Towards WBF with realistic final states and anomalous couplings at NNLO

in collaboration with Fabrizio Caola, Kirill Melnikov, Raoul Röntsch

References:

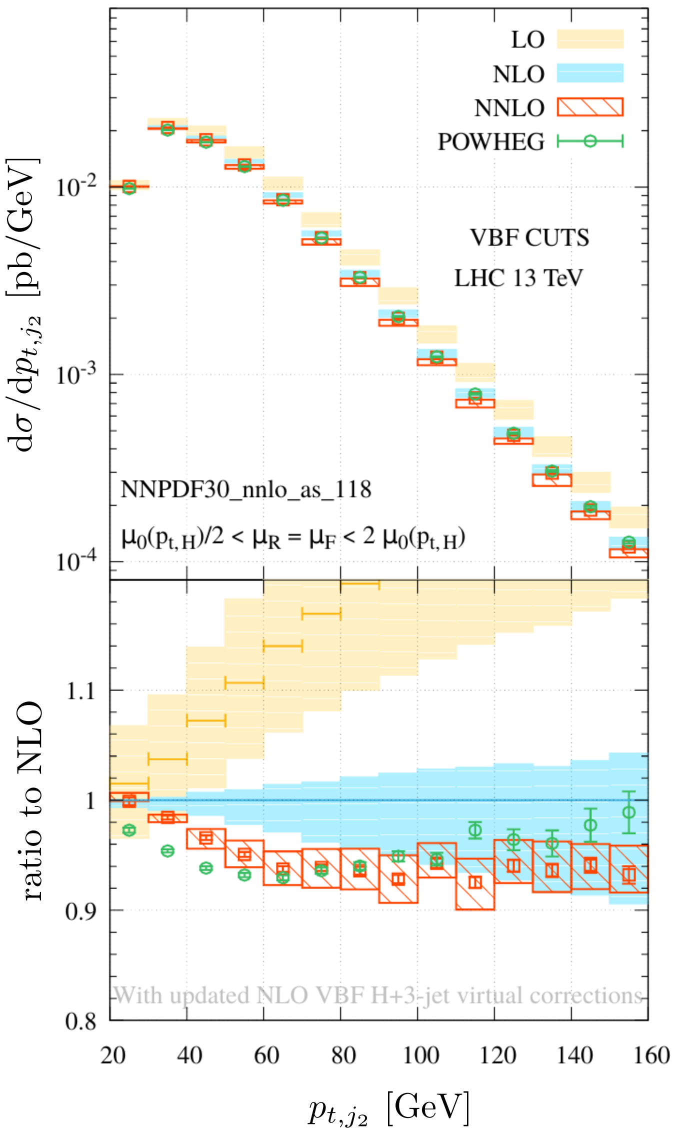
- JHEP 02 (2022) 046 (“realistic” final states)
- arXiv:2206.14630 [hep-ph] (anomalous couplings)

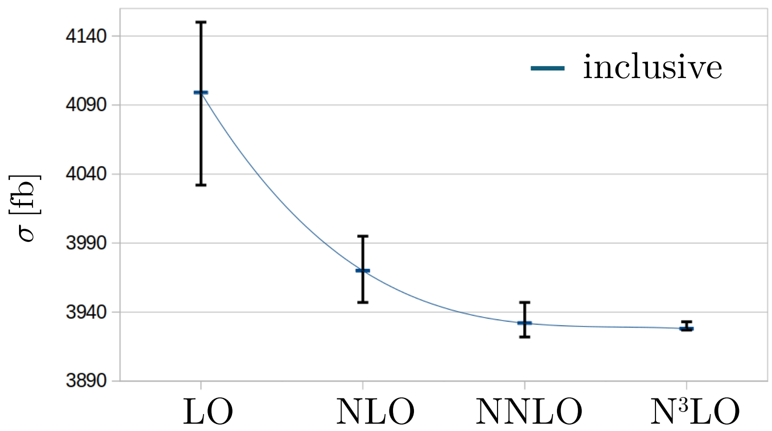
Konstantin Asteriadis | 20.10.2022

Past, present, and future of VBF workshop

State of the art (factorizable) fixed order QCD analysis

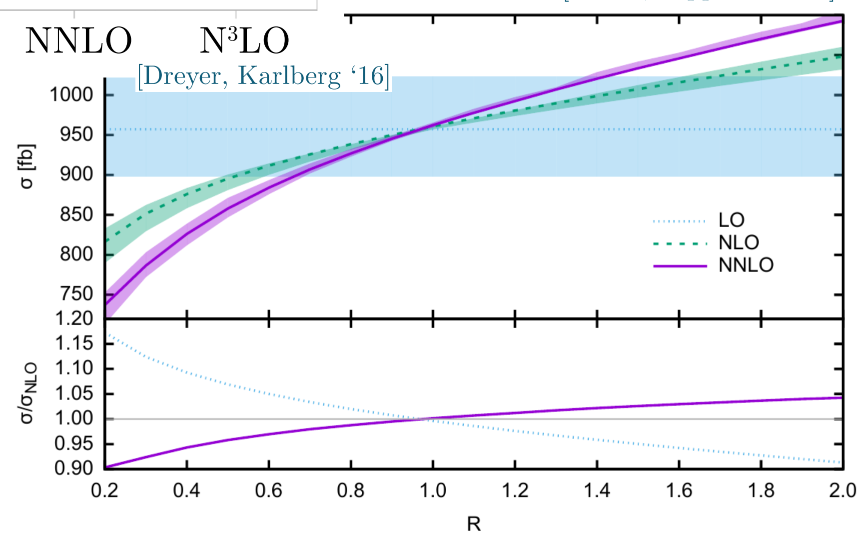
[Matteo Cacciari, Frédéric A. Dreyer, Alexander Karlberg, Gavin P. Salam, Giulia Zanderighi]





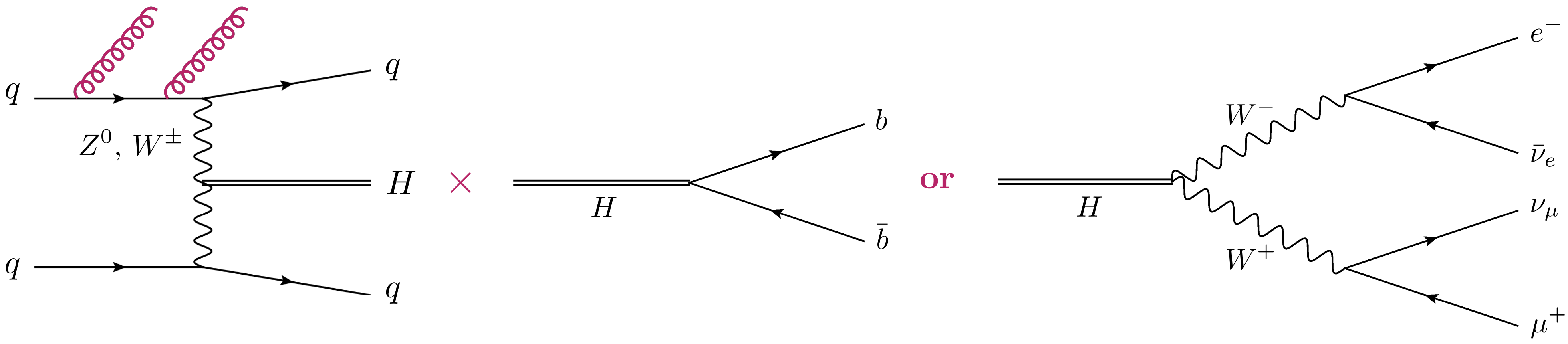
[Rauch, Zeppenfeld '17]

[Dreyer, Karlberg '16]



- Non-trivial jet dynamics in VBF Higgs boson production
- Previously existing computations @NNLO QCD are for stable Higgs boson production → **Effects of additional jets from Higgs decay?**
- **Effect of new tensor structures of anomalous couplings?**

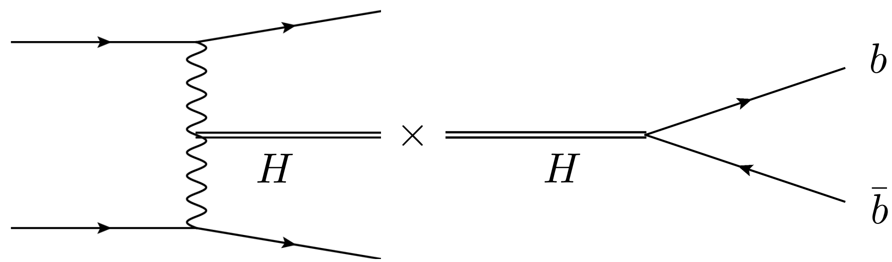
NNLO QCD Higgs boson production + Higgs boson decay



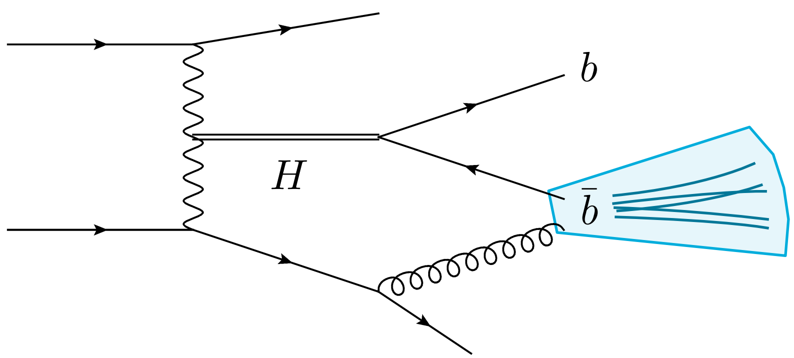
- In this combination, each decay channel comes with its unique challenges:
  - $\mathrm{H} \rightarrow \mathrm{b\bar{b}}$: non-trivial interplay between partonic jets from production and decay with fiducial cuts
  - $\mathrm{H} \rightarrow \mathrm{WW}^* \rightarrow 2\mathrm{l}\ 2\nu$: numerically challenging 21 dimensional phase space integration
- Side note: Good control on complex final state coming from decay crucial for computing radiative corrections to $\mathrm{H} \rightarrow \mathrm{b\bar{b}}$ decay channel
- **In what follows: focus on $\mathrm{H} \rightarrow \mathrm{b\bar{b}}$ decay channel (details on $\mathrm{H} \rightarrow \mathrm{WW}$ in *JHEP02(2022)046*)**

WBF + H → $b\bar{b}$ decay

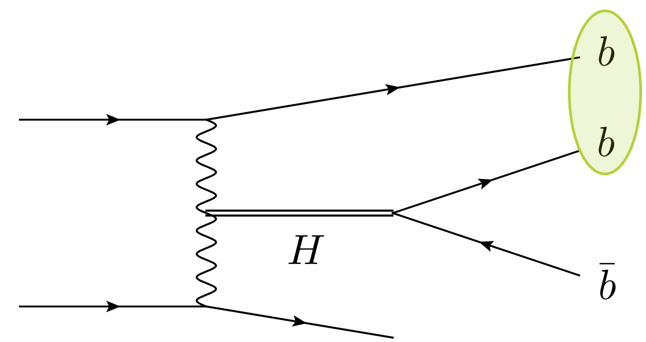
- Narrow width approximation → factorization of on-shell Higgs production and on-shell Higgs decay



- Several effects break factorization of production and decay process. For example



Jet-clustering breaks factorization

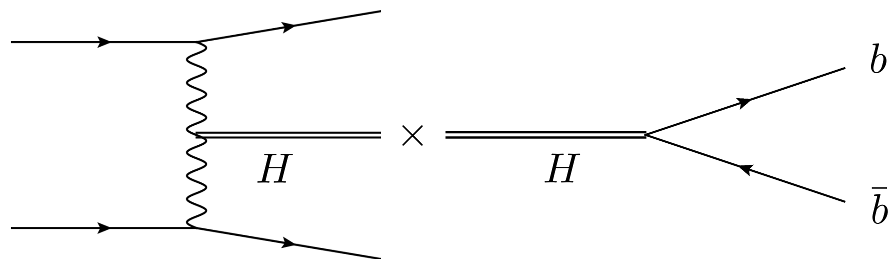


B-tagging breaks factorization

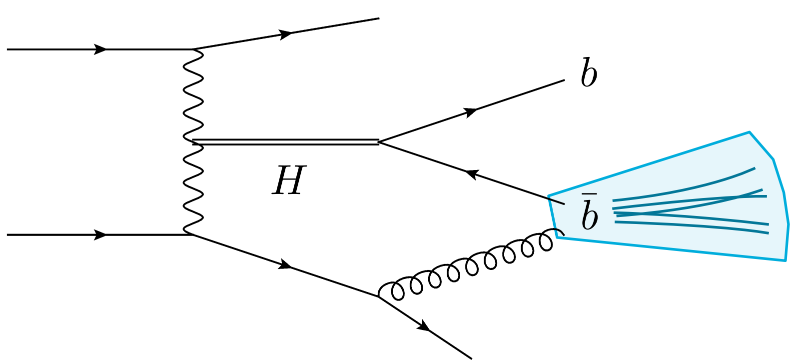
- Impact of decay on NNLO corrections is non-trivial → effects might not be captured by a simple reweighing
- We don’t expect this effects to be very large but it is important to quantify their size
- Finally: cuts on b-jets may change fiducial WBF region

WBF + H → b$\bar{\text{b}}$ decay

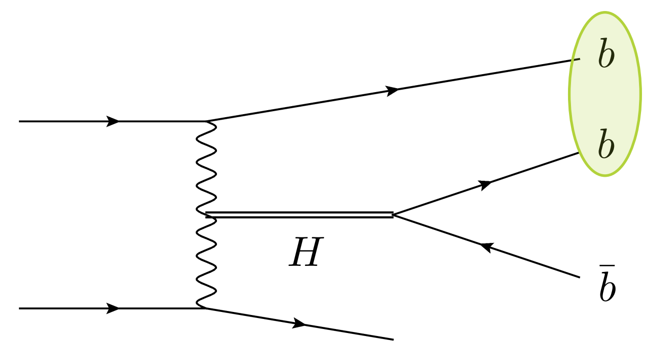
- Narrow width approximation → factorization of on-shell Higgs production and on-shell Higgs decay



- Several effects break factorization of production and decay process. For example



Jet-clustering breaks factorization



B-tagging breaks factorization

- Impact of decay … y a simple reweighing
- We don't expect …
- Finally: cuts on …

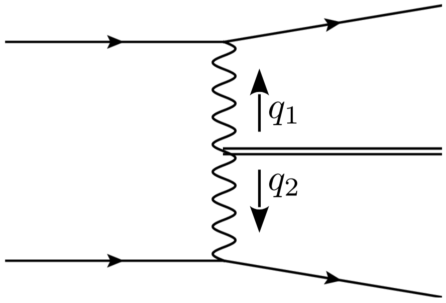
Results of today for b$\bar{\text{b}}$ decay are a first non-trivial step:

- **Only massless b quarks and decay @LO QCD**
- **Production process is flavour "blind"**
- **Including QCD corrections to decay is work-in-process**

Physical setup of WBF Higgs production process

- Only *factorizable* contributions
- 13 TeV center-of-mass energy / NNPDF31-nnlo-as-118 (different PDF choices not studied yet)
- Scale choice [Cacciari, Dreyer, Karlberg, Salam, Zanderighi ‘15; Cruz-Martinez, Glover, Gehrmann, Huss ‘18]

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



Effects of other scale choices, most importantly $\mu_R^2 = \mu_F^2 = \sqrt{-q_2^2}$ / $\mu_R^1 = \mu_F^1 = \sqrt{-q_1^2}$, not studied yet

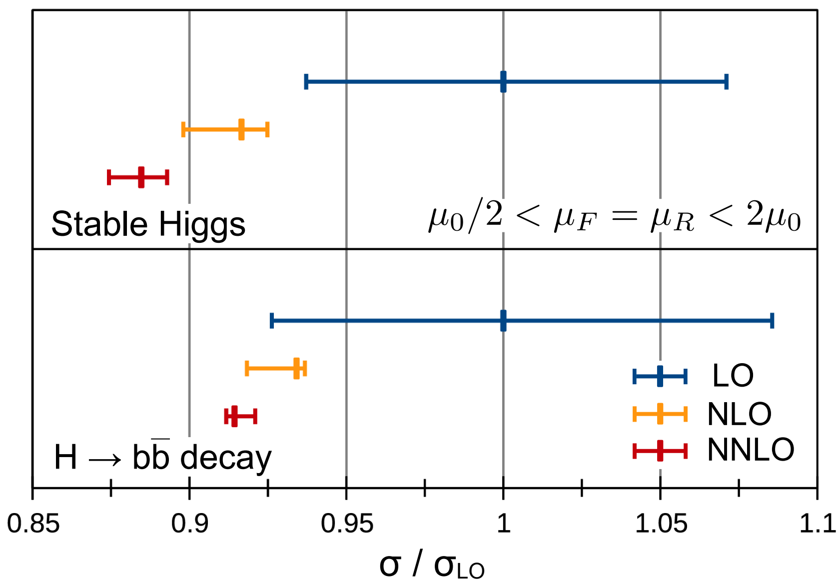
- Typical VBF cuts: at least 2 resolved tag jets with
  - Transverse momentum: $p_{\perp,j} > 25$ GeV;
  - Rapidity $-4.5 < y_j < 4.5$;
  - Separated in rapidity $|y_{j1} - y_{j2}| > 4.5$ and in different hemispheres $y_{j1} \times y_{j2} < 0$;
  - Invariant mass $\sqrt{(p_{j_1} + p_{j_2})^2} > 600\,\mathrm{GeV}$;
  - Jets identified using anti-kt jet-algorithm with R = 0.4.

Results: fiducial cross section

- Cuts on b-jets; loosely following latest ATLAS measurement: 2 resolved b-jets; $p_{\perp,\mathrm{jb}} > 65$ GeV; $|y_{\mathrm{jb}}| < 2.5$ [Eur. Phys. J. C 81, 537 (2021)]
- 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



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

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

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

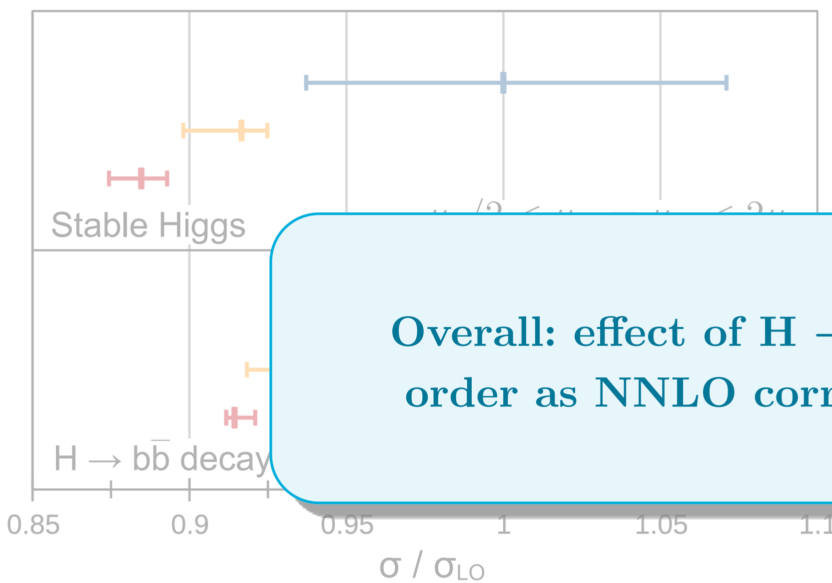
- *Noteworthy features:* smaller residual scale uncertainty and better perturbative convergence compared to stable Higgs production

Results: fiducial cross section

- Cuts on b-jets; loosely following latest ATLAS measurement: 2 resolved b-jets; $p_{\perp,\mathrm{jb}} > 65$ GeV; $|y_{\mathrm{jb}}| < 2.5$ [Eur. Phys. J. C 81, 537 (2021)]
- 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



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

$$\big\downarrow +2.9\%$$

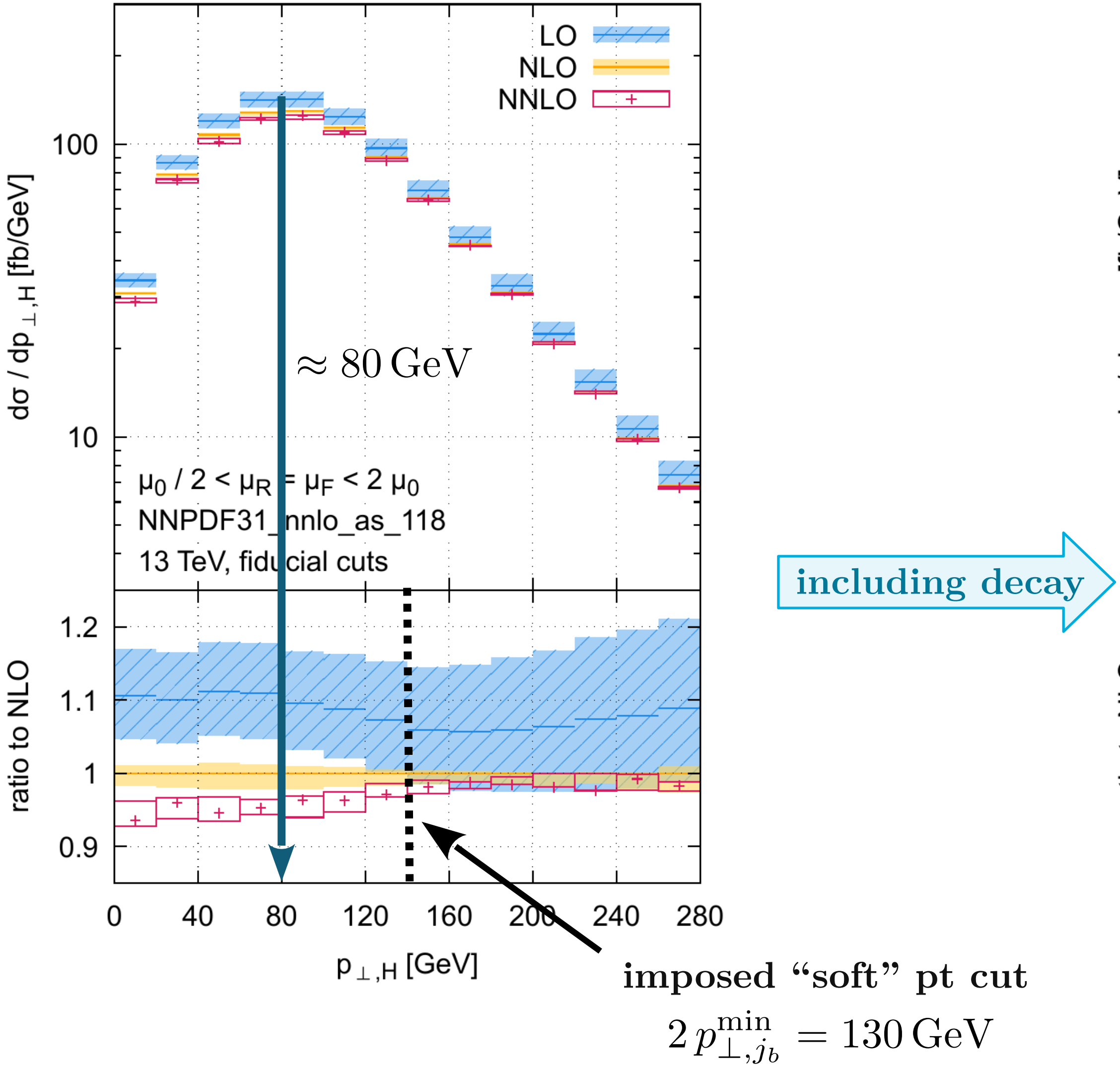
$$\frac{\sigma^{b\bar{b}}_{\mathrm{NNLO}}}{\sigma^{b\bar{b}}_{\mathrm{LO}}} = 0.914(2)$$

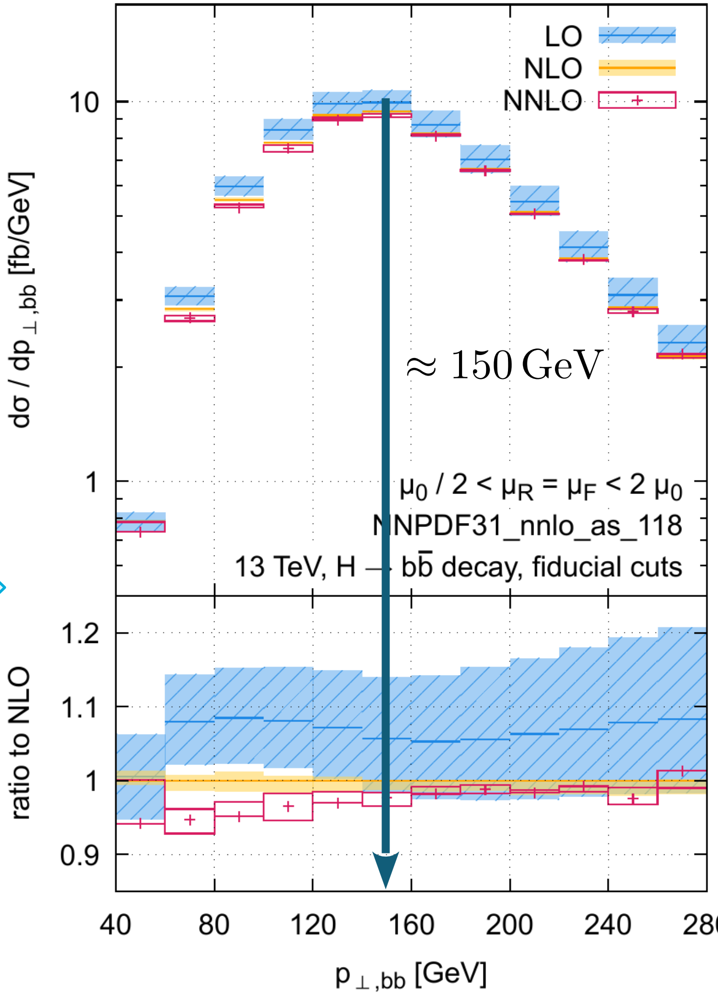
Overall: effect of H → b$\bar{\mathrm{b}}$ decay of same order as NNLO corrections themselves!

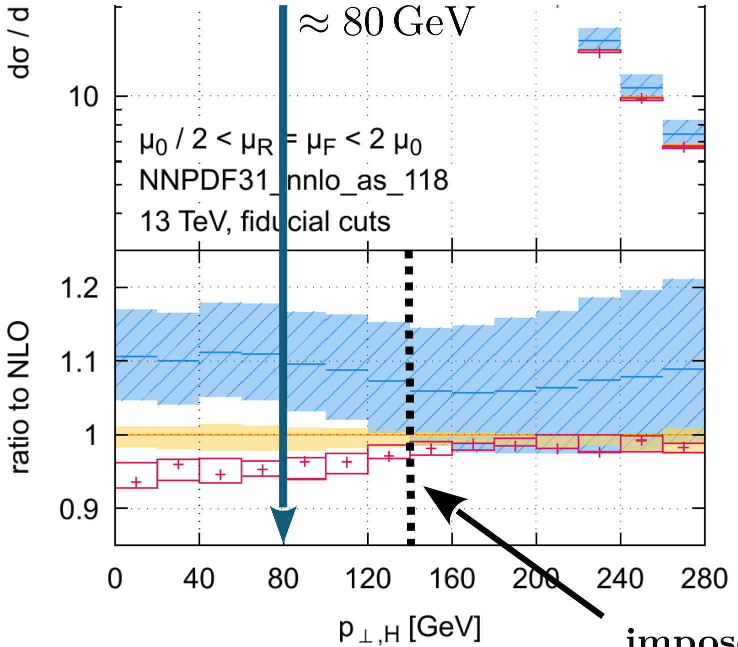
- *Noteworthy features:* smaller residual scale uncertainty and better perturbative convergence compared to stable Higgs production

Results: fiducial cross section

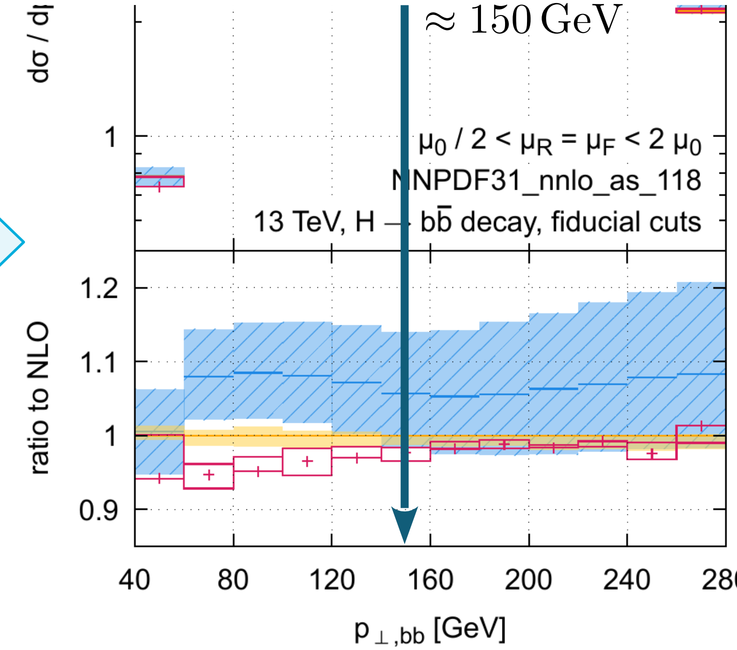
- Simple reason: pt cuts on b-jets ($p_{\perp,j_b} > 65\,\mathrm{GeV}$) preferentially selects events with high Higgs transverse momentum







including decay



imposed "soft" pt cut

$$2\,p_{\perp,j_b}^{\min} = 130\,\mathrm{GeV}$$

- 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 $p_{\perp,H} > 150\,\mathrm{GeV}$

$$\frac{\sigma^H_{\mathrm{NNLO}}}{\sigma^H_{\mathrm{LO}}} = 0.89$$

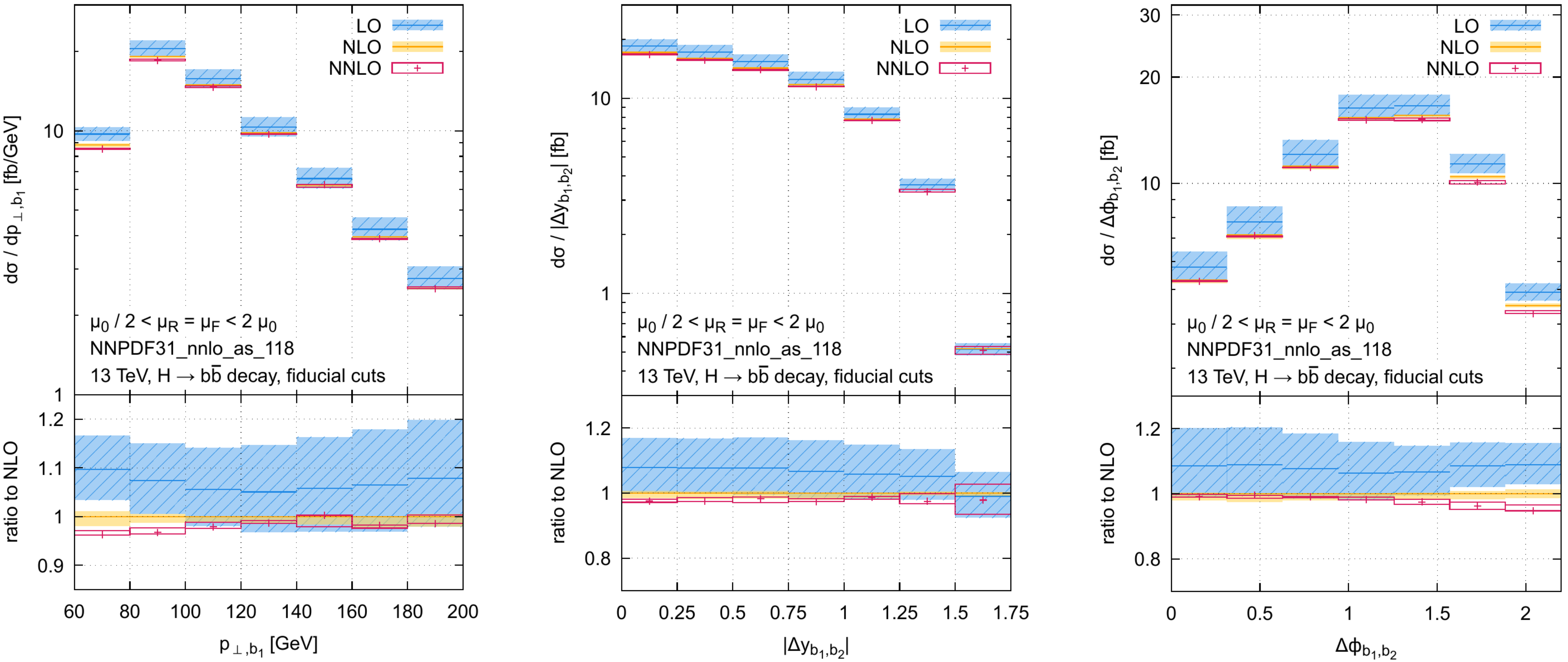
Higgs pt cut

$$\frac{\sigma^H_{\mathrm{NNLO}}}{\sigma^H_{\mathrm{LO}}} = 0.91$$

including decay

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

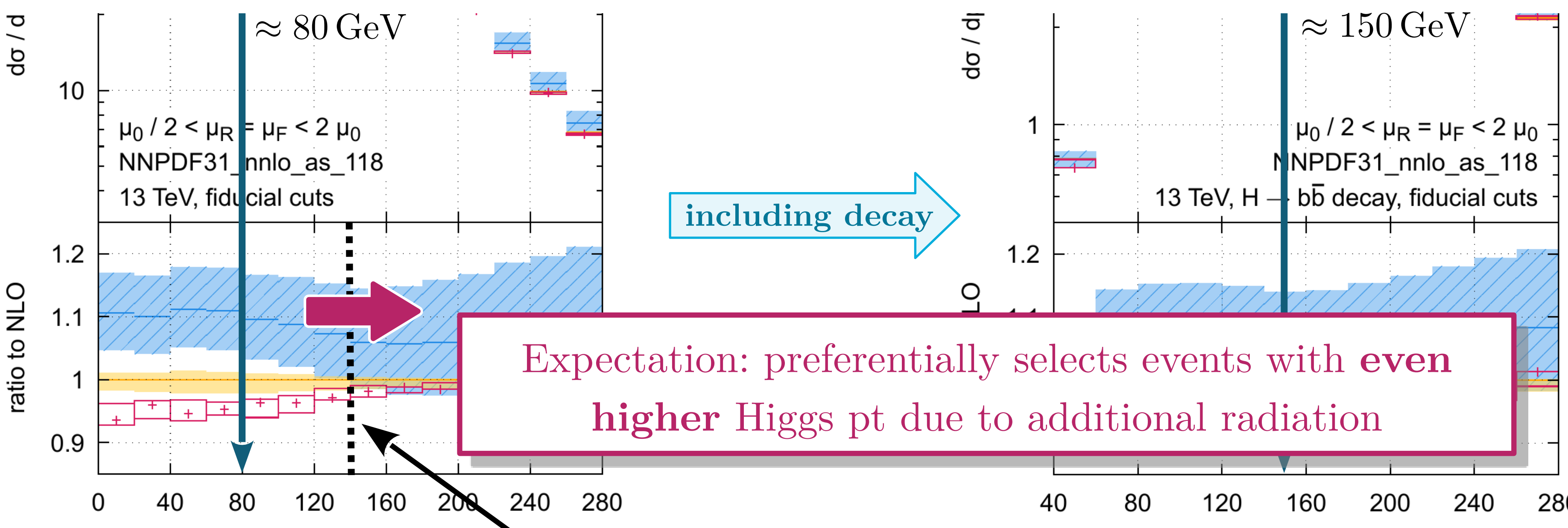
Results: differential cross sections



- 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

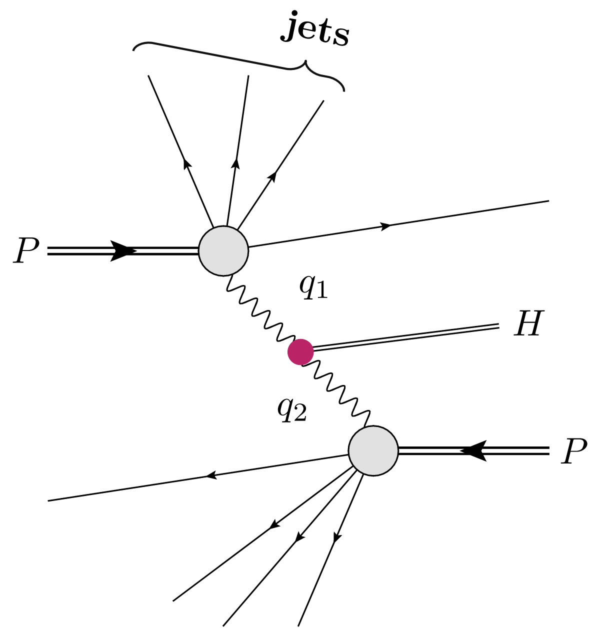
Outlook: Towards a more realistic setup

- $\mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}$ @LO (and $\mathrm{H} \to \mathrm{WW} \to 2\mathrm{l}\ 2\nu$) as prototypes for $\mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}$ @ NNLO QCD
- Fully-differential description of $\mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}$ decay at NNLO QCD (with massive b-quarks) is known
  [Bernreuther, Chen, Si '2018; Behring, Bizoń '19]
- Add flavor tagging in WBF Higgs boson production process



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

Anomalous Higgs couplings and fiducial cuts



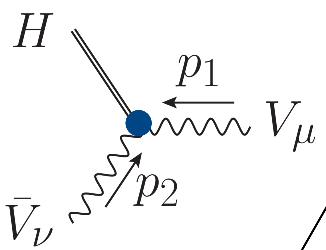
- **Anomalous weak couplings of the Higgs boson**
- Studied at NLO QCD [Hankele, Klämke, Zeppenfeld '06]
- New operators → new tensor structures (interplay with real radiation?)
- Non-trivial jet dynamics "different" at NLO and NNLO

  → Can we trust an NLO analysis?

  → Can NNLO accuracy help to distinguish BSM physics from the SM?

Anomalous HVV interactions

- Most general tensor structure of the HVV vertex (Lorentz invariance / Bose symmetry)



$$= i\Big[g^{\mu\nu} A(p_1^2, p_2^2, p_1\cdot p_2) + p_1^\nu p_2^\mu\ B(p_1^2, p_2^2, p_1\cdot p_2) + i\epsilon^{\mu\nu\rho\sigma} p_{1,\rho} p_{2,\sigma}\ C(p_1^2, p_2^2, p_1\cdot p_2)\Big]$$

only dimension 6 SMEFT [Helset, Martin, Trott '20]

$$= \ i g_{HVV}^{(SM)}\left[g^{\mu\nu}\left(1 + \underbrace{\boxed{\frac{m_H^2}{\Lambda^2}\ c_{HVV}^{(2)}}}_{\text{“rescaling” of SM}} + \underbrace{\boxed{\frac{p_1^2+p_2^2}{\Lambda^2}\ c_{HVV}^{(1)}\Big) + \frac{2p_1^\nu p_2^\mu}{\Lambda^2} c_{HVV}^{(1)}}}_{\text{CP-even coupling}}\right. - \left.\underbrace{\boxed{\tilde{c}_{HVV}(6\pi)\epsilon^{\mu\nu\rho\sigma}\frac{p_{1,\rho}p_{2,\sigma}}{\Lambda^2}}}_{\text{CP-odd coupling}}\right]$$

- (6π) in CP-odd contribution such that $\tilde{c}_{HVV} = 1 \rightarrow O(1\%)$ deviation of the LO fiducial cross section
- **Consider “symmetric” model where non-SM couplings to W and Z are identical (main difference accounted for via factoring out SM coupling)**

Fiducial cross section at any order

$$\sigma_{\text{fid}} = \left(1 + \frac{m_H^2}{\Lambda^2} c_{HVV}^{(2)}\right)^2 X_1 + \left(c_{HVV}^{(1)}\right)^2 X_2 + \left(\tilde{c}_{HVV}\right)^2 X_3 + \left(1 + \frac{m_H^2}{\Lambda^2} c_{HVV}^{(2)}\right) c_{HVV}^{(1)} X_4$$
$$+ \left(1 + \frac{m_H^2}{\Lambda^2} c_{HVV}^{(2)}\right) \tilde{c}_{HVV} X_5 + c_{HVV}^{(1)} \tilde{c}_{HVV} X_6 \, .$$

where

$$X_i = X_i^{\text{LO}} + \frac{\alpha_s}{4\pi} X_i^{\text{NLO}} + \left(\frac{\alpha_s}{4\pi}\right)^2 X_i^{\text{NNLO}} + \mathcal{O}(\alpha_s^3)$$

- $X_5 = X_6 = 0$ for fiducial cross sections because it is integrate over the full angular phase space
- Compute $X_{1,2,3,4}$ individually

Fiducial cross section at any order

$$\sigma_{\text{fid}} = \left(1 + \frac{m_H^2}{\Lambda^2} c_{HVV}^{(2)}\right)^2 X_1 + \left(c_{HVV}^{(1)}\right)^2 X_2 + \left(\tilde{c}_{HVV}\right)^2 X_3 + \left(1 + \frac{m_H^2}{\Lambda^2} c_{HVV}^{(2)}\right) c_{HVV}^{(1)} X_4$$

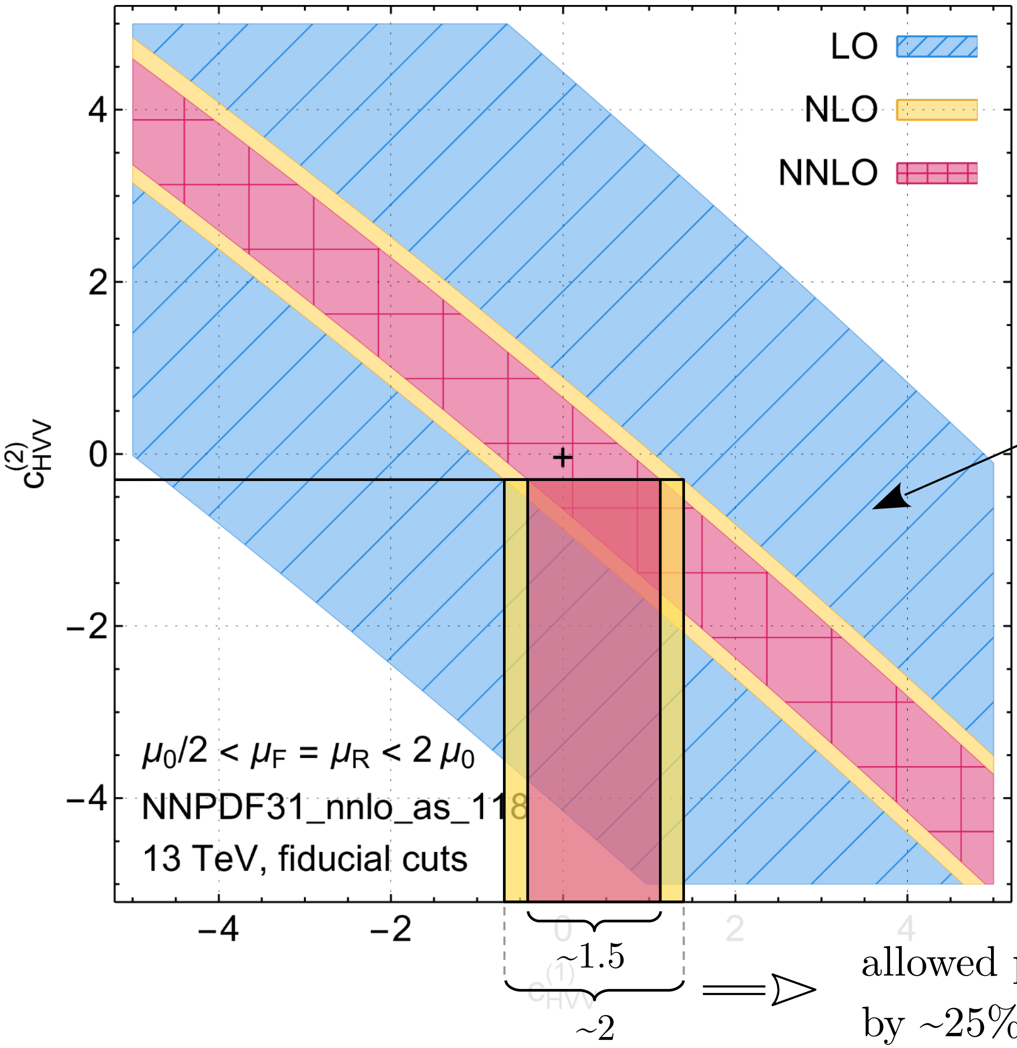
$$+ \left(1 + \frac{m_H^2}{\Lambda^2} c_{HVV}^{(2)}\right) \tilde{c}_{HVV} X_5 + c_{HVV}^{(1)} \tilde{c}_{HVV} X_6 \,.$$

- Results

σ_{fid} (fb)	LO	NLO	NNLO
X_1	971^{-61}_{+69}	890^{+8}_{-18}	859^{+8}_{-10}
X_2	$0.413^{-0.033}_{+0.039}$	$0.398^{-0.001}_{-0.005}$	$0.383^{+0.004}_{-0.005}$
X_3	$19.57^{-1.84}_{+2.22}$	$19.64^{-0.25}_{-0.07}$	$19.25^{+0.08}_{-0.18}$
X_4	$26.43^{-1.61}_{+1.80}$	$23.45^{+0.35}_{-0.66}$	$22.53^{+0.39}_{-0.42}$

- X_1 largest (by construction since it corresponds to the SM contribution)
- Large scale uncertainty decrease from LO → NLO; relatively stable from NLO → NNLO
- Similar k-factors for all $X_{1,2,3,4}$ (~ -4% from NLO → NNLO)
- Having $X_{1,2,3,4}$ available allows to study the allowed parameter space

Allowed parameter space: fiducial cross section



parameter points are accepted if residual scale uncertainty band overlaps with SM residual scale uncertainty band

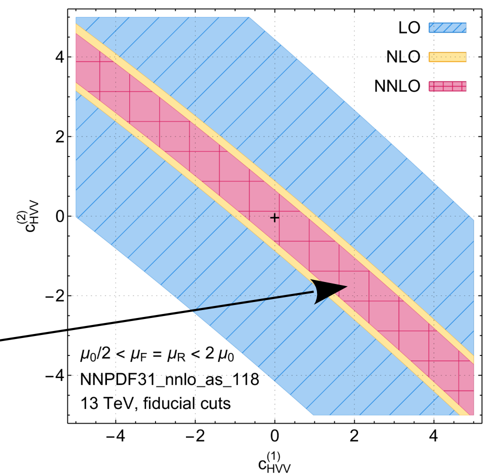
$\Longrightarrow$ allowed parameter space shrinks by ~25% (significant impact)

- Similar results for all pairs of anomalous couplings

Differential distributions

- Computing differential distributions is numerically expensive
- Hence instead of computing differential coefficients $X_{1,2,3,4,5,6}$ we consider two fixed scenarios

$$\text{Sce. A:}\quad c^{(1)}_{HVV} = +1.5\,,\ \ c^{(2)}_{HVV} = -1.9\,,\ \ \tilde{c}_{HVV} = +0.6$$
$$\text{Sce. B:}\quad c^{(1)}_{HVV} = -1.8\,,\ \ c^{(2)}_{HVV} = -0.1\,,\ \ \tilde{c}_{HVV} = -1.5$$



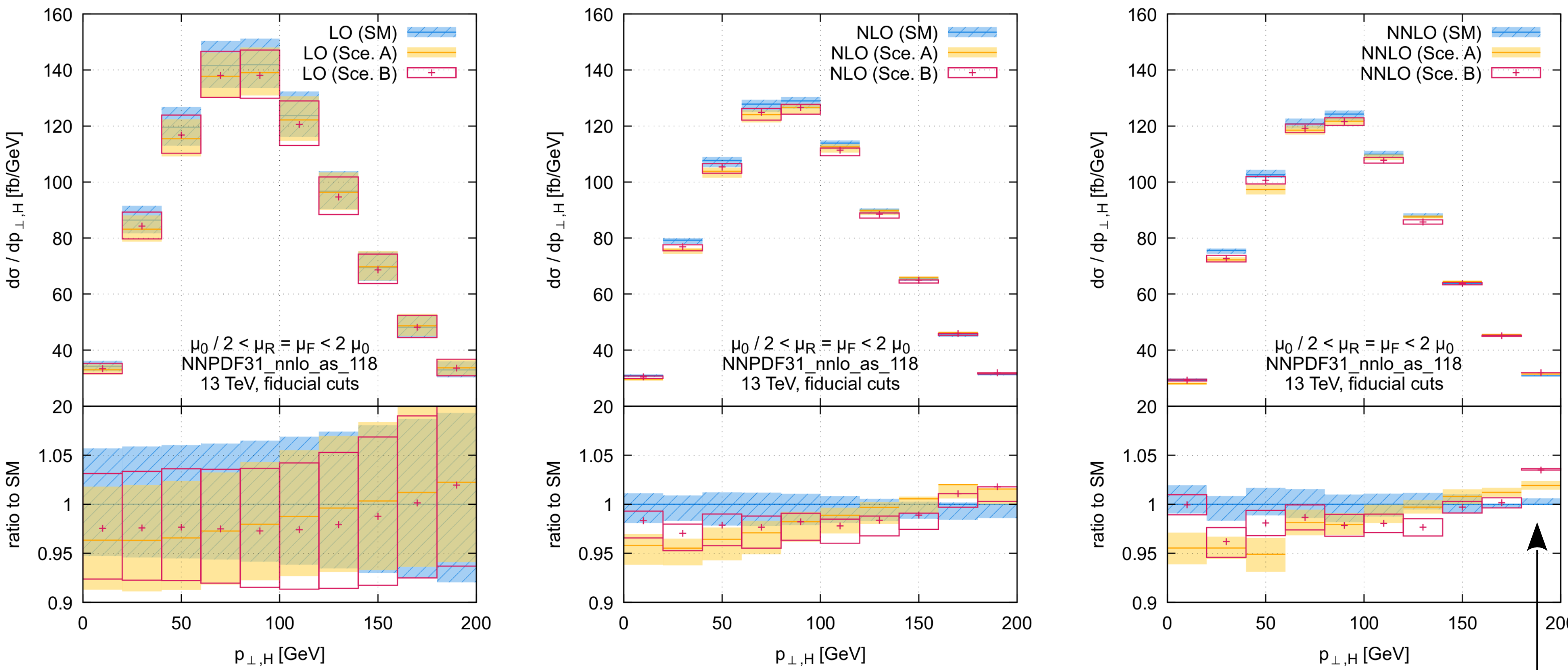
- They are chosen such that fiducial cross section are indistinguishable

σ_{fid} (fb)	SM	Sce. A	Sce. B
LO	971^{-61}_{+69}	960^{-61}_{+68}	965^{-63}_{+71}
NLO	890^{+8}_{-18}	882^{+7}_{-17}	890^{+6}_{-17}
NNLO	859^{+8}_{-10}	851^{+9}_{-8}	860^{+8}_{-8}

$\leq 1\%$ and covered by residual scale uncertainties

Differential distributions

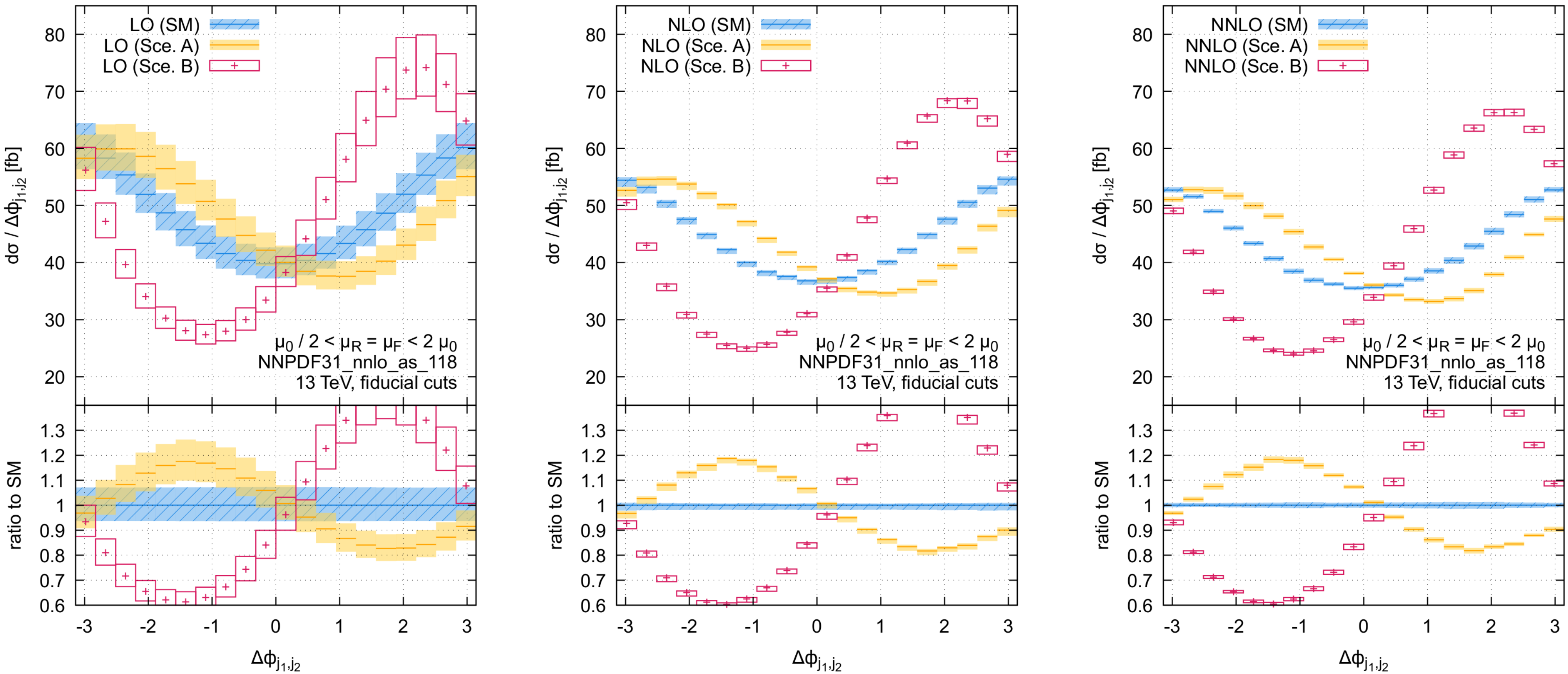
- Most distributions are **NOT** sensitive to anomalous couplings [Hankele, Klämke, Zeppenfeld '06]
- For example consider Higgs transverse momentum distribution



- Sensitive observables: [Hankele, Klämke, Zeppenfeld '06]
  $\Delta\varphi$ (in the following) and $|\Delta\varphi|$ (see 2206.14630)

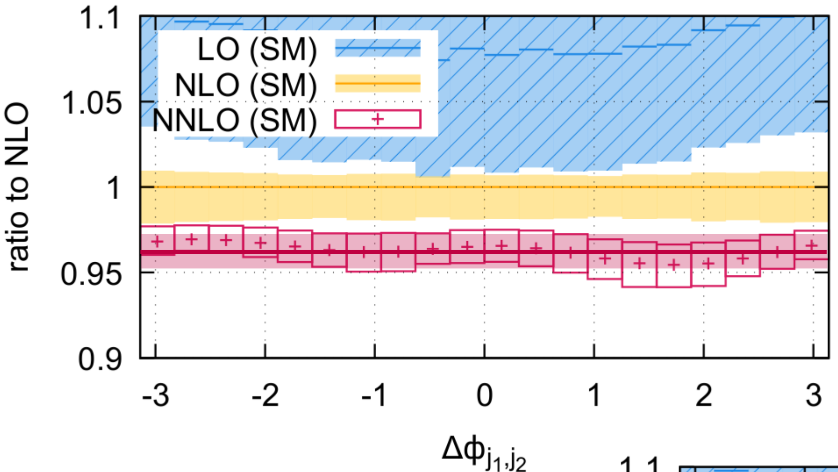
start of diverging distributions, expected but cross section already down by an order

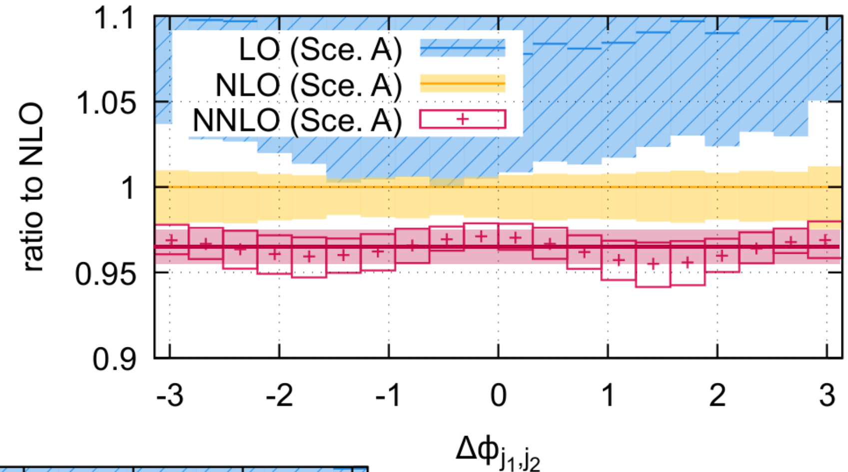
$\Delta\varphi$ a CP sensitive observable

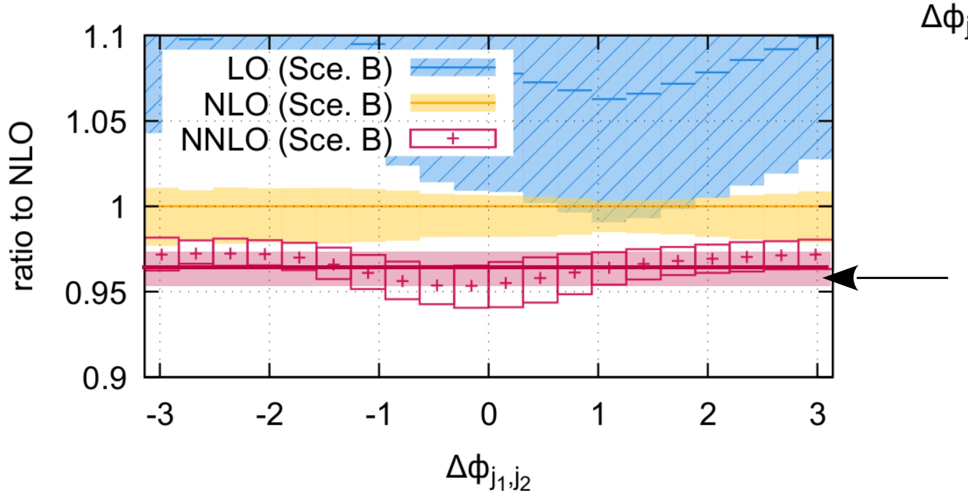


- At LO: Sce. B and SM distinguishable, Sce. A and SM just covered by scale variation
- In this distributions CP-odd / CP-even interference is the dominant contribution
  $\rightarrow$ consider $|\Delta\varphi|$ to isolate symmetric contributions (similar results found, more details in 2206.14630)
- Similar to fiducial cross section: no significant reduction of scale uncertainties from NLO $\rightarrow$ NNLO

$\Delta\varphi$ a CP sensitive observable







$\pm 1\%$ around mean (ruffly residual scale uncertainty at NNLO)

- K-factor rather flat and almost independent of anomalous couplings

$\rightarrow$ Global rescaling from NLO to NNLO should be sufficient for O(1%)

Conclusion and Outlook

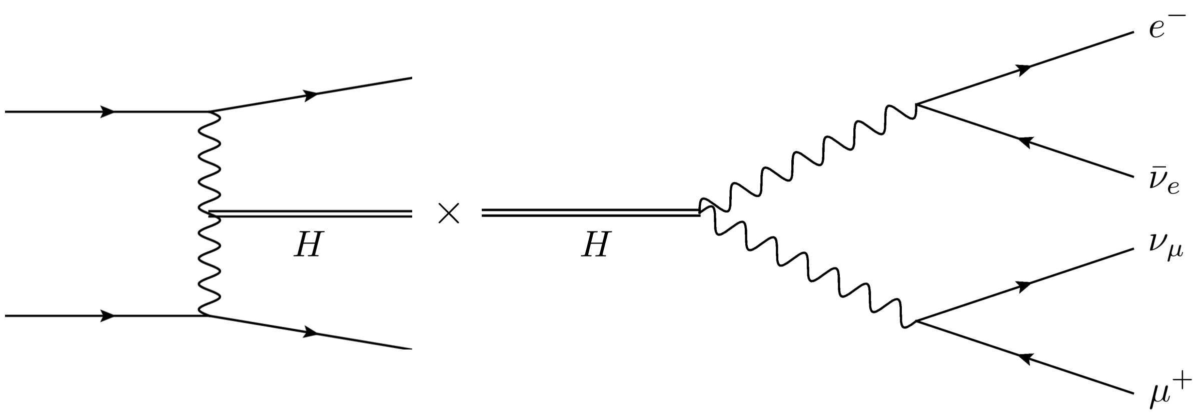
- **WBF including $H \to b\bar{b}$ decay**
  - Non-trivial interplay from jets in production and decay processes
  - Changes in higher order corrections due to cuts on b-jets are comparable to NNLO corrections
  - Smaller residual scale uncertainties and better perturbative convergence
  - **Work-in-progress:** Include decay $H \to b\bar{b}$ massive @ NNLO and flavour tagging in production
  - **Work-in-progress:** Include non-factorizable contributions

- **WBF including $H \to WW^* \to 2l\ 2\nu$ decay (Not presented in this talk)**
  Effects of decay small and higher order corrections well captured by simple reweighting (with K-factors computed from stable Higgs boson production)

- **Anomalous weak couplings of the Higgs boson**
  - Higher order corrections in SMEFT scenarios similar to SM → No significant shape change from NLO → NNLO → May be captured with global K-factor
  - NLO and NNLO have similar "discriminating power" → NNLO study indicates analysis at NLO is robust
  - **Future work:** Include differential data into exclusion plots
  - **Future work:** Include higher order operators (In particular once that are directly affected by QCD) radiation; allow for different HZZ and HWW couplings

Backup

Preliminary results: H $\to$ WW $\to$ 2l2ν



- Experimentally inspired cuts:
  - 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 tag jets **$\leftarrow$ only one to break factorization**
  - Transverse mass: $60\,\text{GeV} < \sqrt{2p_T^{l_1l_2}p_T^{\text{miss}}\left(1-\cos\Delta\phi_{l_1l_2,\vec{p}_T^{\text{miss}}}\right)} < 125\,\text{GeV}$
  - Lepton system: $p_{\perp,l_1l_2} > 30\,\text{GeV}$, $m_{l_1l_2} > 12\,\text{GeV}$
  - Missing pt: $p_T^{\text{miss}} > 20\,\text{GeV}$
- Only very mild imposed cuts on pt of Higgs

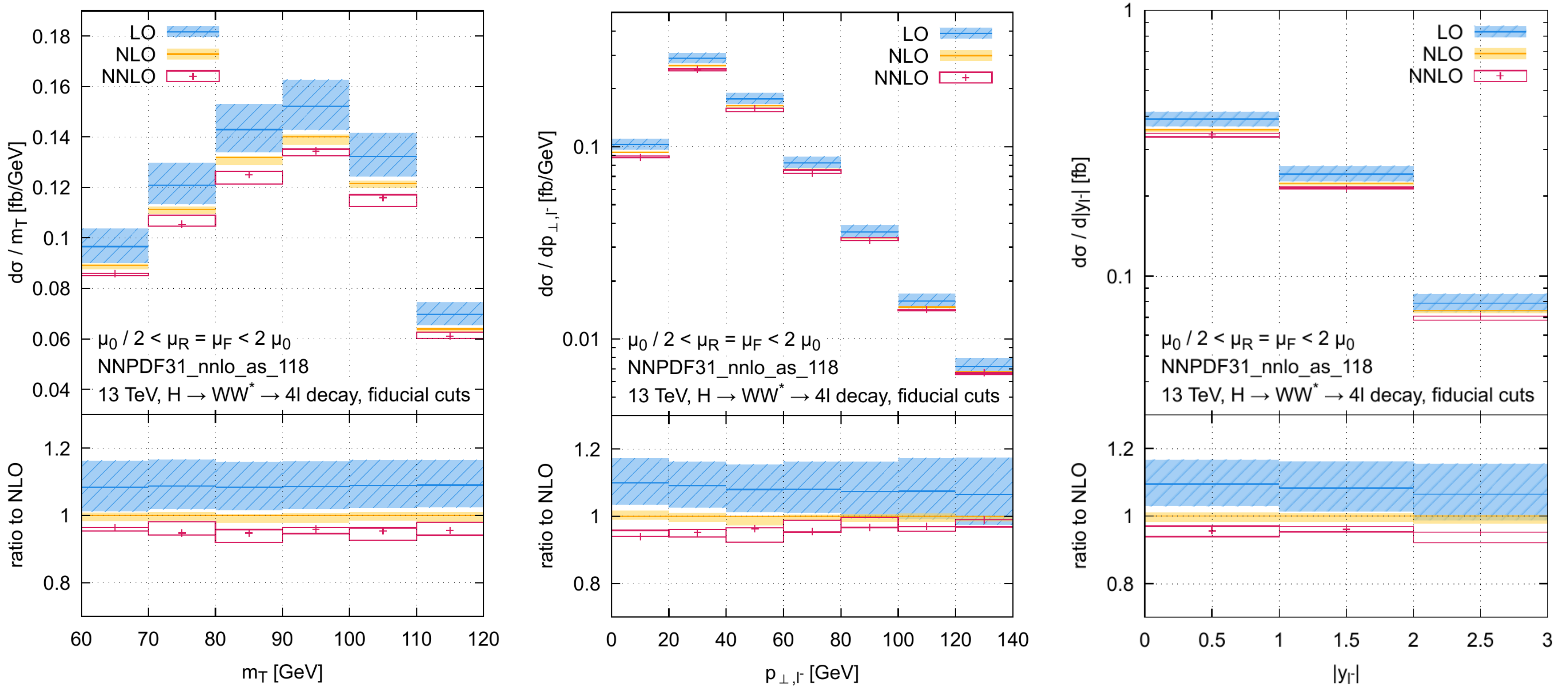
  $\to$ Similar corrections as in case of stable Higgs expected and found!

$$\sigma_{\text{NNLO}}^{l^-\bar{\nu}l^+\nu} = \underbrace{0.719\,\text{fb}}_{\text{LO}} + \underbrace{(-0.054)\,\text{fb}}_{\Delta\text{NLO}} + \underbrace{(-0.025)\,\text{fb}}_{\Delta\text{NNLO}}$$

	-8%	-3%
(stable Higgs)	-8%	-3%

VBF + H → WW* → 2l 2ν

- Also no shape change expected for decay histograms

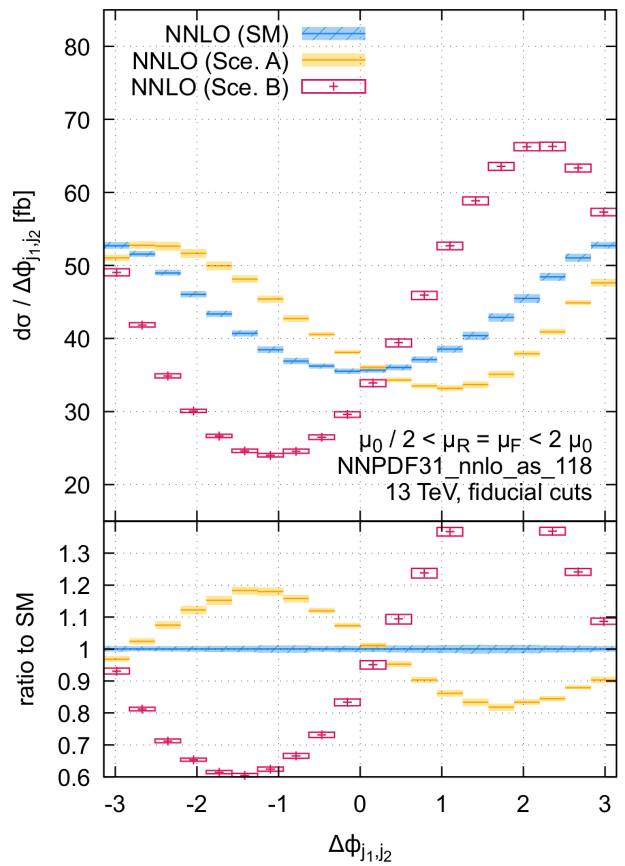


- Differential K-factors rather flat
- NNLO/NLO K-factor computed with stable Higgs is a good approximation within O(1%) precision

Connection to Wilson coefficients

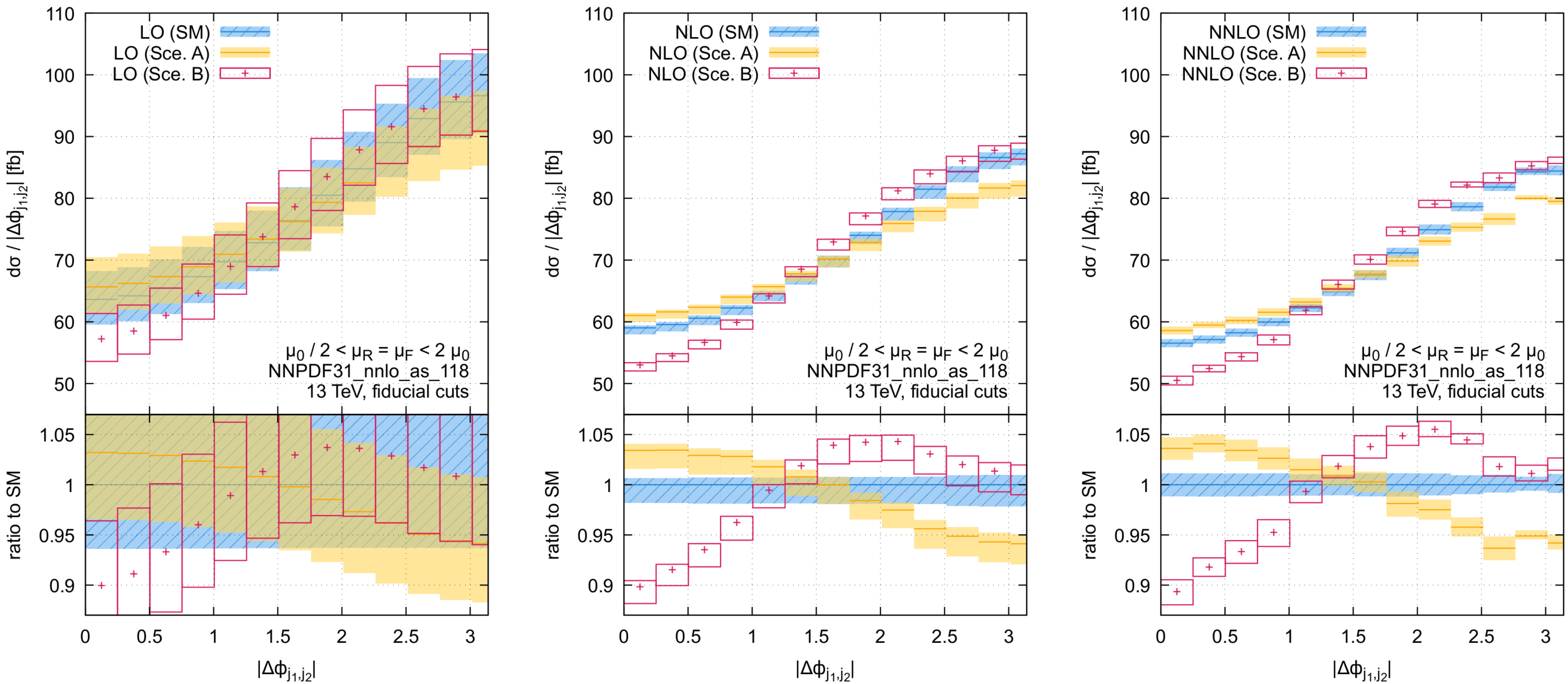
$$
\begin{aligned}
c^{(1)}_{HWW} &= \frac{C_{\varphi W}}{\sqrt{2} G_f m_W^2}\,, \\
c^{(2)}_{HWW} &= -\frac{1}{\sqrt{2} G_f}\left[\frac{C_{\varphi W}}{m_W^2} + \frac{2C^{(3)}_{\varphi l} - C_{ll}}{2m_H^2} - \frac{1}{m_H^2}\left(C_{\varphi\Box} - \frac{C_{\varphi D}}{4}\right)\right], \\
\tilde{c}_{HWW} &= -\frac{2C_{\varphi\tilde{W}}}{(6\pi)\sqrt{2} G_f m_W^2}\,, \\
c^{(1)}_{HZZ} &= \frac{1}{\sqrt{2} G_f m_Z^4}\left[C_{\varphi B}(m_Z^2 - m_W^2) + C_{\varphi W}\, m_W^2 + C_{\varphi WB}\, m_W \sqrt{m_Z^2 - m_W^2}\right], \\
c^{(2)}_{HZZ} &= -\frac{1}{\sqrt{2} G_f}\left[\frac{C_{\varphi B}(m_Z^2 - m_W^2)}{m_Z^4} + \frac{C_{\varphi W}\, m_W^2}{m_Z^4} + \frac{C_{\varphi WB}\, m_W \sqrt{m_Z^2 - m_W^2}}{m_Z^4} + \frac{2C^{(3)}_{\varphi l} - C_{ll}}{2m_H^2}\right. \\
&\qquad \left. - \frac{1}{m_H^2}\left(C_{\varphi\Box} - \frac{C_{\varphi D}}{4}\right)\right], \\
\tilde{c}_{HZZ} &= -\frac{2}{\sqrt{2} G_f m_Z^4}\left[C_{\varphi\tilde{B}}(m_Z^2 - m_W^2) + C_{\varphi\tilde{W}}\, m_W^2 + C_{\varphi\tilde{W}B}\, m_W \sqrt{m_Z^2 - m_W^2}\right].
\end{aligned}
$$

$\Delta\varphi$ a CP sensitive observable



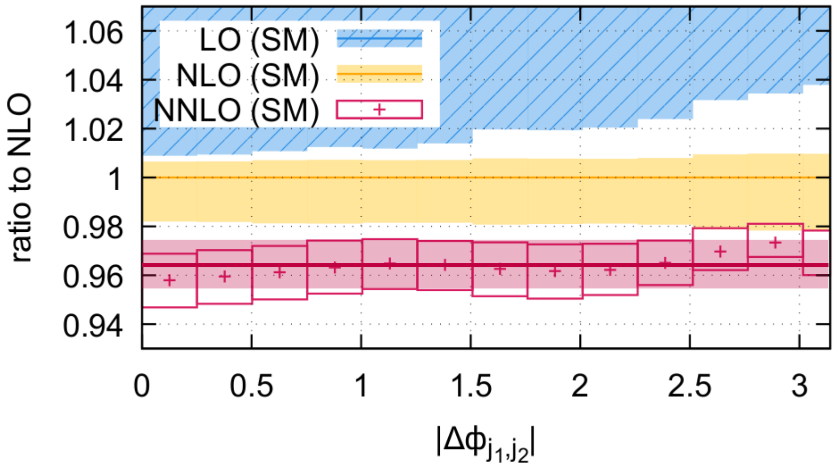
- Ratio of events with $\Delta\varphi < 0$ and $\Delta\varphi > 0$ might be useful to include differential data in exclusion plots in a efficient way (cut-and-count approach)
- Deviation(s) from SM dominated by antisymetric contributions $\rightarrow$ CP-odd / CP-even interference
- To study CP-even couplings, consider absolute value of $\Delta\varphi$ where CP-odd / CP-even interference again drops out

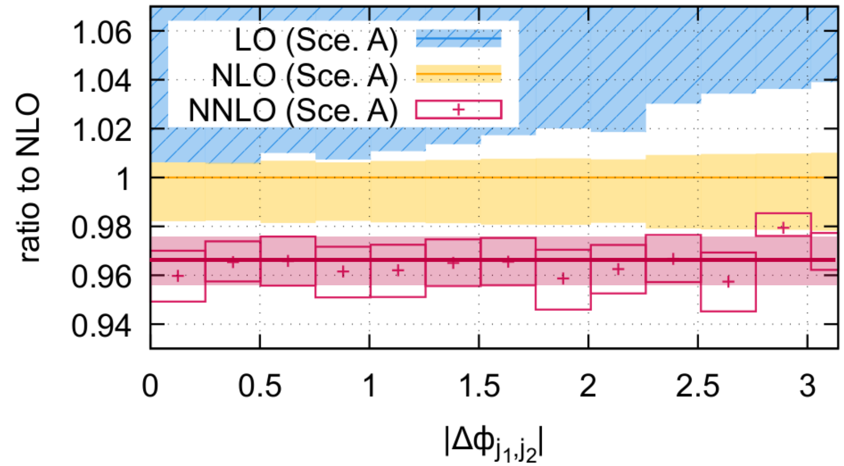
$|\Delta\varphi|$ a CP insensitive observable

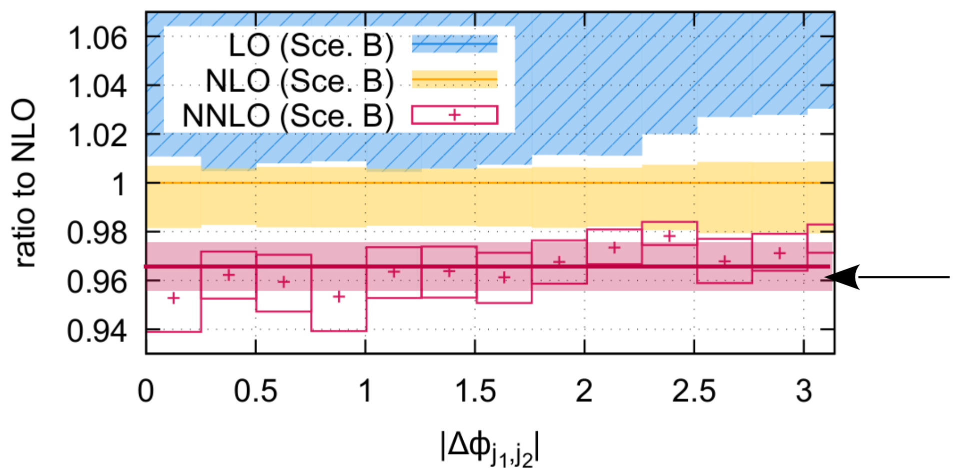


- At LO differences are swamped by scale uncertainty
- Starting from NLO scale uncertainties sufficiently reduced to distinguish between different scenarios and SM; NNLO might help to distinguish from SM
- Ratio of events with $|\Delta\varphi| < \pi/2$ and $|\Delta\varphi| > \pi/2$ might be useful to include differential data in exclusion plots in a efficient way (cut-and-count approach)

$|\Delta\varphi|$ a CP insensitive observable







$\pm 1\%$ around mean

- K-factor rather flat and almost independent of anomalous couplings
- K-factors rather flat $\rightarrow$ global rescaling from NLO to NNLO should be sufficient for O(1%)