Standard Model at the LHC 2025

April 7-10, Durham

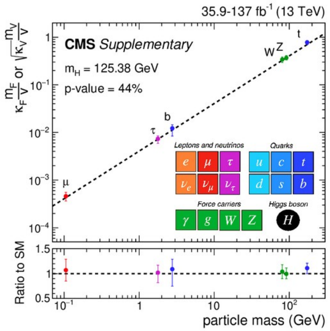
Higgs Boson Production and Decay in Weak Boson Fusion

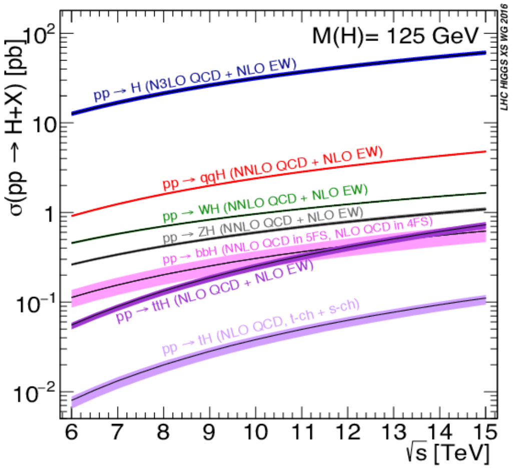
Raoul Röntsch

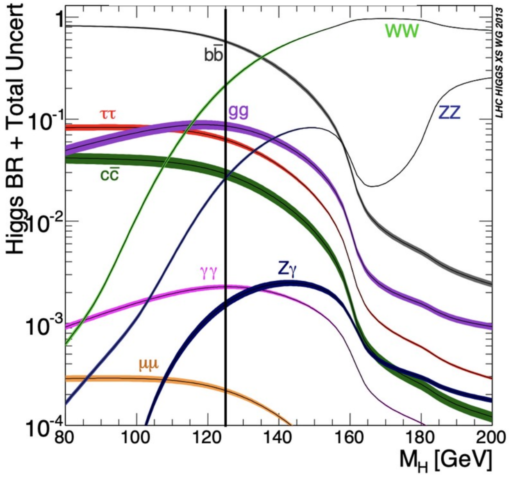
Higgs Physics at the LHC

Measurements of Higgs properties are central to exploring SM at LHC:

- Properties: mass, width, CP nature, …
- Couplings to other SM particles → explore EWSB.
- Self-coupling → explore Higgs potential.
- …







Multiple production and decay modes available at LHC → complementary measurements of Higgs properties and couplings.

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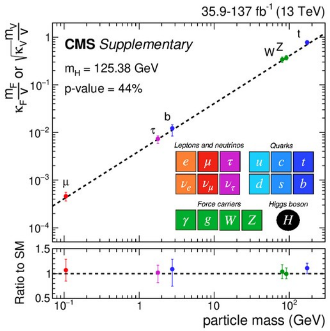
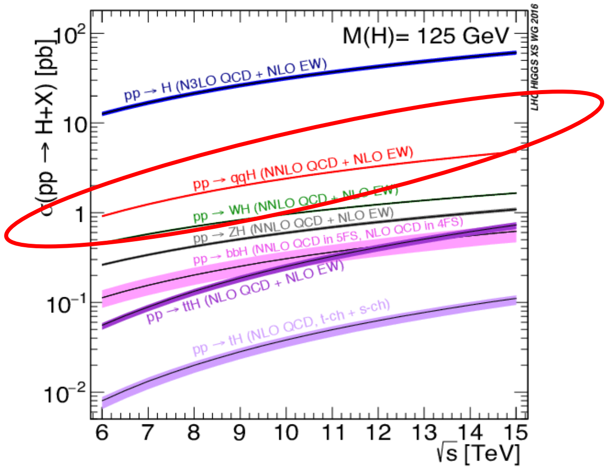
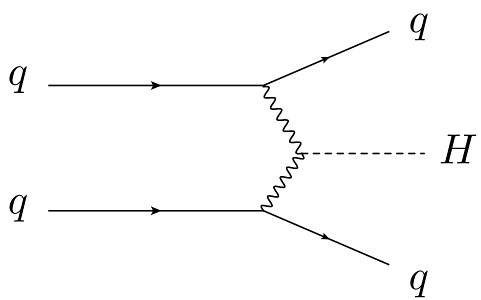




Weak **B**oson **F**usion:

Second largest production cross section



- Measure couplings of Higgs to weak gauge bosons.
- Study CP-structure.
- Higgs decays into invisible particles / *b*-quarks
- …

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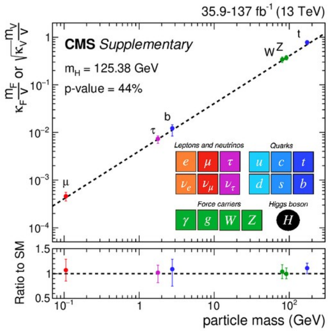
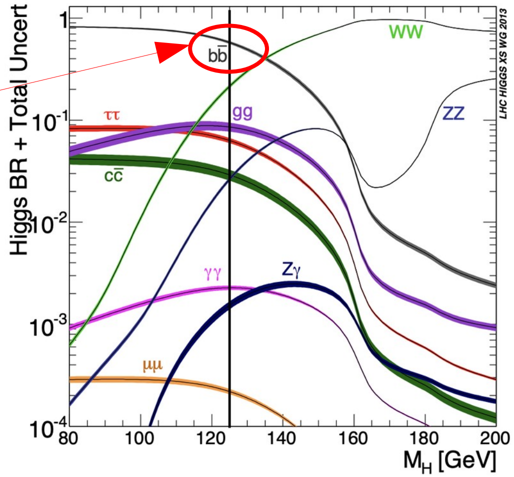


$H \to b\bar{b}$ decay:

- ✔ Largest branching ratio.
- ✗ Very large QCD background.



- Measure Yukawa coupling to b-quarks.
- …

Experimental status

ATLAS:

- WBF + $H \to b\bar{b}$ decay: [EPJC 81, 6 (2021)]

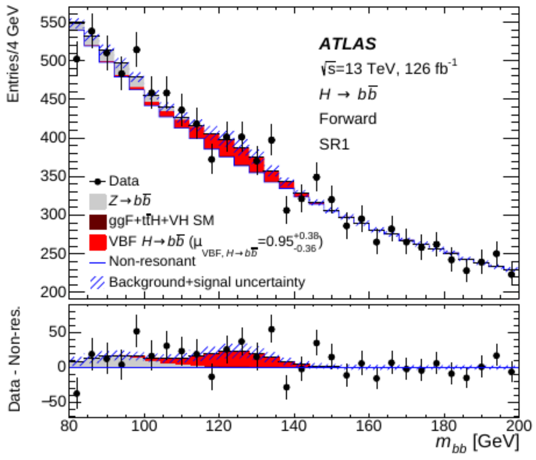
  Signal strength: $0.95^{+0.32}_{-0.32}(\mathrm{stat.})^{+0.20}_{-0.17}(\mathrm{syst.})$

  2.6-sigma significance.

- WBF + H $\to WW^*$ decay

  $$\sigma^{\mathrm{fid}} = 1.68 \pm 0.33\ (\mathrm{stat.}) \pm 0.23\ (\mathrm{syst.})\ \mathrm{fb}$$

  [PRD 108, 072003 (2023)]



CMS:

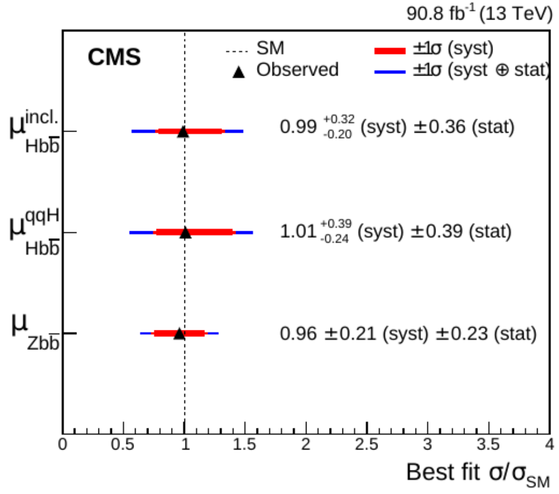
- WBF + $H \to b\bar{b}$ decay: [JHEP 12, 173 (2023)]

  Signal strength: $1.01^{+0.39}_{-0.39}(\mathrm{stat.})^{+0.39}_{-0.24}(\mathrm{syst.})$

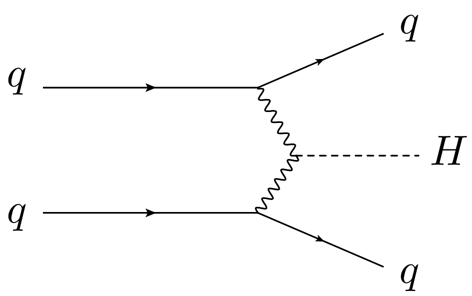
  2.4-sigma significance.

- WBF + $H \to b\bar{b}$ decay, boosted:

  Signal strength: $4.9^{+1.9}_{-1.6}$ [JHEP 12, 035 (2024)]



Weak boson fusion



Colourless *t*-channel exchange:

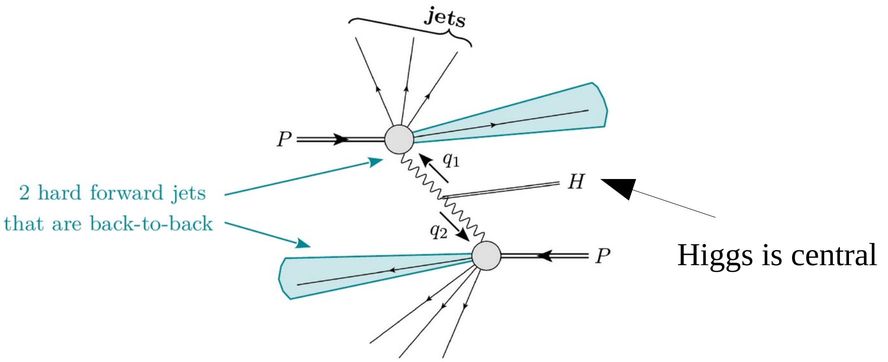


Image: K. Asteriadis

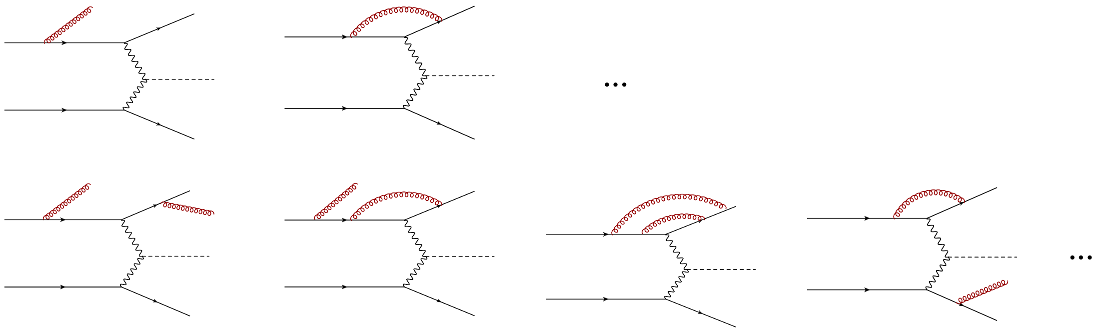
WBF cuts: $m_{j_1 j_2} > 600 \text{ GeV}, \quad \Delta y_{j_1 j_2} > 4.5, \quad y_{j_1} y_{j_2} < 0$

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

"Double-DIS (factorized) approximation" for QCD corrections:

- Radiation connecting quark lines is zero at NLO, colour-suppressed at NNLO.
- Identical-flavour interference < 1% of LO cross section.

[Ciccolini, Denner, Dittmaier '07]



Precision Results for WBF

In double-DIS approximation:

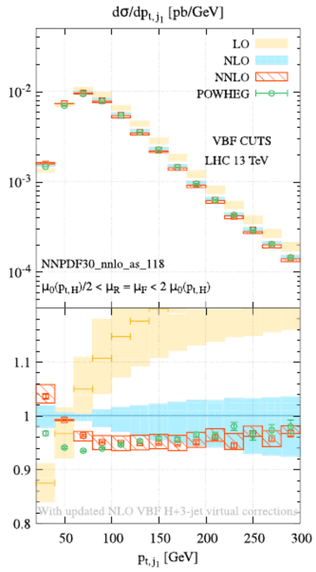
- Fully differential results at NNLO QCD:
  - corrections at 1%-5% level.
  - Residual scale uncertainties ~ 1%.

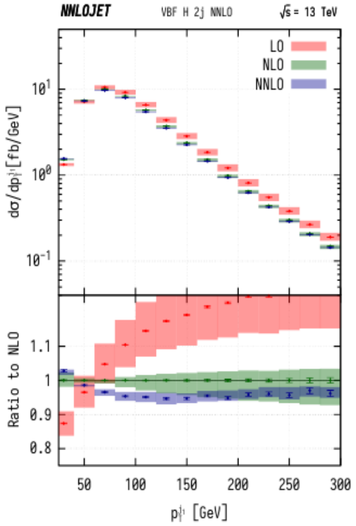
  [Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15; Cruz-Martinez, Gehrmann, Glover, Huss '18]

- Inclusive results at N3LO QCD:
  - Corrections ~ 1%-2%.
  - Residual scale uncertainty < 1%.

  [Dreyer, Karlberg '16]

NLO EW corrections known: [Ciccolini, Denner, Dittmaier '07, '07]





	$\sigma^{(13\text{ TeV})}$ [pb]	$\sigma^{(14\text{ TeV})}$ [pb]	$\sigma^{(100\text{ TeV})}$ [pb]
LO	$4.099^{+0.051}_{-0.067}$	$4.647^{+0.037}_{-0.058}$	$77.17^{+6.45}_{-7.29}$
NLO	$3.970^{+0.025}_{-0.023}$	$4.497^{+0.032}_{-0.027}$	$73.90^{+1.73}_{-1.94}$
NNLO	$3.932^{+0.015}_{-0.010}$	$4.452^{+0.018}_{-0.012}$	$72.44^{+0.53}_{-0.40}$
N^3LO	$3.928^{+0.005}_{-0.001}$	$4.448^{+0.006}_{-0.001}$	$72.34^{+0.11}_{-0.02}$

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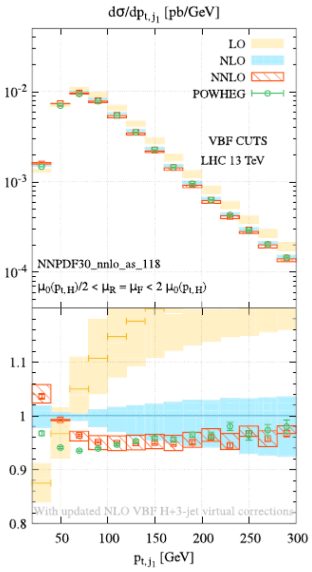
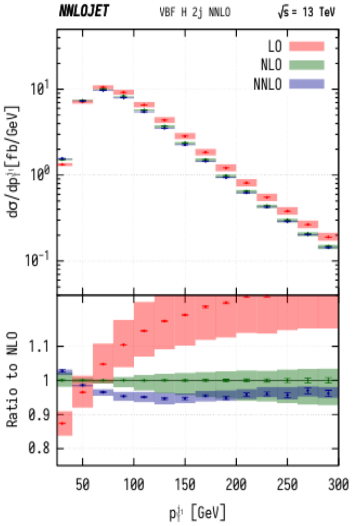
QCD corrections well-controlled in double-DIS approximation.





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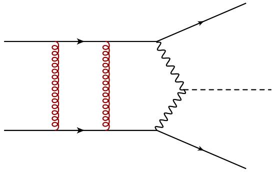
Non-factorizable corrections

Non-factorizable corrections at NNLO: need 2-loop 5 point amplitudes with internal masses – very challenging!



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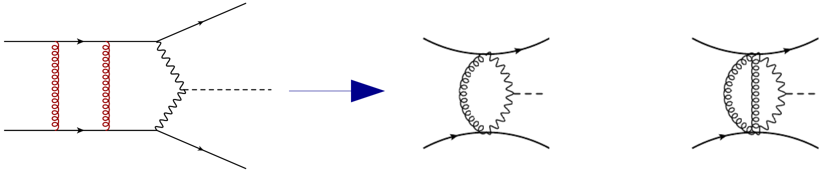

For WBF cuts: forward jets → use eikonal expansion $(p_{T,j}/\sqrt{s})$

- Two-loop non-factorizable corrections color-suppressed but enhanced by Glauber phase → 0.5%-1% corrections

[Liu, Melnikov, Penin ‘19; Dreyer, Karlberg, Tancredi ‘20]

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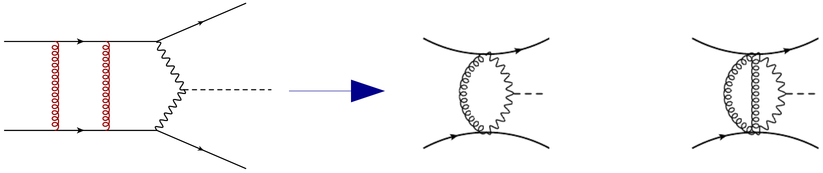

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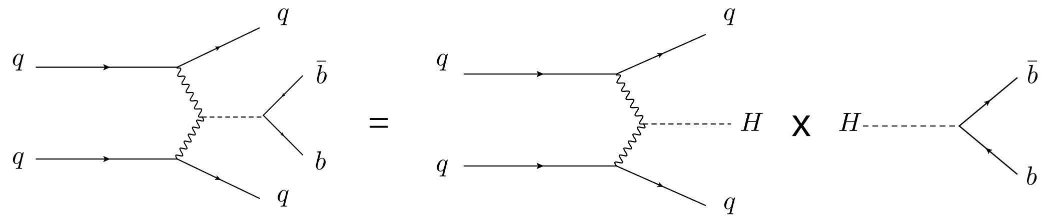
[Liu, Melnikov, Penin '19; Dreyer, Karlberg, Tancredi '20]

- Other non-factorizable contributions at NNLO (real-real and real-virtual) negligible. [Asteriadis, Brønnum-Hansen, Melnikov '23]
- Sub-leading eikonal effects ~ 20% of leading eikonal contribution. [Long, Melnikov, Quarroz '23]
- $\mathcal{O}(\beta_0 \alpha_s^3)$ corrections ~ 20% of leading eikonal and reduce scale uncertainty on eikonal to ~ 5%. [Brønnum-Hansen, Long, Melnikov '23]

Non-factorizable effects under control.

WBF with Higgs decays

- Use WBF signature (forward jets + central Higgs) to identify *b*-jets from $H \to b\bar{b}$ decays.



- Higgs is narrow-width scalar particle $\rightarrow$ treat production and decay processes separately.

- Jet clustering/tagging and kinematic cuts can correlate production and decay subprocesses:
  - Impact of QCD corrections can change depending on cuts.
  - Especially true for hadronic Higgs decays, e.g. $H \to b\bar{b}$.

- No new calculation needed, but computationally expensive:
  - $H \to WW^* \to 2\ell\ 2\nu$: 21-dimensional phase space + NNLO calculation!

- Generate decay kinematics in Higgs rest frame;
- Use importance-sampling grids for WBF production of stable Higgs;
- For each production point, choose 10-100 randomly generated decay events;
- Reweight events according to decays;
- Boost back to laboratory frame to apply cuts and evaluate observables.

WBF with $H \to WW^* \to 2\ell\ 2\nu$ decay

Setup for WBF production:

[Asteriadis, Caola, Melnikov, RR '21]

- 13 TeV LHC, `NNPDF31_nnlo_as_0118`
- Renormalization/factorization scale: $\mu_R = \mu_F = \mu = \sqrt{\frac{m_H}{2}\sqrt{\frac{m_H^2}{4} + p_{\perp,H}^2}}$

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

- Jets defined with anti-kT algorithm with R=0.4.
- WBF cuts

$p_{\perp,j} \geq 25$ GeV $\quad |y_j| \leq 4.5 \quad |y_{j_1} - y_{j_2}| \geq 4.5 \quad y_{j_1} y_{j_2} \leq 0 \quad m_{j_1 j_2} \geq 600$ GeV

Large rapidity gap — Opposite hemispheres — Large invariant mass

$H \to WW^* \to 2\ell\ 2\nu$ decays:

Following CMS analysis, Phys. Lett. B 791 (2019)

- $p_{\perp,l_1} \geq 25$ GeV $\quad p_{\perp,l_2} \geq 13$ GeV $\quad m_{l_1 l_2} \geq 12$ GeV $\quad p_{\perp,l_1 l_2} \geq 30$ GeV $\quad p_{\perp,\text{miss}} \geq 20$ GeV $\quad 60 \text{ GeV} \leq m_T \leq 125$ GeV
- Rapidity of leptons required to be between rapidity of two hardest jets – selects central Higgs bosons, correlates production and decay.

$$m_T = \sqrt{2 p_\perp^{l_1 l_2} p_\perp^{\text{miss}} \left(1 - \cos\Delta\phi_{l_1 l_2, \vec{p}_\perp^{\text{miss}}}\right)},$$

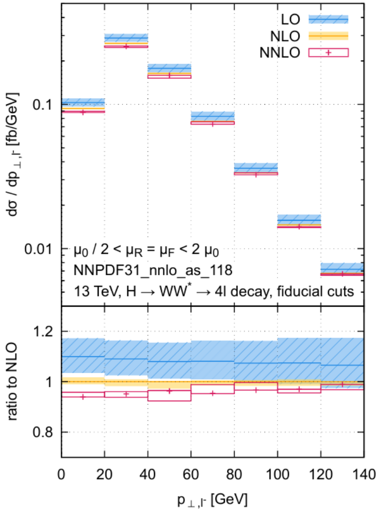
WBF with $H \to WW^* \to 2\ell\ 2\nu$ decay

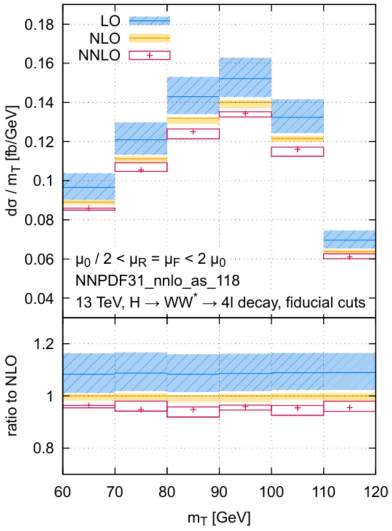
Impact of decay on QCD corrections quite mild – cuts on decay products don't change kinematics of Higgs significantly.

$$\sigma_{\rm LO}^{e\bar\nu_e\bar\mu\nu_\mu} = 0.719^{-0.045}_{+0.051}\ \text{fb}, \qquad \sigma_{\rm NLO}^{e\bar\nu_e\bar\mu\nu_\mu} = 0.662^{+0.005}_{-0.012}\ \text{fb}, \qquad \sigma_{\rm NNLO}^{e\bar\nu_e\bar\mu\nu_\mu} = 0.632^{+0.008}_{-0.008}\ \text{fb}.$$

Similar to corrections for stable Higgs.

-8% -4.5%



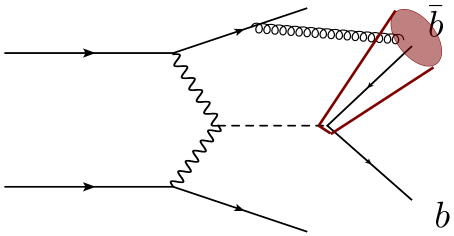


K-factors for leptonic distributions relatively flat.

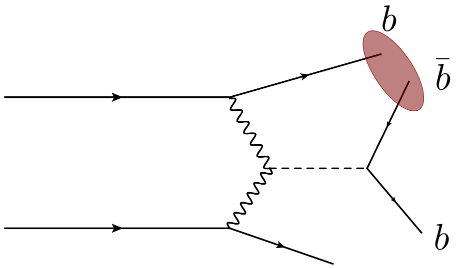
[Asteriadis, Caola, Melnikov, RR '21]

WBF with $H \to b\bar{b}$ decay

- Higgs reconstructed from observed *b*-tagged jets.
- Factorization of production and decay can be broken in several ways:



Jet clustering



b-tagging

Following ATLAS analysis,
Eur. Phys. J. C. 81 (2021)

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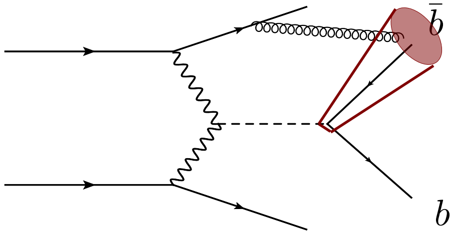

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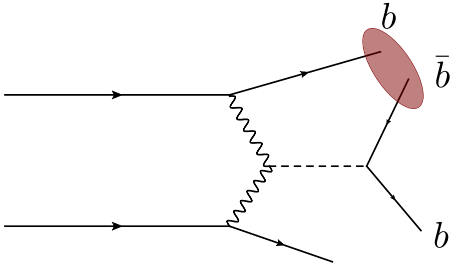

b-tagging

First computation:

- WBF production at NNLO, decay at LO, massless b-quarks.
- Decay scale $\mu_{\text{dec.}} = m_H$.
- Treat all quarks from production as flavourless:
  - ➢ Final state b-quarks ~ 1% of cross section at NLO.
- Require two b-tagged jets with $p_{\perp,b} \geq 65\ \text{GeV}, \quad |y_b| \leq 2.5$

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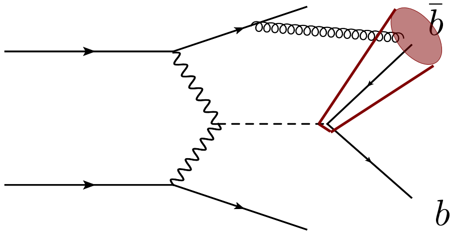

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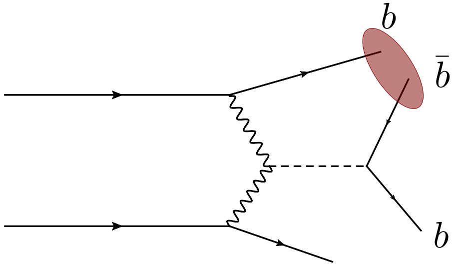

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Requires boosted Higgs.

Following ATLAS analysis,
Eur. Phys. J. C. 81 (2021)

[Asteriadis, Caola, Melnikov, RR '21]

WBF with $H \to b\bar{b}$ decay at LO

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

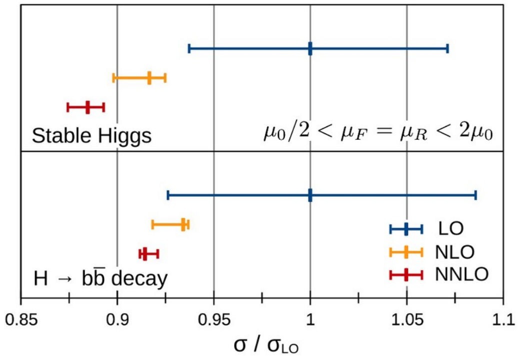
Sizeable cross sections: ~ 10k events already!

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

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

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

- Effect of decay comparable to NNLO corrections!



Images: K. Asteriadis

With decays:

- Smaller scale uncertainties;
- Improved perturbative convergence.

[Asteriadis, Caola, Melnikov, RR ‘21]

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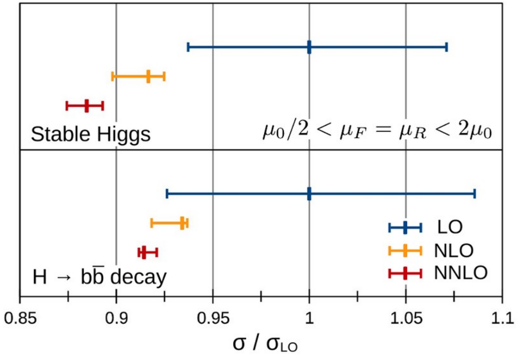
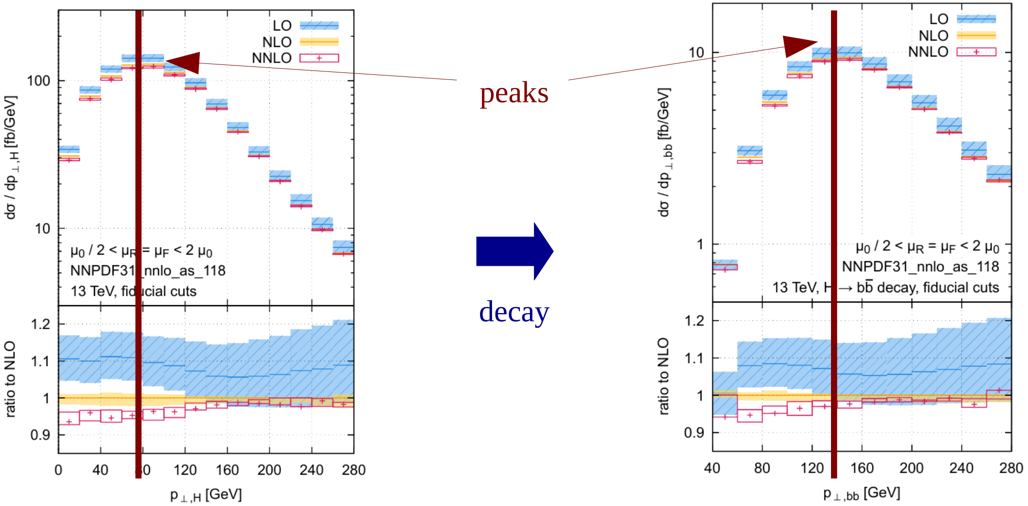


Images: K. Asteriadis



- Cuts on *b*-jets → harder transverse momentum distribution for Higgs.
  - Reduces effect of higher order corrections.
- Can obtain similar results for stable Higgs by imposing $p_{\perp,H} \geq 150\ \text{GeV}$.

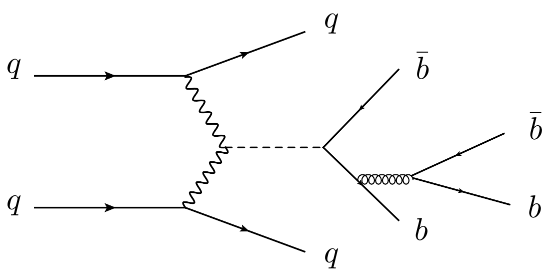
[Asteriadis, Caola, Melnikov, RR ‘21]

WBF with $H \to b\bar{b}$ decay at NNLO

Include NNLO effects in decay:

- Massive b-quarks – use anti-kT algorithm. (IR safe.)

[Behring, Bizoń '19]



- Quarks in production still considered flavourless.
- Events with 4 b-jets due to corrections to decay:
  - Choose pair with invariant mass closest to Higgs mass to reconstruct Higgs kinematics.
- Yukawa coupling renormalized in $\overline{\text{MS}}$ scheme, pole bottom mass used in amplitudes.
- All cuts on production and decay products unchanged.

[Asteriadis, Behring, Melnikov, Novikov, RR '24]

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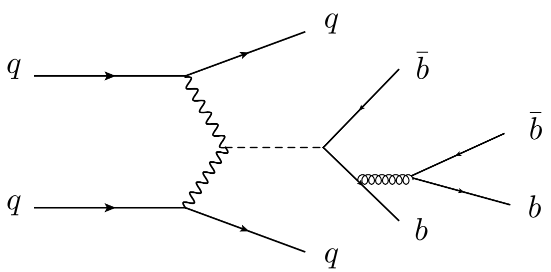
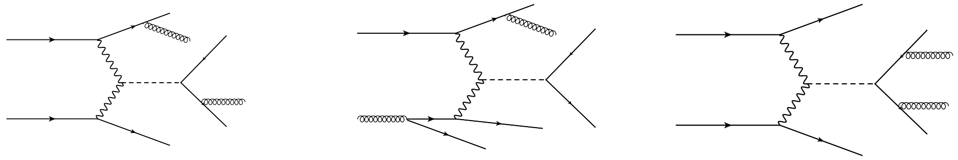


Rich jet environment: interplay between "WBF jets", jets from decay, radiation from production and/or decay.



[Asteriadis, Behring, Melnikov, Novikov, RR '24]

WBF with $H \to b\bar{b}$ decay at NNLO

- Write differential cross section as $\mathrm{d}\sigma = \mathrm{Br}_{H\to b\bar{b}}\, \mathrm{d}\sigma_{\mathrm{WBF}}\, \mathrm{d}\gamma_b$ with $\mathrm{d}\gamma_b = \dfrac{\mathrm{d}\Gamma_b}{\Gamma_b}.$
- Keep branching ratio fixed and expand other factors:

$$\mathrm{d}\sigma^{\mathrm{N}^n\mathrm{LO}} = \mathrm{Br}_{H\to b\bar{b}} \sum_{k=0}^{n} \mathrm{d}\sigma_{\mathrm{WBF}}^{(n-k)} \times \mathrm{d}\gamma^{\mathrm{N}^k\mathrm{LO}} \quad \text{with} \quad \mathrm{d}\gamma^{\mathrm{N}^n\mathrm{LO}} = \frac{\sum_{k=0}^{n} \mathrm{d}\Gamma_b^{(k)}}{\Gamma_b^{\mathrm{N}^n\mathrm{LO}}} \qquad \Gamma_b^{\mathrm{N}^n\mathrm{LO}} = \sum_{k=0}^{n} \Gamma_b^{(k)}$$

[Asteriadis, Behring, Melnikov, Novikov, RR ‘24]

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

- Very large corrections: -30% at NLO, -10% at NNLO.
- Scale uncertainties dramatically underestimate effect of QCD corrections.

[Asteriadis, Behring, Melnikov, Novikov, RR ‘24]

WBF with $H \to b\bar{b}$ decay at NNLO

Write QCD corrections as $\sigma^{\mathrm{N}^n\mathrm{LO}} = \mathrm{d}\sigma^{\mathrm{LO}} + \sum_{k=1}^{n} \mathrm{d}\Delta^{\mathrm{N}^k\mathrm{LO}}$

$\sigma^{\mathrm{LO}} = 75.6^{-5.6}_{+6.5}$ fb

$$\mathrm{d}\Delta^{\mathrm{NLO}} = \mathrm{d}\Delta^{(1,0)}_{\mathrm{prod}} + \mathrm{d}\Delta^{(0,1)}_{\mathrm{dec}} + \mathrm{d}\Delta^{(0,1)}_{\mathrm{exp}}$$

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

Corrections to production, decay, Higgs width expansion.

[Asteriadis, Behring, Melnikov, Novikov, RR ‘24]

WBF with $H \to b\bar{b}$ decay at NNLO

Write QCD corrections as $\sigma^{\mathrm{N}^n\mathrm{LO}} = \mathrm{d}\sigma^{\mathrm{LO}} + \sum_{k=1}^{n} \mathrm{d}\Delta^{\mathrm{N}^k\mathrm{LO}}$

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

Corrections to production, decay, Higgs width expansion.

$\mathrm{d}\Delta^{(1,0)}_{\mathrm{prod}} = -4.9$ fb $\mathrm{d}\Delta^{(0,1)}_{\mathrm{dec}} = -5.3$ fb $\mathrm{d}\Delta^{(0,1)}_{\mathrm{exp}} = -13.0$ fb

$\mathrm{d}\Delta^{(2,0)}_{\mathrm{prod}} = -1.5$ fb $\mathrm{d}\Delta^{(1,1)}_{\mathrm{dec}} = +0.4$ fb $\mathrm{d}\Delta^{(0,2)}_{\mathrm{dec}} = -5.0$ fb

$\mathrm{d}\Delta^{(1,1)}_{\mathrm{exp}} = +0.8$ fb $\mathrm{d}\Delta^{(0,2)}_{\mathrm{exp}} = -2.5$ fb

Corrections to production mild, similar to situation with stable Higgs.

[Asteriadis, Behring, Melnikov, Novikov, RR ‘24]

WBF with $H \to b\bar{b}$ decay at NNLO

Write QCD corrections as $$\sigma^{\mathrm{N}^n\mathrm{LO}} = \mathrm{d}\sigma^{\mathrm{LO}} + \sum_{k=1}^{n} \mathrm{d}\Delta^{\mathrm{N}^k\mathrm{LO}}$$

$$\sigma^{\mathrm{LO}} = 75.6^{-5.6}_{+6.5}\ \mathrm{fb}$$

$$\mathrm{d}\Delta^{\mathrm{NLO}} = \mathrm{d}\Delta^{(1,0)}_{\mathrm{prod}} + \mathrm{d}\Delta^{(0,1)}_{\mathrm{dec}} + \mathrm{d}\Delta^{(0,1)}_{\mathrm{exp}}$$

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

Corrections to production, decay, Higgs width expansion.

$\mathrm{d}\Delta^{(1,0)}_{\mathrm{prod}} = -4.9\ \mathrm{fb}$ $\quad$ $\mathrm{d}\Delta^{(0,1)}_{\mathrm{dec}} = -5.3\ \mathrm{fb}$ $\quad$ $\mathrm{d}\Delta^{(0,1)}_{\mathrm{exp}} = -13.0\ \mathrm{fb}$

$\mathrm{d}\Delta^{(2,0)}_{\mathrm{prod}} = -1.5\ \mathrm{fb}$ $\quad$ $\mathrm{d}\Delta^{(1,1)}_{\mathrm{dec}} = +0.4\ \mathrm{fb}$ $\quad$ $\mathrm{d}\Delta^{(0,2)}_{\mathrm{dec}} = -5.0\ \mathrm{fb}$

$\mathrm{d}\Delta^{(1,1)}_{\mathrm{exp}} = +0.8\ \mathrm{fb}$ $\quad$ $\mathrm{d}\Delta^{(0,2)}_{\mathrm{exp}} = -2.5\ \mathrm{fb}$

Corrections to width expansion **large** at NLO, **moderate** at NNLO.

[Asteriadis, Behring, Melnikov, Novikov, RR ‘24]

WBF with $H \to b\bar{b}$ decay at NNLO

Write QCD corrections as $\sigma^{\mathrm{N}^n\mathrm{LO}} = \mathrm{d}\sigma^{\mathrm{LO}} + \sum_{k=1}^{n} \mathrm{d}\Delta^{\mathrm{N}^k\mathrm{LO}}$

$\sigma^{\mathrm{LO}} = 75.6^{-5.6}_{+6.5}$ fb

$$\mathrm{d}\Delta^{\mathrm{NLO}} = \mathrm{d}\Delta^{(1,0)}_{\mathrm{prod}} + \mathrm{d}\Delta^{(0,1)}_{\mathrm{dec}} + \mathrm{d}\Delta^{(0,1)}_{\mathrm{exp}}$$

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

Corrections to production, decay, Higgs width expansion.

$\mathrm{d}\Delta^{(1,0)}_{\mathrm{prod}} = -4.9$ fb $\quad$ $\mathrm{d}\Delta^{(0,1)}_{\mathrm{dec}} = -5.3$ fb $\quad$ $\mathrm{d}\Delta^{(0,1)}_{\mathrm{exp}} = -13.0$ fb

$\mathrm{d}\Delta^{(2,0)}_{\mathrm{prod}} = -1.5$ fb $\quad$ $\mathrm{d}\Delta^{(1,1)}_{\mathrm{dec}} = +0.4$ fb $\quad$ $\mathrm{d}\Delta^{(0,2)}_{\mathrm{dec}} = -5.0$ fb

$\mathrm{d}\Delta^{(1,1)}_{\mathrm{exp}} = +0.8$ fb $\quad$ $\mathrm{d}\Delta^{(0,2)}_{\mathrm{exp}} = -2.5$ fb

Corrections to decay ~ -7% at NLO and NNLO

[Asteriadis, Behring, Melnikov, Novikov, RR ‘24]

WBF with $H \to b\bar{b}$ decay at NNLO

Write QCD corrections as $\sigma^{\mathrm{N}^n\mathrm{LO}} = \mathrm{d}\sigma^{\mathrm{LO}} + \sum_{k=1}^{n} \mathrm{d}\Delta^{\mathrm{N}^k\mathrm{LO}}$

$\sigma^{\mathrm{LO}} = 75.6^{-5.6}_{+6.5}\ \mathrm{fb}$

$$\mathrm{d}\Delta^{\mathrm{NLO}} = \mathrm{d}\Delta^{(1,0)}_{\mathrm{prod}} + \mathrm{d}\Delta^{(0,1)}_{\mathrm{dec}} + \mathrm{d}\Delta^{(0,1)}_{\mathrm{exp}}$$

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Corrections to production, decay, Higgs width expansion.

$\mathrm{d}\Delta^{(1,0)}_{\mathrm{prod}} = -4.9\ \mathrm{fb}$ $\mathrm{d}\Delta^{(0,1)}_{\mathrm{dec}} = -5.3\ \mathrm{fb}$ $\mathrm{d}\Delta^{(0,1)}_{\mathrm{exp}} = -13.0\ \mathrm{fb}$

$\mathrm{d}\Delta^{(2,0)}_{\mathrm{prod}} = -1.5\ \mathrm{fb}$ $\mathrm{d}\Delta^{(1,1)}_{\mathrm{dec}} = +0.4\ \mathrm{fb}$ $\mathrm{d}\Delta^{(0,2)}_{\mathrm{dec}} = -5.0\ \mathrm{fb}$

$\mathrm{d}\Delta^{(1,1)}_{\mathrm{exp}} = +0.8\ \mathrm{fb}$ $\mathrm{d}\Delta^{(0,2)}_{\mathrm{exp}} = -2.5\ \mathrm{fb}$

➡

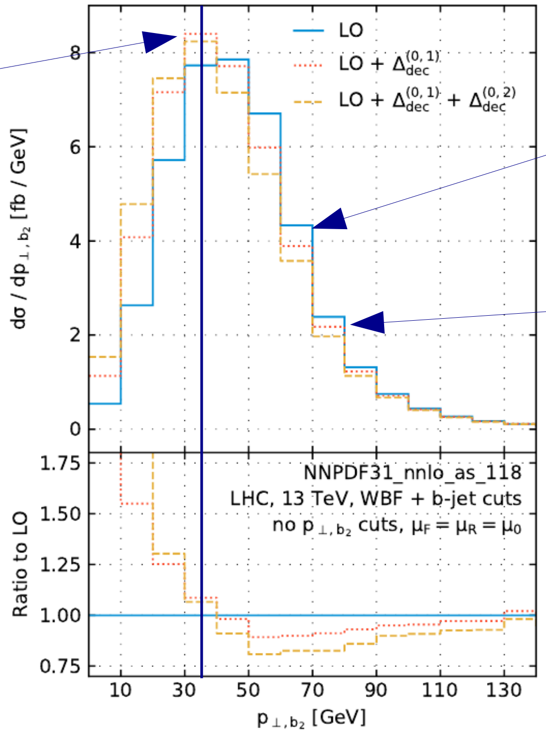
- Large corrections due to combination of more moderate effects.
- Poor perturbative convergence driven by radiation from decay.

[Asteriadis, Behring, Melnikov, Novikov, RR ‘24]

WBF with $H \to b\bar{b}$ decay at NNLO

To understand origin of large corrections to decay, remove cut on sub-leading b-jet transverse momentum:

Peaks at $p_{\perp,b_2} \approx 30$ GeV



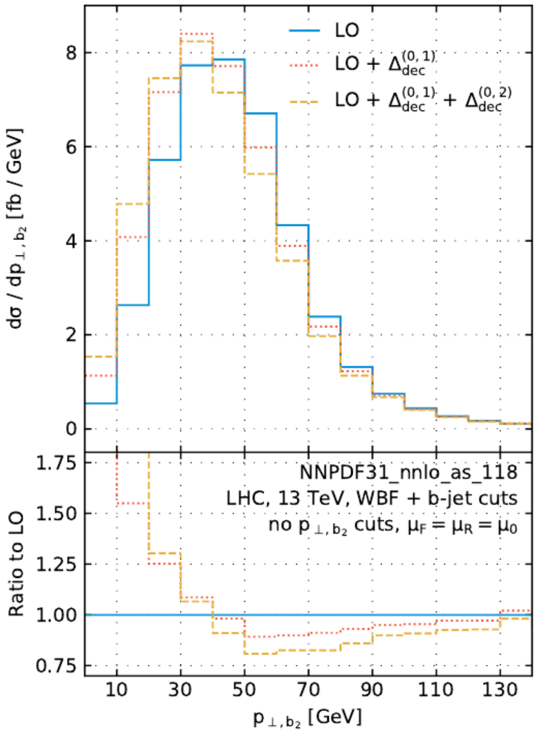
Decreases rapidly for $40 \text{ GeV} \lesssim p_{\perp,b_2} \lesssim 80 \text{ GeV}$

Real emissions make spectrum softer – less likely to pass cuts.

[Asteriadis, Behring, Melnikov, Novikov, RR ‘24]

WBF with $H \to b\bar{b}$ decay at NNLO

To understand origin of large corrections to decay, remove cut on sub-leading b-jet transverse momentum:

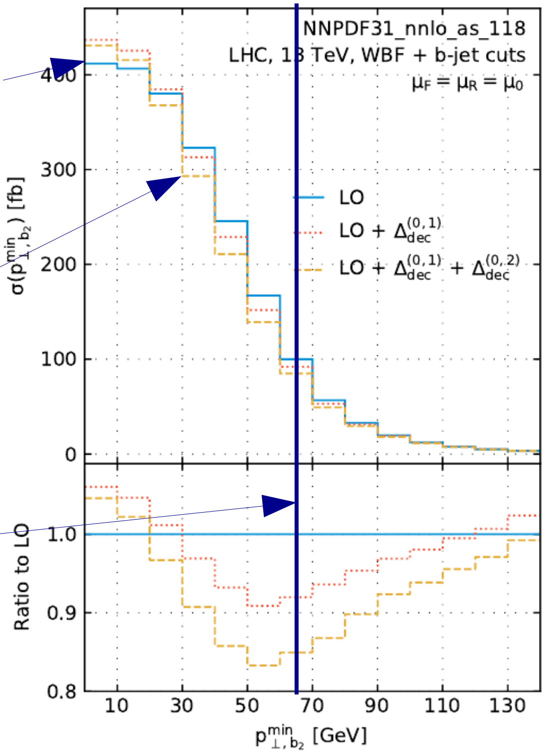


Cumulative distribution $\quad \sigma(p_{\perp,b_2}^{\rm min}) = \int_{p_{\perp,b_2}^{\rm min}}^{\infty} {\rm d}p_{\perp,b_2} \frac{{\rm d}\sigma}{{\rm d}p_{\perp,b_2}}$

Perturbative convergence for $p_{\perp,b_2}^{\rm min} \lesssim 30$ GeV

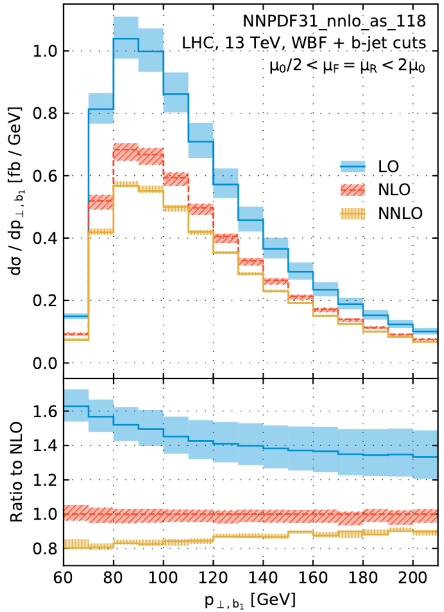
Poor perturbative convergence for $p_{\perp,b_2}^{\rm min} \gtrsim 30$ GeV

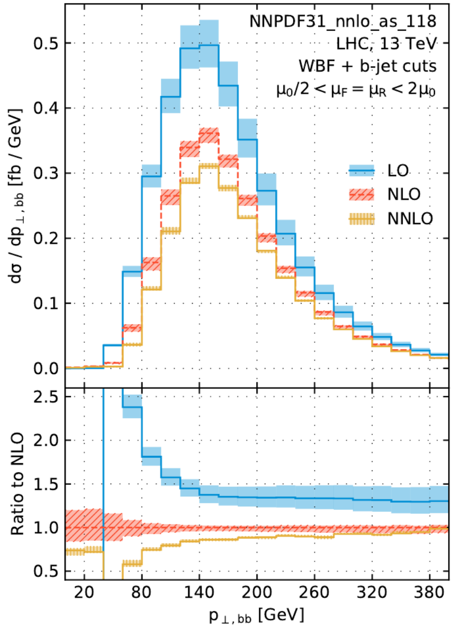
Cut $p_{\perp,b_2} \geq 65$ GeV



WBF with $H \to b\bar{b}$ decay at NNLO

Restore cut $p_{\perp,b_2} \geq 65\ \mathrm{GeV}$





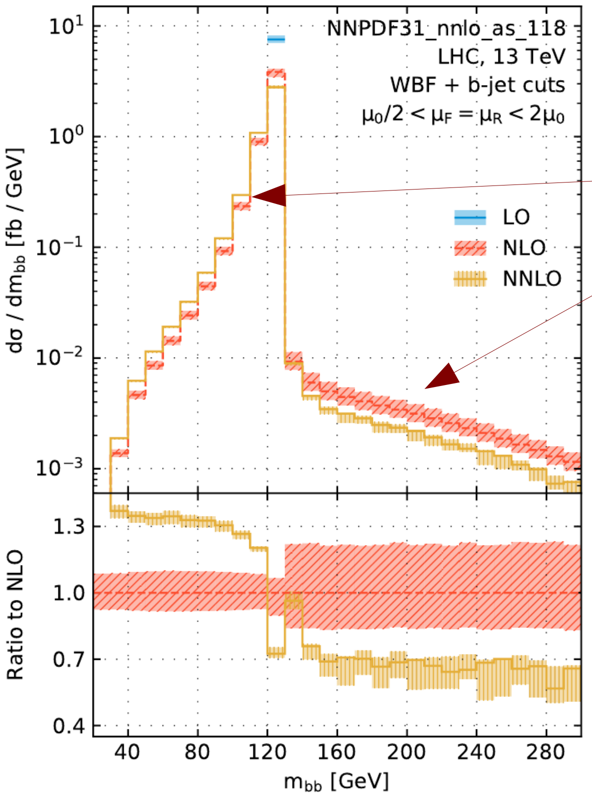
Strong correlation between Higgs transverse momentum and ability to pass cuts

→ k-factor is strongly dependent on reconstructed Higgs transverse momentum.

QCD corrections to *b*-jet transverse momentum distributions relatively flat.

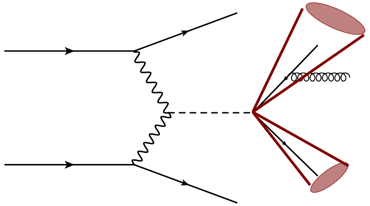
[Asteriadis, Behring, Melnikov, Novikov, RR ‘24]

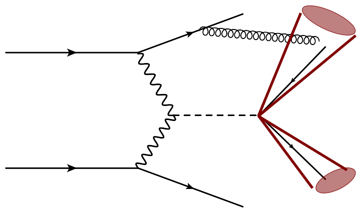
WBF with $H \to b\bar{b}$ decay at NNLO



m_{bb} : “reconstructed” Higgs mass

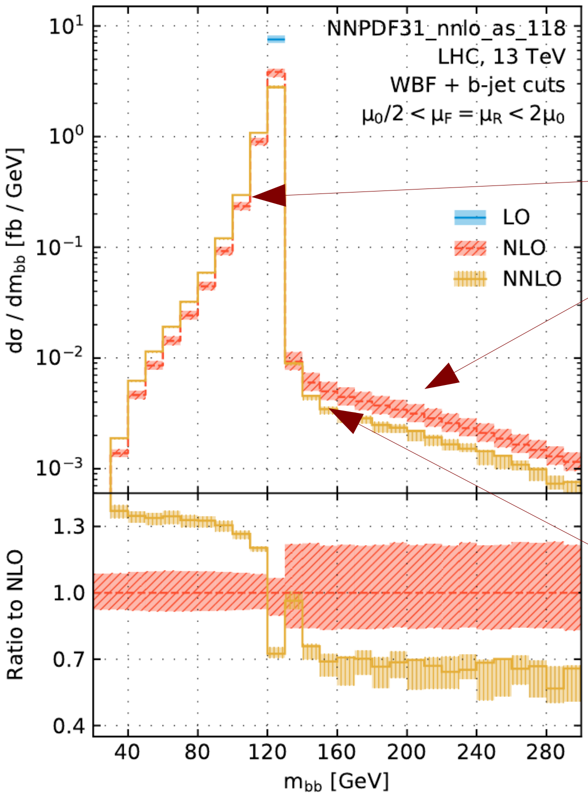
- If no corrections to decay or interplay between production and decay: single bin at $m_{bb} = m_H$.
- Corrections to decay decrease m_{bb}.
- Clustering of QCD radiation from production with decay products increases m_{bb}.





[Asteriadis, Behring, Melnikov, Novikov, RR ‘24]

WBF with $H \to b\bar{b}$ decay at NNLO



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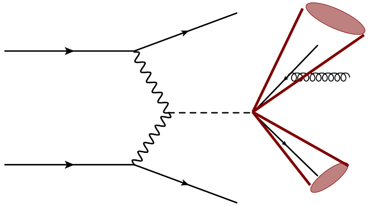
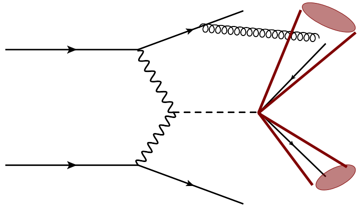




- ~ 1% of events have $m_{bb} > m_H$.

  → clustering of *any* production parton and decay products ~ 1% of events.
- ~ 1% of WBF events at LO have an additional final state *b*-quark.
- *A posteriori* justification of flavourless treatment of WBF production.

[Asteriadis, Behring, Melnikov, Novikov, RR ‘24]

Conclusions

- For stable Higgs bosons, fixed-order WBF predictions well-controlled:
  - ✔ In double-DIS approximation;
  - ✔ Eikonal approximation for non-factorizable corrections;
- Including realistic final states with decaying Higgs can change the picture, depending on decay mode and kinematics cuts:
  - Fairly similar for $H \to WW^* \to 2\ell\, 2\nu$ decay with mild cuts;
  - Effect of $H \to b\bar{b}$ decay at LO ~ NNLO corrections;
  - Including NNLO corrections to $H \to b\bar{b}$ decay → large changes, poor perturbative convergence, largely due to strong cut on *b*-jet transverse momentum.
- *Large logs? Captured by resummation/parton shower?*

THANK YOU FOR YOUR ATTENTION

QUESTIONS?

BACKUP SLIDES

WBF with $H \to b\bar{b}$ decay at NNLO

Definitions of corrections to production, decay, and Higgs width expansion:

$$\mathrm{d}\Delta^{(1,0)}_{\mathrm{prod}} = \mathrm{Br}_{H\to b\bar{b}} \left(\mathrm{d}\sigma^{(1)}_{\mathrm{WBF}} \times \frac{\mathrm{d}\Gamma^{(0)}_b}{\Gamma^{(0)}_b} \right),$$

$$\mathrm{d}\Delta^{(0,1)}_{\mathrm{dec}} = \mathrm{Br}_{H\to b\bar{b}} \frac{\Gamma^{(1)}_b}{\Gamma^{\mathrm{NLO}}_b} \left(\mathrm{d}\sigma^{(0)}_{\mathrm{WBF}} \times \frac{\mathrm{d}\Gamma^{(1)}_b}{\Gamma^{(1)}_b} \right)$$

$$\mathrm{d}\Delta^{(0,1)}_{\mathrm{exp}} = -\mathrm{Br}_{H\to b\bar{b}} \frac{\Gamma^{(1)}_b}{\Gamma^{\mathrm{NLO}}_b} \left(\mathrm{d}\sigma^{(0)}_{\mathrm{WBF}} \times \mathrm{d}\gamma^{\mathrm{LO}} \right)$$

$$\mathrm{d}\Delta^{(2,0)}_{\mathrm{prod}} = \mathrm{Br}_{H\to b\bar{b}} \left(\mathrm{d}\sigma^{(2)}_{\mathrm{WBF}} \times \frac{\mathrm{d}\Gamma^{(0)}_b}{\Gamma^{(0)}_b} \right),$$

$$\mathrm{d}\Delta^{(1,1)}_{\mathrm{dec}} = \mathrm{Br}_{H\to b\bar{b}} \frac{\Gamma^{(1)}_b}{\Gamma^{\mathrm{NLO}}_b} \left(\mathrm{d}\sigma^{(1)}_{\mathrm{WBF}} \times \frac{\mathrm{d}\Gamma^{(1)}_b}{\Gamma^{(1)}_b} \right),$$

$$\mathrm{d}\Delta^{(0,2)}_{\mathrm{dec}} = \mathrm{Br}_{H\to b\bar{b}} \frac{\Gamma^{(2)}_b}{\Gamma^{\mathrm{NNLO}}_b} \left(\mathrm{d}\sigma^{(0)}_{\mathrm{WBF}} \times \frac{\mathrm{d}\Gamma^{(2)}_b}{\Gamma^{(2)}_b} \right)$$

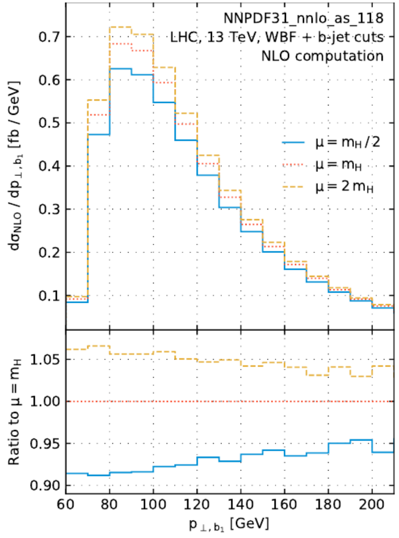
$$\mathrm{d}\Delta^{(1,1)}_{\mathrm{exp}} = -\mathrm{Br}_{H\to b\bar{b}} \frac{\Gamma^{(1)}_b}{\Gamma^{\mathrm{NLO}}_b} \left(\mathrm{d}\sigma^{(1)}_{\mathrm{WBF}} \times \mathrm{d}\gamma^{\mathrm{LO}} \right),$$

$$\mathrm{d}\Delta^{(0,2)}_{\mathrm{exp}} = -\mathrm{Br}_{H\to b\bar{b}} \frac{\Gamma^{(2)}_b}{\Gamma^{\mathrm{NNLO}}_b} \left(\mathrm{d}\sigma^{(0)}_{\mathrm{WBF}} \times \mathrm{d}\gamma^{\mathrm{NLO}} \right)$$

WBF with $H \to b\bar{b}$ decay at NNLO

- Decay scale $\mu_{\text{dec.}} = m_H$: $\quad \mathrm{d}\Delta^{(0,1)}_{\text{dec}} = -5.3 \text{ fb} \quad \mathrm{d}\Delta^{(0,1)}_{\text{exp}} = -13.0 \text{ fb} \quad \mathrm{d}\Delta^{(0,1)}_{\text{dec+exp}} = -18.3 \text{ fb}$
- Decay scale $\mu_{\text{dec.}} = m_H/2$: $\quad \mathrm{d}\Delta^{(0,1)}_{\text{dec}} = -13.8 \text{ fb} \quad \mathrm{d}\Delta^{(0,1)}_{\text{exp}} = -8.3 \text{ fb} \quad \mathrm{d}\Delta^{(0,1)}_{\text{dec+exp}} = -22.1 \text{ fb}$

➡ Decay scale variations do not capture large corrections observed.



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