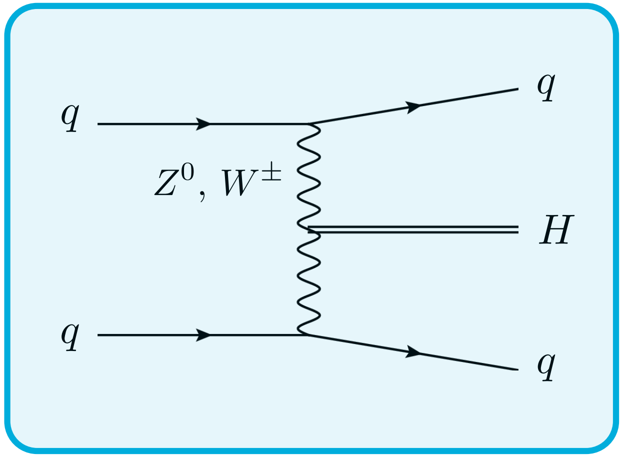
Towards Higgs boson production in weak boson fusion at higher orders with realistic final states

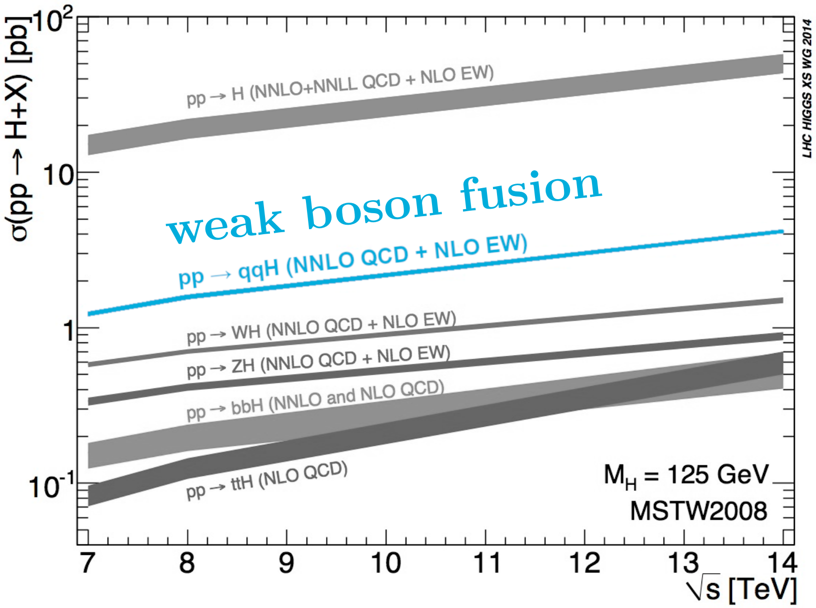
In collaboration with Fabrizio Caola, Kirill Melnikov and Raoul Röntsch
Details in arXiv:2110.02818 / JHEP02(2022)046

Konstantin Asteriadis | 05/12/2022
LoopFest XX, Pittsburgh

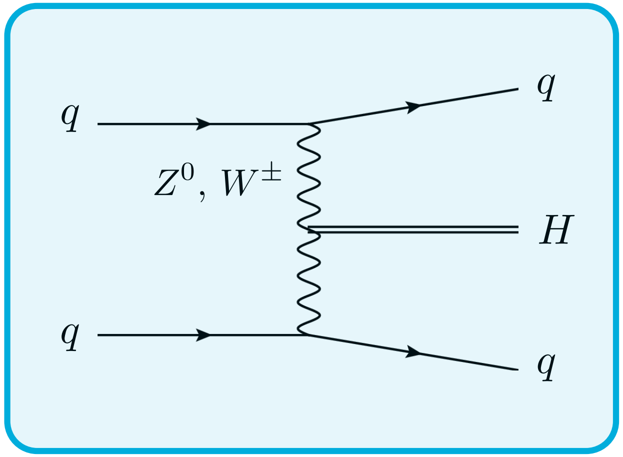
Higgs boson production in vector boson fusion



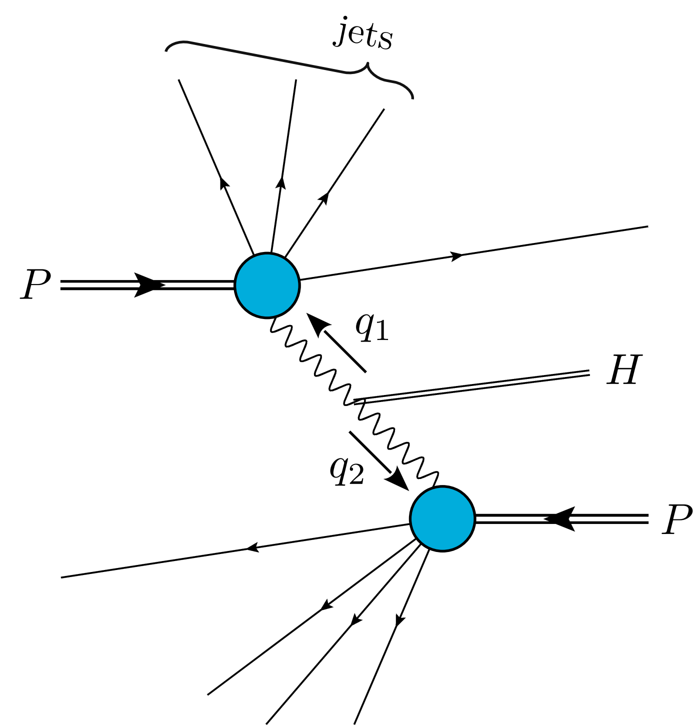
- Production channel with the highest cross section that probes electroweak couplings of the Higgs boson
- Fiducial region: non-trivial jet structure [Rauch, Zeppenfeld '17; ...] → important to control radiative corrections
- State of the art:
  - Inclusive @ N³LO QCD [Dreyer, Karlberg '16];
  - Fully differential @ NNLO QCD [Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15; Cruz-Martinez, Glover, Gehrmann, Huss '18, Caola, Melnikov, Roentsch KA '21]



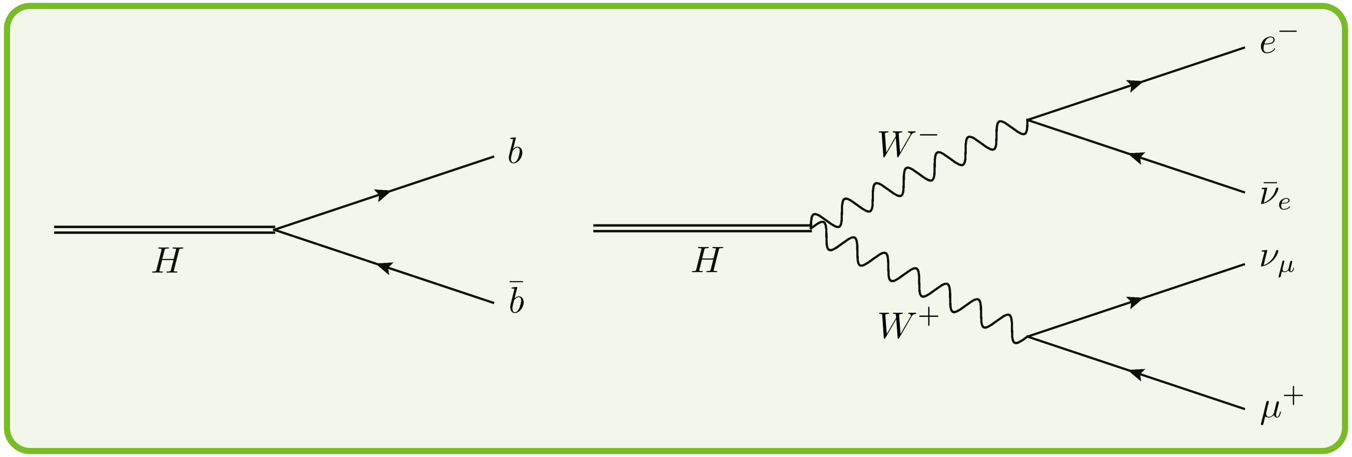
A closer look at QCD corrections

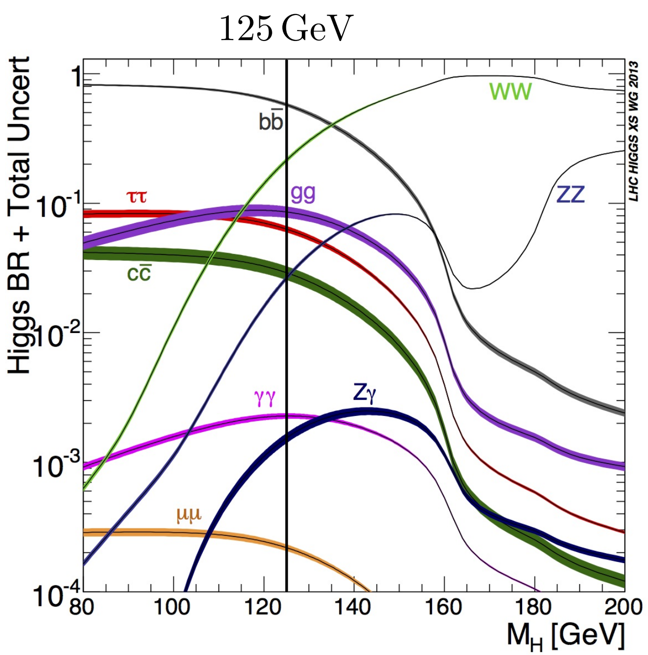


- Largest contribution from **factorizable** corrections [Liu, Melnikov, Penin '19] $\rightarrow$ focus of this talk
- Effectively DIS scattering of two **protons**
- **However: All current computations are for stable Higgs boson production**



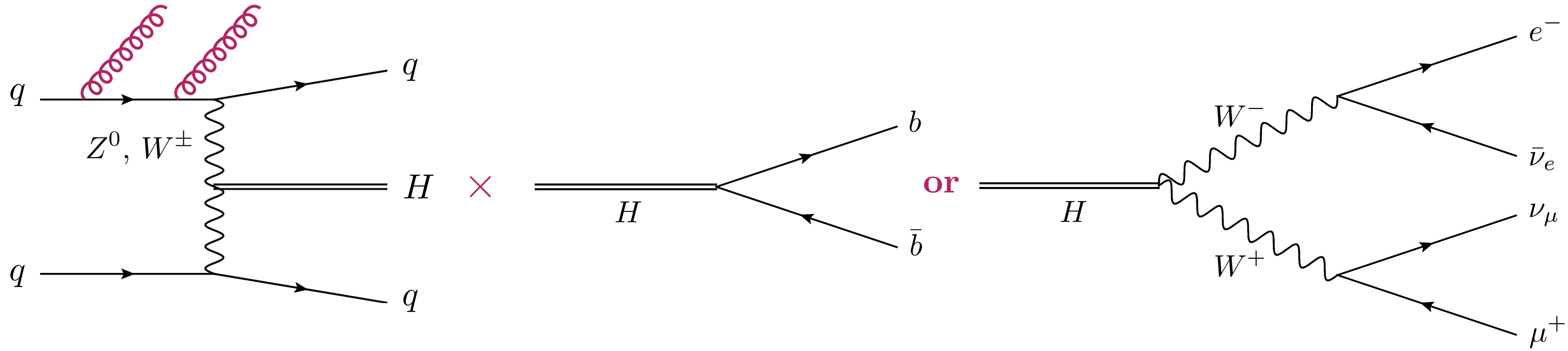
Detecting WBF through realistic final states





- **H → bb̄** and **H → WW* → 2l 2ν**
- 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**

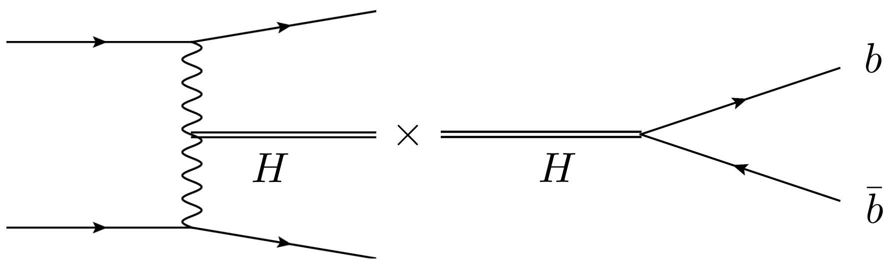
NNLO QCD Higgs boson production + Higgs boson decay



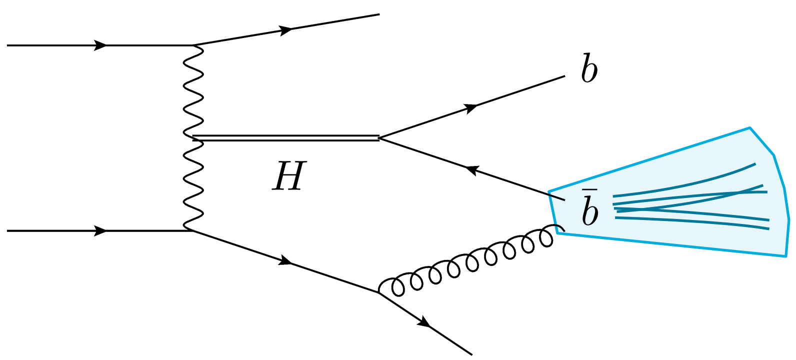
- In this combination, each decay channel comes with its unique challenges:
    - $\mathrm{H} \to \mathrm{b}\overline{\mathrm{b}}$: non-trivial interplay between partonic jets from production and decay when fiducial cuts are applied
    - $\mathrm{H} \to \mathrm{WW}^* \to 2\mathrm{l}\ 2\nu$: up to 21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

WBF + H → $b\bar{b}$ decay

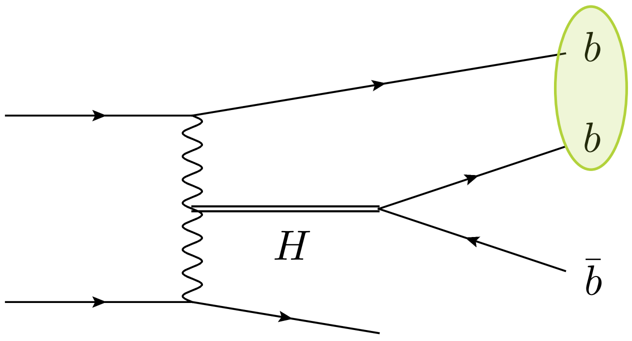
- Narrow width approximation → factorization of on-shell Higgs production and on-shell Higgs decay



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



Jet-clustering breaks factorization

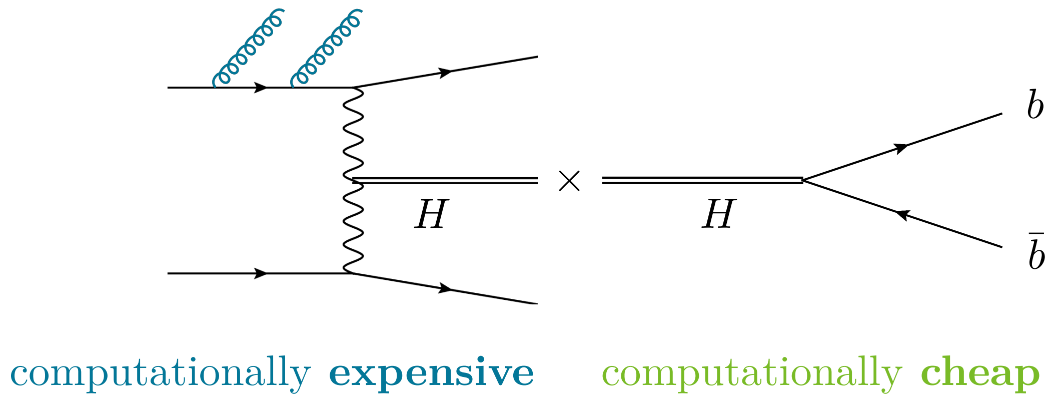


B-tagging breaks factorization

- We don't expect this effects to be very large but it is important to quantify their size

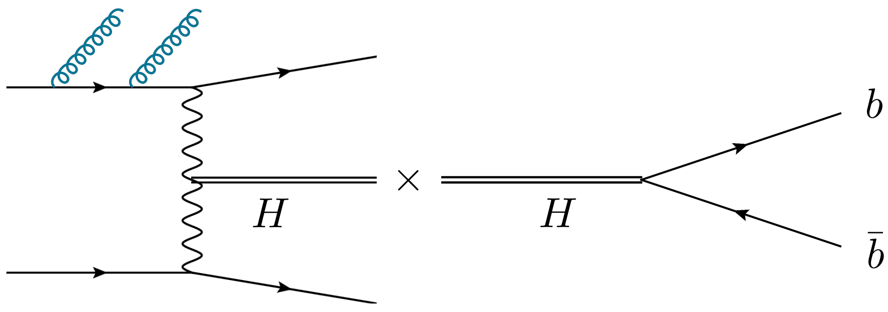
- Finally: cuts on b-jets may change fiducial WBF region

The technical challenge: phase space integration



- Naive approach: simply enlarge the phase space dimension and let the MC integrator do its job
- However, extremely inefficient: it does not take the peculiarities of the situation into account:
  - Huge difference in complexity of production and decay kinematics
  - **Production**: NNLO radiation with already non-trivial Born kinematics
  - **$H \to b\bar{b}$ @ LO decay**: back-to-back and equally distributed over the angular phase space
- ($H \to WW$ decay has more complicated kinematics but still far simpler than complexity of WBF production @ NNLO)

The technical challenge: phase space integration



- To take advantage of this situation:
  1) Generate high-precision integration grids for stable Higgs boson production
  2) Generate production events according to these grids and for each of them generate O(100) decay events
  3) When this fails (typically in regions where the NNLO cross section receives large positive and negative contributions) $\rightarrow$ naive "brute-force" integration ($\sim$ 15% of the time)
- However, $\sim$ **85% of the time the computation can be done relatively cheaply**

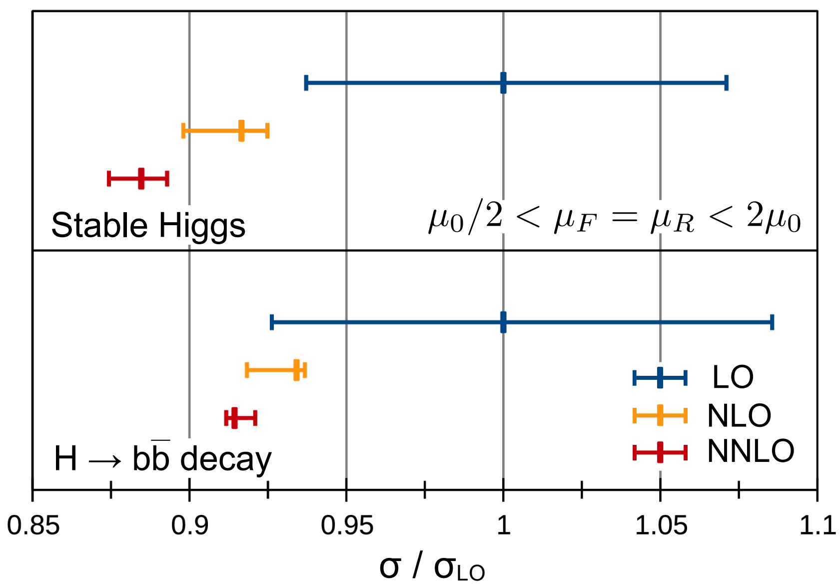
Results: fiducial cross section

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

- Cross section for b-jets from production process small → at this stage: no flavour tagging in Higgs production process

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

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



$$\frac{\sigma^{H}_{\mathrm{NLO}}}{\sigma^{H}_{\mathrm{LO}}} = 0.917(1) \qquad \frac{\sigma^{H}_{\mathrm{NNLO}}}{\sigma^{H}_{\mathrm{LO}}} = 0.885(1)$$

-3.2%

+1.7%

+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

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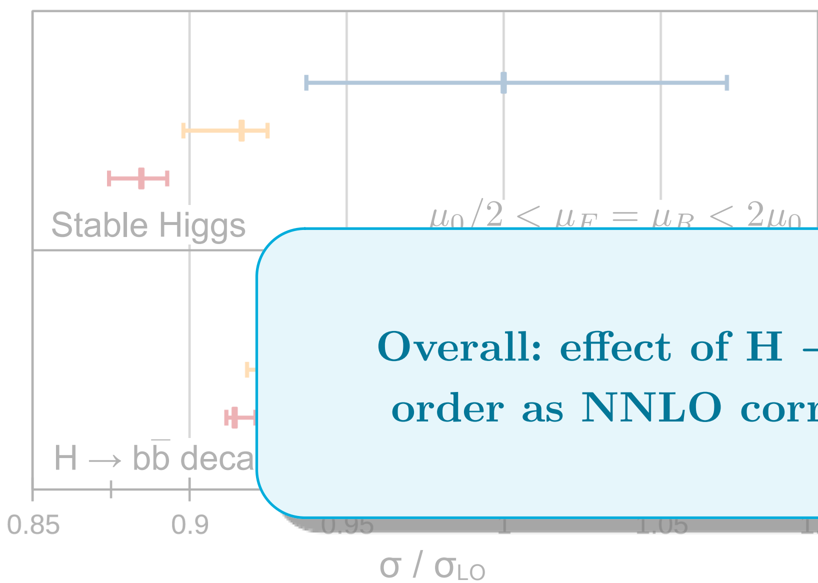

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-3.2%

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+2.9%

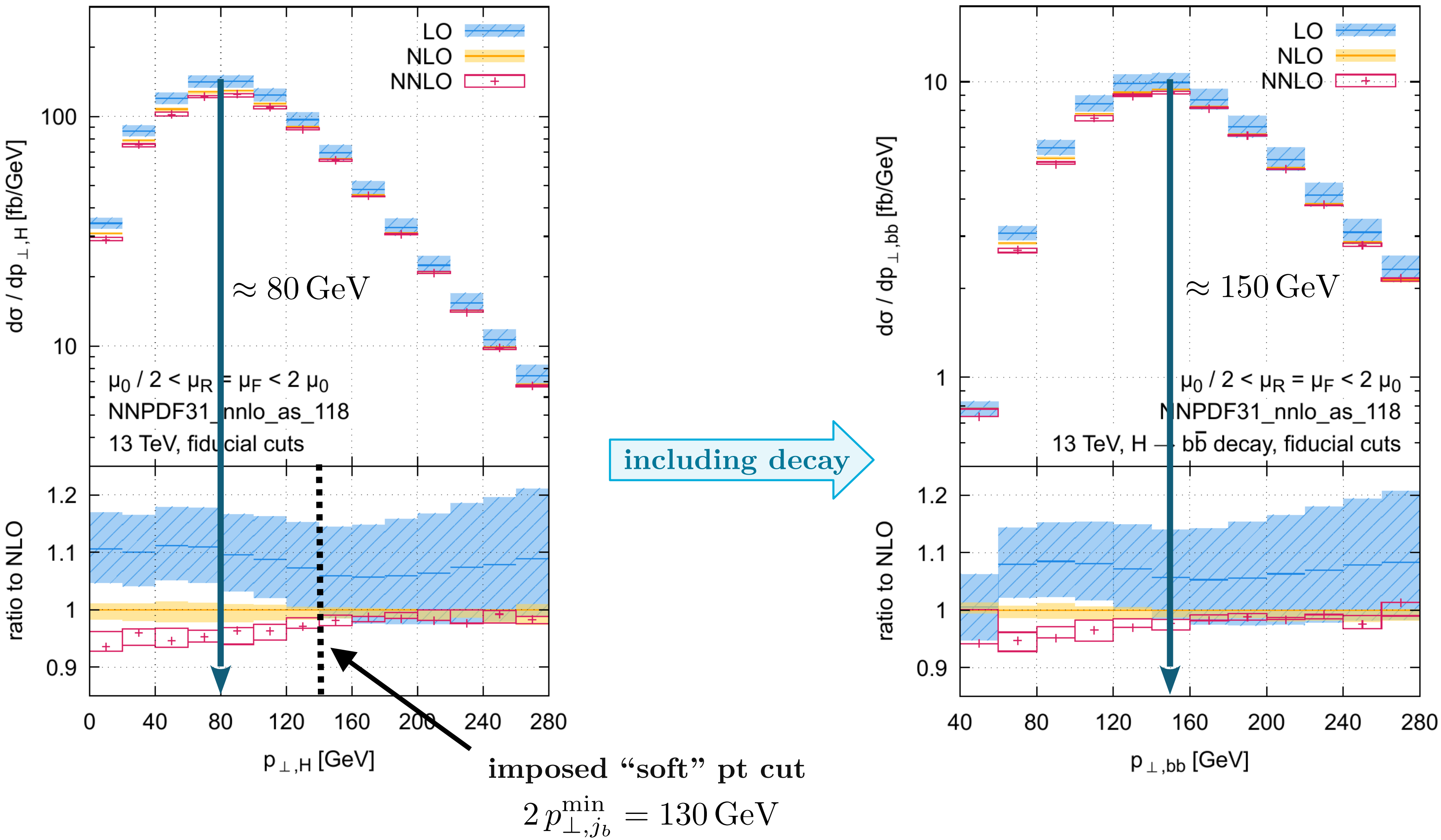
$$\frac{\sigma^{b\bar{b}}_{\mathrm{NNLO}}}{\sigma^{b\bar{b}}_{\mathrm{LO}}} = 0.914(2)$$

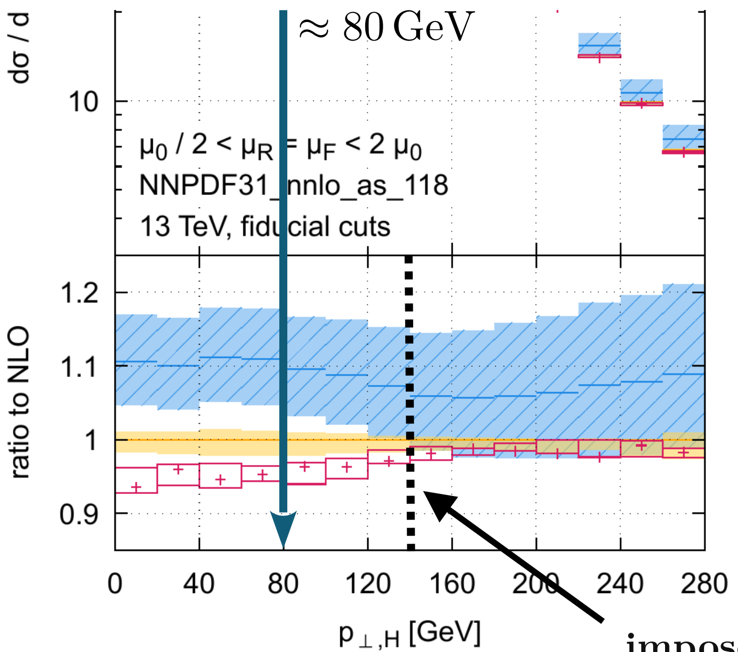
Overall: effect of H → bb̄ decay of same order as NNLO corrections themselves!

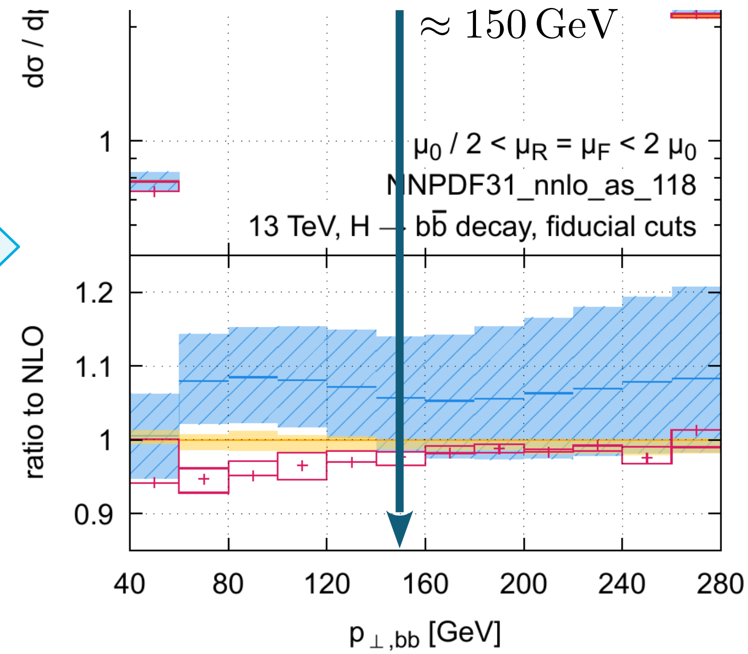
- *Noteworthy features:* smaller residual scale uncertainty and better perturbative convergence compared to stable Higgs production

Results: fiducial cross section

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







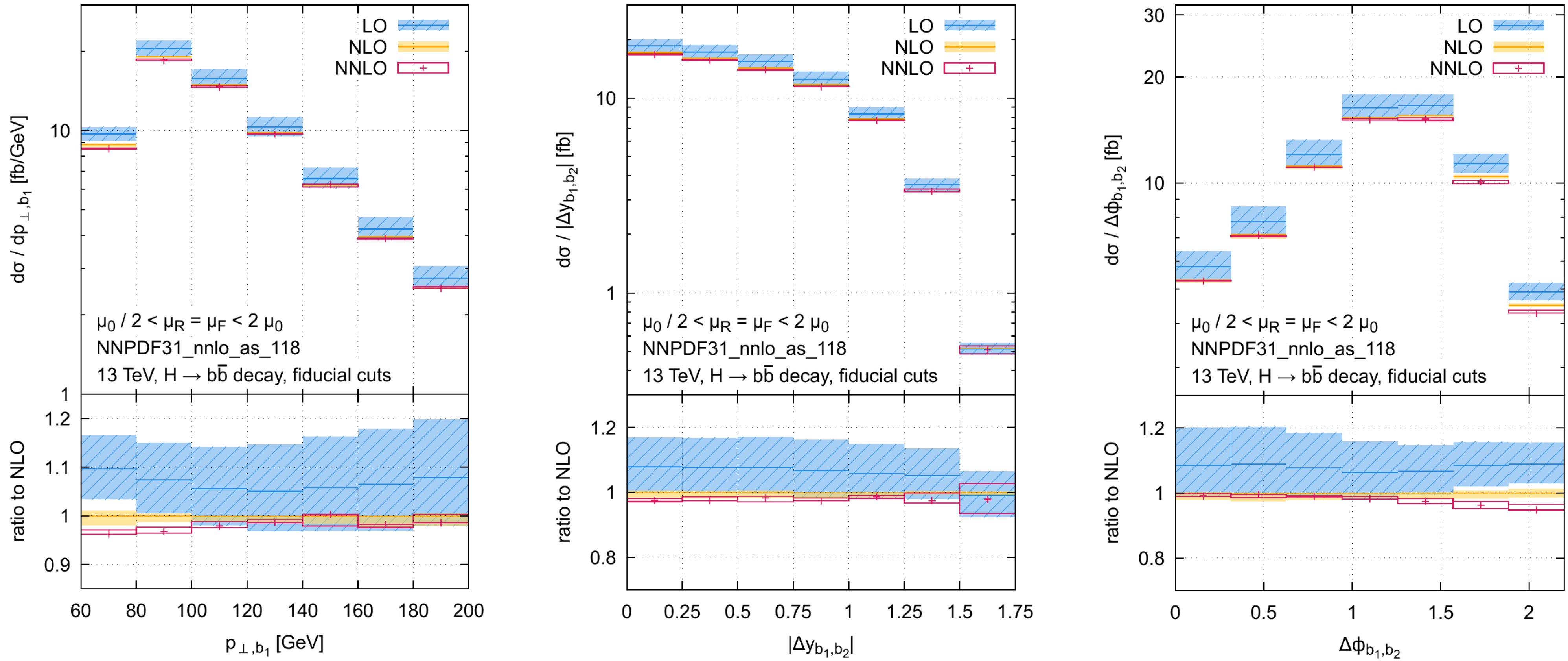
imposed "soft" pt cut

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

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

$$\frac{\sigma^H_{\mathrm{NNLO}}}{\sigma^H_{\mathrm{LO}}} = 0.89 \quad \xrightarrow{\textbf{Higgs pt cut}} \quad \frac{\sigma^H_{\mathrm{NNLO}}}{\sigma^H_{\mathrm{LO}}} = 0.91 \quad \xrightarrow{\textbf{including decay}} \quad \frac{\sigma^{b\bar{b}}_{\mathrm{NNLO}}}{\sigma^{b\bar{b}}_{\mathrm{LO}}} = 0.914(2)$$

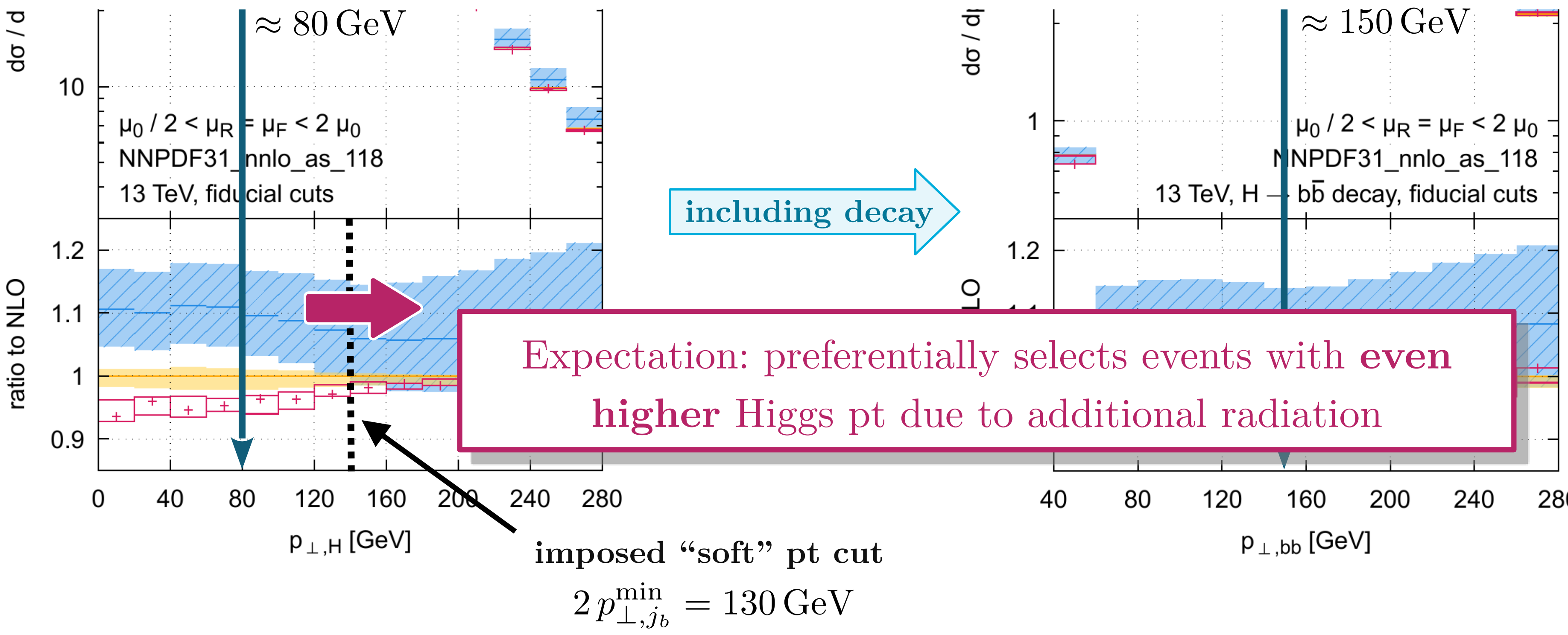
Results: differential cross sections



- 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



Conclusion

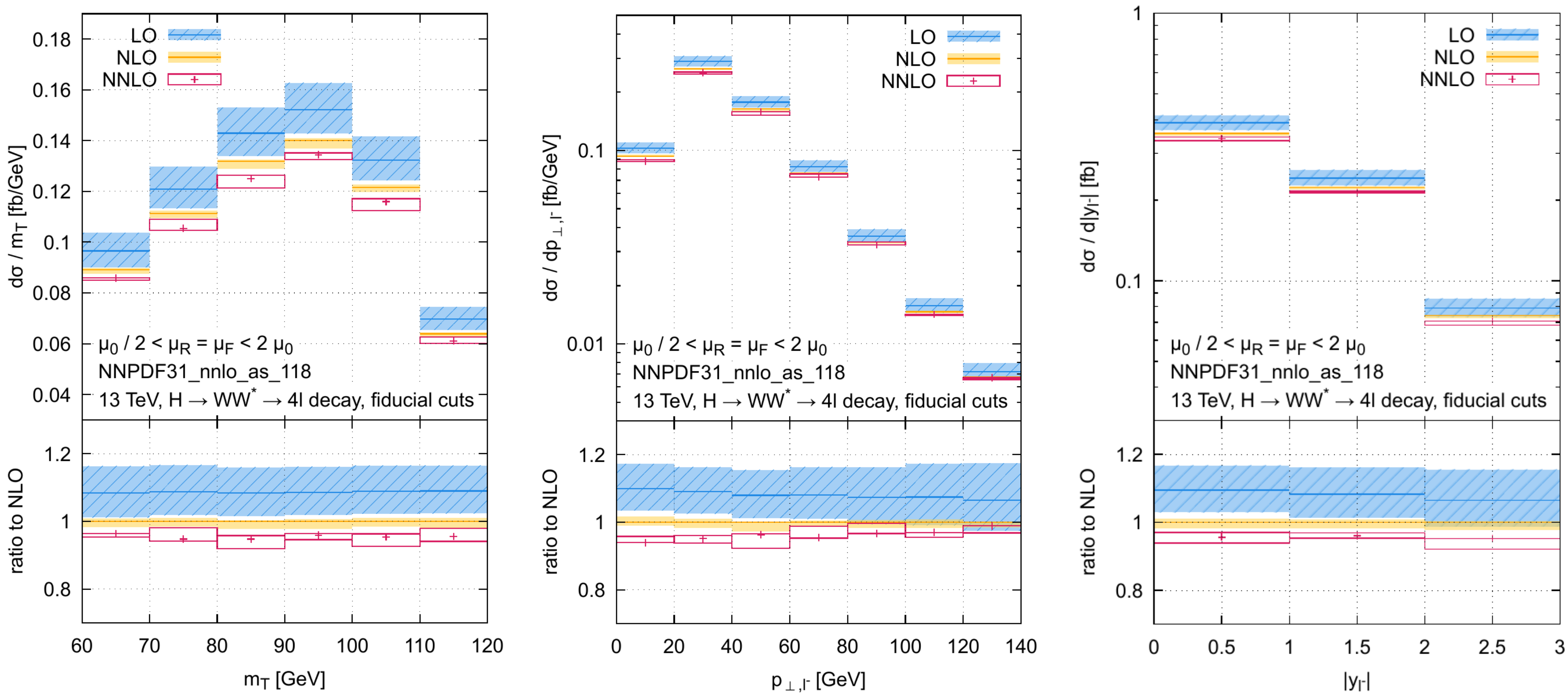
- First NNLO QCD study of Higgs boson production in vector boson fusion that includes the decay of the Higgs boson
- Naively trivial; challenging in practice

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

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

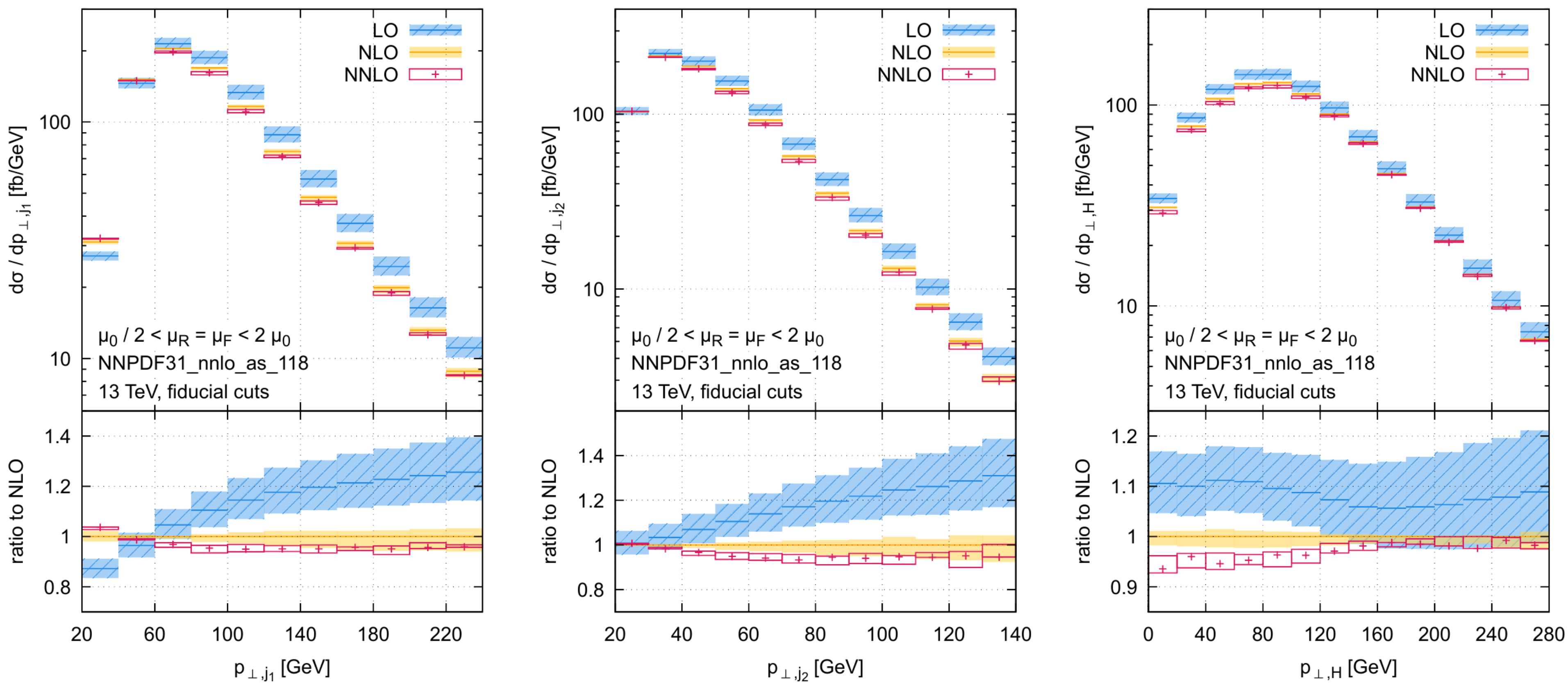
Differential results

Results: differential cross sections

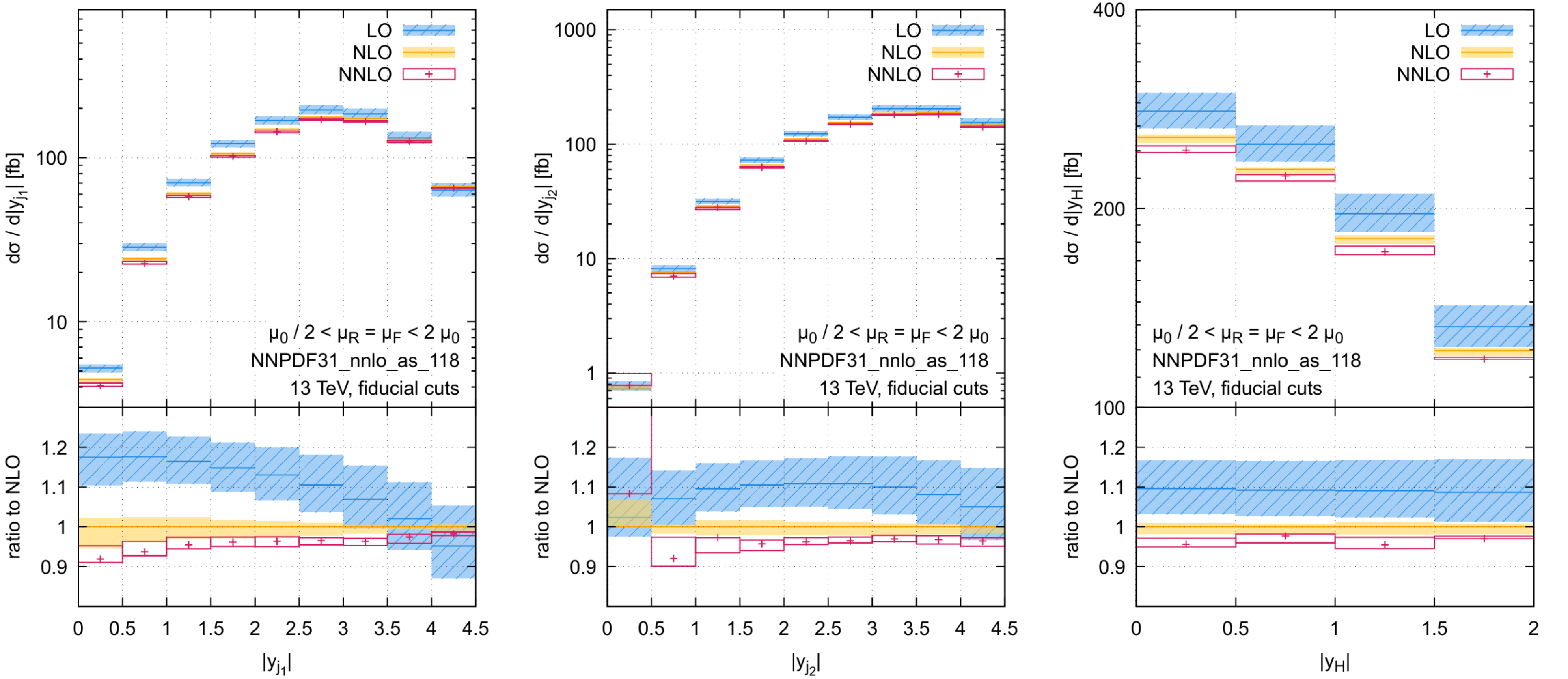


- Differential K-factors rather flat
- NNLO/NLO K-factor computed with stable Higgs is a good approximation within O(1%) precision

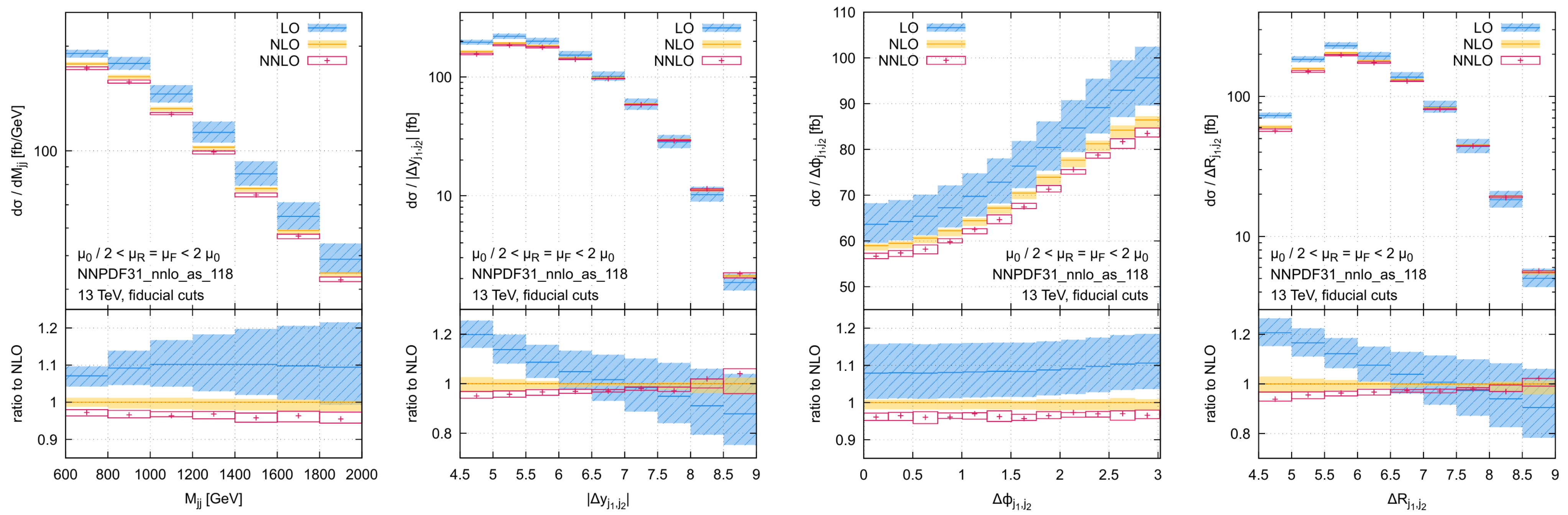
Stable Higgs boson production (I)



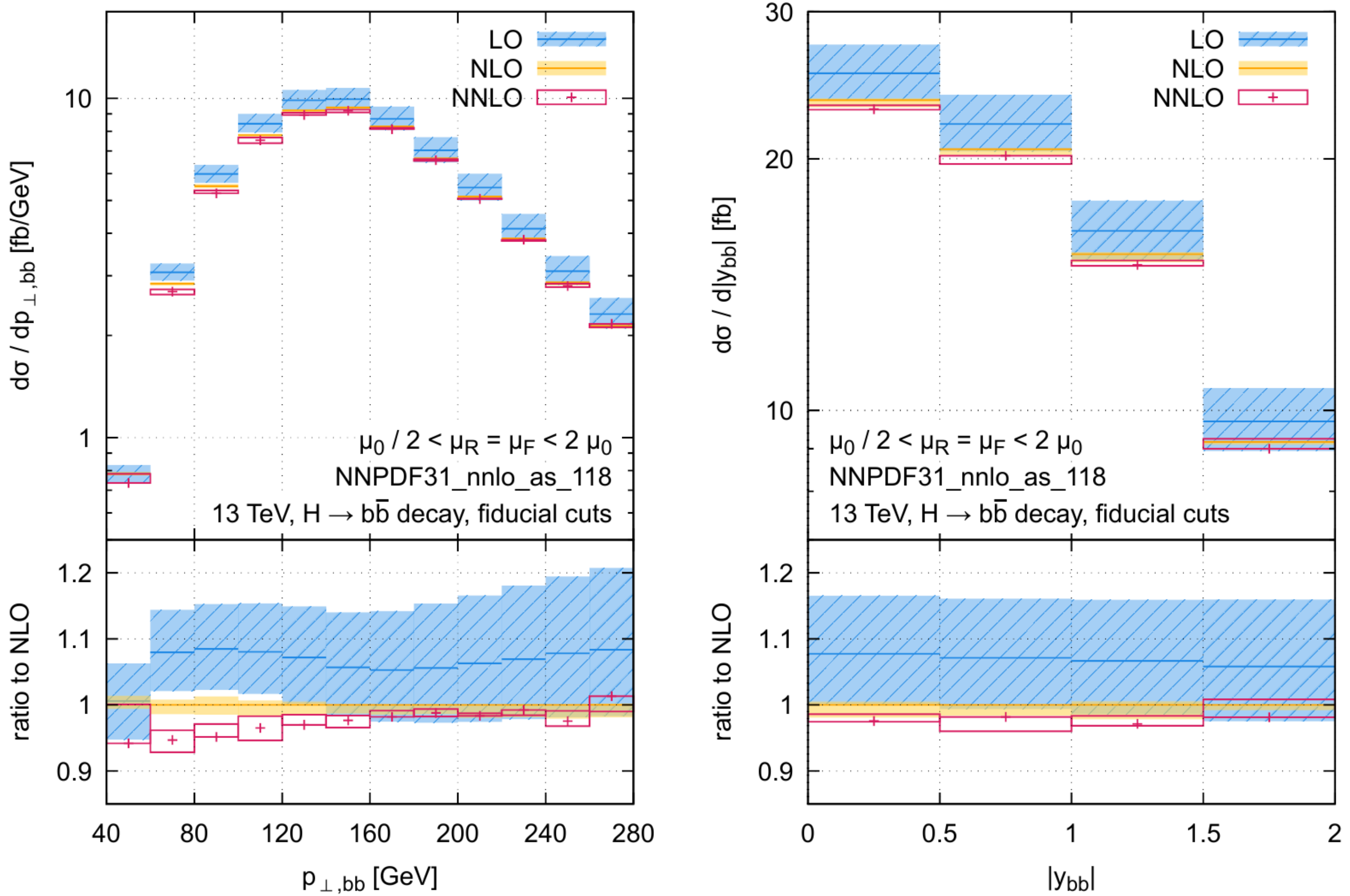
Stable Higgs boson production (II)



Stable Higgs boson production (III)



$H \to b\bar{b}$ decay (I)



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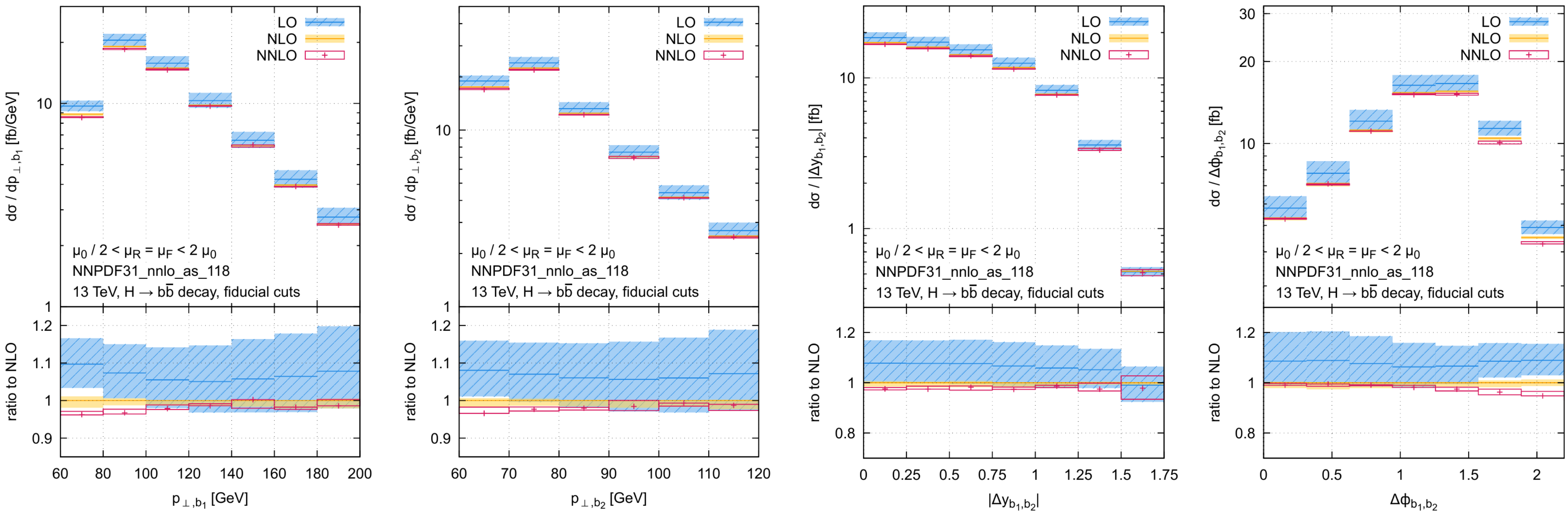
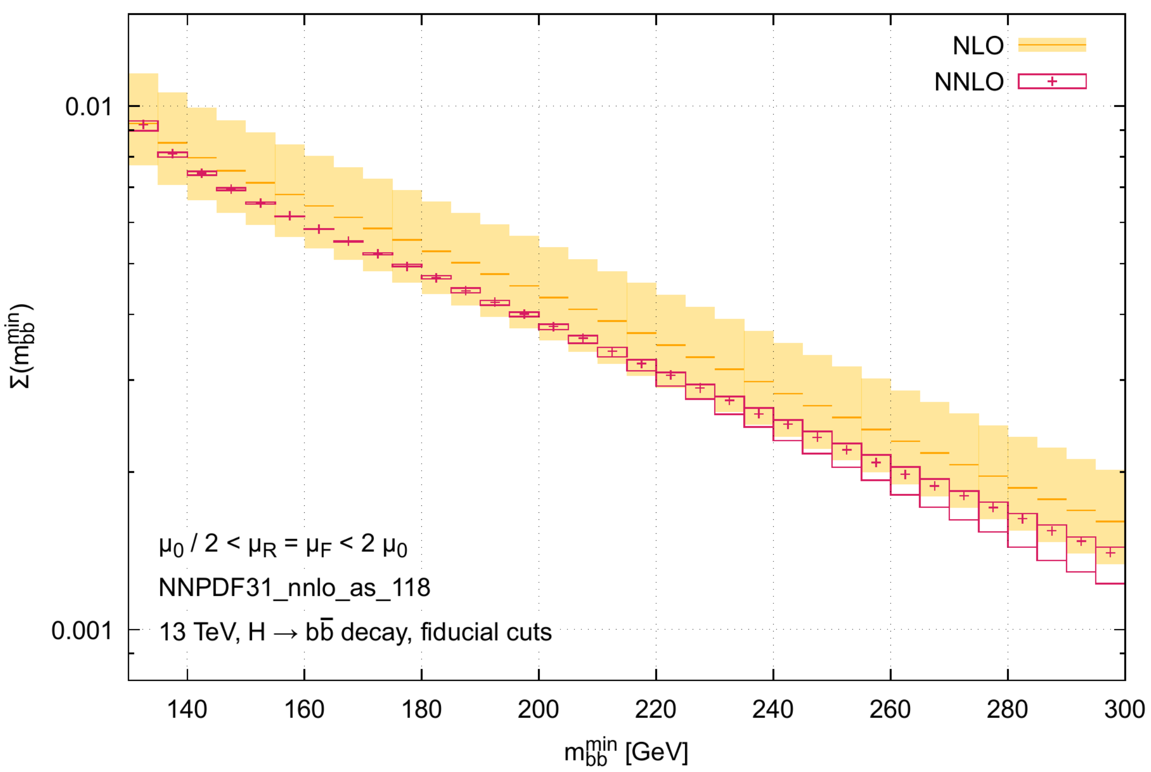


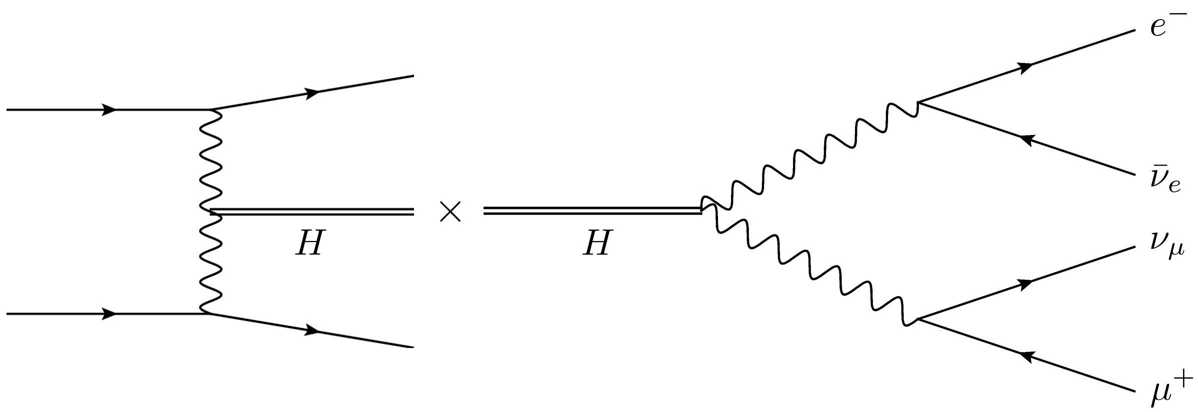
Higgs mass reconstruction



Miscellaneous

WBF + H $\to$ WW* $\to$ 2l 2ν

- Integration trick of before enables efficient computations of even more complex final states



- Cuts loosely following latest CMS measurement [Phys. Lett. B 791, 96 (2019)]
  - Leading lepton $p_{\perp,l_1} > 25\,\mathrm{GeV}$ / Subleading lepton $p_{\perp,l_2} > 13\,\mathrm{GeV}$
  - Rapidity of leptons between rapidity of VBF tagged jets
  - Transverse mass: $60\,\mathrm{GeV} < m_T \equiv \sqrt{2p_T^{l_1 l_2} p_T^{\mathrm{miss}} \left(1 - \cos\Delta\phi_{l_1 l_2, \vec{p}_T^{\mathrm{miss}}}\right)} < 125\,\mathrm{GeV}$
  - Lepton system: $p_{\perp,l_1 l_2} > 30\,\mathrm{GeV}\,,\quad m_{l_1 l_2} > 12\,\mathrm{GeV}$
  - Missing pt: $p_T^{\mathrm{miss}} > 20\,\mathrm{GeV}$

WBF + H → WW* → 2l 2ν

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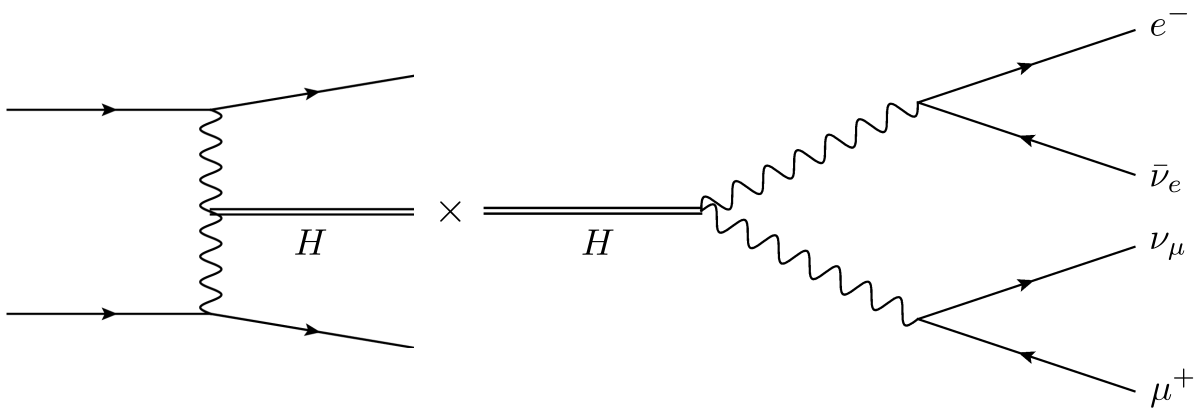

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  - Missing pt: $p_T^{\text{miss}} > 20\,\text{GeV}$

- Mild cuts on Higgs decay products
  $\rightarrow$ no significant change in fiducial WBF region expected ...

WBF + H → WW* → 2l 2ν

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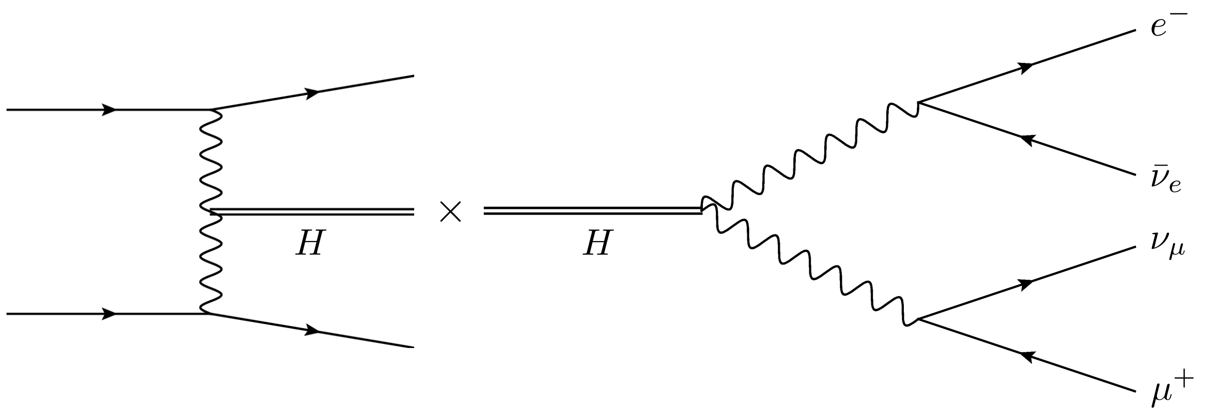

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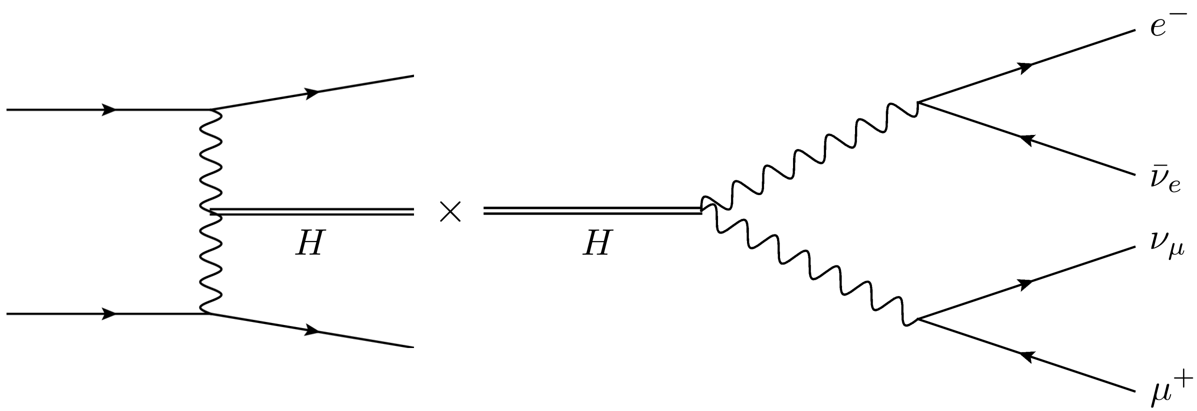
  - Missing pt: $p_T^{\mathrm{miss}} > 20\,\mathrm{GeV}$

- Factorization of production and decay »practically« unbroken
  → no huge difference in shapes of decay observables for NLO → NNLO expected ...

WBF + H → WW* → 2l 2ν

- Integration trick of before enables efficient computations of even more complex final states



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  - Leading lepton $p_{\perp,l_1} > 25\,\mathrm{GeV}$ / Subleading lepton $p_{\perp,l_2} > 13\,\mathrm{GeV}$
  - Rapidity of leptons between rapidity of VBF tagged jets

Similar corrections as in case of stable Higgs production found!

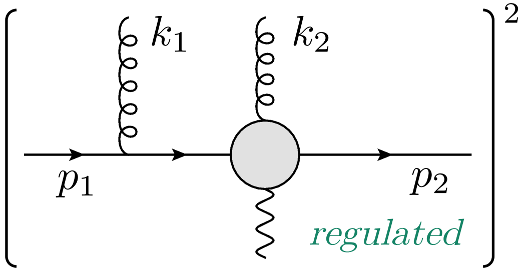
$$\sigma_{\mathrm{NNLO}}^{l^-\bar{\nu}l^+\nu} = \underbrace{0.719\,\mathrm{fb}}_{\mathrm{LO}} + \underbrace{(-0.057)\,\mathrm{fb}}_{\Delta\mathrm{NLO}} + \underbrace{(-0.03)\,\mathrm{fb}}_{\Delta\mathrm{NNLO}}$$

	ΔNLO	ΔNNLO
	-7.9%	-4.2%
(stable Higgs)	-8.3%	-3.2%

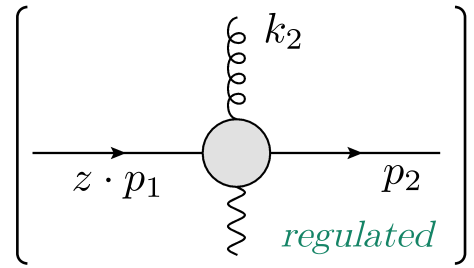
Phase space parametrization (partonic center-of-mass frame)

- Consider a single collinear integrated subtraction term (schematically)

$$\int \frac{\mathrm{d}^3\vec{k}_1}{(2\pi)^3 2E_{k_1}} \lim_{k_1 \| p_1}$$

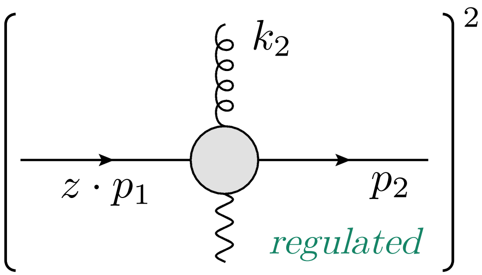


$$\sim \int^1 \mathrm{d}z \left[\frac{1}{1-z}\right]_+ \times \frac{1}{z}$$

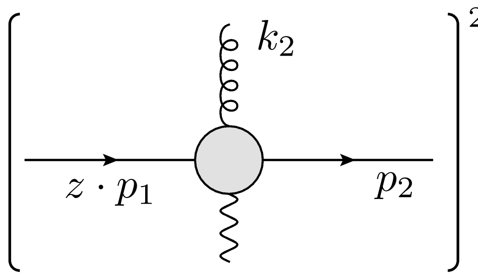


$$+ \ldots$$

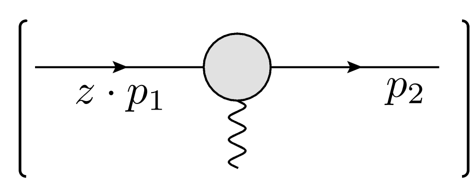
- It contains "boosted" and regulated NLO matrix element squared



$$\approx$$

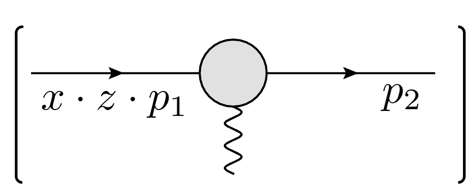


$$- \mathrm{Eikonal}(z \cdot p_1, p_2, k_1)$$



subtract ***soft*** *singularity*

$$- \frac{1}{z p_1 \cdot k_2} P_{qq}\left(\frac{zE_1 - E_{k_2}}{zE_1}\right)$$



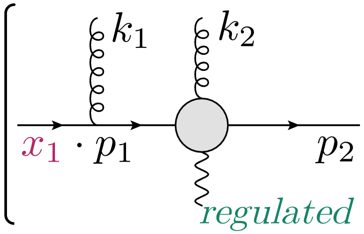
$$- \ \ldots$$

subtract ***collinear*** $\mathbf{k_2} \ || \ \mathbf{p_1}$ *singularity*

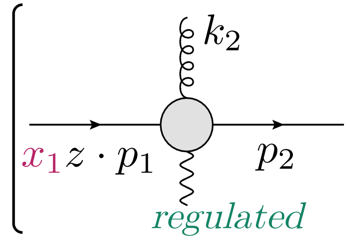
Phase space parametrization (hadronic center-of-mass frame)

- Partonic $\rightarrow$ **hadronic** center-of-mass frame
- Consider a single collinear integrated subtraction term

$$\int \mathrm{d}x_1 f(x_1) \int \frac{\mathrm{d}^3\vec{k}_1}{(2\pi)^3 2E_{k_1}} \lim_{k_1 \| p_1} \Bigg[$$



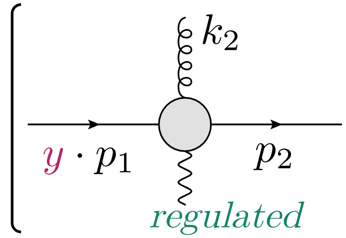
$$\Bigg]^2 \approx \int \mathrm{d}x_1 f(x_1) \int^1 \mathrm{d}z \left[\frac{1}{1-z}\right]_+ \times \frac{1}{z} \Bigg[$$



$$\Bigg]^2$$

- Use integration over parton fraction $\mathbf{x_1}$ to substitute $\mathbf{x_1 z \rightarrow y}$ (ignoring finite pieces for $\mathbf{z < y}$)

$$\approx \int \mathrm{d}y \underbrace{\left[\int_y^1 \mathrm{d}z \left[\frac{1}{1-z}\right]_+ \frac{f(y/z)}{z^2}\right]}_{\equiv \tilde{f}(y)} \times \Bigg[$$



$$\Bigg]^2$$

- Integration over "soft singularity" $\mathbf{z}$ factorizes from resolved matrix element
- Use redefined parton distribution functions

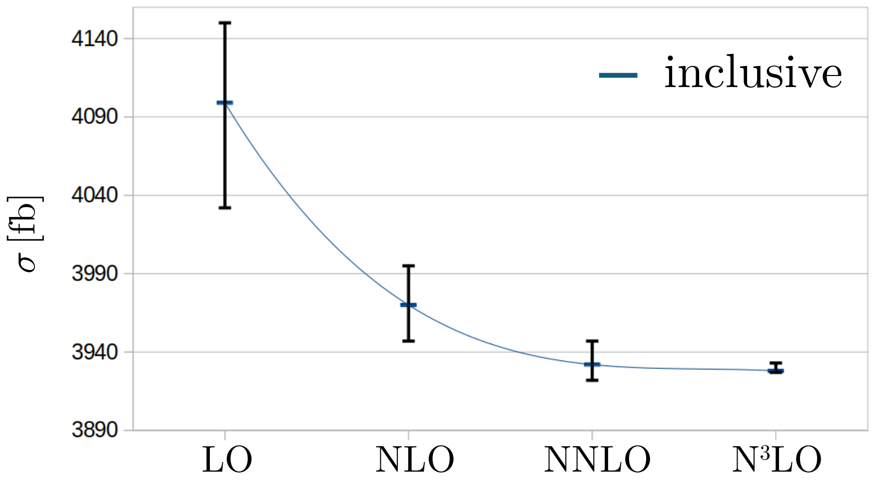
State of the art of QCD analysis

- Historically focus on corrections to ***factorizable*** contributions:
  - **2015 (differential)** *"Fully differential VBF Higgs production at NNLO"* [Matteo Cacciari, Frédéric A. Dreyer, Alexander Karlberg, Gavin P. Salam, Giulia Zanderighi]; Projection-to-Born method; Used for checks of our implementation
  - **2016 (inclusive)** *"Vector-boson fusion Higgs production at N^3LO in QCD"* [Dreyer, Karlberg '16]
  - **2018 (differential)** *"NNLO corrections to VBF Higgs boson production"* [Juan Cruz-Martinez, Nigel Glover, Thomas Gehrmann, Alexander Huss]; Antenna-subtraction

- Recent growing interest in *non-factorizable* contributions

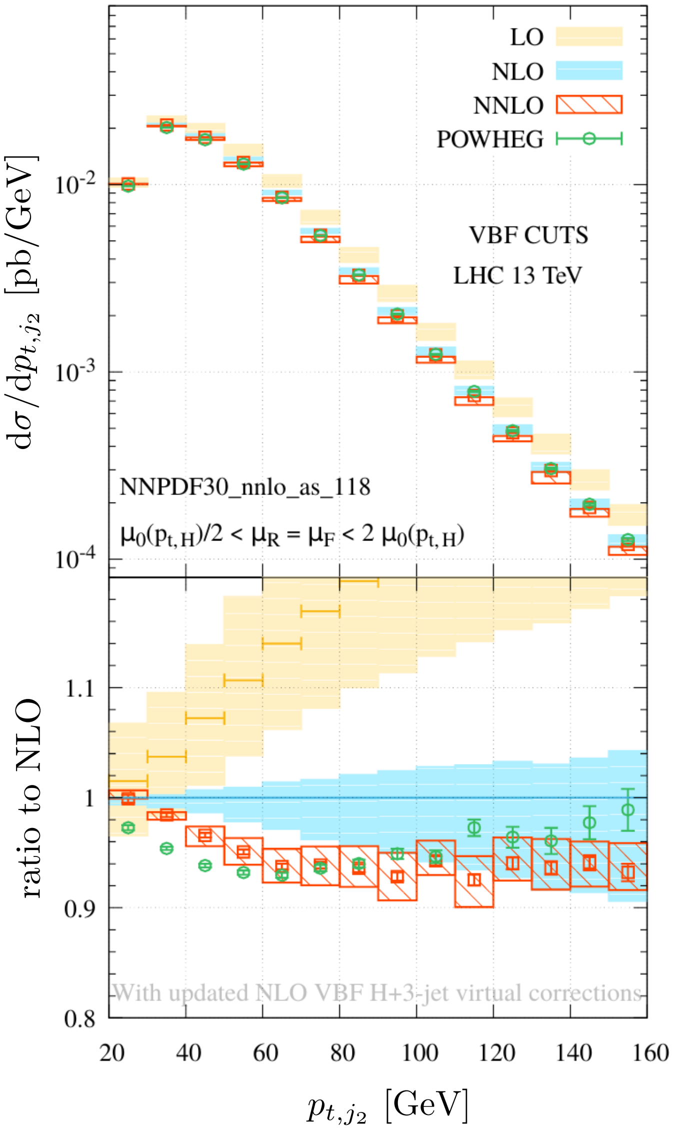
  $\rightarrow$ First studies available [Dreyer, Karlberg, Tancredi '20; Chen, Figy, Plätzer '21]

- **Inclusive:** Nicely converging, N^3LO within residual scale uncertainties
- **Fiducial cuts:** NNLO corrections outside of scale uncertainties



State of the art of QCD analysis

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



[Rauch, Zeppenfeld '17]