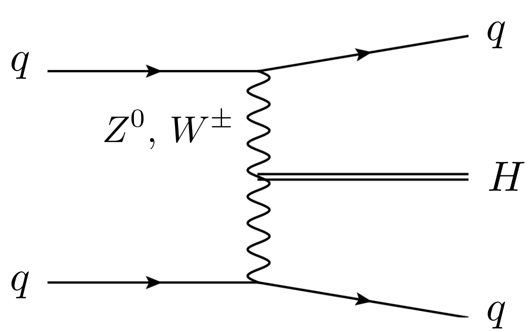
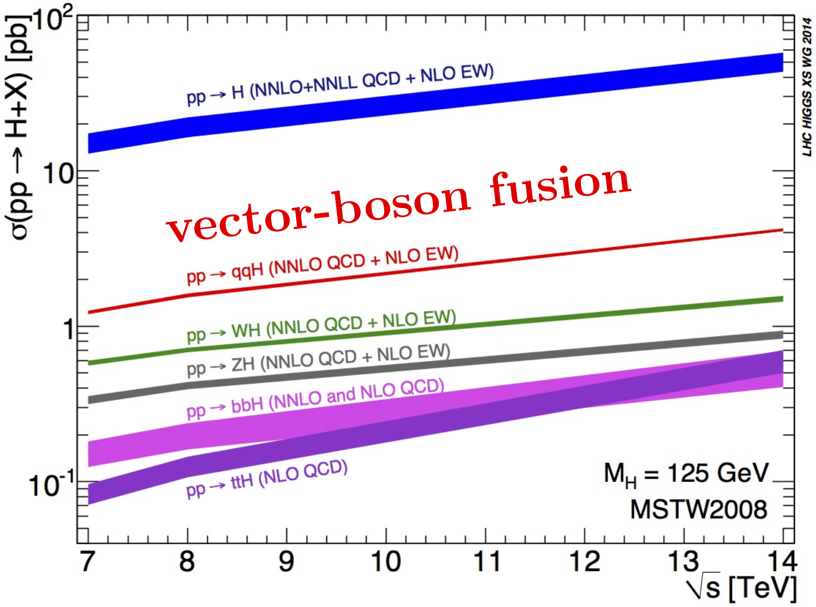
Brookhaven National Laboratory

Higgs boson production in weak boson fusion at high precision

Konstantin Asteriadis | 09/08/2022
Fermi National Accelerator Laboratory – Theory Seminar

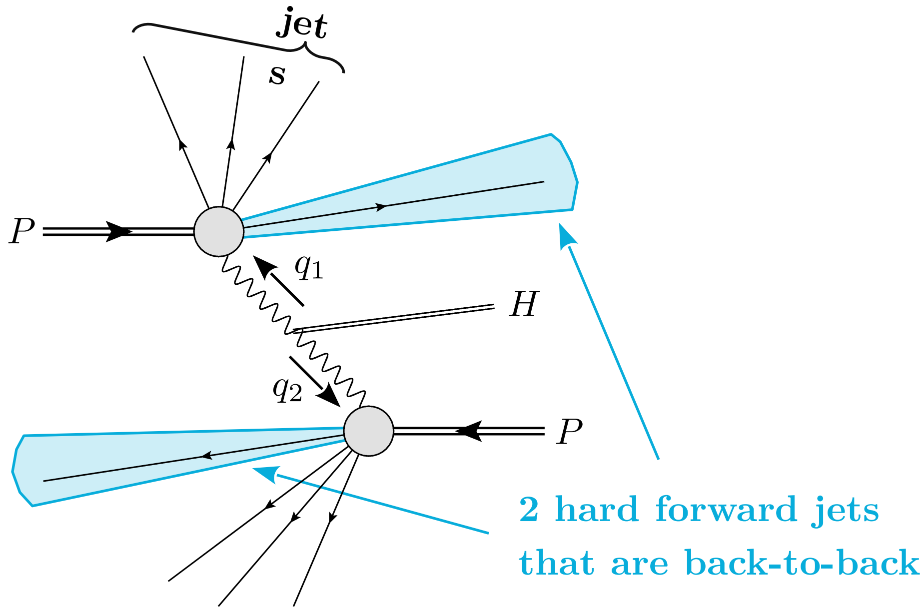
Higgs-boson production in vector-boson fusion (VBF)





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

VBF signature

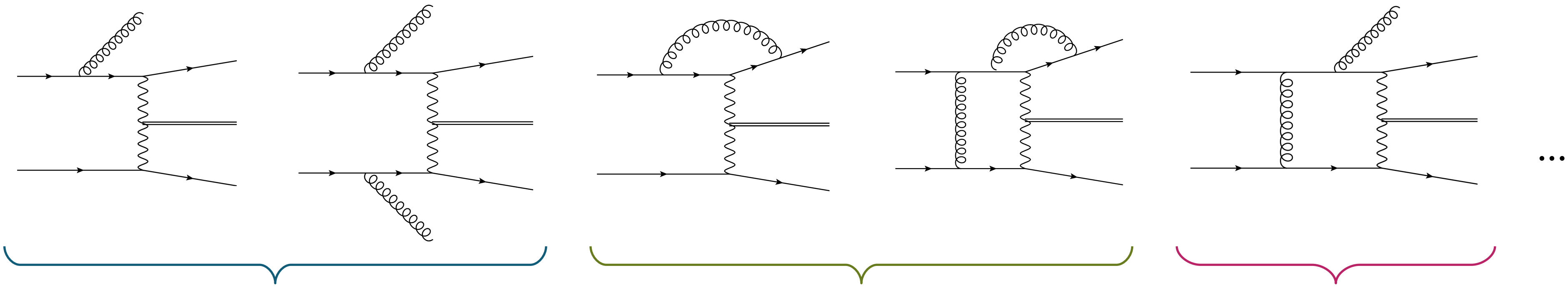


- **Typical VBF cuts:** at least 2 resolved "tag" jets with $p_{\perp,j} > 25\,\text{GeV}$ and $-4.5 < y_j < 4.5$
  - Separated in rapidity $|y_{j_1} - y_{j_2}| > 4.5$ and in different hemispheres $y_{j_1} \times y_{j_2} < 0$
  - Invariant mass $\sqrt{(p_{j_1} + p_{j_2})^2} > 600\,\text{GeV}$
  - Jets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

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

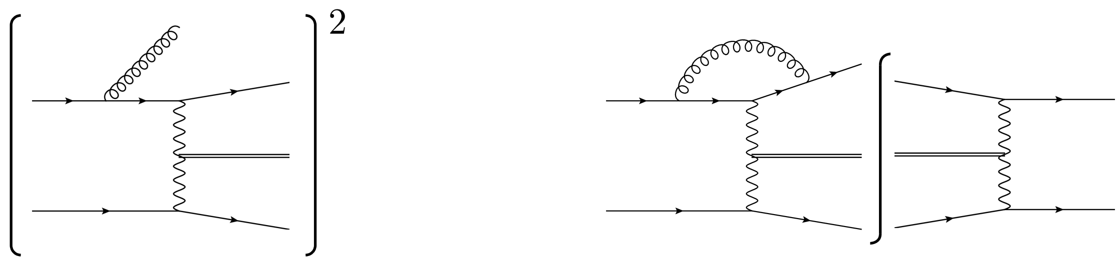
- What can we do with this experimental precision and more important: are we ready for it?

Higher order QCD correction to vector-boson fusion

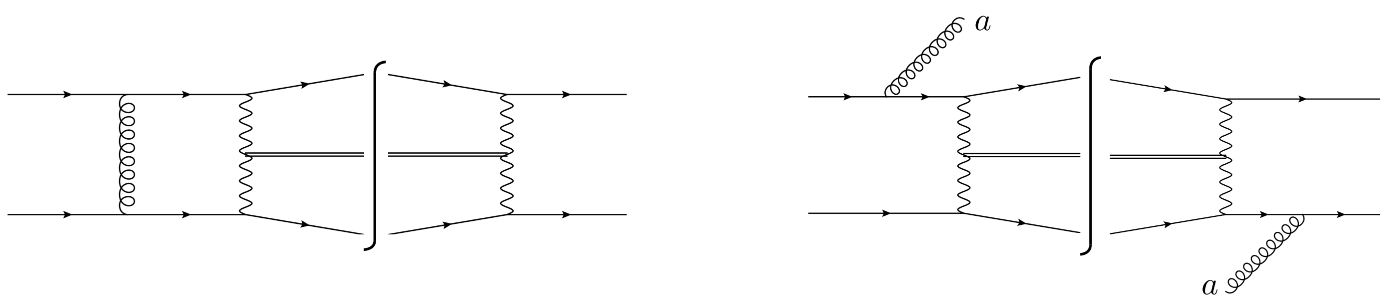


Real corrections   Virtual corrections   Real-virtual corrections

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

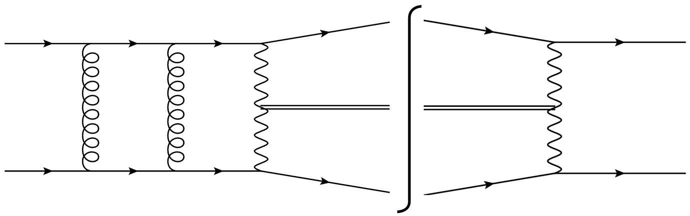


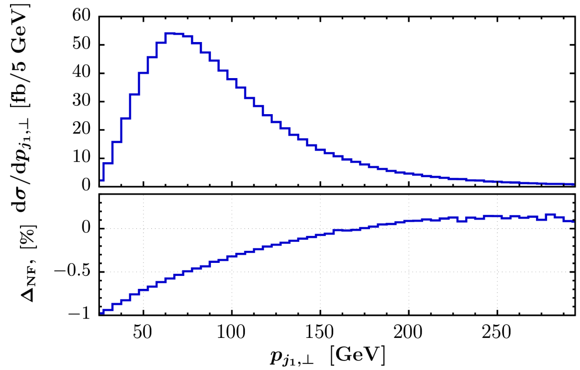
- *Non-factorizable* correction not present at NLO QCD due to colour conservation $\sim \mathrm{Tr}(T^a) = 0$



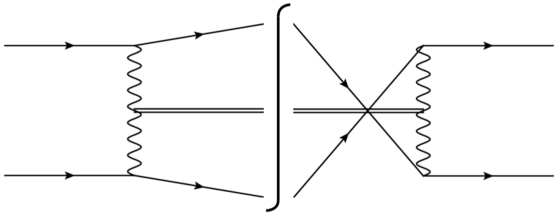
Non-factorizable corrections to VBF

- 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]





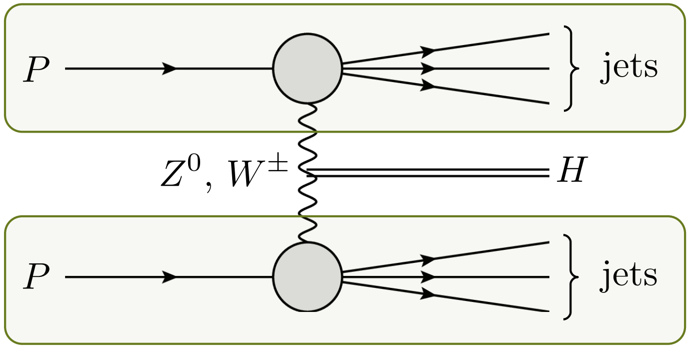
- More exotic contributions in case of identical flavours are not only colour suppressed but also suppressed by large momentum transfer in the weak-boson propagators [Bolzoni et al. '11]



- First studies [Dreyer, Karlberg, Tancredi '20; Chen, Figy, Plätzer '21]

- Include contributions at least in enhanced (forward) regions of the phase space **(work in progress)**

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



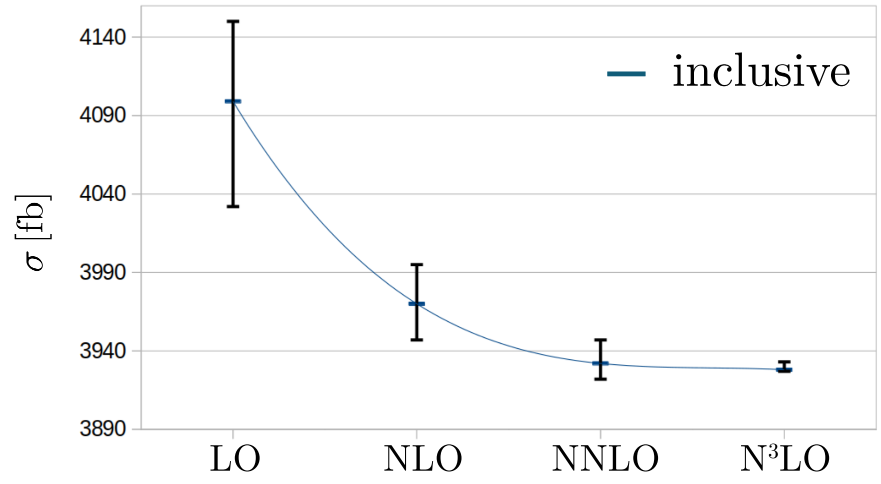
(Deep inelastic scattering)²

- 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?

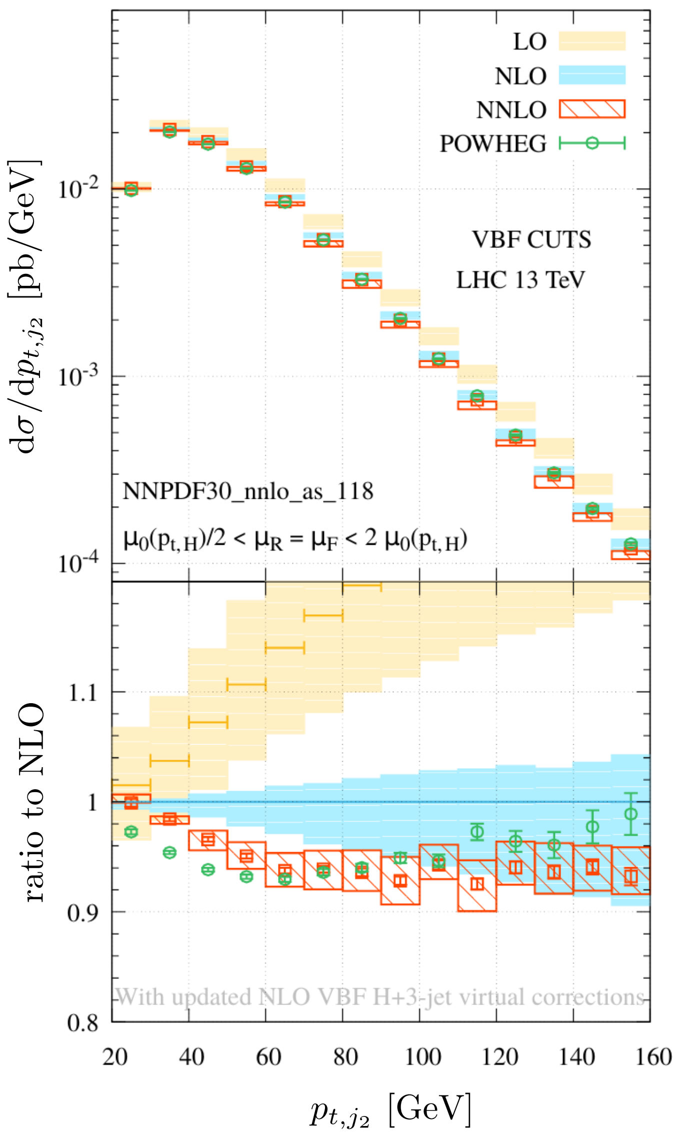
- **Inclusive known till N³LO**
  [Dreyer, Karlberg **2016**]
  - Nicely converging, N³LO within residual scale uncertainties

- **Fully differential known till NNLO**
  [Cacciari, Dreyer, Karlberg, Salam, Zanderighi **2015**]
  [Cruz-Martinez, Glover, Gehrmann, Huss **2018**]
  - **Fiducial cuts:** NNLO corrections outside of residual NLO scale uncertainties

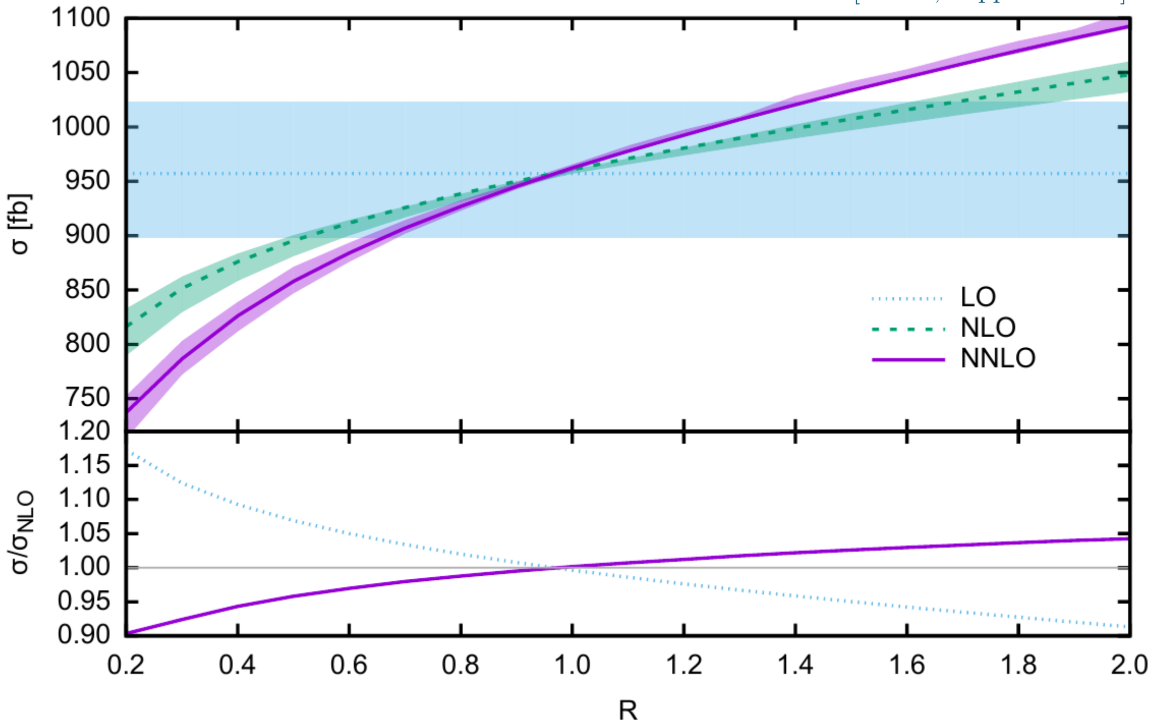


State of the art of QCD analysis

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



[Rauch, Zeppenfeld '17]



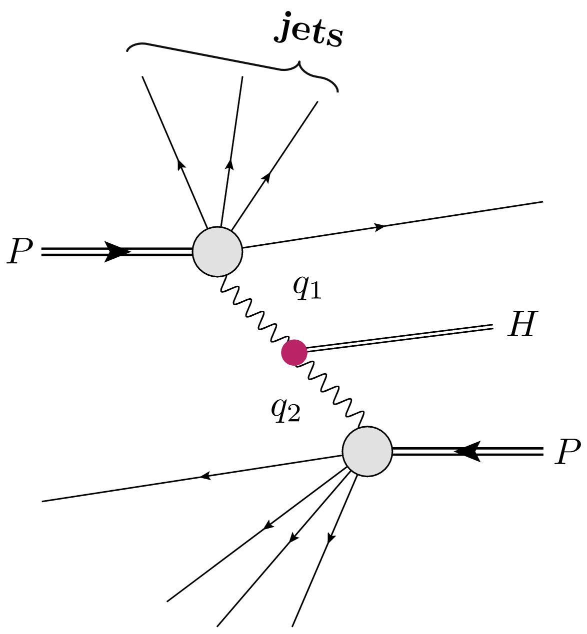
- Non-trivial jet dynamics in VBF Higgs boson poduction
- All current computations are for stable Higgs boson production

→ **Effects of additional jets from Higgs decay?**

Anomalous Higgs couplings and fiducial cuts

- **Anomalous weak couplings of the Higgs boson**
- Higgs coupling to weak bosons measured to O(30%)
- Studied at NLO QCD [Hankele, Klämke, Zeppenfeld '06]
  - Inclusive N^{3}LO covered by NNLO result, but NNLO not by NLO (differential even worse)
  - New operators → new tensor structures (interplay with real radiation?)

    → Can we trust an NLO analysis?
- Can NNLO accuracy help to distinguish SMEFT from SM?

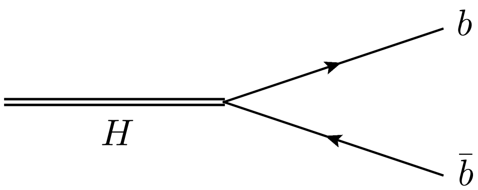


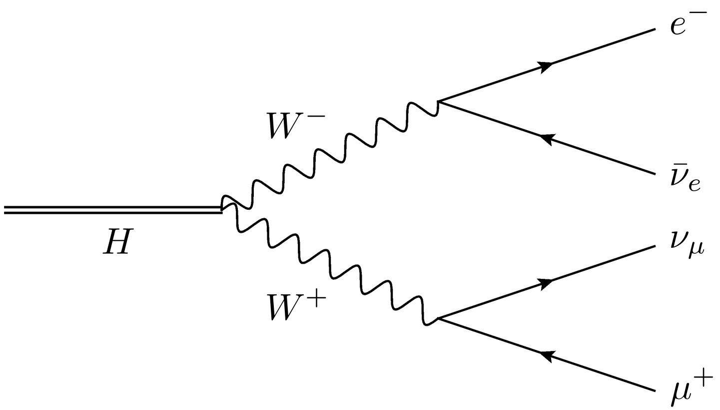
- Traditional SMEFT approach: "bottom-up"
  Start with higher dimesnional operators and add more and more SM
- To address above questions here instead: "top-down"
  Start with best SM description and add a little bit of SMEFT

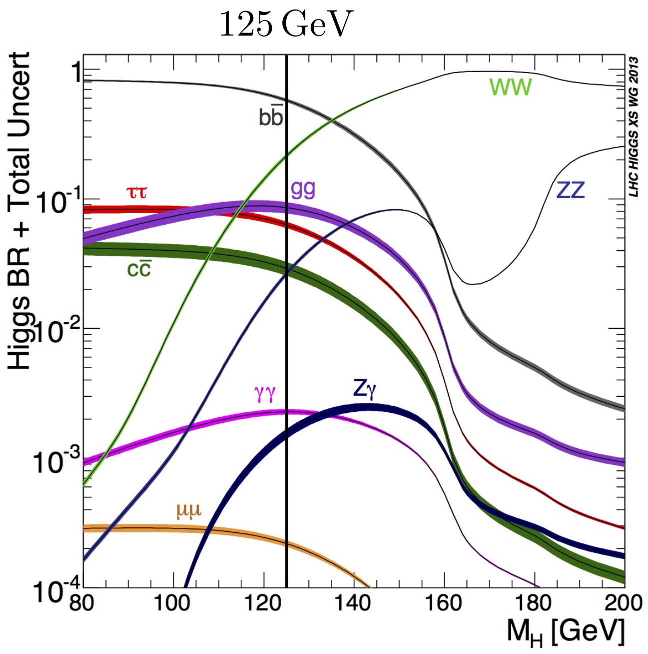
Realistic final states

JHEP 02 (2022) 046 in collaboration with Fabrizio Caola, Kirill Melnikov, Raoul Röntsch

Detecting WBF through realistic final states

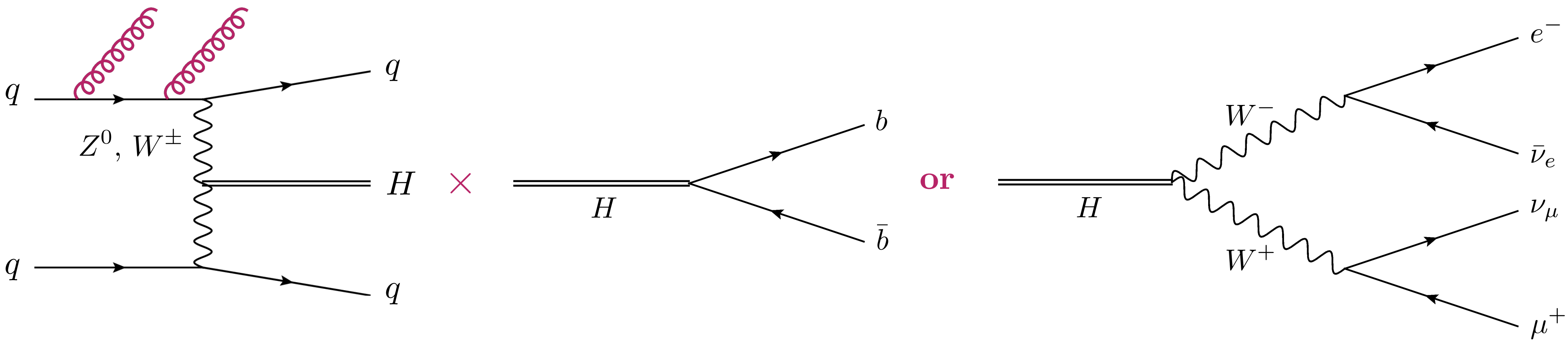






- $\mathbf{H \to b\bar{b}}$ and $\mathbf{H \to WW^* \to 2l\, 2\nu}$
- Highest branching ratios
- Both studied by ATLAS and CMS
  [e.g. Eur. Phys. J. C 81, 537 (2021); Phys. Lett. B 791, 96 (2019)]
- Doing this at NNLO QCD naively simple, in practice very complicated

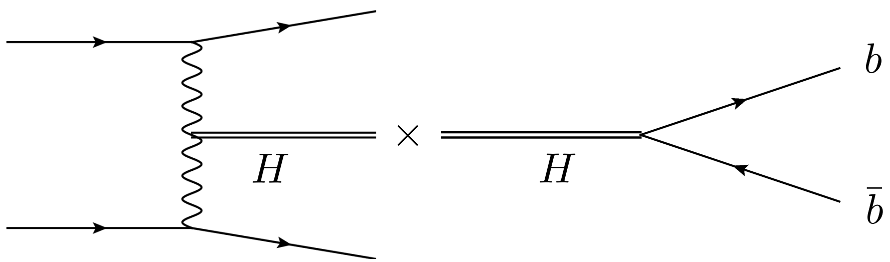
NNLO QCD Higgs boson production + Higgs boson decay



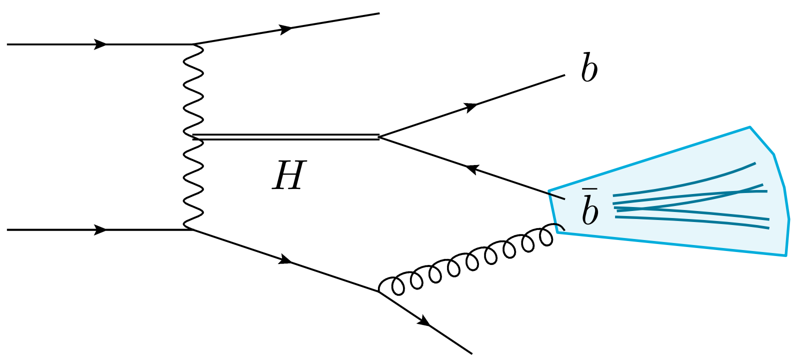
- In this combination, each decay channel comes with its unique challenges:
  - $\mathrm{H} \to \mathrm{b\bar{b}}$: **for now only at LO** but non-trivial interplay between partonic jets from production and decay when fiducial cuts are applied
  - $\mathrm{H} \to \mathrm{WW^*} \to 2\mathrm{l}\ 2\nu$: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

WBF + H → $b\bar{b}$ decay

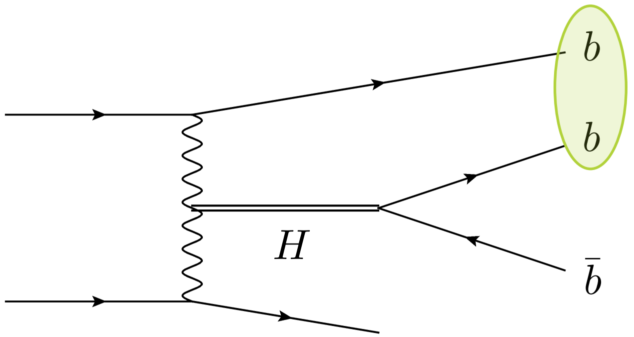
- Narrow width approximation → factorization of on-shell Higgs production and on-shell Higgs decay



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



Jet-clustering breaks factorization



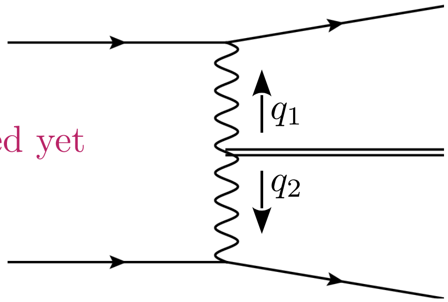
B-tagging breaks factorization

- 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

Physical setup

- 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]

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



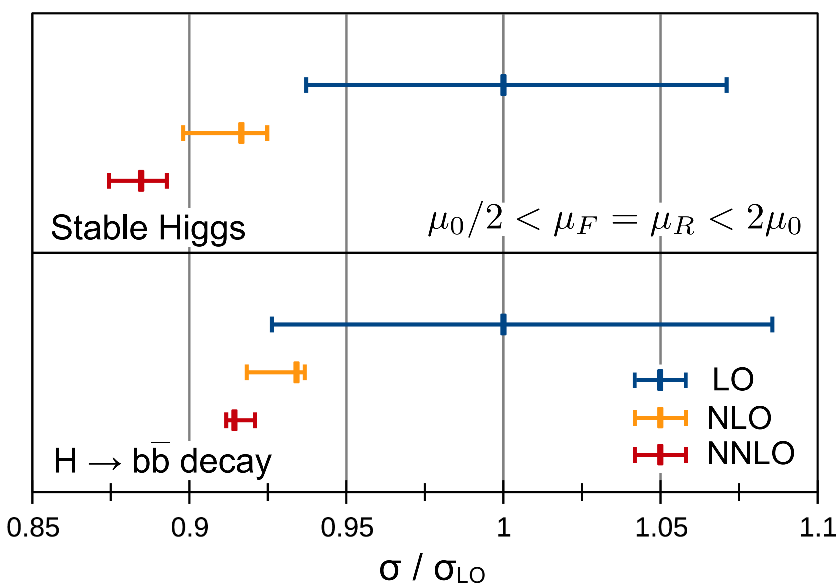
- Effects of other scale choices, e.g. $\mu_R^1 = \mu_F^1 = \sqrt{-q_1^2}$ / $\mu_R^2 = \mu_F^2 = \sqrt{-q_2^2}$, not studied yet
- Results of today for bb decay are a first non-trivial step:
  - Massless b quarks and decay @LO QCD
  - Production process is flavour "blind"
- Cuts on b-jets; loosely following latest ATLAS measurement [Eur. Phys. J. C 81, 537 (2021)]
  - 2 resolved b-jets
  - $p_{\perp,jb} > 65$ GeV
  - $|y_{jb}| < 2.5$

Results: fiducial cross section

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

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

- Comparison to stable Higgs results



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

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

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

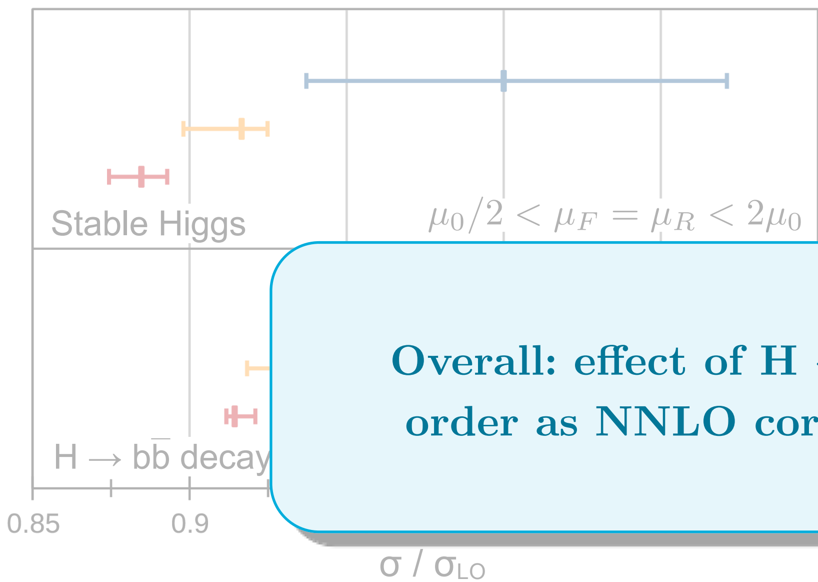
- *Noteworthy features:* smaller residual scale uncertainty and better perturbative convergence compared to stable Higgs production

Results: fiducial cross section

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

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

- Comparison to stable Higgs results



$$\frac{\sigma^H_{\rm NLO}}{\sigma^H_{\rm LO}} = 0.917(1)$$

-3.2%

$$\frac{\sigma^H_{\rm NNLO}}{\sigma^H_{\rm LO}} = 0.885(1)$$

+1.7%

+2.9%

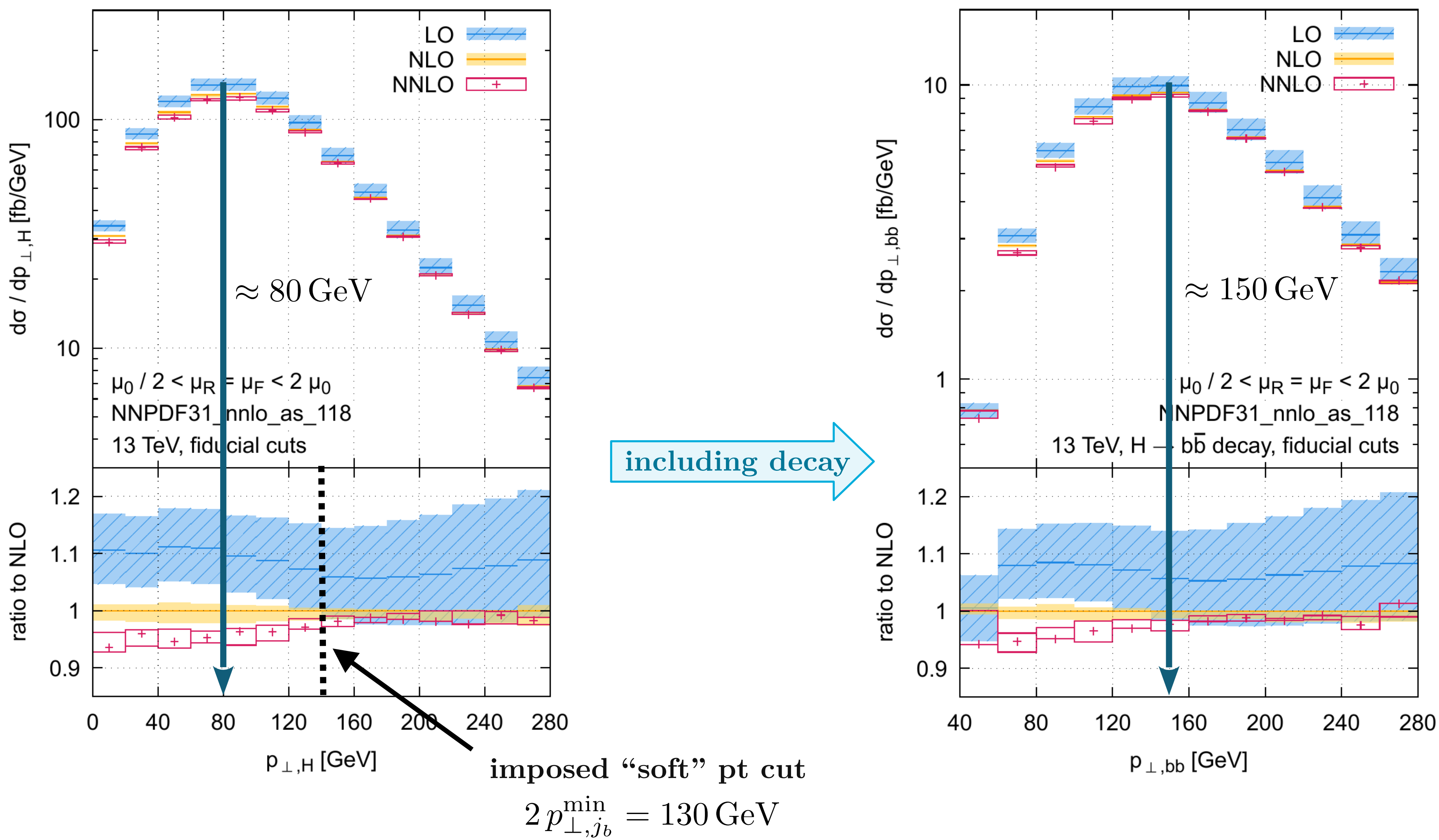
$$\frac{\sigma^{b\bar{b}}_{\rm NNLO}}{\sigma^{b\bar{b}}_{\rm LO}} = 0.914(2)$$

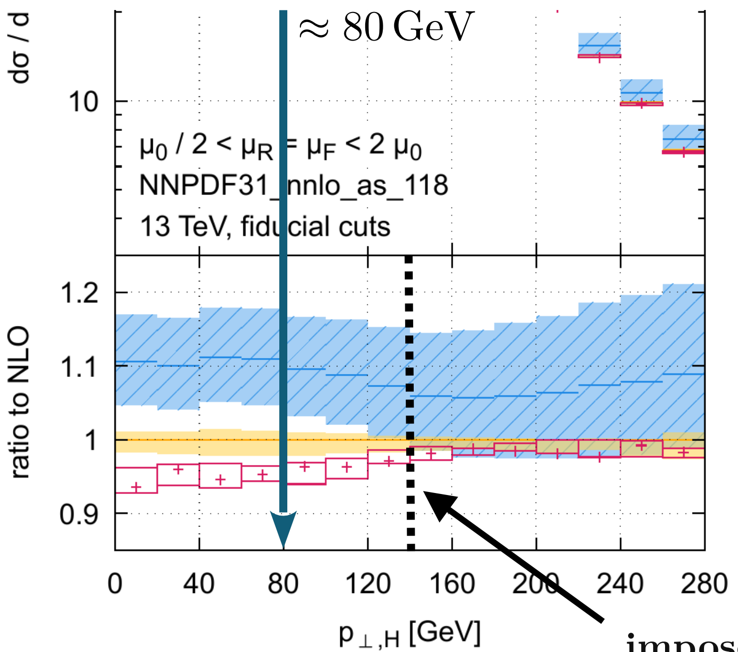
Overall: effect of H → bb̄ decay of same order as NNLO corrections themselves!

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

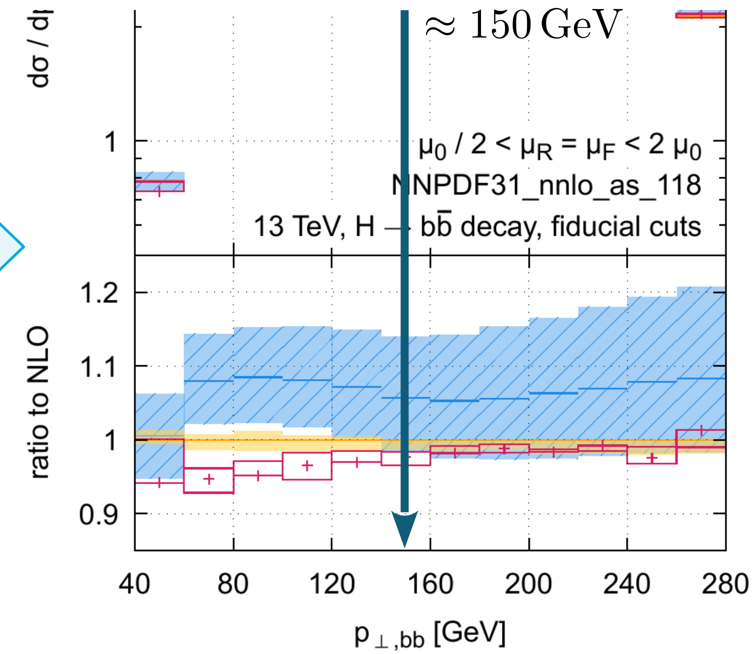
Results: fiducial cross section

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





including decay →



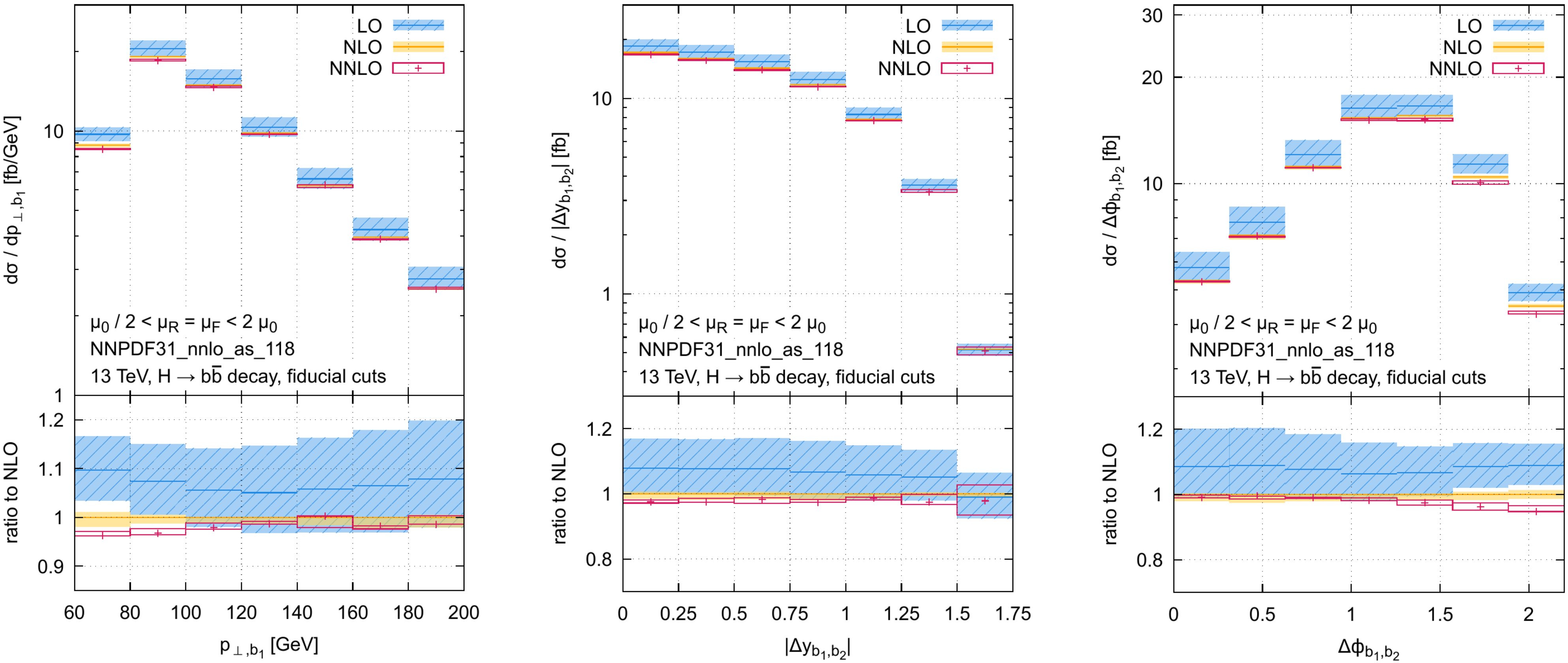
imposed "soft" pt cut

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

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

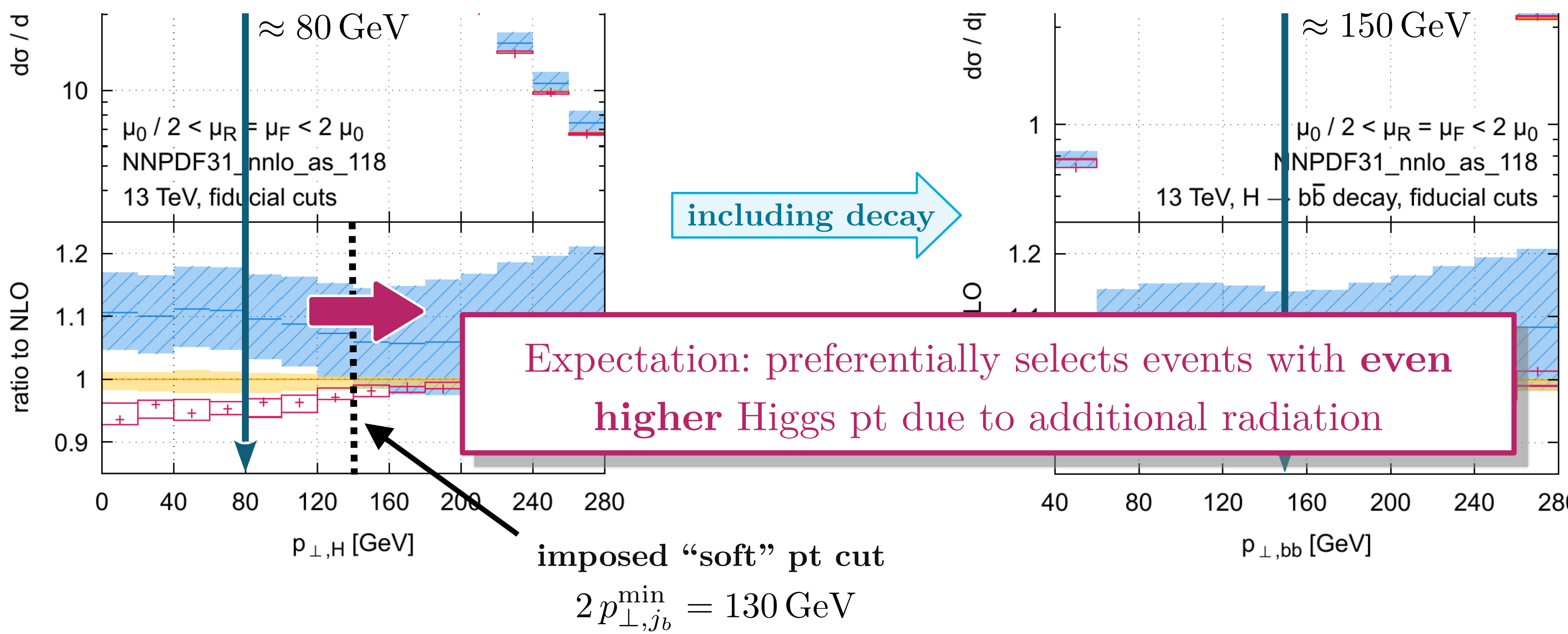
Results: differential cross sections



- 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

- $H \to b\bar{b}$ @LO (and $H \to WW \to 2l\,2\nu$) as prototypes for $H \to b\bar{b}$ @ NNLO QCD
- Fully-differential description of $H \to b\bar{b}$ 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

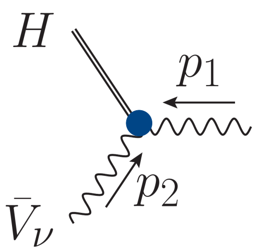


Anomalous Higgs boson weak couplings

arXiv:2206.14630 [hep-ph] in collaboration with Fabrizio Caola, Kirill Melnikov, Raoul Röntsch

Anomalous HVV interactions

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



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

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

$$= \; i g_{HVV}^{(SM)} \left[g^{\mu\nu} \left(1 + \boxed{\frac{m_H^2}{\Lambda^2} \; c_{HVV}^{(2)}} + \boxed{\frac{p_1^2 + p_2^2}{\Lambda^2} \; c_{HVV}^{(1)} \Big) + \frac{2 p_1^\nu p_2^\mu}{\Lambda^2} c_{HVV}^{(1)}} - \boxed{\tilde{c}_{HVV} (6\pi) \epsilon^{\mu\nu\rho\sigma} \frac{p_{1,\rho} p_{2,\sigma}}{\Lambda^2}} \right]$$

"rescaling" of SM — CP-even coupling — CP-odd coupling

- (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

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

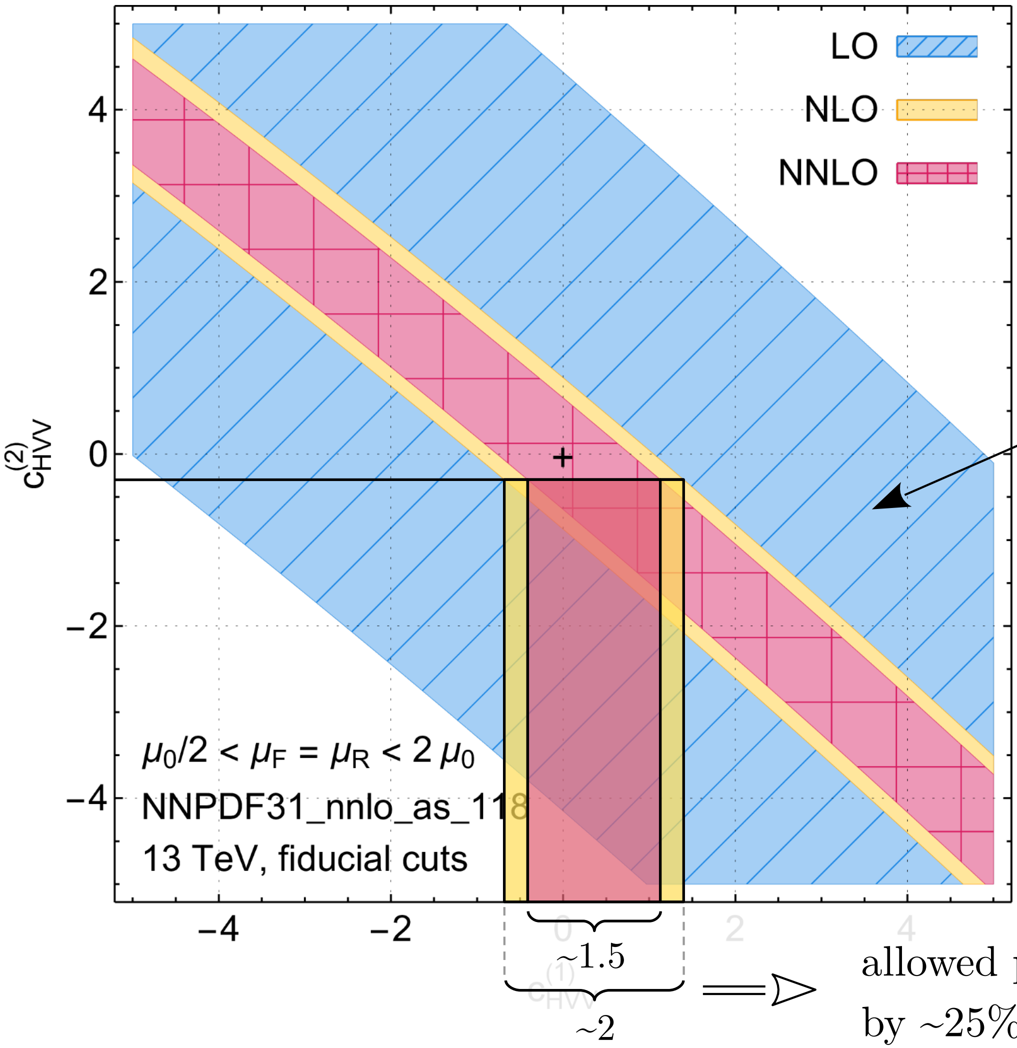
$$+ \left(1 + \frac{m_H^2}{\Lambda^2} c_{HVV}^{(2)}\right) \tilde{c}_{HVV} X_5 + c_{HVV}^{(1)} \tilde{c}_{HVV} X_6 \,.$$

- 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 $\to$ NLO; relatively stable from NLO $\to$ NNLO
- Similar k-factors for all $X_{1,2,3,4}$ ($\sim$ -4% from NLO $\to$ 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

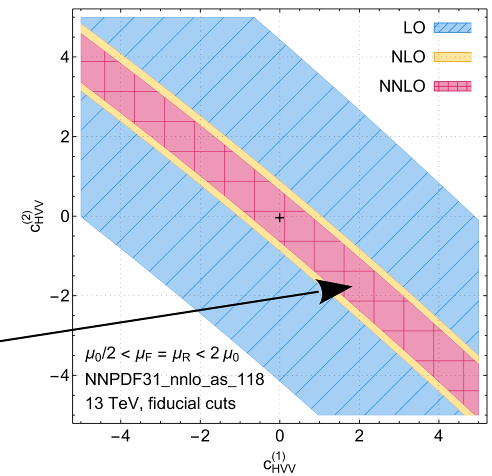
$\Longrightarrow$ allowed parameter space shrinks by ~25% (significant impact)

- 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

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



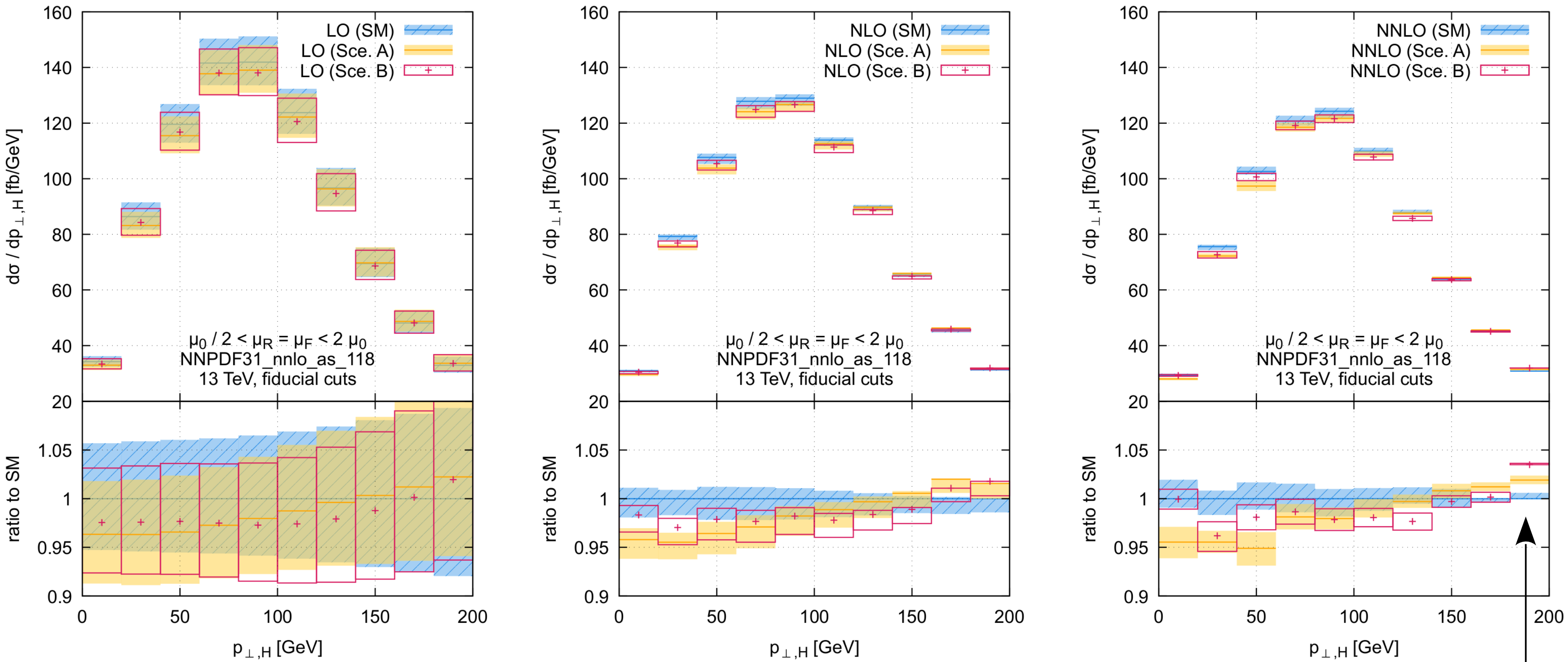
- They are chosen such that fiducial cross section are indistinguishable

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

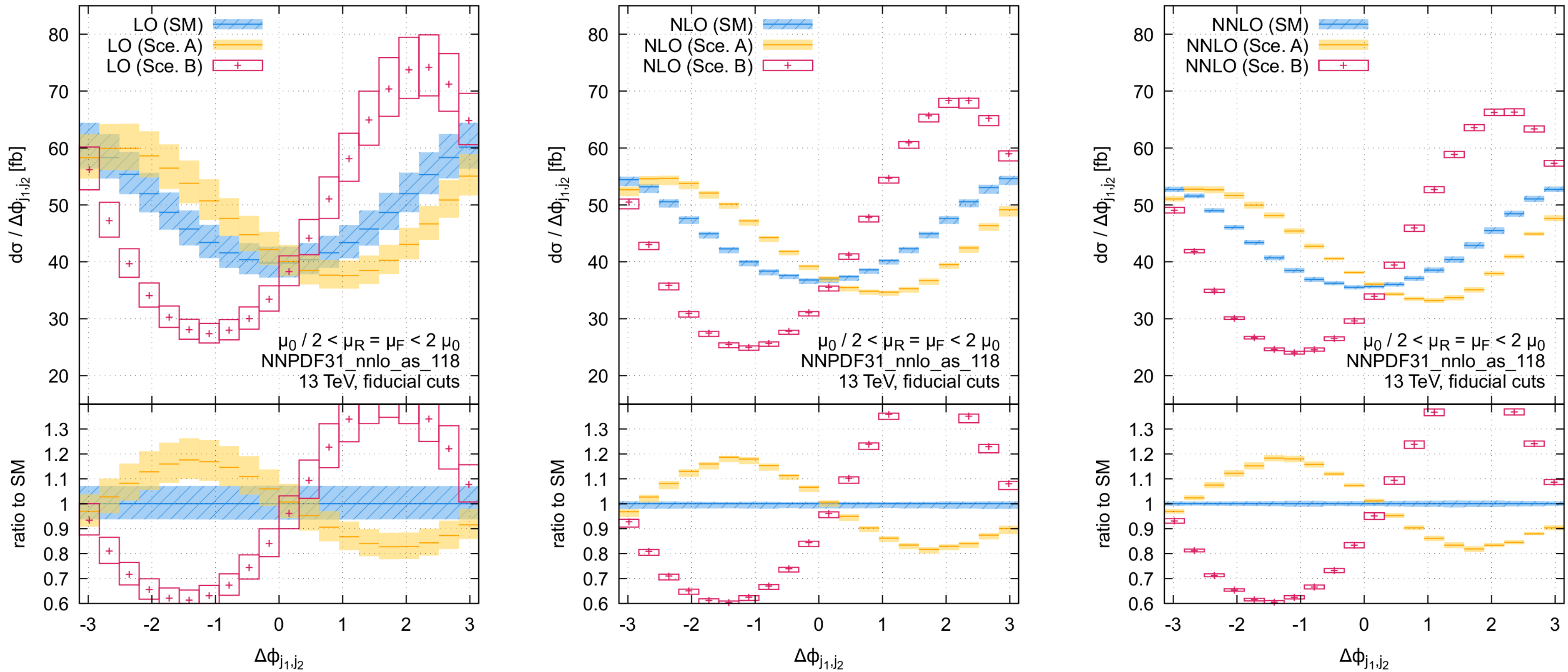
Differential distributions

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



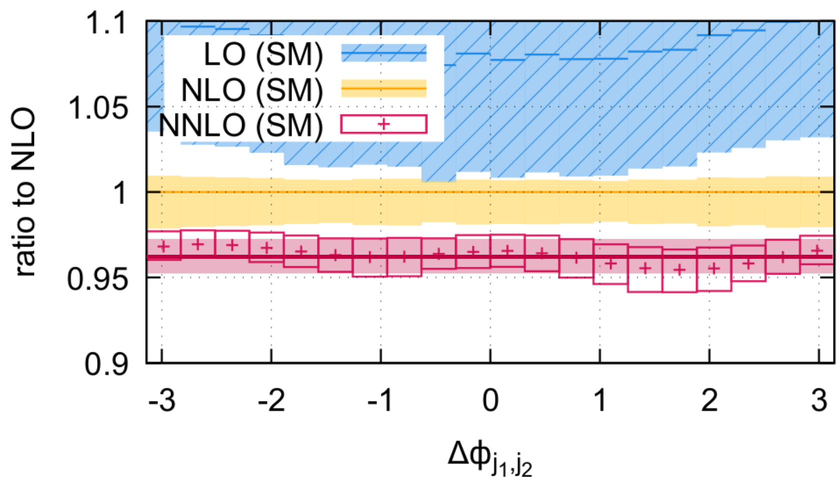
start of diverging distributions, expected but cross section already down by an order

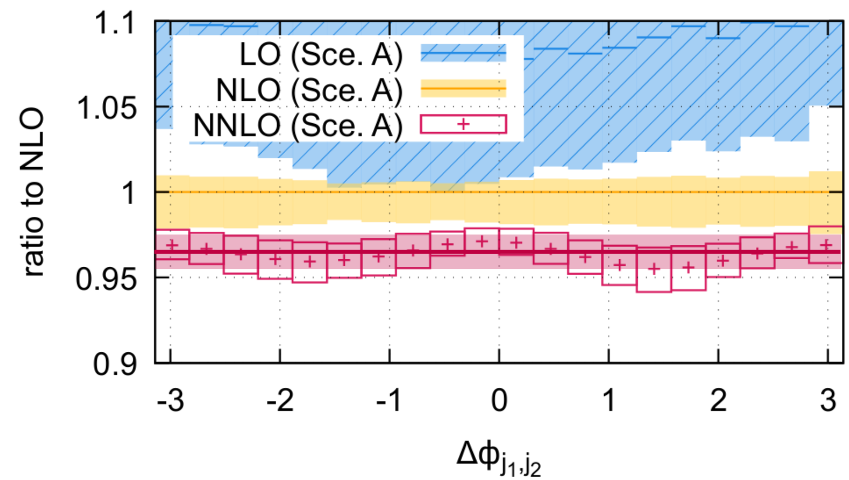
$\Delta\varphi$ a CP sensitive observable

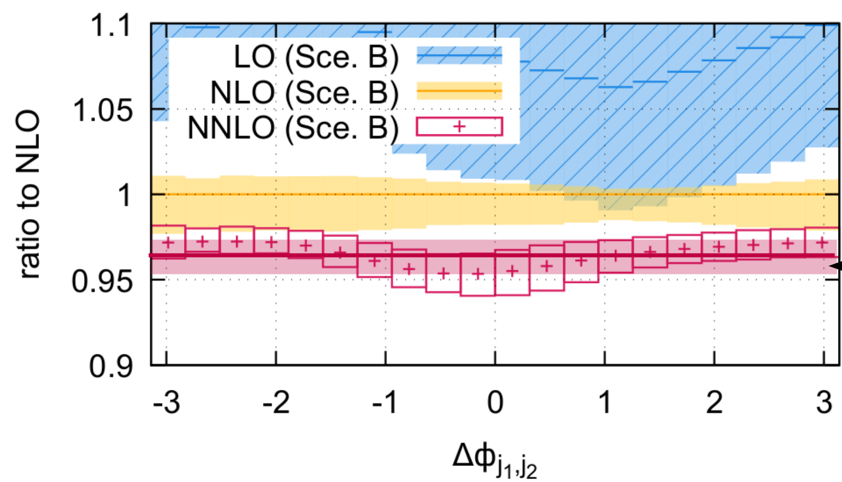


- At LO: Sce. B and SM distinguishable, Sce. A and SM just covered by scale variation
- Similar to fiducial cross section: no significant reduction of scale uncertainties from NLO $\rightarrow$ NNLO
- In this distributions CP-odd / CP-even interference (dim-6) is the dominant contribution

$\Delta\varphi$ a CP sensitive observable



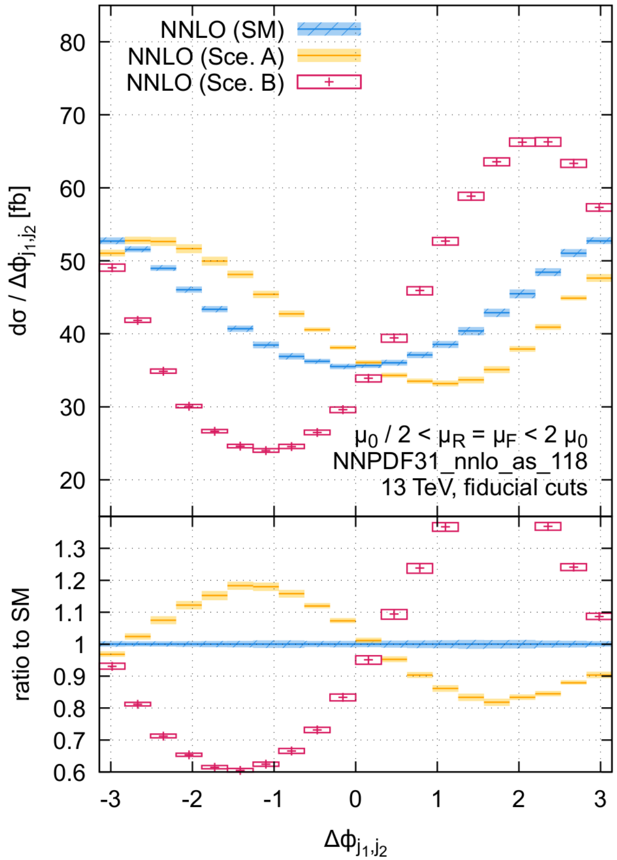




$\pm 1\%$ around mean

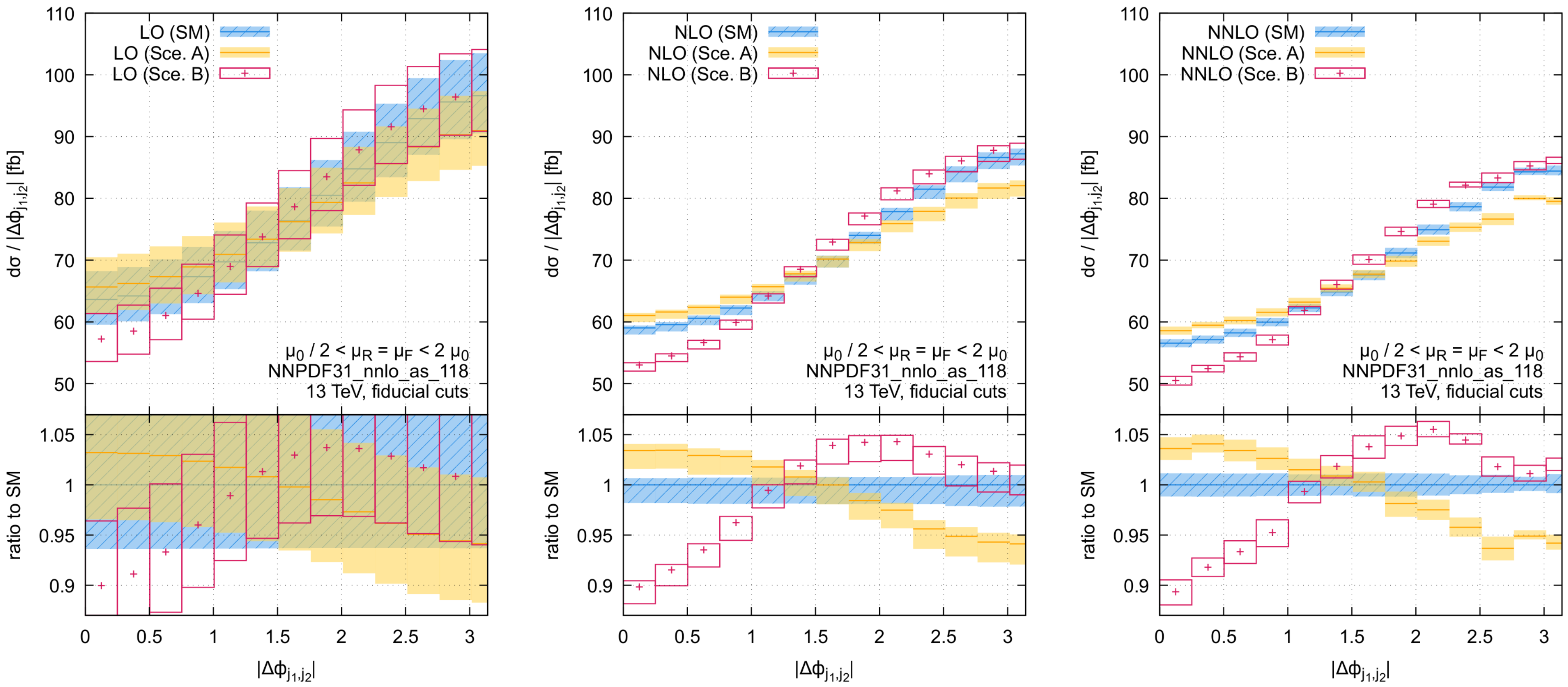
- K-factor rather flat and almost independent of anomalous couplings
- K-factors rather flat $\rightarrow$ global rescaling from NLO to NNLO should be sufficient for O(1%)

$\Delta\varphi$ a CP sensitive observable



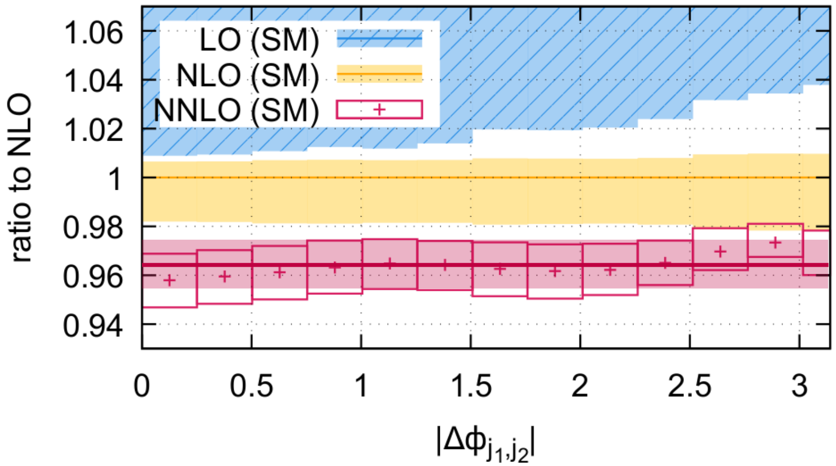
- Ratio of events with $\Delta\varphi < 0$ and $\Delta\varphi > 0$ might be useful to include differential data in exclusion plots in a efficient way (cut-and-count approach)
- Deviation(s) from SM dominated by antisymetric contributions $\rightarrow$ CP-odd / CP-even interference
- To study CP-even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

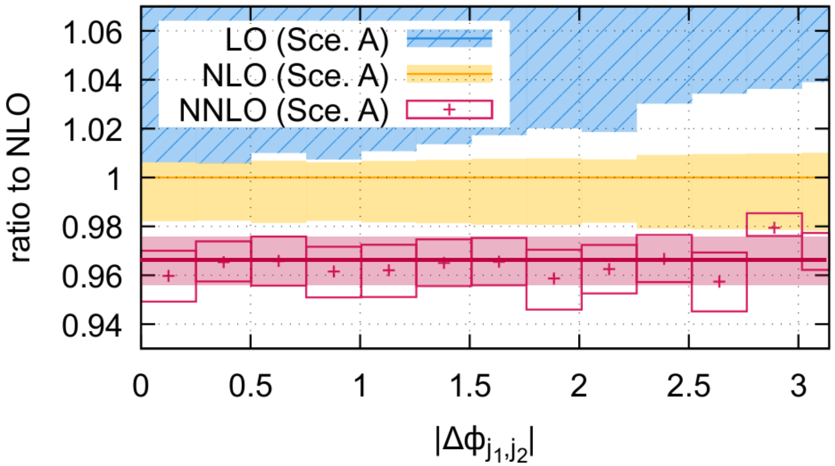
$|\Delta\varphi|$ a CP insensitive observable

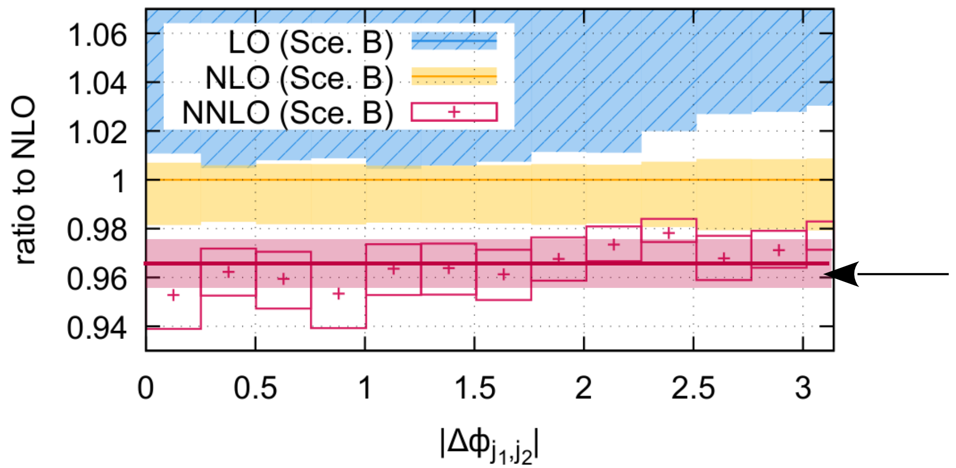


- At LO differences are swamped by scale uncertainty
- Starting from NLO scale uncertainties sufficiently reduced to distinguish between different scenarios and SM; NNLO might help to distinguish from SM
- Ratio of events with $|\Delta\varphi| < \pi/2$ and $|\Delta\varphi| > \pi/2$ might be useful to 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 $O(1\%)$

Conclusion and Outlook

- **WBF including H → $b\bar{b}$ 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 uncertainty / better perturbative convergence
  - **Future work:** Include decay H → $b\bar{b}$ massive @ NNLO [Bernreuther, Chen, Si '18; Behring, Bizoń '19]
- **WBF including H → WW* → 2l 2v 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 sutdy 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