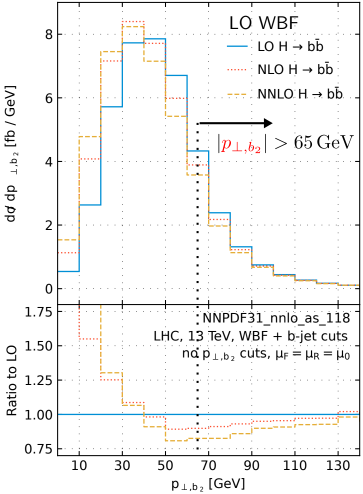
Corrections to the total $H \to b\bar{b}$ decay width $\Gamma_{H\to b\bar{b}}$ are *positive*,
but they are large and *negative* with the used event selection criteria

Effect of QCD radiation

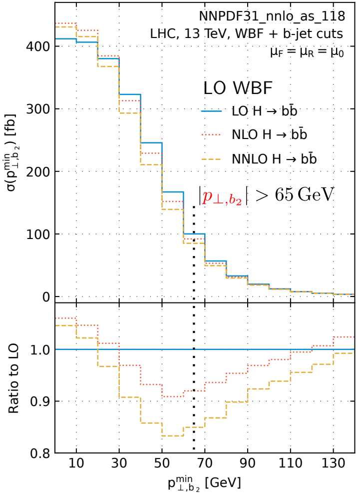




QCD radiation in the $H \to b\bar{b}$ decay tends to reduce the transverse momentum $p_{\perp,b}$ of the b-jet, lowering the probability that they pass the b-jet selection criteria.

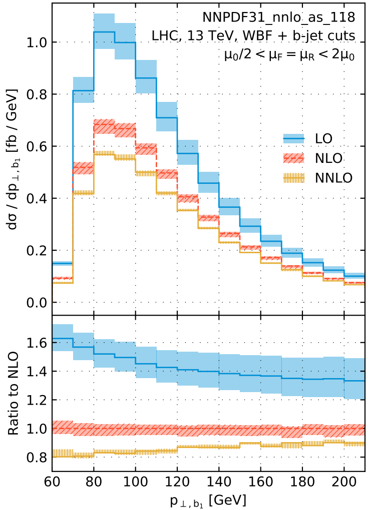


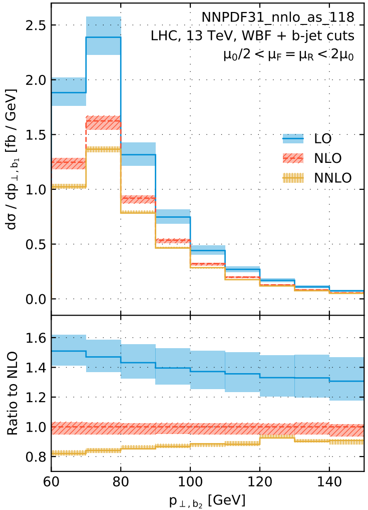
cumulative →



With the chosen $p_{\perp b_2}$ threshold the decay corrections do not seem to converge.
Relaxing this threshold seems to improve perturbative convergence,
but might degrade purity of event selection

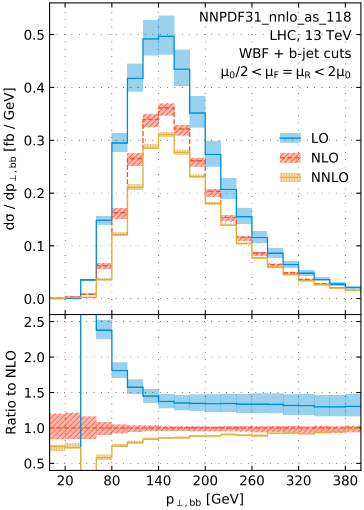
$p_{\perp b}$ distributions





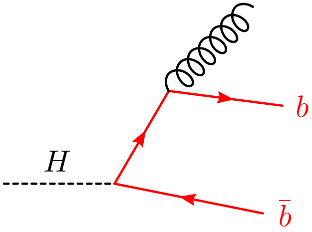
The K-factor $\mathrm{d}\sigma/\mathrm{d}\sigma^{\mathrm{LO}}$ is more-or-less flat for distributions of transverse momenta $p_{\perp b}$ for leading ($p_{\perp b_1}$) and subleading ($p_{\perp b_2}$) b jets

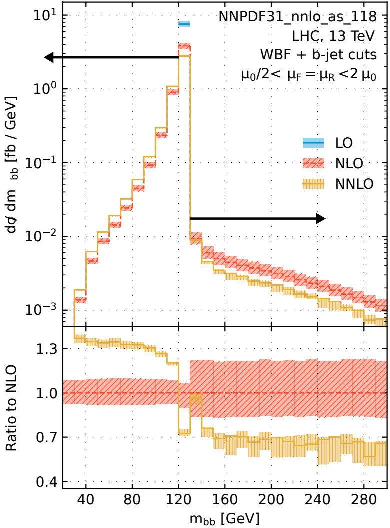
p_{bb} distribution

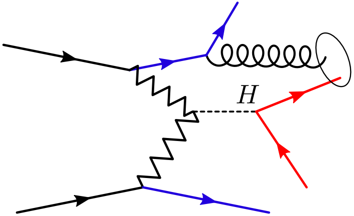


The distribution of the transverse momentum $p_{\perp b\bar{b}}$ of the reconstructed Higgs boson shows stronger suppression at small transverse momentum.

m_{bb} distribution







(b jets originating in WBF are not included)

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

Conclusions

- We provide, for the first time, an NNLO-QCD-accurate fully-differential description of the combined WBF process $pp \to H(\to b\bar{b})jj$.
- b-jets originating in WBF are not tagged, a calculation of WBF with *massive* b-quarks would be necessary to account for them.
- There are large negative corrections, the NNLO fiducial cross-section is $\sim 40\%$ smaller than the LO cross-section.
- QCD radiation in the $H \to b\bar{b}$ decay makes a large impact because of stringent restrictions on b-jet momenta.

In the future, it would be interesting to try to resum these fixed-order results and/or match them to a parton shower.

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Thank you for your attention!

Backup

Definition of perturbative truncation

$$\mathrm{d}\sigma_{\mathrm{WBF}} = \mathrm{d}\sigma^{(0)}_{\mathrm{WBF}} + \mathrm{d}\sigma^{(1)}_{\mathrm{WBF}} + \mathrm{d}\sigma^{(2)}_{\mathrm{WBF}} + \ldots$$

$$\mathrm{d}\sigma^{\mathrm{N}^n\mathrm{LO}} = \mathrm{Br}_{H\to b\bar{b}} \sum_{k=0}^{n} \mathrm{d}\sigma^{(n-k)}_{\mathrm{WBF}} \frac{\mathrm{d}\Gamma^{\mathrm{N}^k\mathrm{LO}}_{H\to b\bar{b}}}{\Gamma^{\mathrm{N}^k\mathrm{LO}}_{H\to b\bar{b}}}$$

$$\Longrightarrow \int_{\mathrm{inclusive}} \mathrm{d}\sigma^{\mathrm{N}^n\mathrm{LO}} = \sigma^{\mathrm{N}^n\mathrm{LO}}_{\mathrm{inclusive}}$$

The $\mathrm{N}^n\mathrm{LO}$ cross-section is defined such that upon integration over all events the inclusive cross-section at the same order is exactly reproduced

$$\sigma^{(1)} = \Delta^{(1,0)}_{\mathrm{prod}} + \Delta^{(0,1)}_{\mathrm{dec}} + \Delta^{(0,1)}_{\mathrm{exp}} \qquad \sigma^{(2)} = \Delta^{(2,0)}_{\mathrm{prod}} + \Delta^{(1,1)}_{\mathrm{dec}} + \Delta^{(0,2)}_{\mathrm{dec}} + \Delta^{(1,1)}_{\mathrm{exp}} + \Delta^{(0,2)}_{\mathrm{exp}}$$

$$\mathrm{d}\Gamma_{H\to b\bar{b}} = \mathrm{d}\Gamma^{(0)} + \mathrm{d}\Gamma^{(1)} + \mathrm{d}\Gamma^{(2)} + \dots$$

$$\Delta^{(i,0)}_{\mathrm{prod}} = \frac{\mathrm{Br}_{H\to b\bar{b}}}{\Gamma^{\mathrm{LO}}} \int \mathrm{d}\sigma^{(i)}_{\mathrm{WBF}} \mathrm{d}\Gamma^{(0)} \qquad \Delta^{(i,1)}_{\mathrm{exp}} = -\frac{\mathrm{Br}_{H\to b\bar{b}}\Gamma^{(1)}}{\Gamma^{\mathrm{LO}}\Gamma^{\mathrm{NLO}}} \int \mathrm{d}\sigma^{(i)}_{\mathrm{WBF}} \mathrm{d}\Gamma^{(0)}$$

$$\Delta^{(i,j)}_{\mathrm{dec}} = \frac{\mathrm{Br}_{H\to b\bar{b}}}{\Gamma^{\mathrm{N}^j\mathrm{LO}}} \int \mathrm{d}\sigma^{(i)}_{\mathrm{WBF}} \mathrm{d}\Gamma^{(j)} \qquad \Delta^{(0,2)}_{\mathrm{exp}} = -\frac{\mathrm{Br}_{H\to b\bar{b}}\Gamma^{(2)}}{\Gamma^{\mathrm{NLO}}\Gamma^{\mathrm{NNLO}}} \int \mathrm{d}\sigma^{(0)}_{\mathrm{WBF}} \mathrm{d}\Gamma^{\mathrm{NLO}}$$

We split perturbative corrections into *production*, *decay*, and *expansion* corrections

Sources of corrections

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

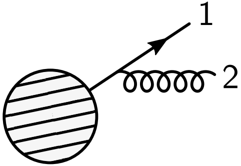
$$\Delta^{(1,0)}_{\mathrm{prod}} = -4.9\,\mathrm{fb}$$
$$\Delta^{(2,0)}_{\mathrm{prod}} = -1.5\,\mathrm{fb}$$
$$\Delta^{(0,1)}_{\mathrm{dec}} = -5.3\,\mathrm{fb}$$
$$\Delta^{(0,2)}_{\mathrm{dec}} = -5.0\,\mathrm{fb}$$
$$\Delta^{(1,1)}_{\mathrm{dec}} = +0.4\,\mathrm{fb}$$
$$\Delta^{(0,1)}_{\mathrm{exp}} = -13.0\,\mathrm{fb}$$
$$\Delta^{(0,2)}_{\mathrm{exp}} = -2.5\,\mathrm{fb}$$
$$\Delta^{(1,1)}_{\mathrm{exp}} = +0.8\,\mathrm{fb}$$

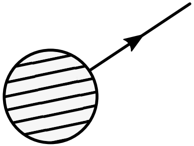
$$\sigma_{\mathrm{LO}} = 75.6\,\mathrm{fb}$$

This large effect is a sum of corrections to the Higgs production in WBF (-8%), to $H \to b\bar{b}$ decay (-14%), and the positive corrections to the total $H \to b\bar{b}$ width $\Gamma_{H\to b\bar{b}}$ (-19%)

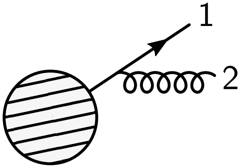
Factorization in soft and collinear limits

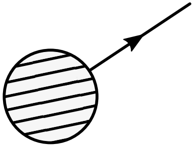
$$S_i = \lim_{E_i \to 0}$$

S_2 

$= L_S(p_2) \otimes$ 

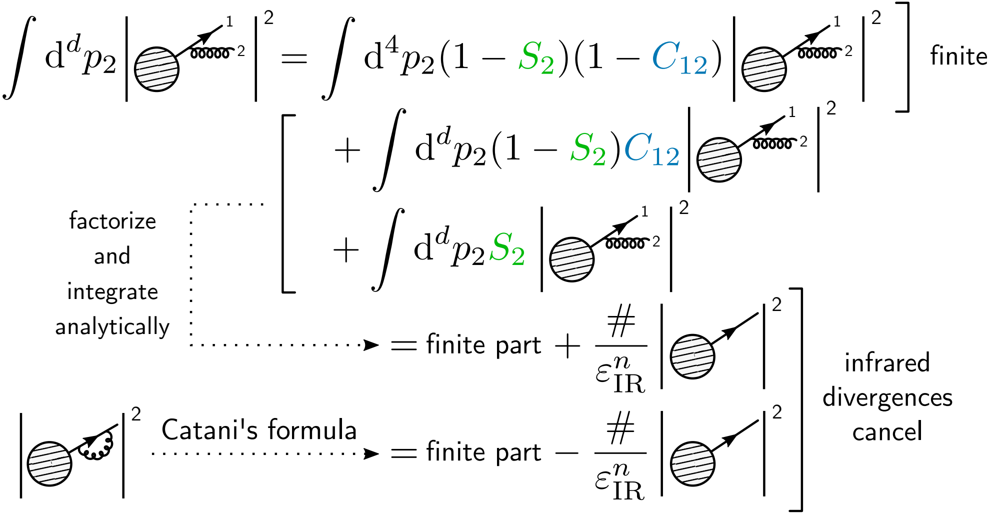
$$C_{ij} = \lim_{\theta_{ij} \to 0}$$

C_{12} 

$= L_C(p_2) \otimes$ 

Amplitudes with soft and/or collinear emissions factorize
into amplitudes of lower multiplicity and some universal limit factors.

Nested soft-collinear subtraction scheme



We use nested soft-collinear subtraction scheme to cancel infrared divergences between real and virtual corrections.