MAX-PLANCK-INSTITUT
FÜR PHYSIK

NNLO+PS predictions for Higgs production via bottom fusion

Christian Biello

in collaboration with
Aparna Sankar, Marius Wiesemann, Giulia Zanderighi [Eur.Phys.J.C 84 (2024) 5, 479]
+ Javier Mazzitelli [in progress]

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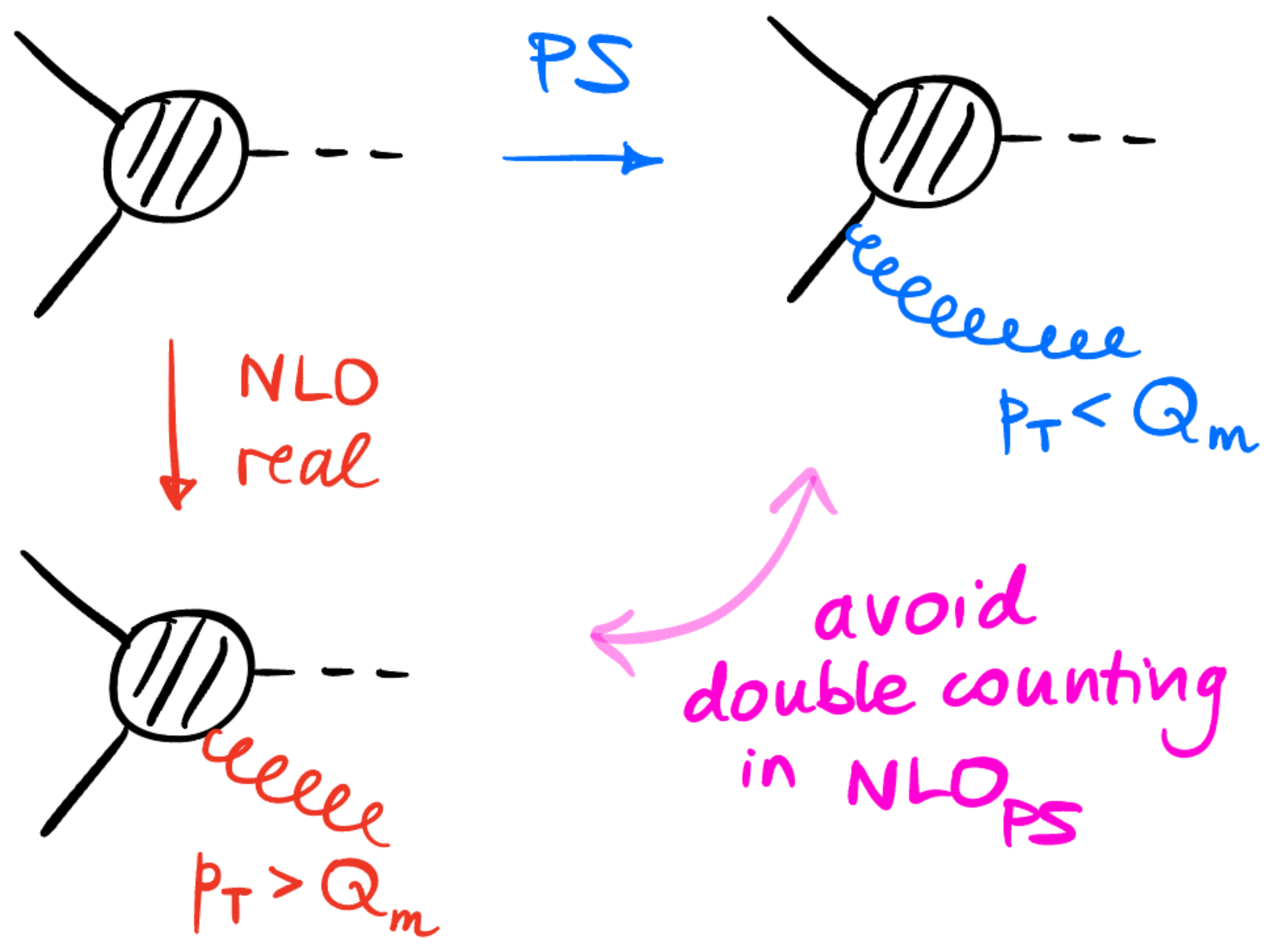
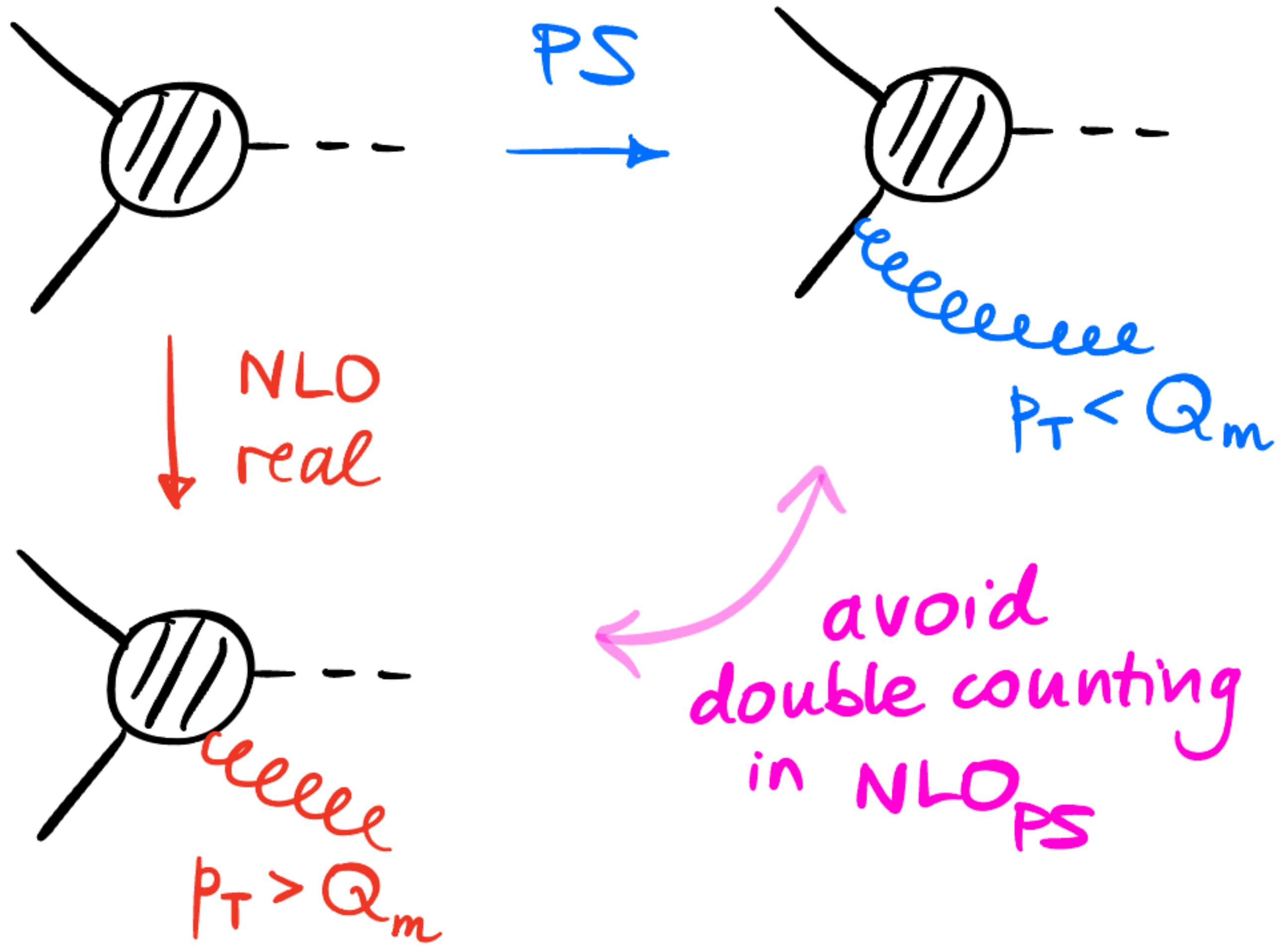
Prague, Czech Republic
July 18th, 2024



Problem: Match fixed-order predictions with parton shower avoiding an unphysical matching scale.

POWHEG idea: implement a Monte Carlo generator that produces just the first shower emission using exact NLO matrix elements.

Nason [hep-ph/0409146]



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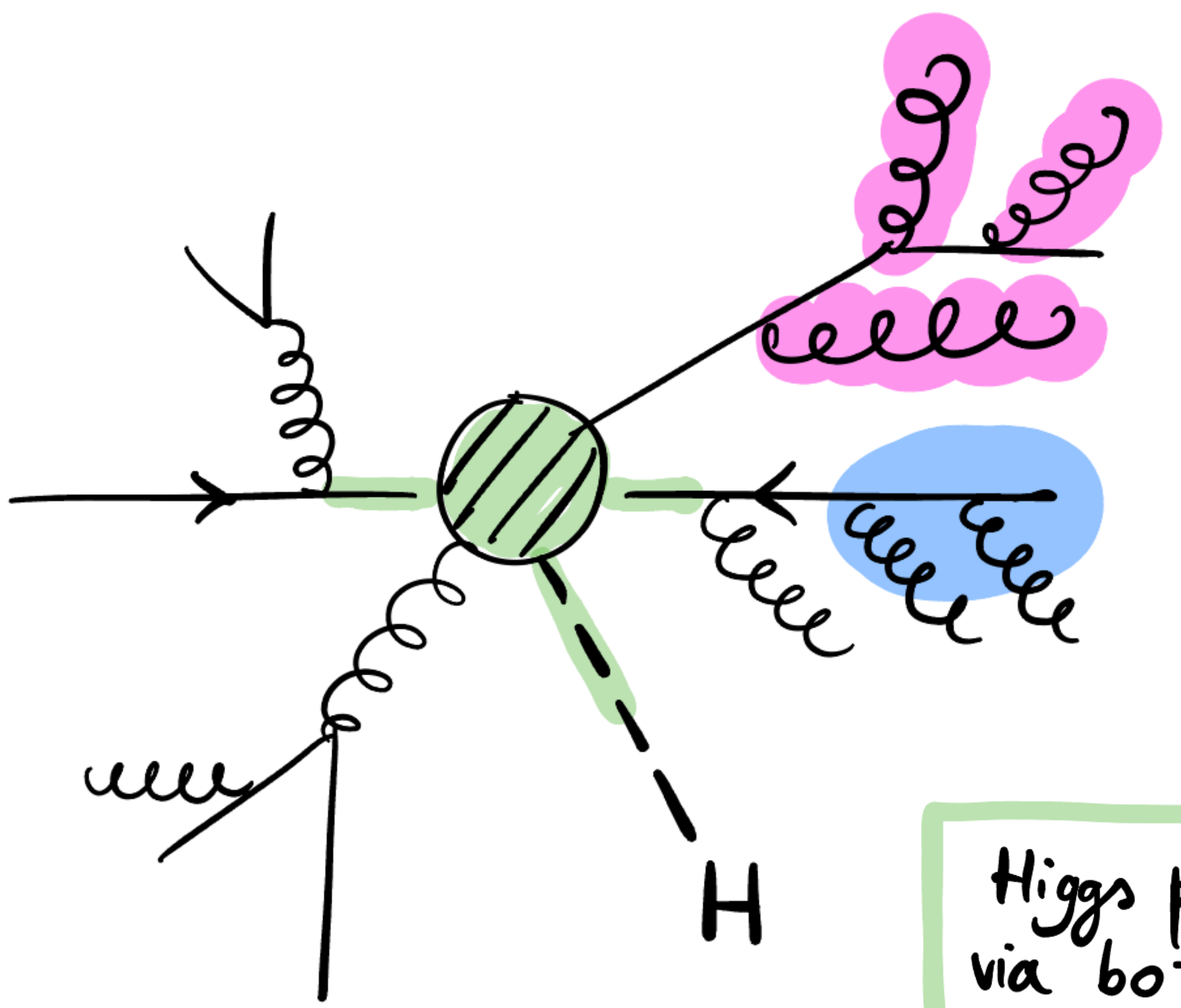
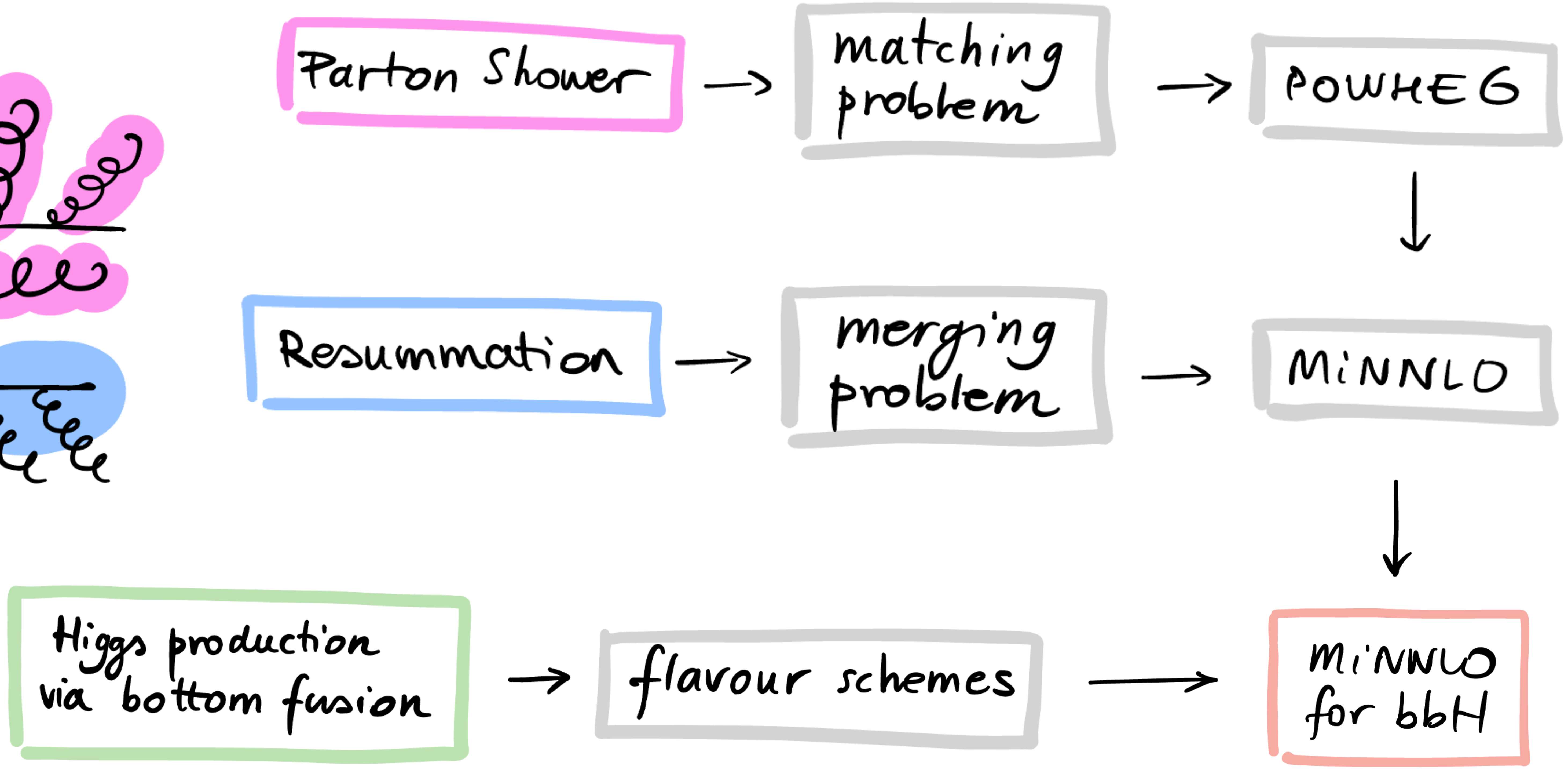
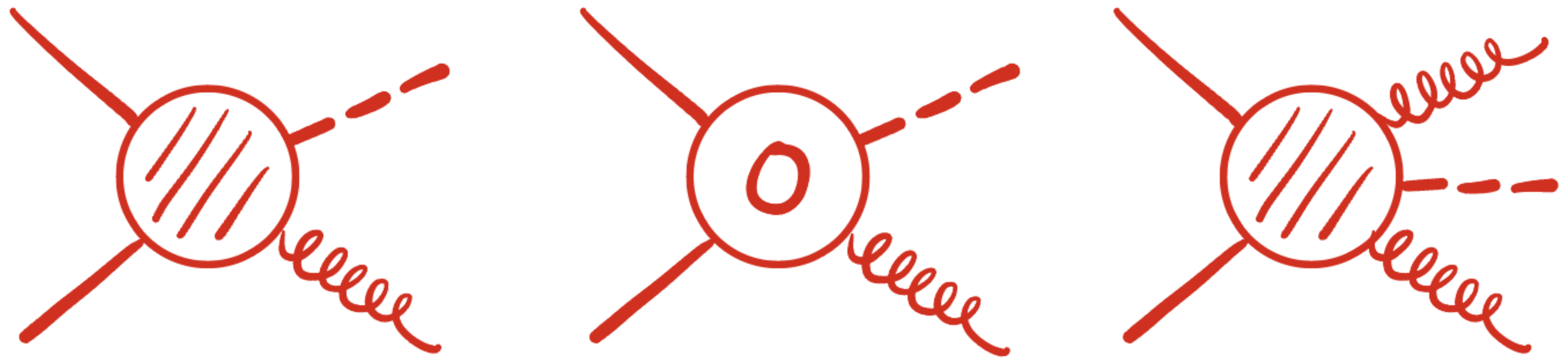




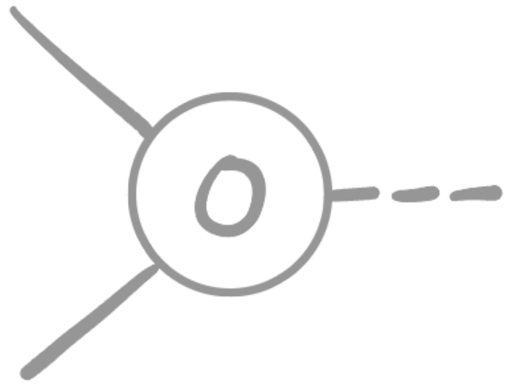
Hamilton, Nason, Oleari, Zanderighi [1212.4504]

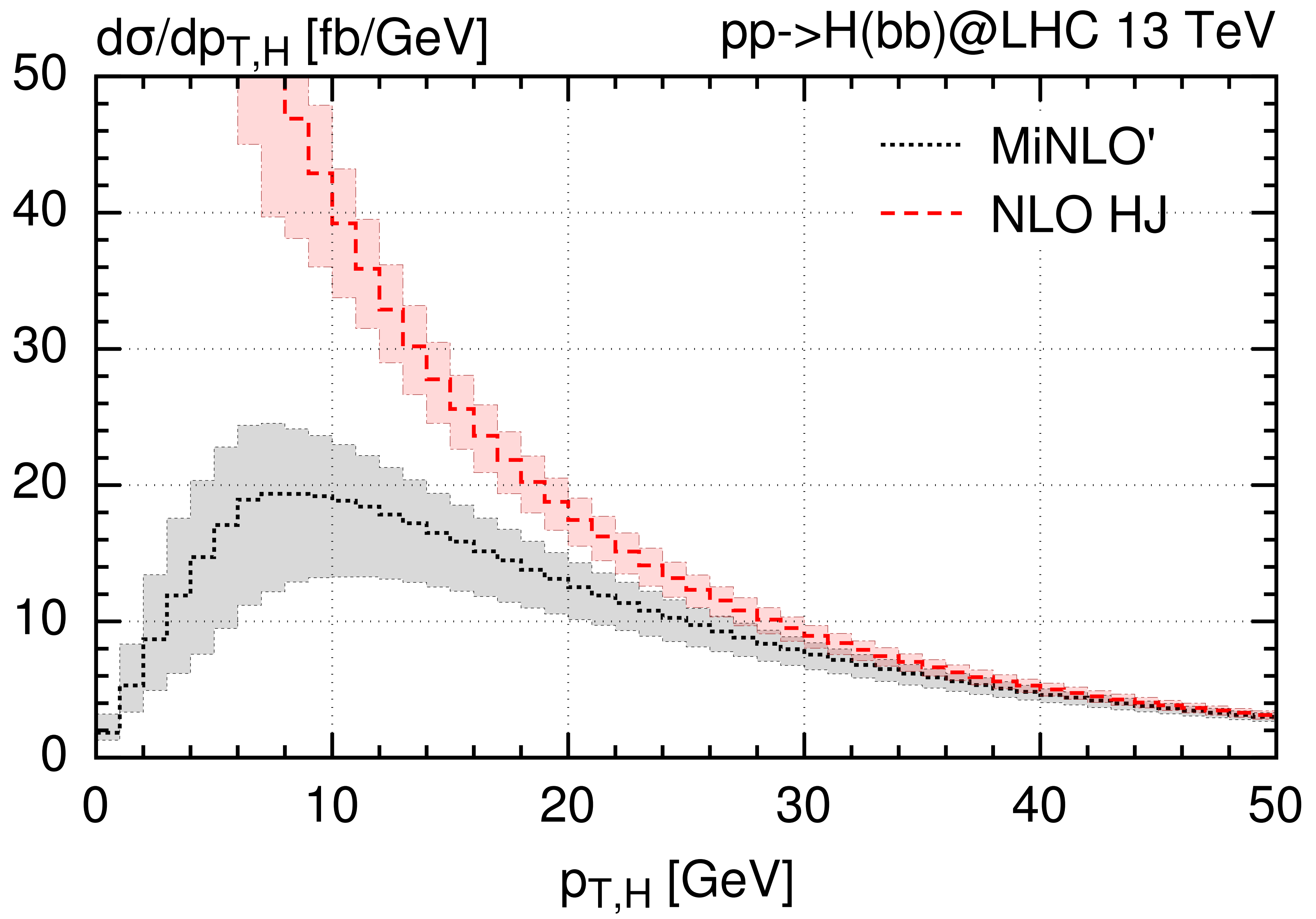
MiNLO'

Start form an HJ generator and perform the PS matching in **POWHEG**.



Obtain NLO accurate predictions for H production with particular scale choices and a **special Sudakov factor**.





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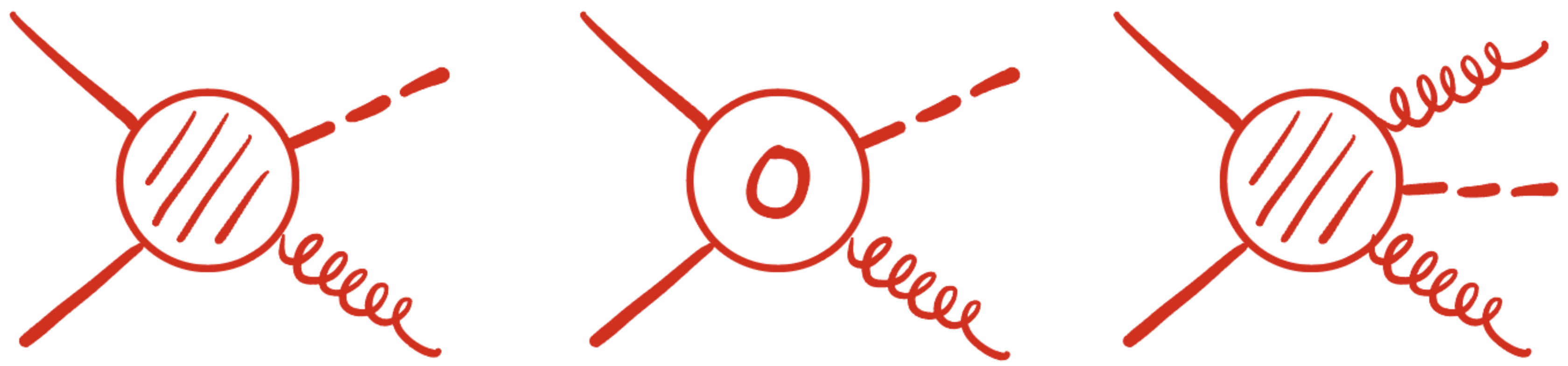

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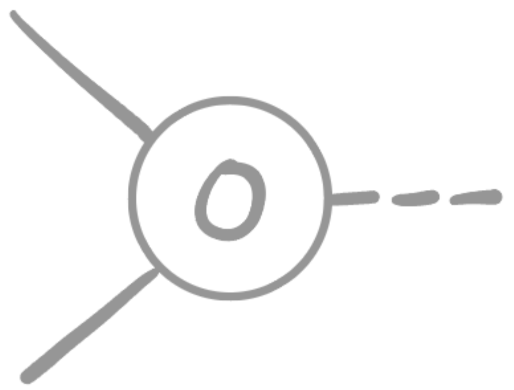
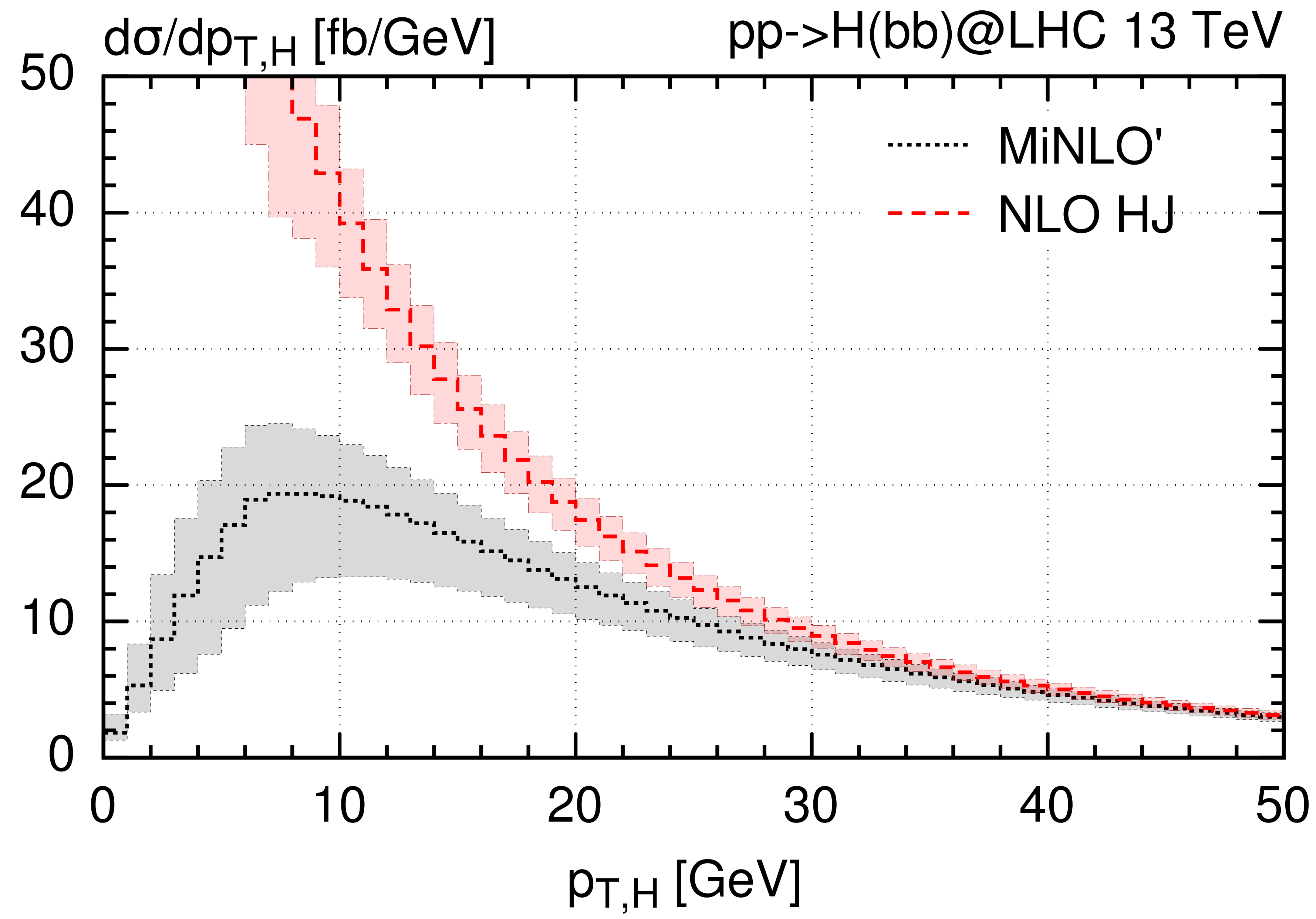
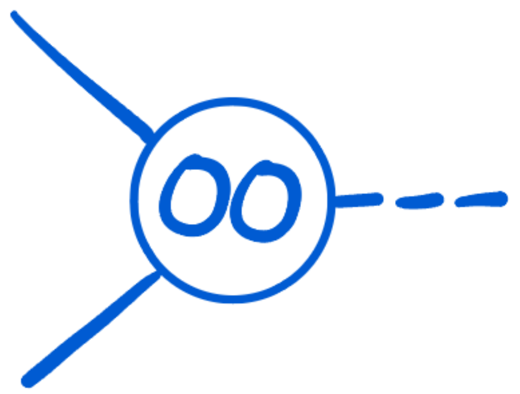




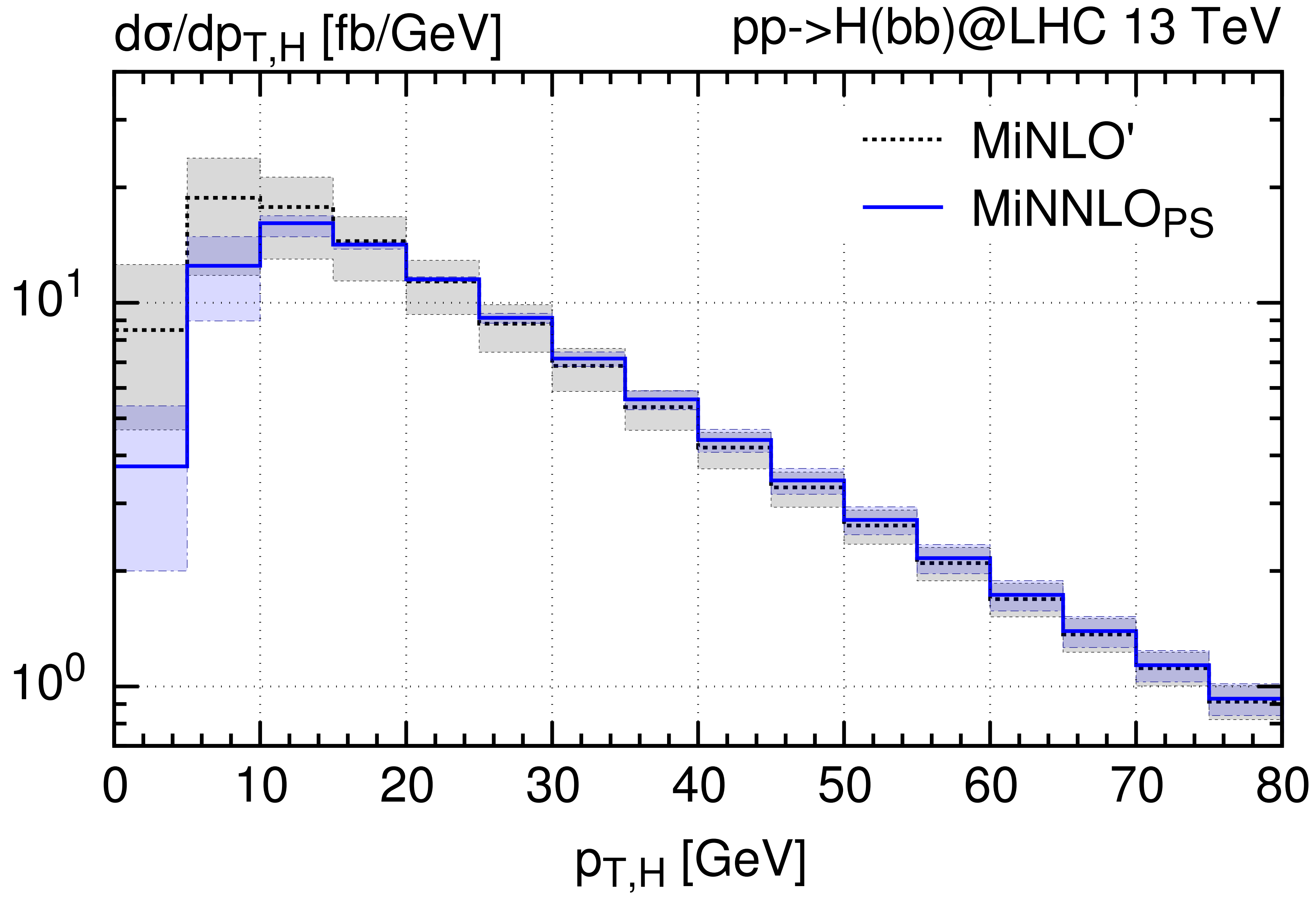
MiNNLOPS is an extension of MiNLO'.

It includes all the terms required to reach NNLO+PS accuracy for the inclusive observables.



Crucial scale choice:

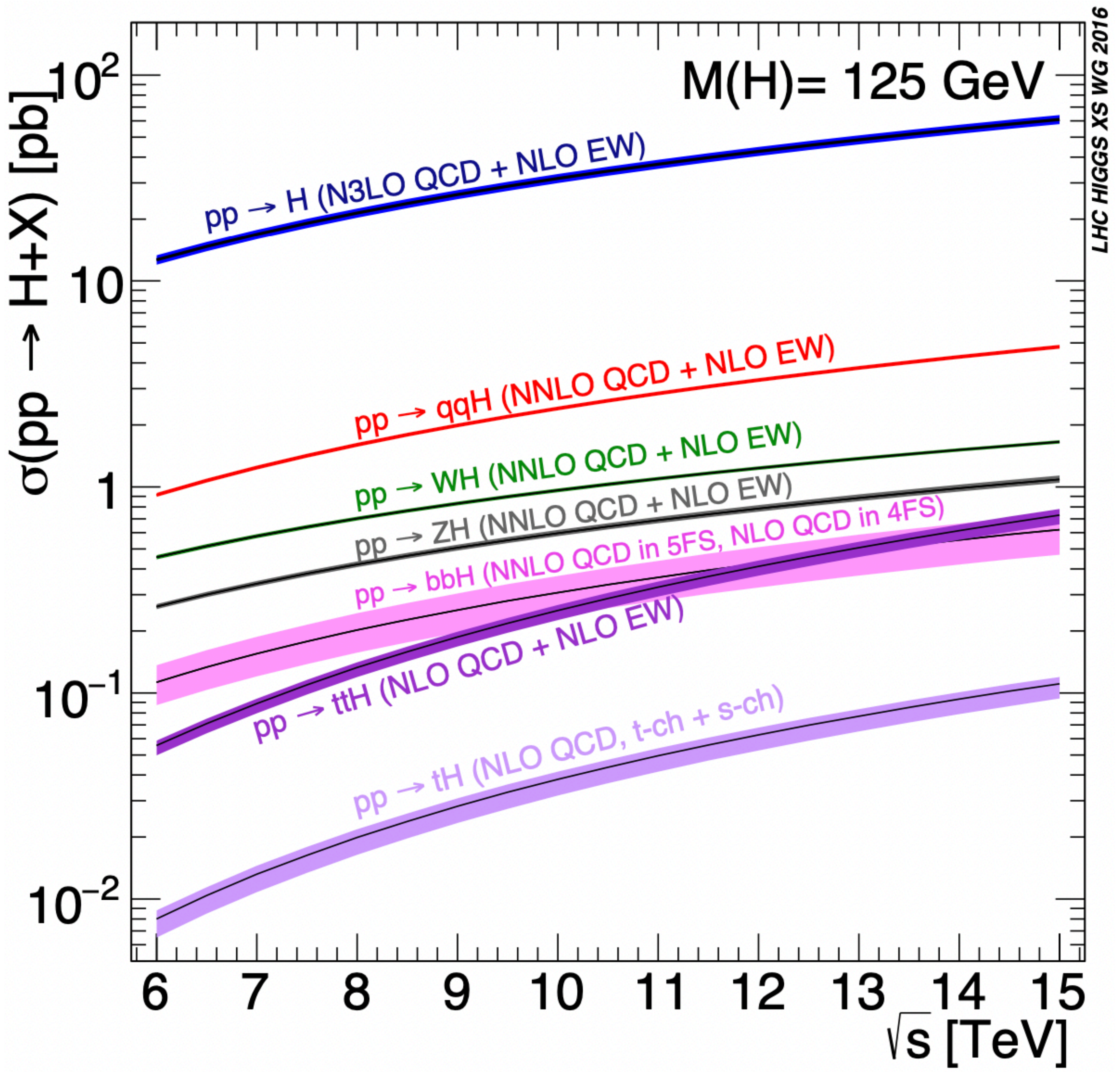
$\mu_R \sim \mu_F \sim p_T$



MiNNLOPS

Monni, Nason, Re, Wiesemann, Zanderighi [1908.06987]

Why Higgs production via bottom fusion?



Although it is not the main production channel, the Higgs creation via bottom fusion

- allows a **direct** evaluation of the **bottom Yukawa** coupling
- is **enhanced in SUSY theories** with large $\tan\beta$ and can become the dominant channel
- is the dominant irreducible **background** in searches for **HH production**

see Elena Mazzeo's talk

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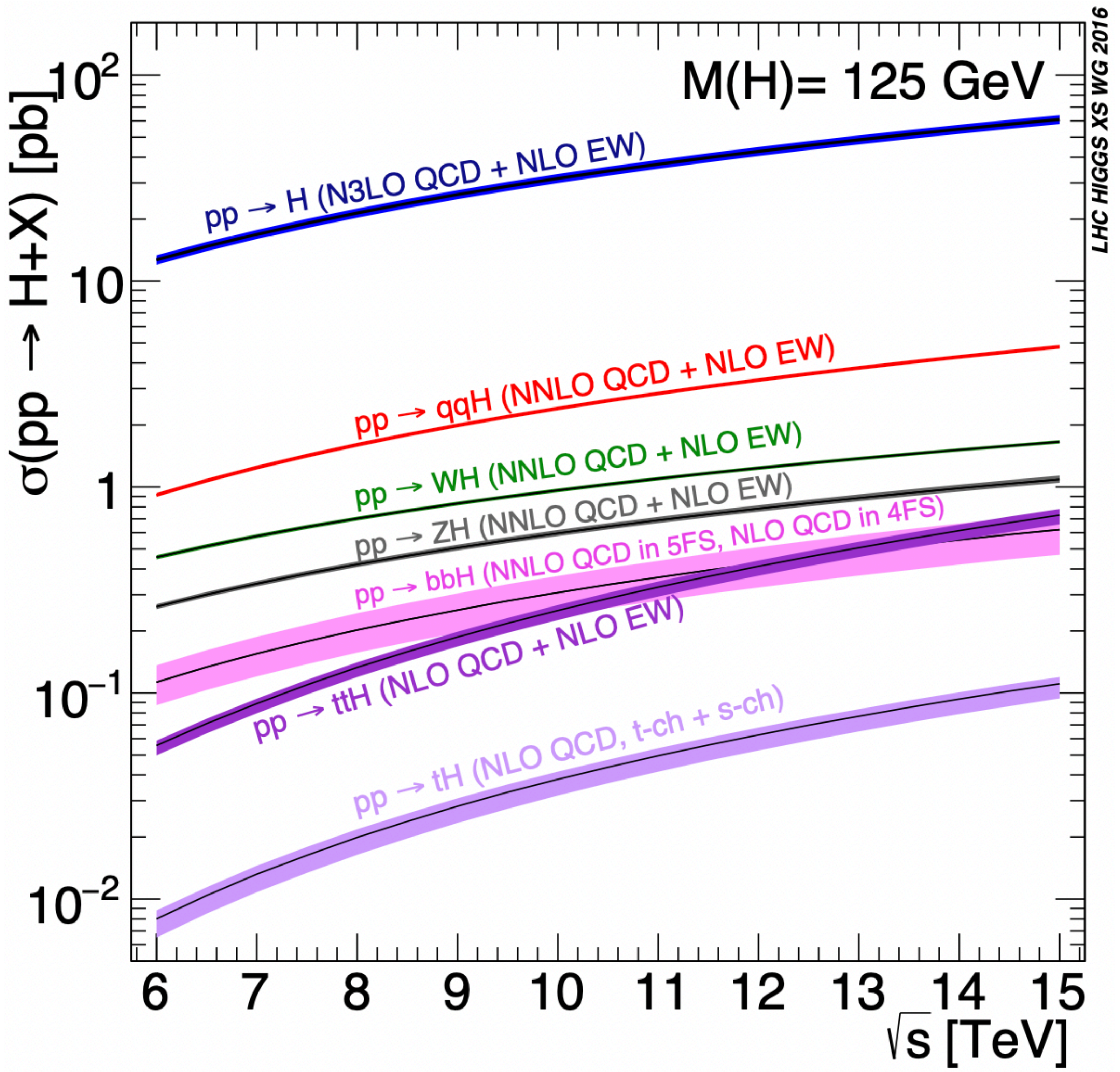

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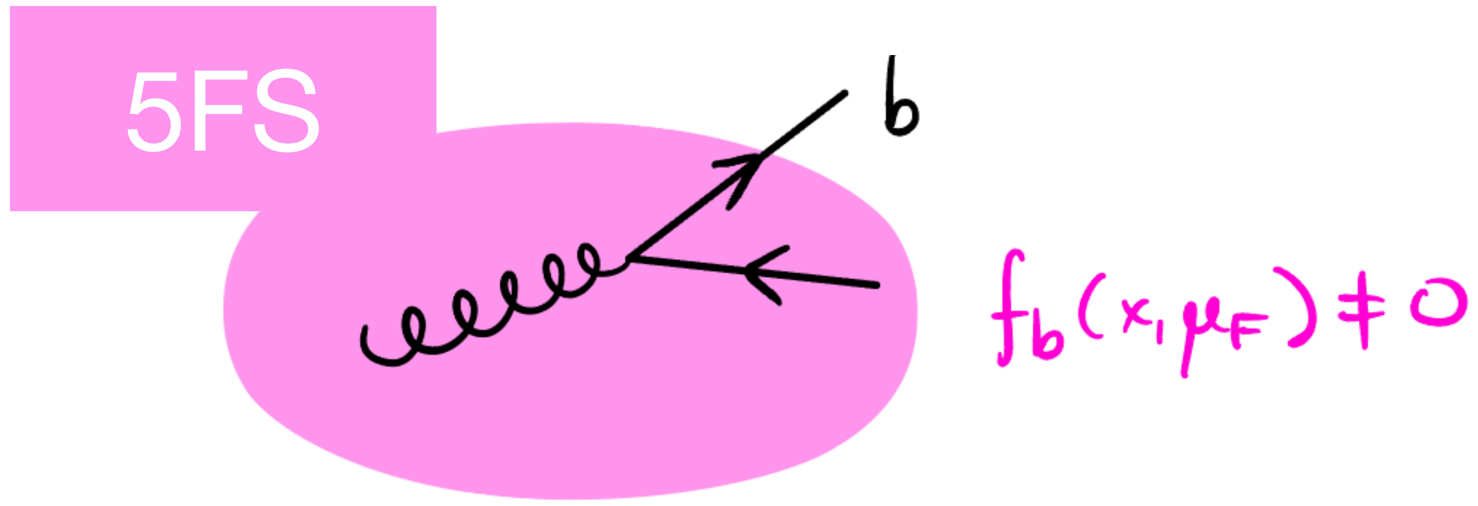
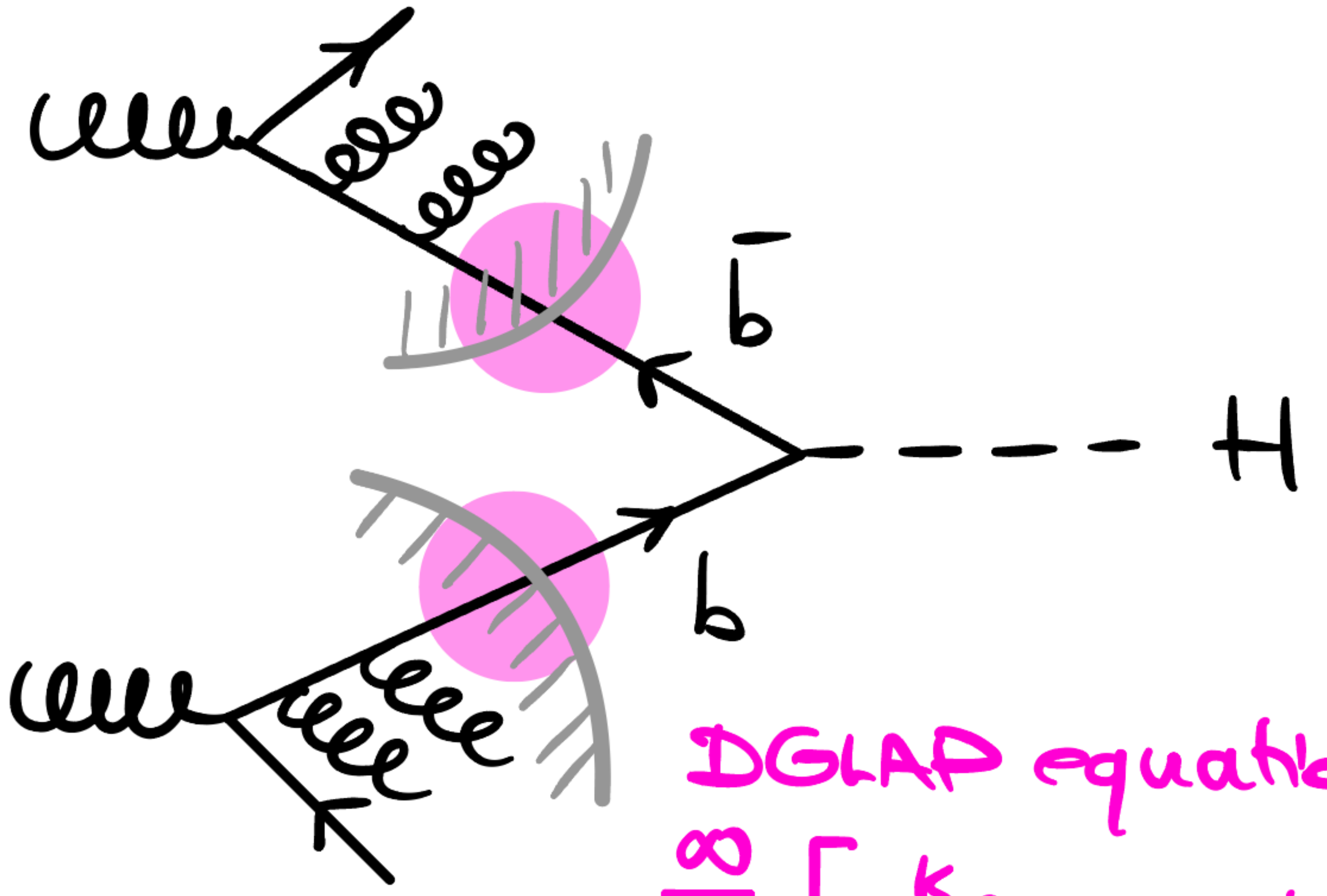
$b\bar{b}H$ is also of theoretical interest for the **different schemes** of calculations that can be used



5FS



DGLAP equations

$$\sum_{k=1}^{\infty}\left[\alpha_s^k(\mu_F)\log^k\left(\frac{\mu_F^2}{m_b^2}\right)\right]$$

massless scheme

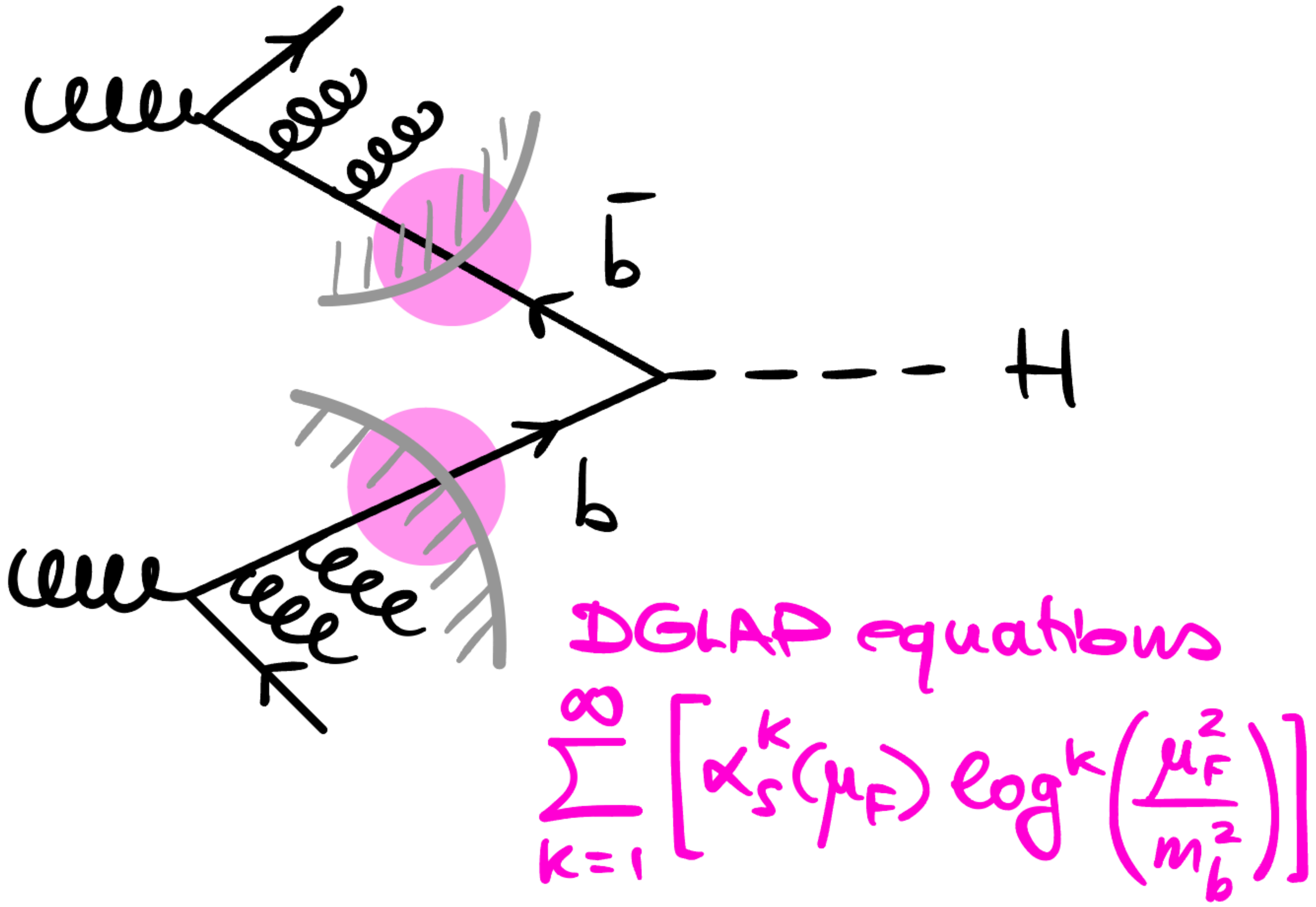
✓ DGLAP evolution resums initial state logs into f_b

✓ Computing higher orders is easier

- Neglecting $O(m_b/m_H)$, it yields less accurate description of bottom kinematic distribution

NNLO_{QCD} + PS

5FS



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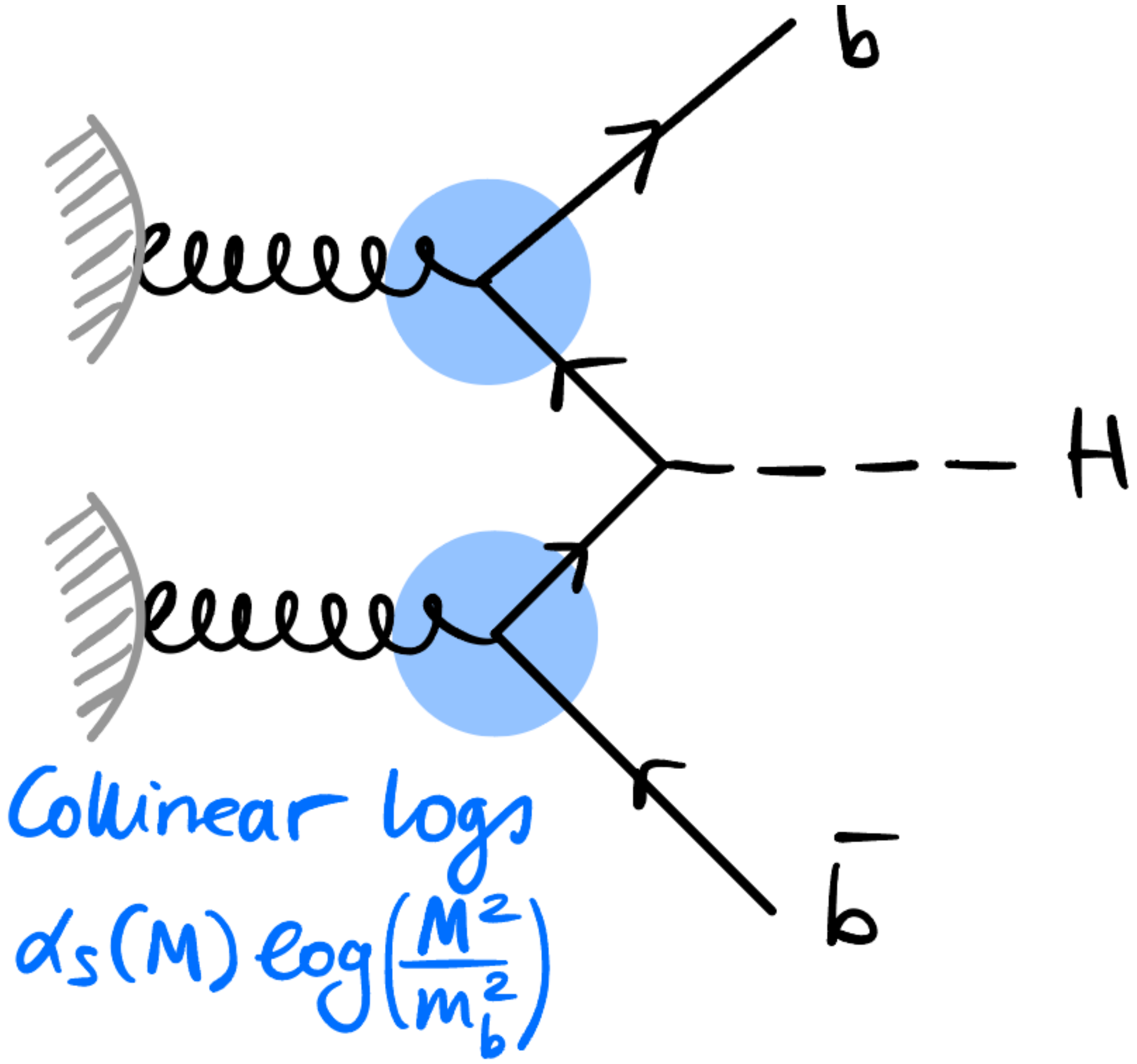
$\mathrm{NNLO}_{QCD} + \mathrm{PS}$

4FS



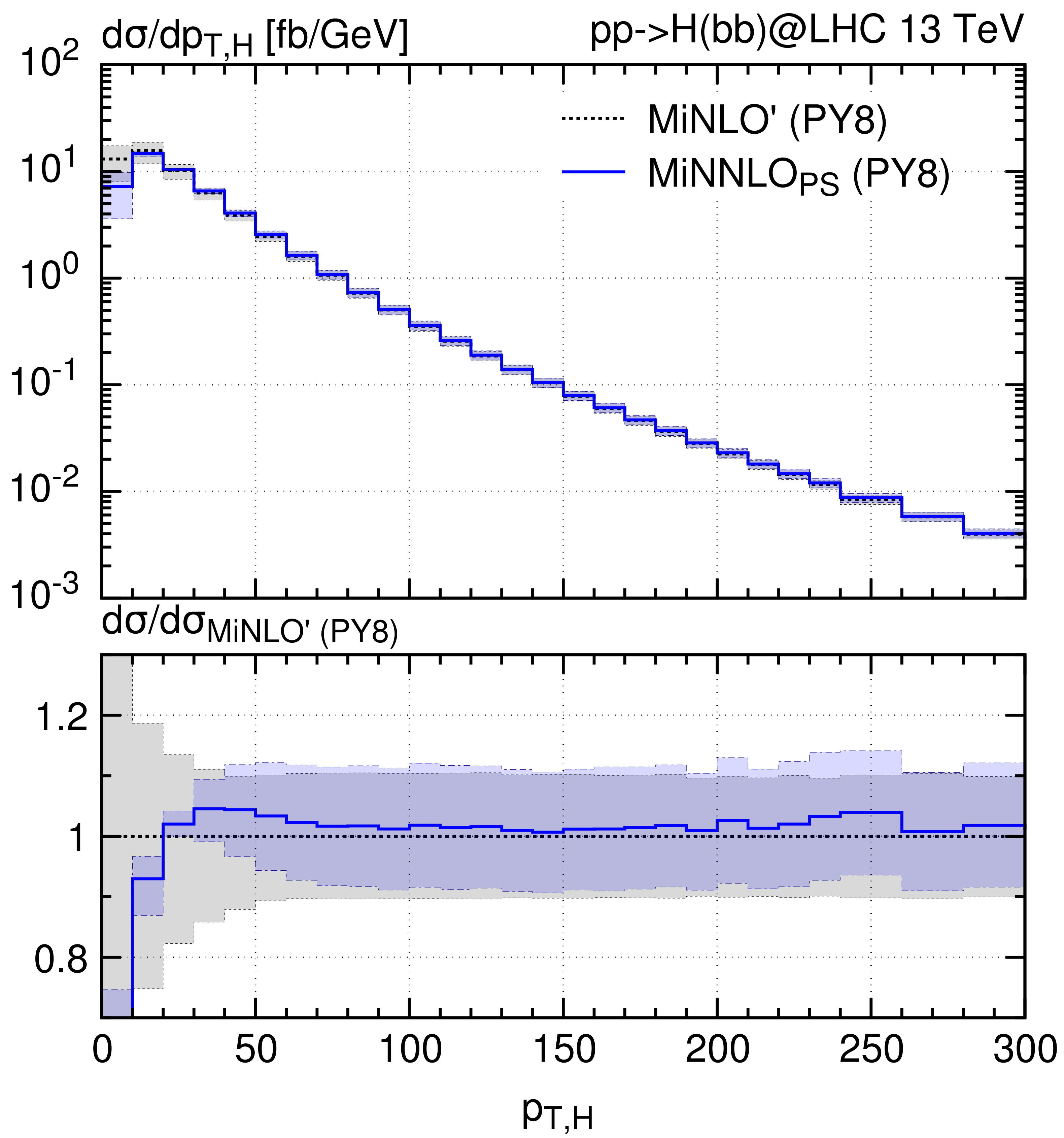
decoupling/massive scheme

- It does not resum possibly large collinear logs
- Computing higher orders is more difficult due to higher multiplicity
- ✓ Mass effects $O(m_b/m_H)$ are there at any order

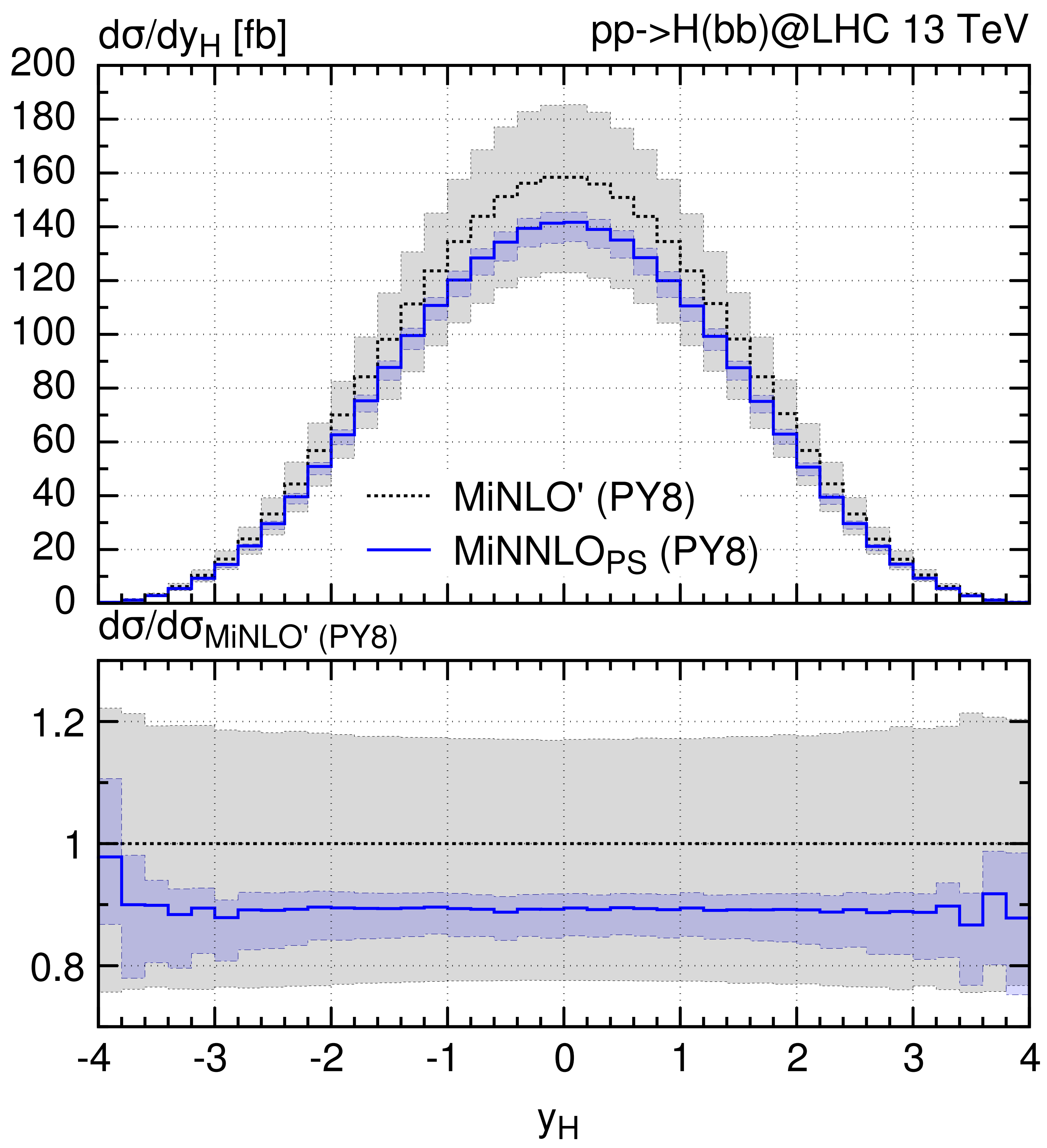
$\mathrm{NNLO}_{QCD} + \mathrm{PS}$

5FS results

Transverse momentum spectrum of the Higgs boson



Rapidity distribution of the Higgs boson



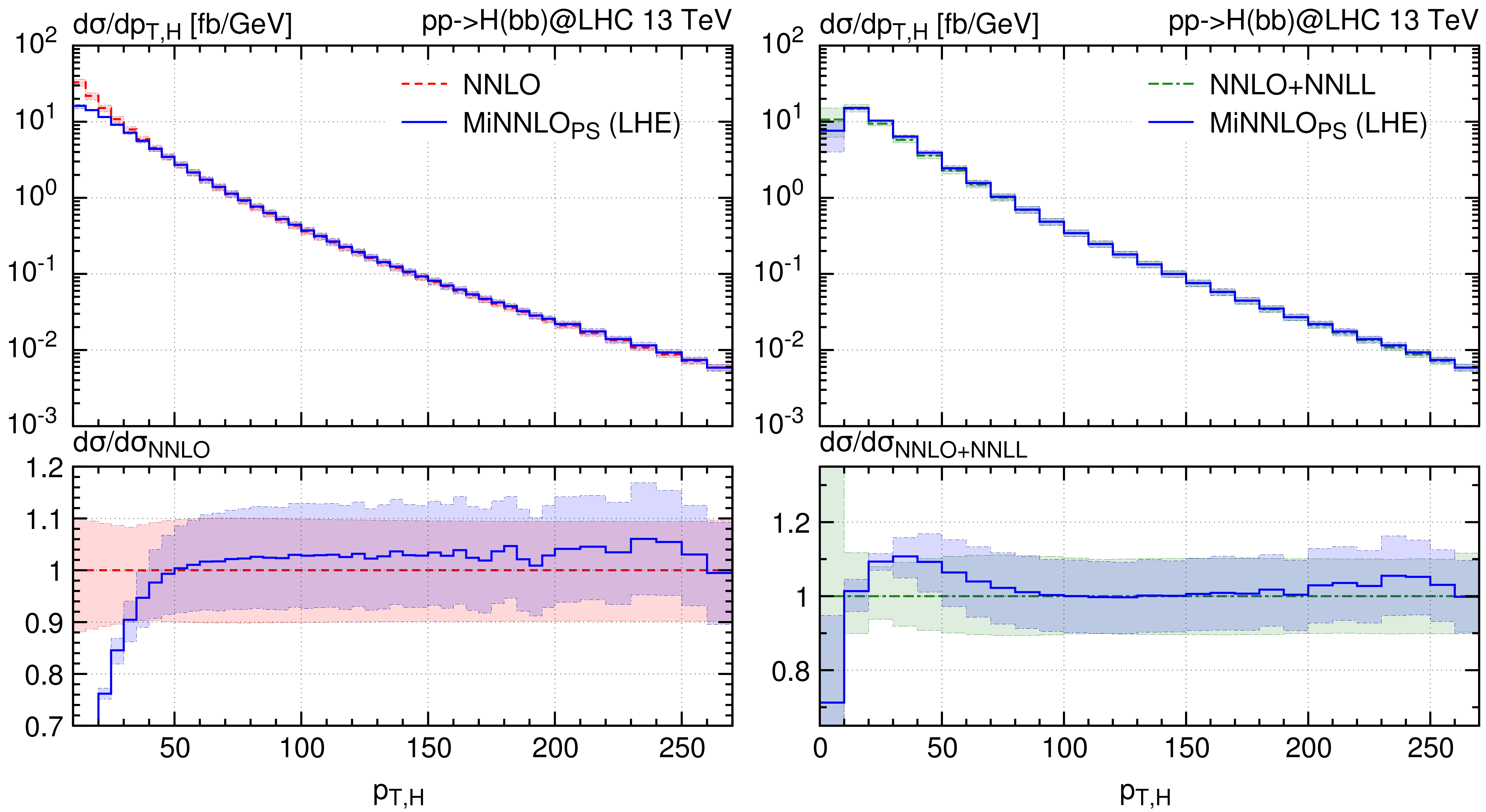
MiNLO′	MiNNLO$_{PS}$
$0.571(1)^{+17.4\%}_{-22.7\%}$ pb	$0.509(8)^{+2.9\%}_{-5.3\%}$ pb

- At small $p_{T,H}$, MiNNLOPS significantly dampens the distribution.
- At high $p_{T,H}$, MiNNLOPS and MiNLO' coincide, both NLO accurate
- MiNNLOPS has a flat negative correction in the rapidity y_H distribution

CB, Sankar, Wiesemann, Zanderighi [2402.04025]

Comparison with analytic results

Transverse momentum spectrum of the Higgs

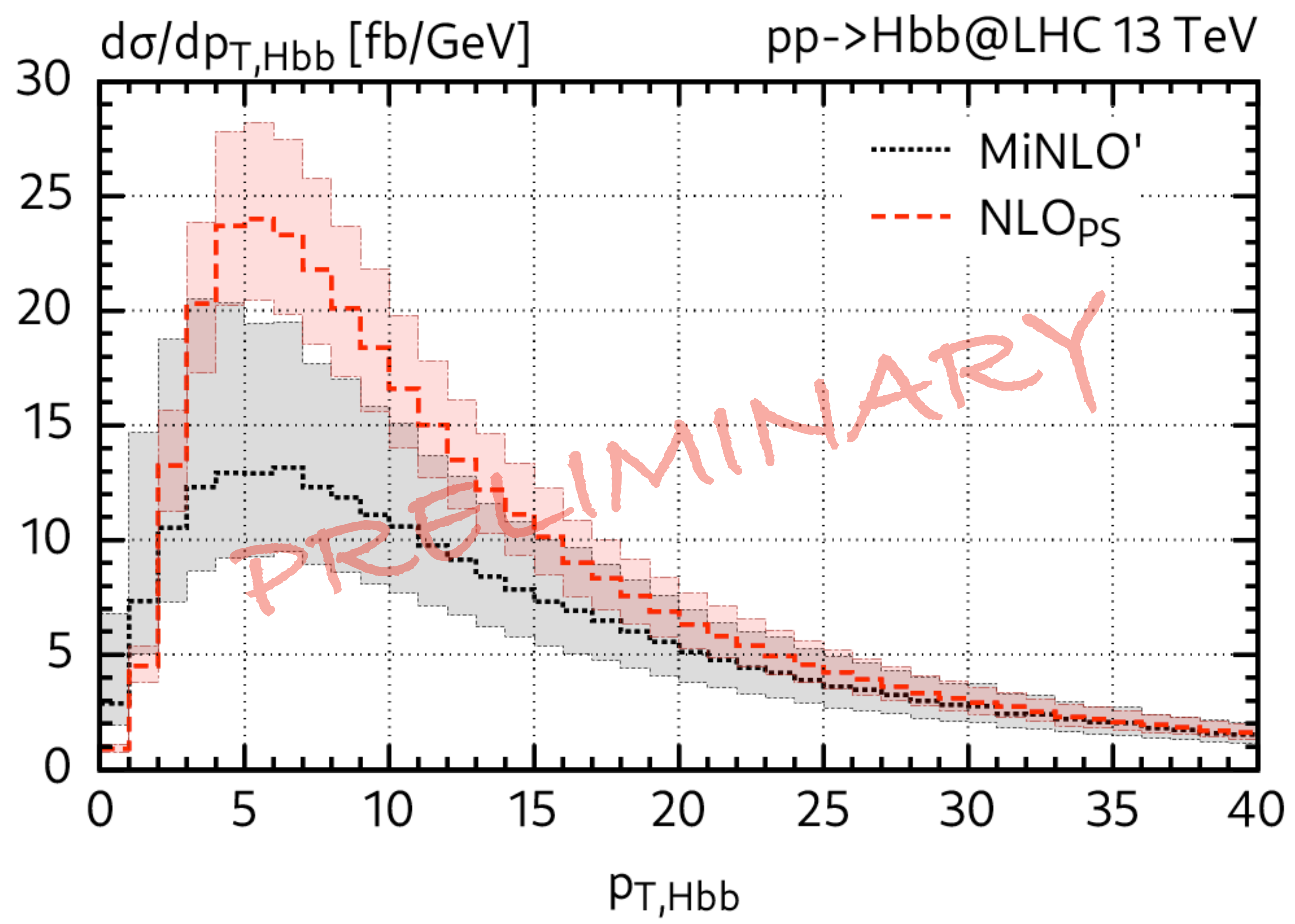


We compare the MiNNLOPS implementation with the NNLO+NNLL results for high $p_{T,H}$

- **Better agreement** at high $p_{T,H}$ with the resumed results compared to NNLO

NNLO Harlander, Tripathi, Wiesemann [1403.7196]
NNLO+NNLL Harlander, Tripathi, Wiesemann [1403.7196]

The missing logs in 4FS MiNLO'

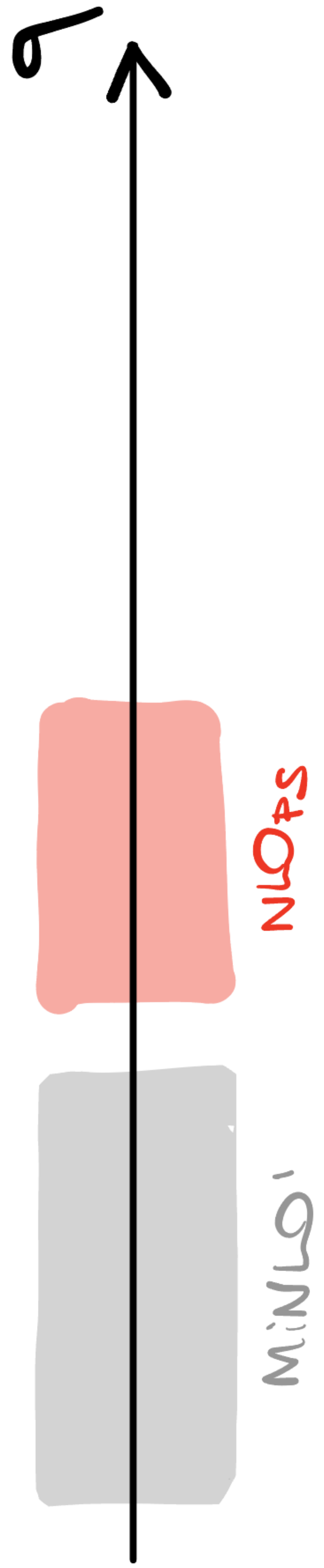


In MiNLO' there are no cancellations of the large $\log(m_b)$ in the real (RV, RR) contributions.

We need the VV contribution to cancel the quasi-collinear divergences.

Same behaviour observed in $b\bar{b}\ell^+\ell^-$.

Mazzitelli, Sotnikov, Wiesemann [2404.08598]



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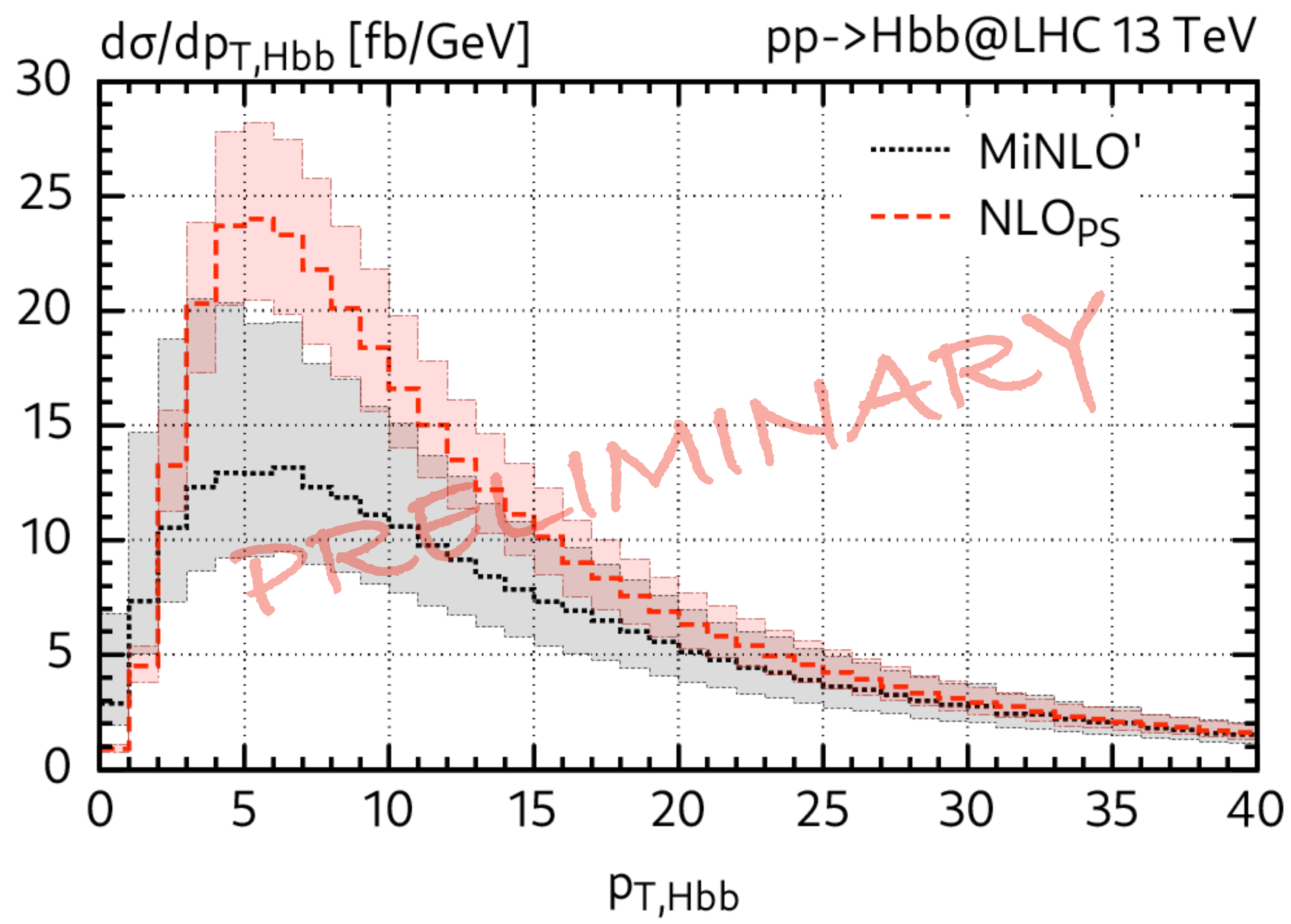

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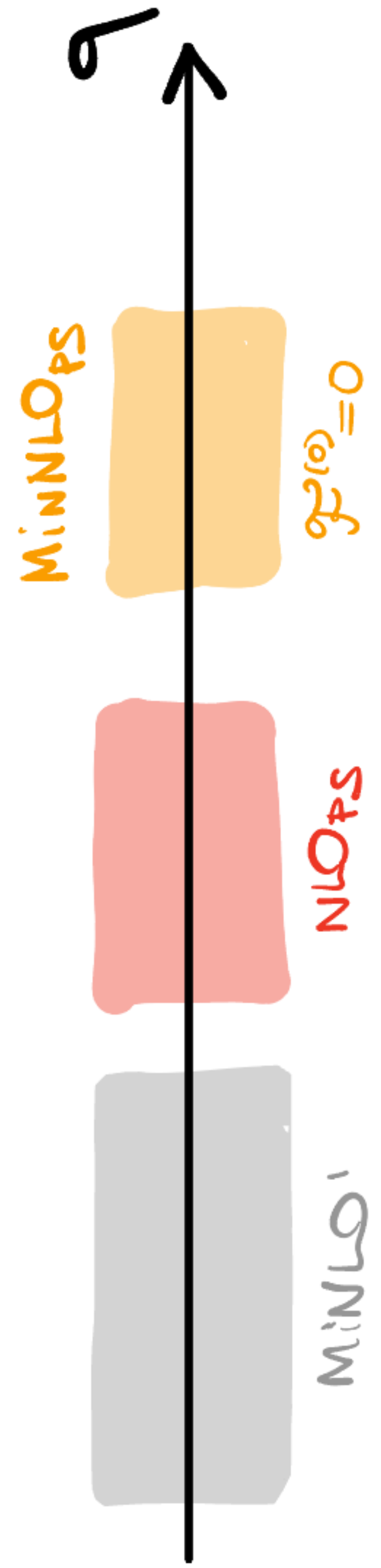


VV approximation by retaining all the log-enhanced contributions through the massification procedure

$$|\mathscr{A}^{(2)}\rangle = \log(m_b)\text{-terms} + \text{const.} + \mathcal{O}\left(\frac{m_b}{Q}\right)$$

$$\mathscr{F}^{(2)}|\mathscr{A}^{(0)}_{m_b=0}\rangle + \mathscr{F}^{(1)}|\mathscr{A}^{(1)}_{m_b=0}\rangle + \mathscr{F}^{(0)}|\mathscr{A}^{(2)}_{m_b=0}\rangle$$

Massless two-loop
Badger, Hartanto, Kryś, Zoia [2107.14733]

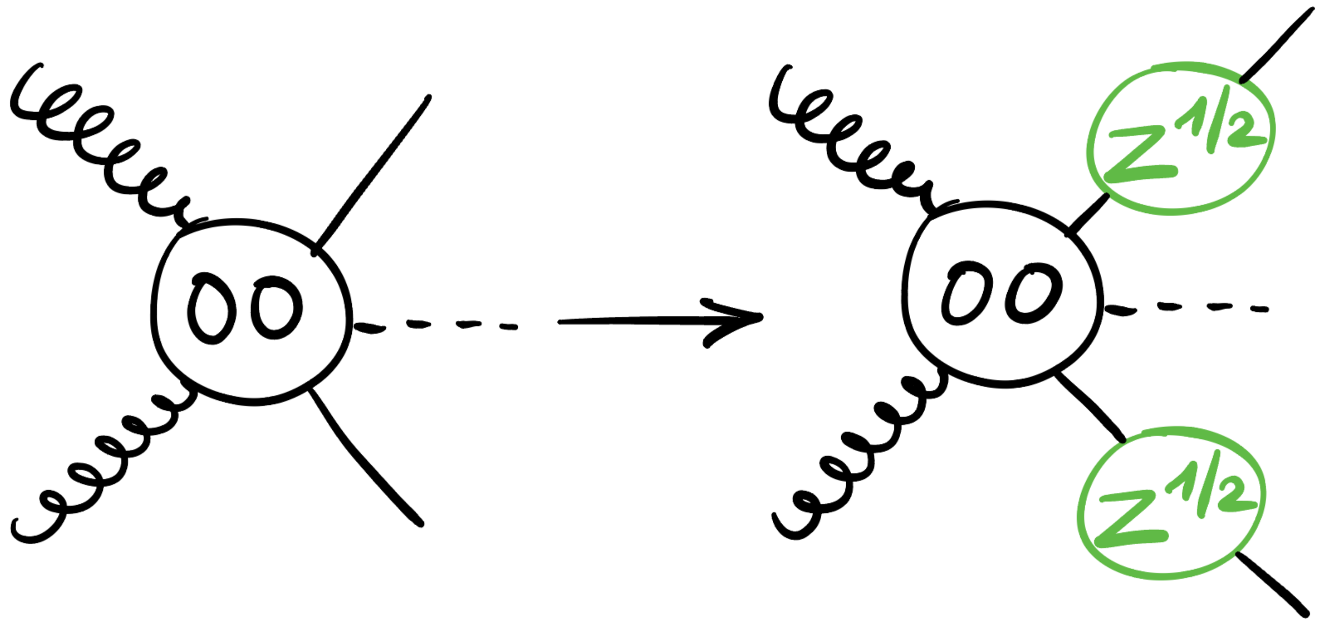
Massification

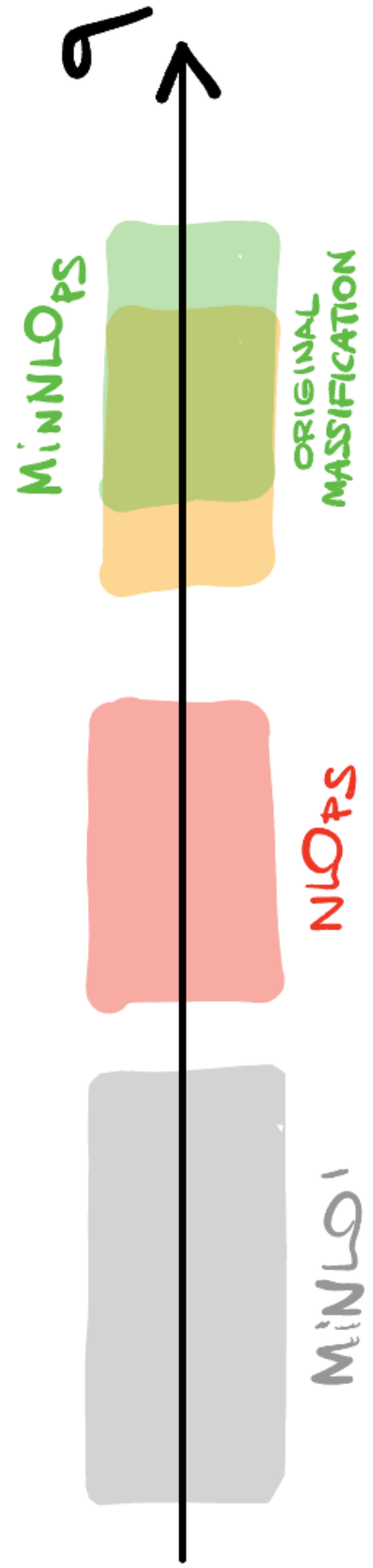
First two-loop massification for Bhabha scattering

Penin [hep-ph/0508127]

Extension for non-abelian theories from factorisation principles

Mitov, Moch [hep-ph/0612149]





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Extension for non-abelian theories from factorisation principles

Mitov, Moch [hep-ph/0612149]

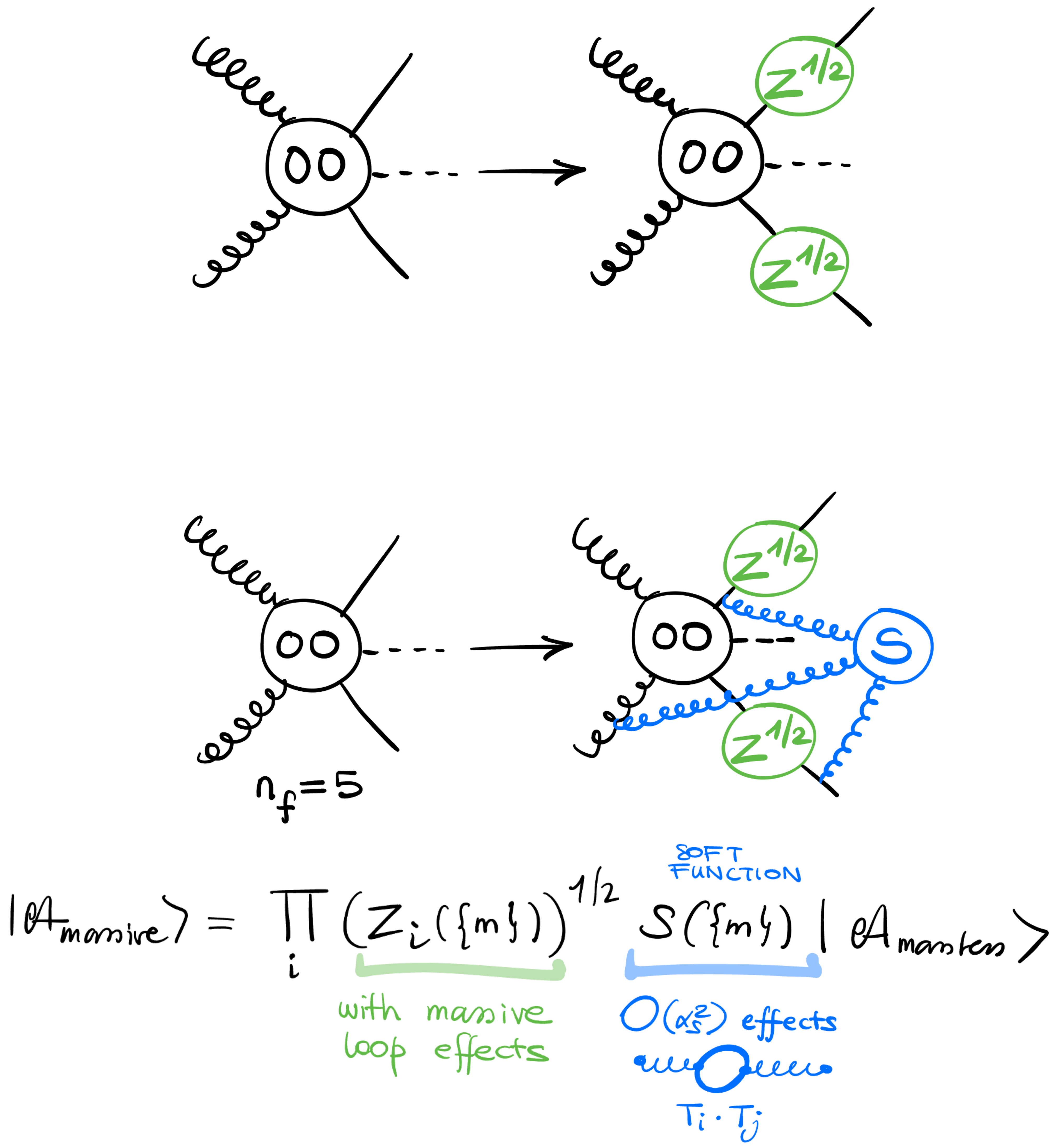
First massification of internal loops for Bhabha using the SCET formalism

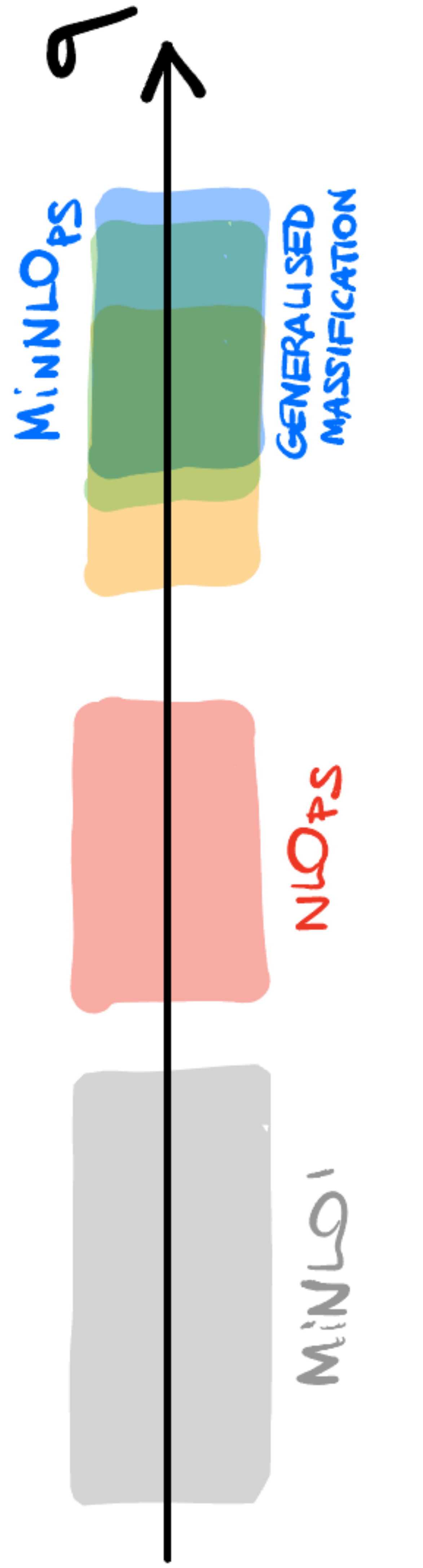
Becher, Melnikov [0704.3582]

Recent application for QCD amplitudes

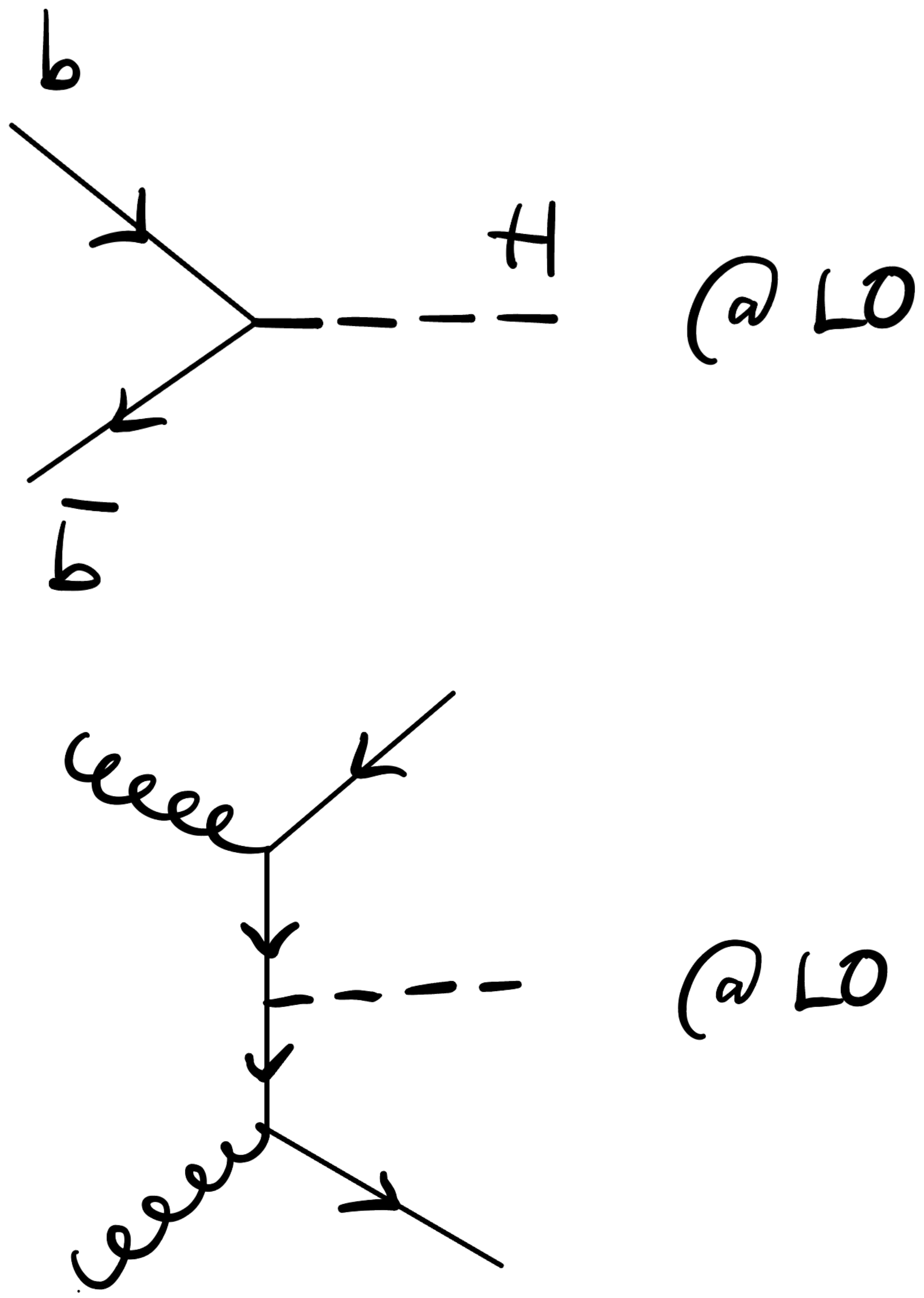
Wang, Xia, Yang, Ye [2312.12242]

We applied decoupling relations for α_s and $\overline{\mathrm{MS}}$ Yukawa

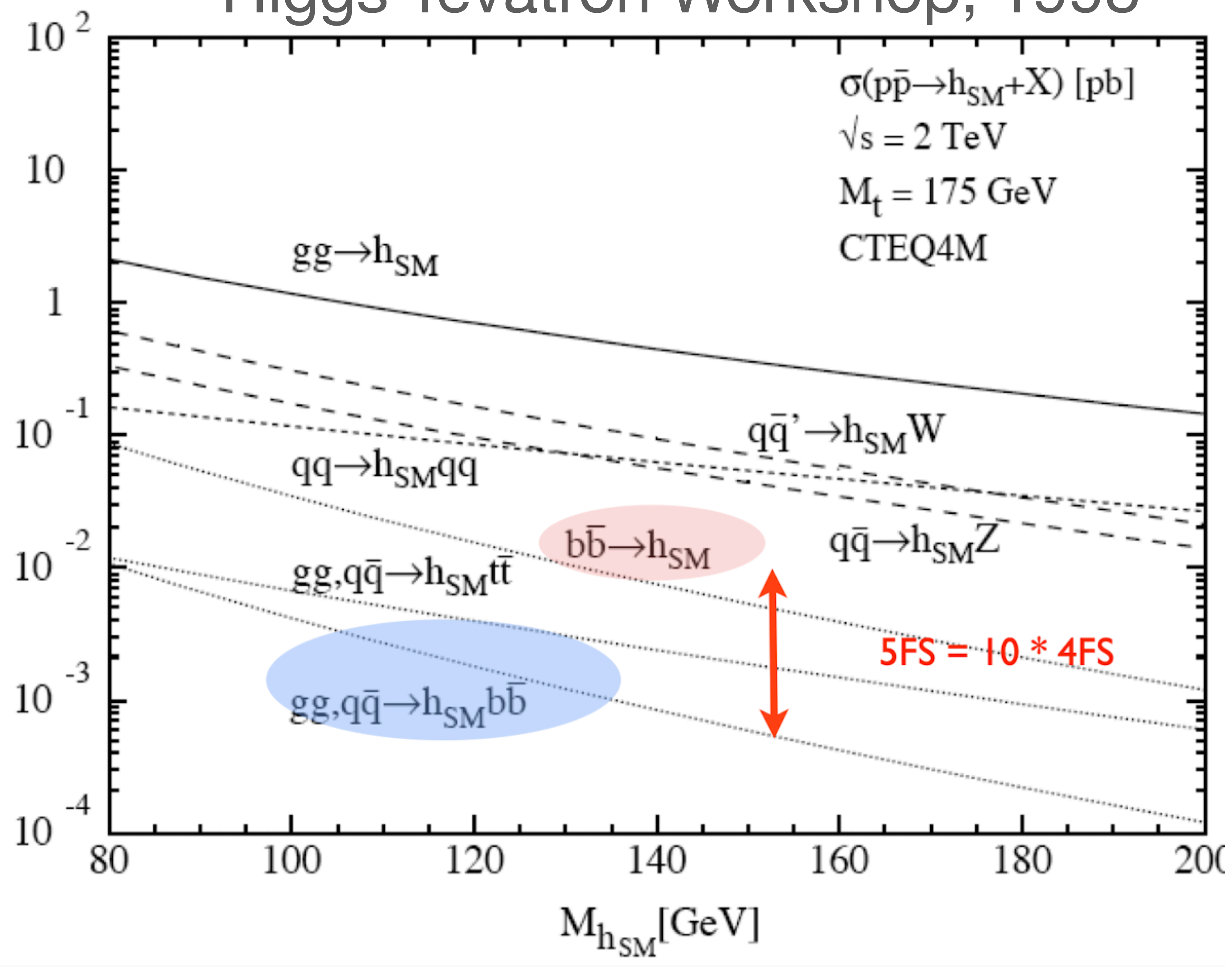




Flavour-scheme comparison



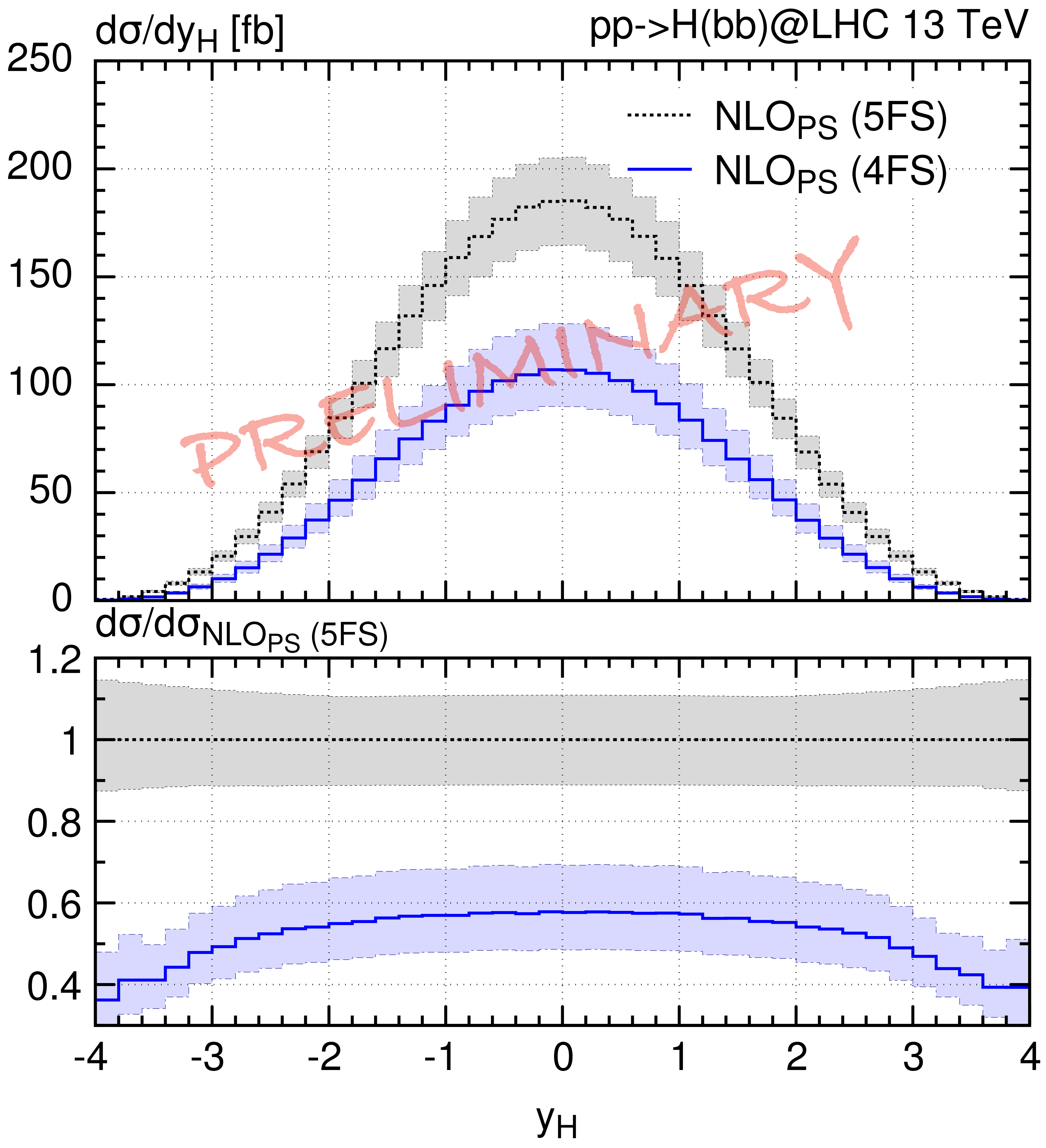
Higgs Tevatron Workshop, 1998

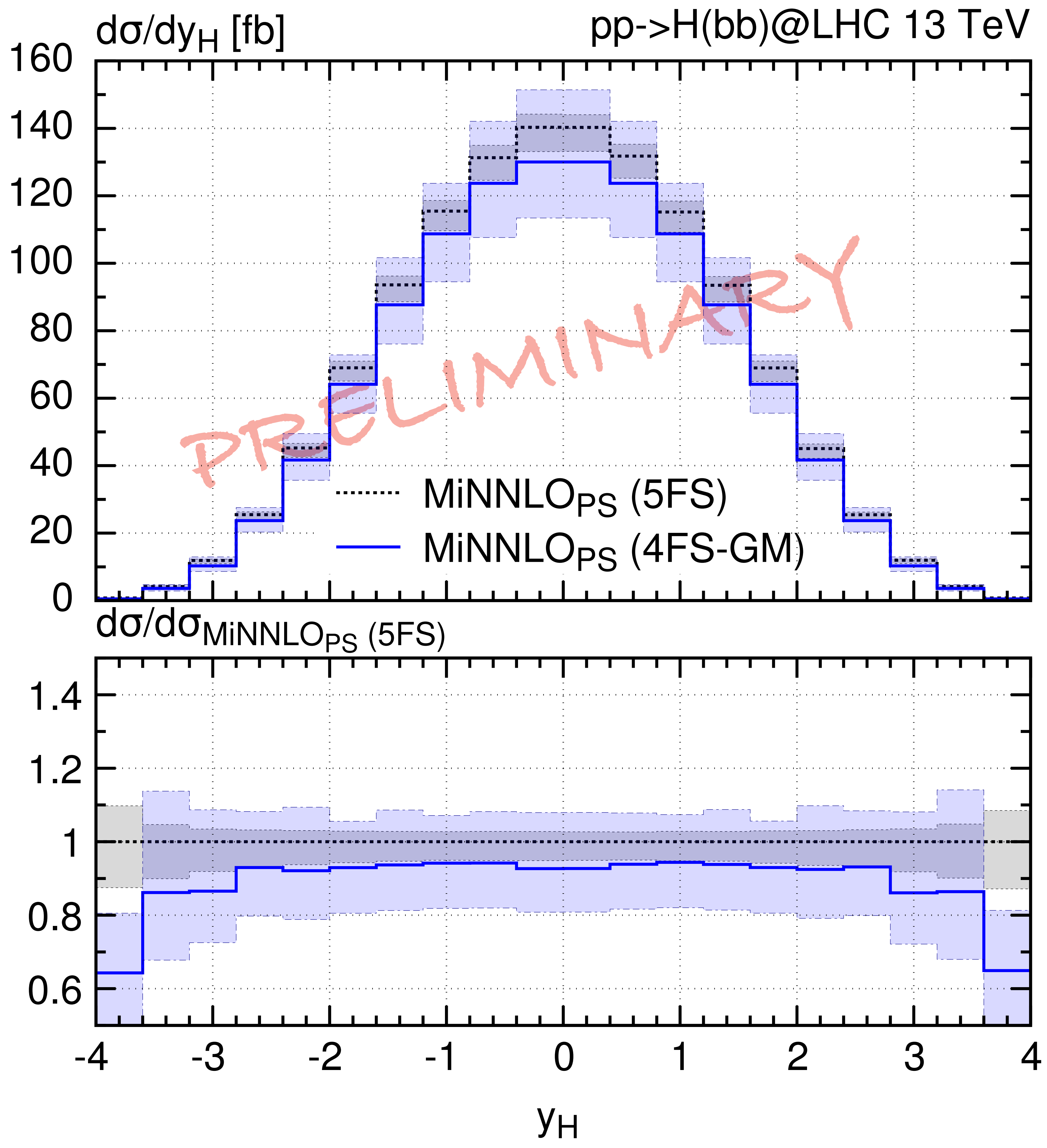


Large differences in the predictions were first observed at leading order: the effect of collinear resummation is extremely large.

Factorisation scales were tuned in order to improve the agreement $\left(\mu_F^{5FS} = \mu_F^{4FS}/4\right)$.

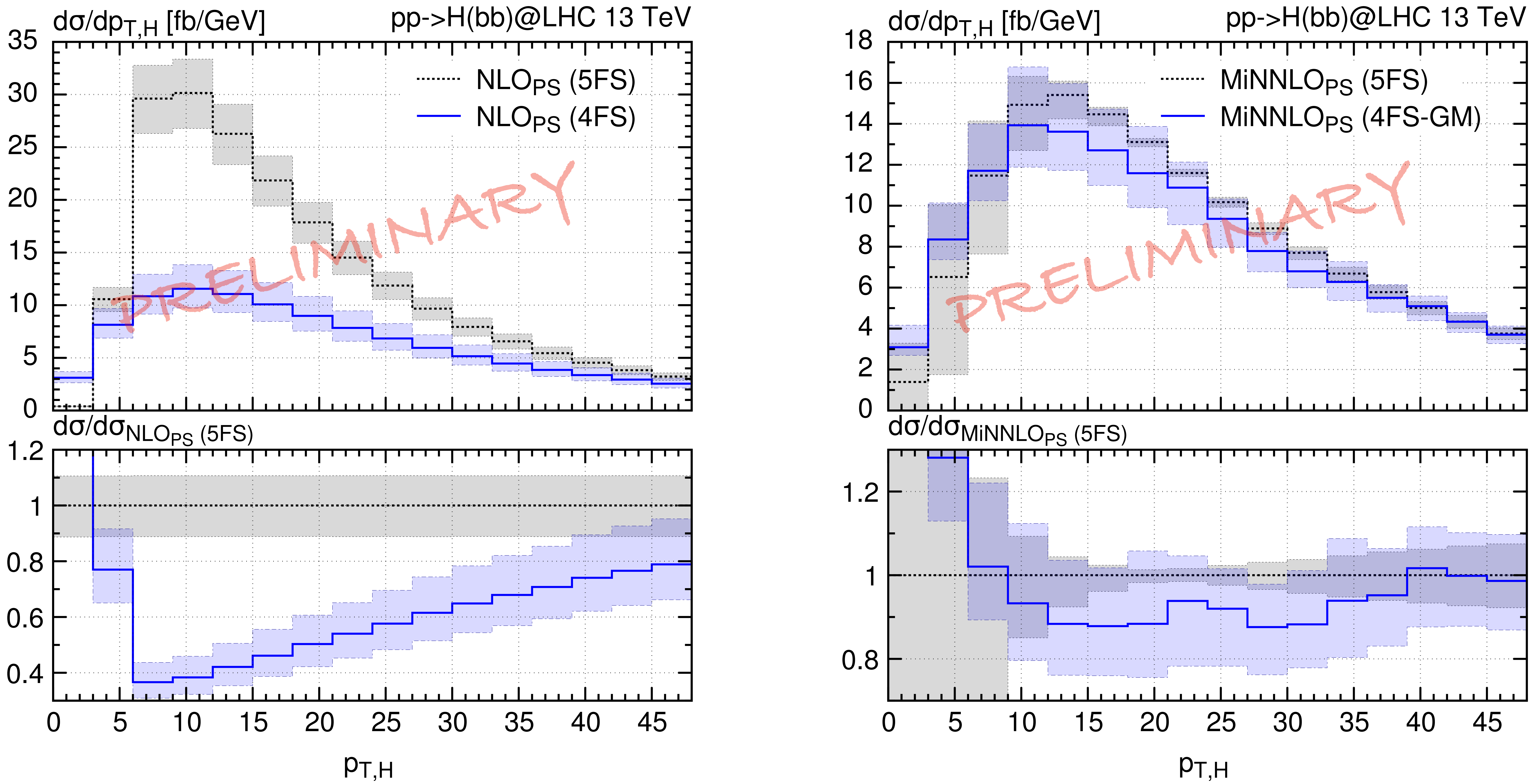
FS comparison: Higgs rapidity





CB, Mazzitelli, Sankar, Wiesemann, Zanderighi [in progress]

FS comparison: Higgs spectrum



CB, Mazzitelli, Sankar, Wiesemann, Zanderighi [in progress]

Summary and outlook

- Implementation of the MiNNLOPS method for bbH production in 5FS and 4FS with $\overline{\text{MS}}$ Yukawa coupling y_b^2

- The theoretical tension between the 4FS and 5FS predictions significantly decreases at NNLO: they agree within the scale uncertainty

- The analysis can perform a b-tagging of the MiNNLOPS events
- A combination of 4FS and 5FS results can improve the description of the process in the whole phase space at differential level

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Thank you for your attention!

Backup slides

Massive-massless mapping for massification

We fix the 4-momenta of the incoming partons and the Higgs state k_5. We want to maintain the invariant mass of the pair

$$m_{QQ} = (k_3 + k_4)^2 = (\tilde{k}_3 + \tilde{k}_4)^2.$$

We introduce the factors

$$\rho_{\pm} = \frac{1 \pm \rho}{2\rho}, \; \rho = \sqrt{1 - \frac{4m_Q^2}{m_{QQ}^2}} \tag{3}$$

and we define the new momenta as a linear combination of the old ones as follows in the quark-channel,

$$\tilde{k}_3^\mu = \rho_+ k_3^\mu - \rho_- k_4^\mu, \tag{4}$$

$$\tilde{k}_4^\mu = \rho_+ k_4^\mu - \rho_- k_3^\mu. \tag{5}$$

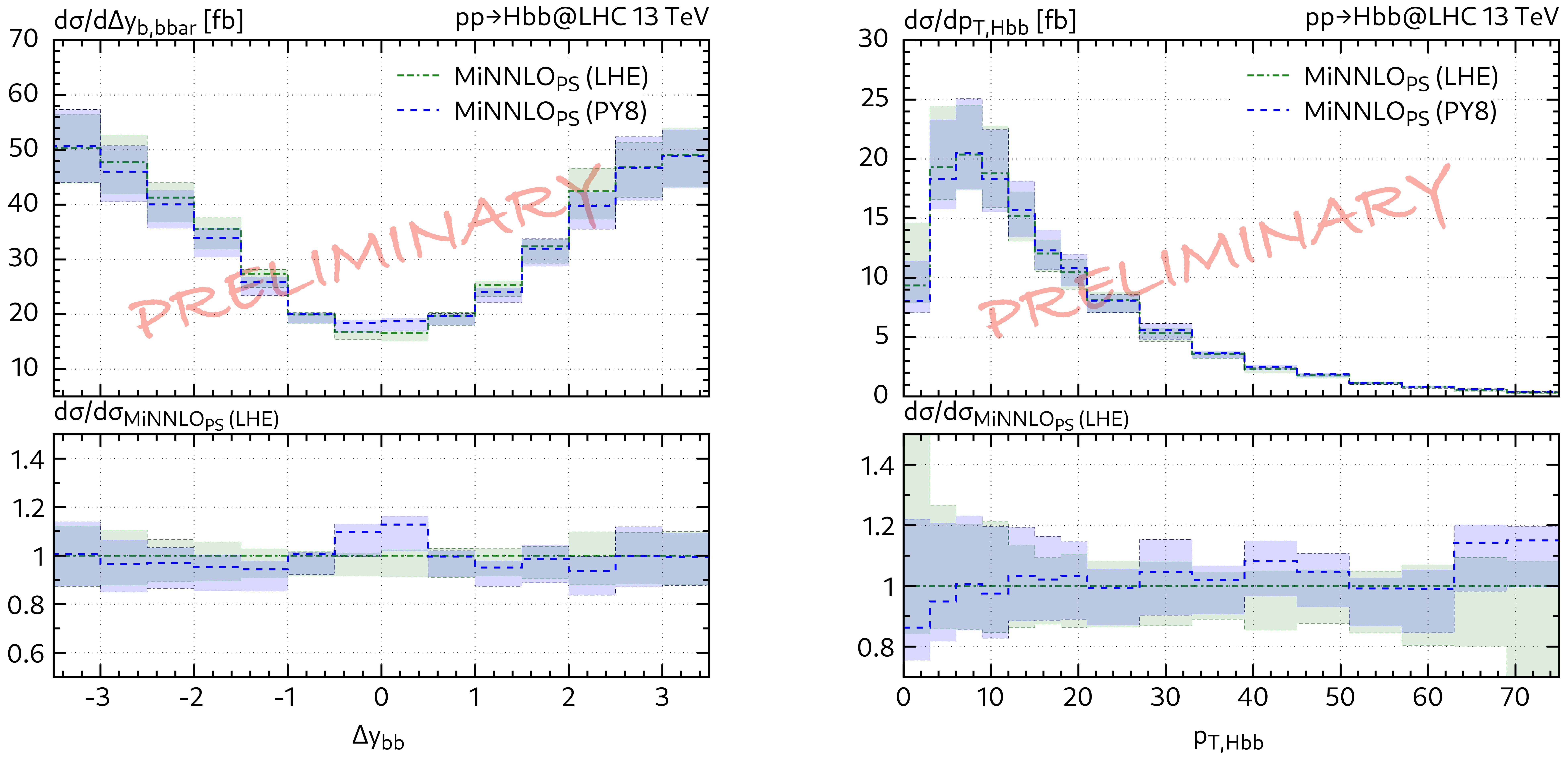
For the gluon channel, we have to avoid the collinear divergence,

$$\tilde{k}_i^\mu = k_i^\mu + \left(\sqrt{1 - \frac{m_Q^2 n_x^2}{(p_i \cdot n_i)^2}} - 1 \right) \frac{p_i \cdot n_i}{n_i}, \quad \text{for i=3,4,} \tag{6}$$

where n_i is the transverse component to both k_1 and k_2. The momentum conservation is restored by performing a Boost such that

$$\tilde{k}_1 + \tilde{k}_2 = k_1 + k_2 - (k_3 + k_4 - \tilde{k}_3 - \tilde{k}_4). \tag{7}$$

Shower effects in 4FS



POWHEG in a nutshell

$$\bar{B} = B + V + \int d\phi_{rad}\, R$$

The exact NLO prediction is

$$\langle \mathcal{O} \rangle = \int d\Phi_n\, \mathcal{O}(\Phi_n)\, \bar{B}(\Phi_n) + \int d\Phi_n\, d\phi_{rad} \left(\mathcal{O}(\Phi_n, \phi_{rad}) - \mathcal{O}(\Phi_n) \right) R(\Phi_n, \phi_{rad})$$

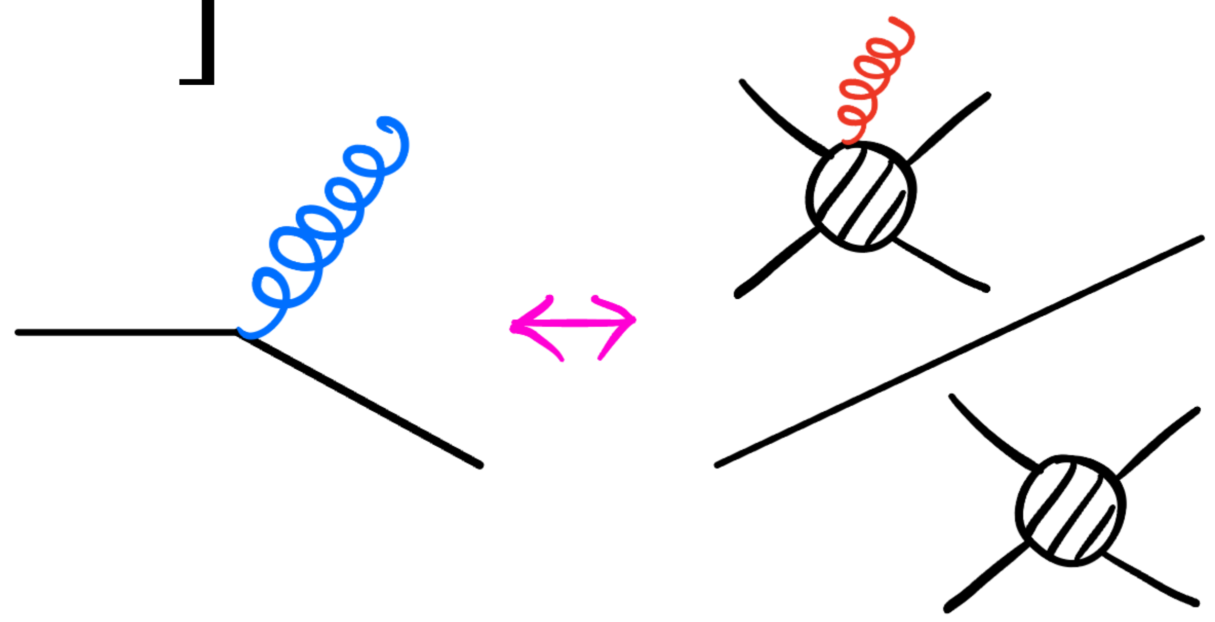
Comparing with the SMC

$$\langle \mathcal{O} \rangle_{SMC} \simeq \int d\Phi_n \left[\mathcal{O}(\Phi_n) B(\Phi_n) + B(\Phi_n) \int_{t_0} \frac{dt}{t} dz d\varphi \left(\mathcal{O}(\Phi_n, \phi_r) - \mathcal{O}(\Phi_n) \right) \frac{\alpha_s}{2\pi} P(z) \right],$$

we deduce the Sudakov form factor and the shower formula in POWHEG

$$\langle \mathcal{O} \rangle = \int d\Phi_n\, \bar{B}(\Phi_n) \left[\mathcal{O}(\Phi_n)\, \Delta_{t_0}^{pwg} + \int d\phi_{rad}\, \mathcal{O}(\Phi_n, \phi_{rad})\, \Delta_t^{pwg} \frac{R(\Phi_n, \phi_{rad})}{B(\Phi_n)}) \right]$$

with $\Delta_t^{pwg} = \exp \left[- \int d\phi'_{rad} \frac{R(\Phi_n, \phi'_{rad})}{B(\Phi_n)} \Theta(t' - t) \right]$



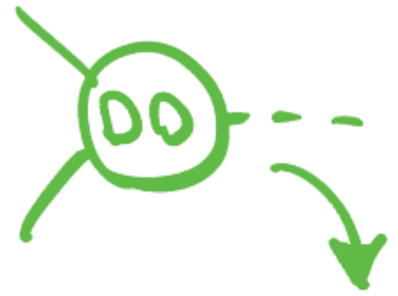
MiNNLOPS in a nutshell

NLO Xj ⟶ NNLO X

MiNNLOPS is an extension of MiNLO’ to achieve NNLO+PS accuracy for inclusive observables.

Monni, Nason, Re, Wiesemann, Zanderighi [1908.06987]

The modified POWHEG function is



$$\bar{B}(\Phi_{XJ}) = e^{-\tilde{S}(p_T)}\left\{ B\left(1-\alpha_s(p_T)\,\tilde{S}^{(1)}\right) + V + \int \mathrm{d}\phi_{rad}\, R + \left[D^{(3)}(p_T)\right] \times F^{corr} \right\}$$

Sudakov form factor

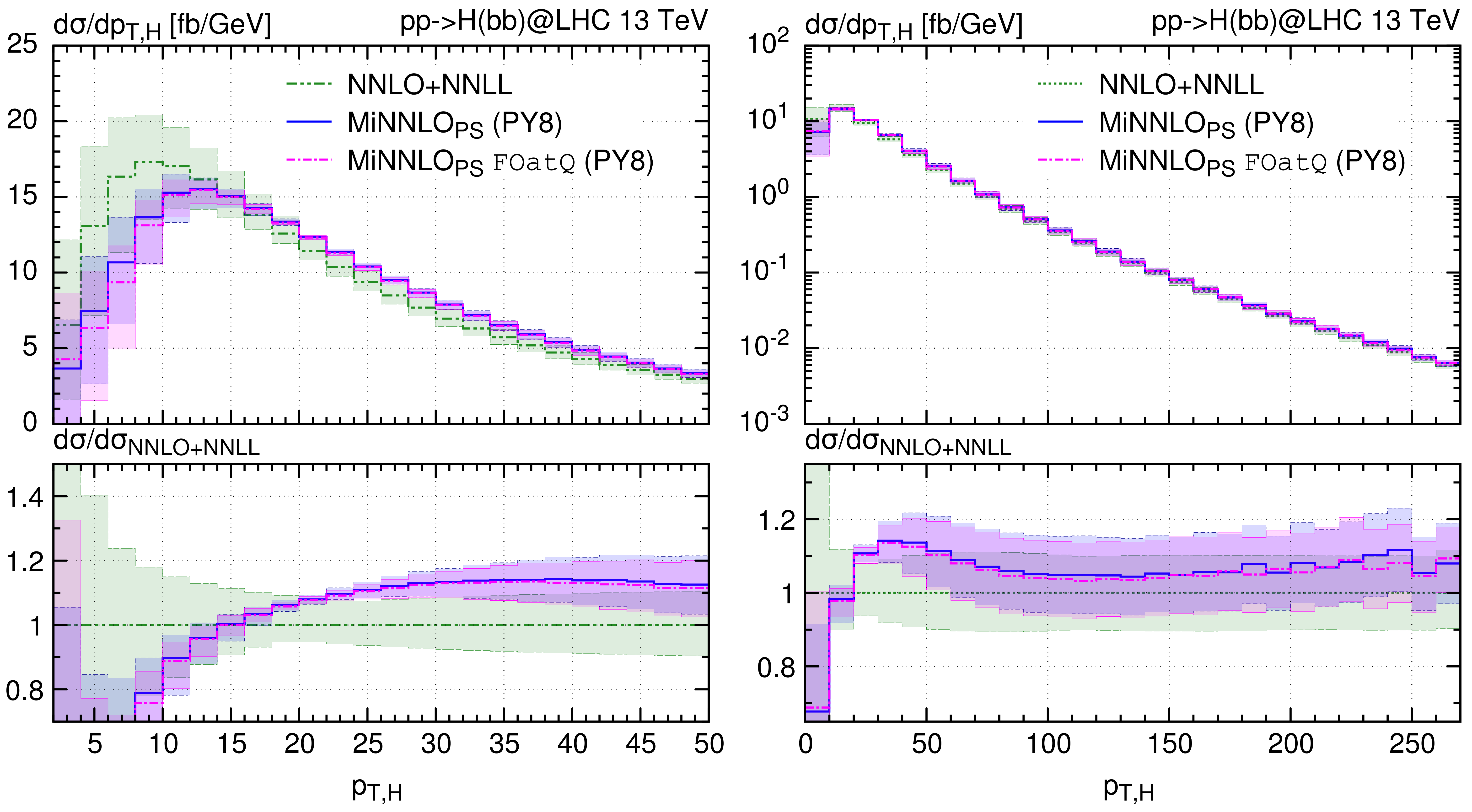
MiNLO’ structure

Extra term:
it ensures NNLO accuracy.
F^{corr} encodes the spreading upon the full Φ_{XJ}.

The QCD scales must be $\mu_F \sim \mu_R \sim p_T$ in the singular region.

Comparison with resummed results (PS)

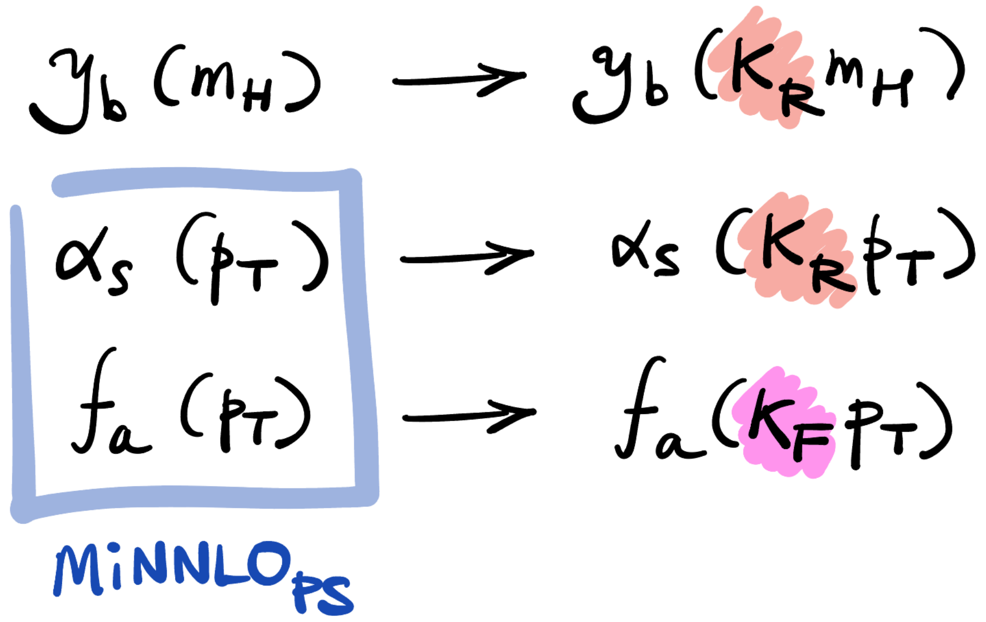
Transverse momentum spectrum of the Higgs



- Acceptable agreement for small $p_{T,H}$
- The shower has an effect on the tail

NNLO+NNLL Harlander, Tripathi, Wiesemann [1403.7196]

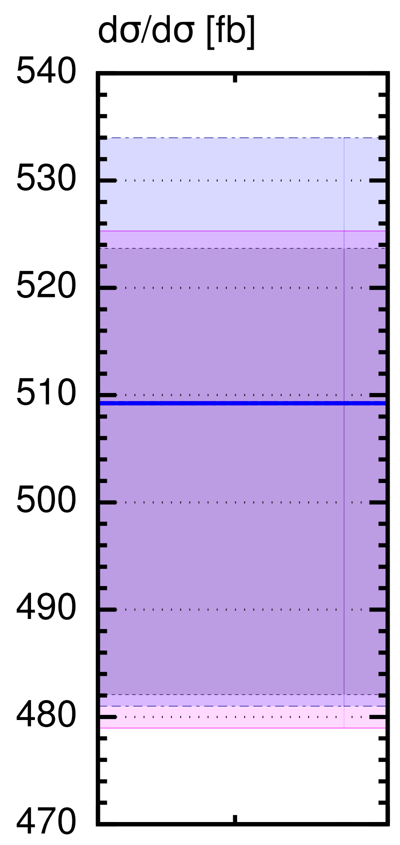
5FS scale variation

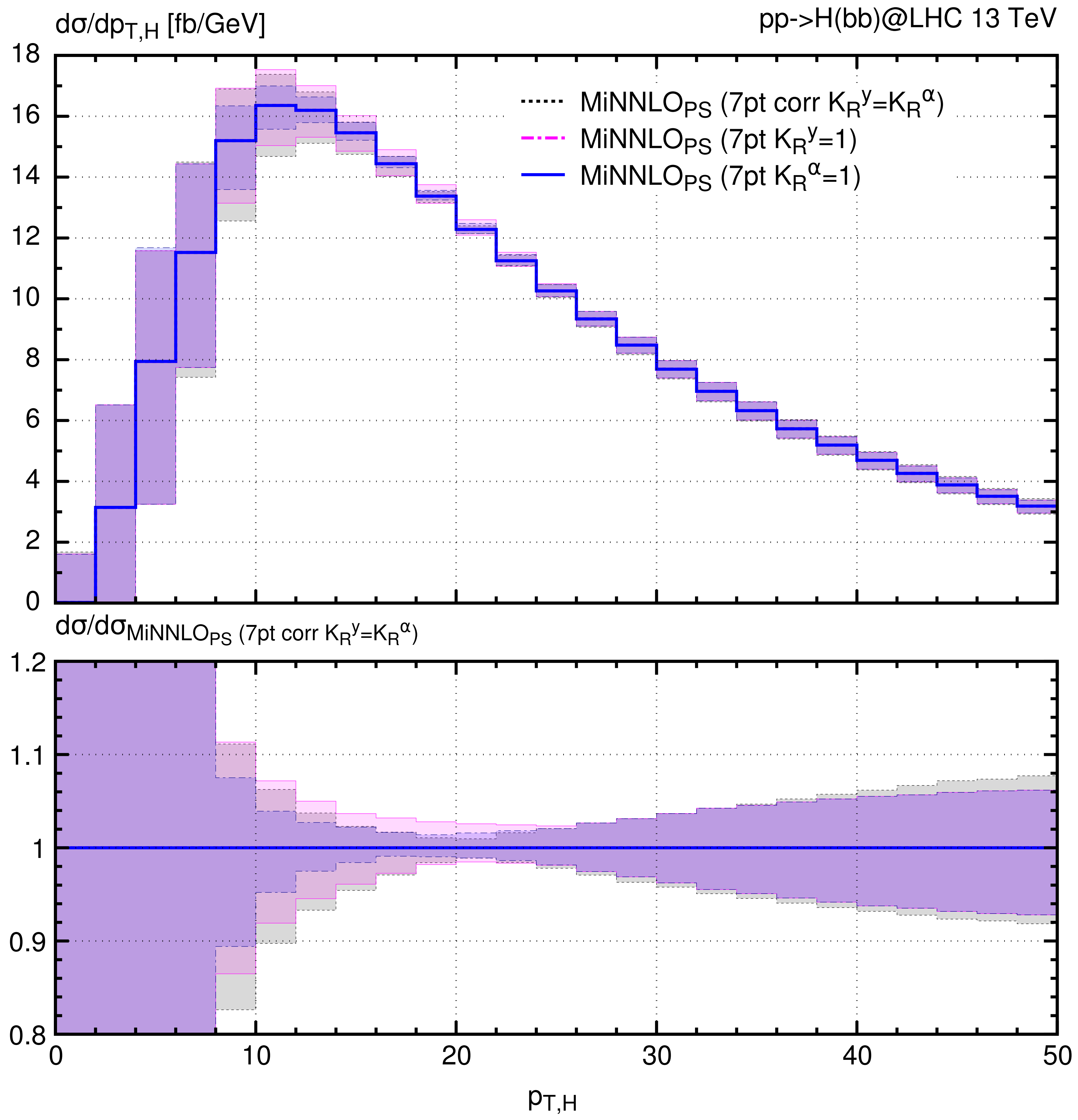


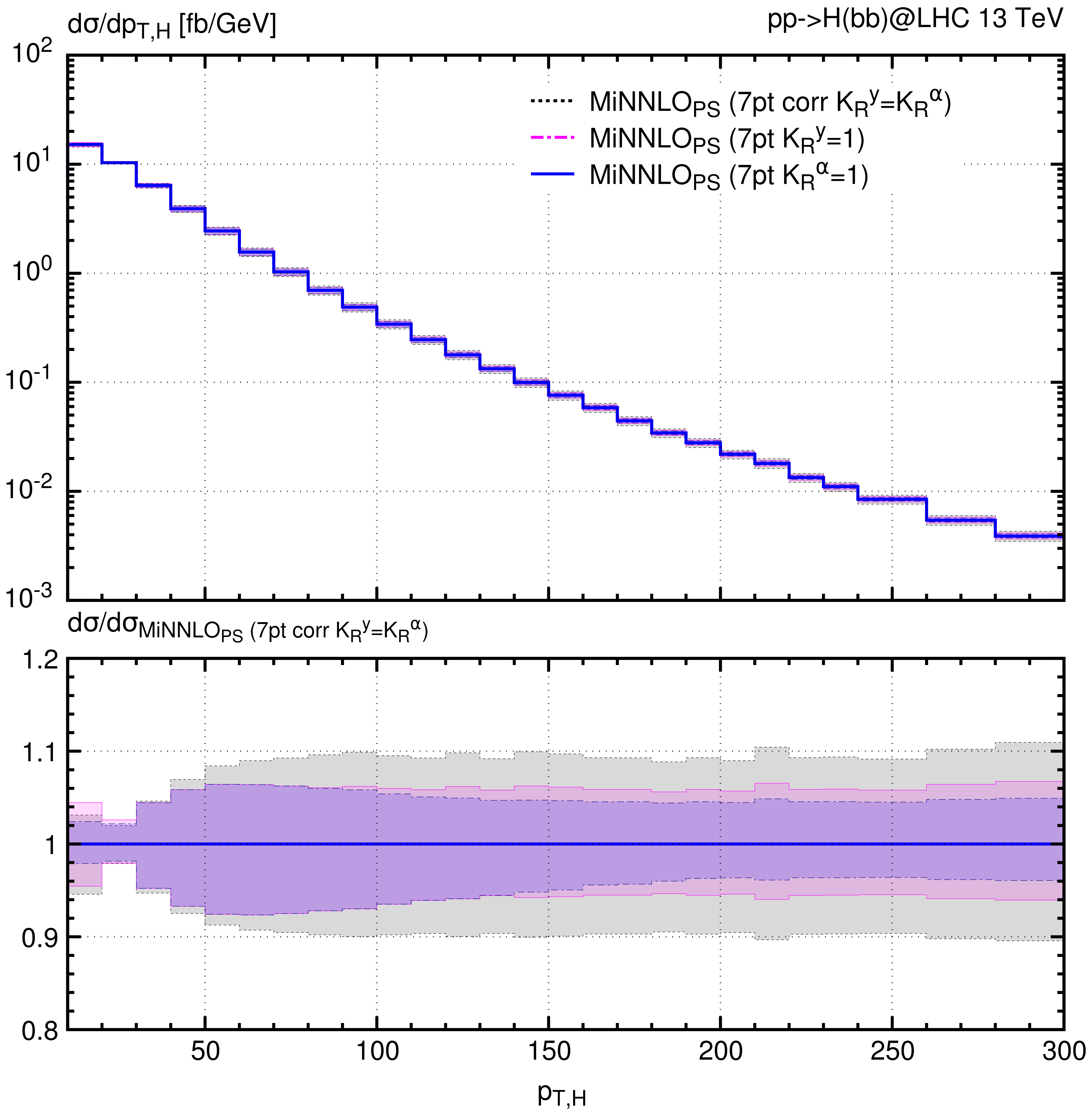
We studied the effects of the correlation between the renormalisation scale factors.

We compare:

- The standard prediction
- 7pt s.v. for (K_R^α, K_F)
- 7pt s.v. for (K_R^y, K_F)

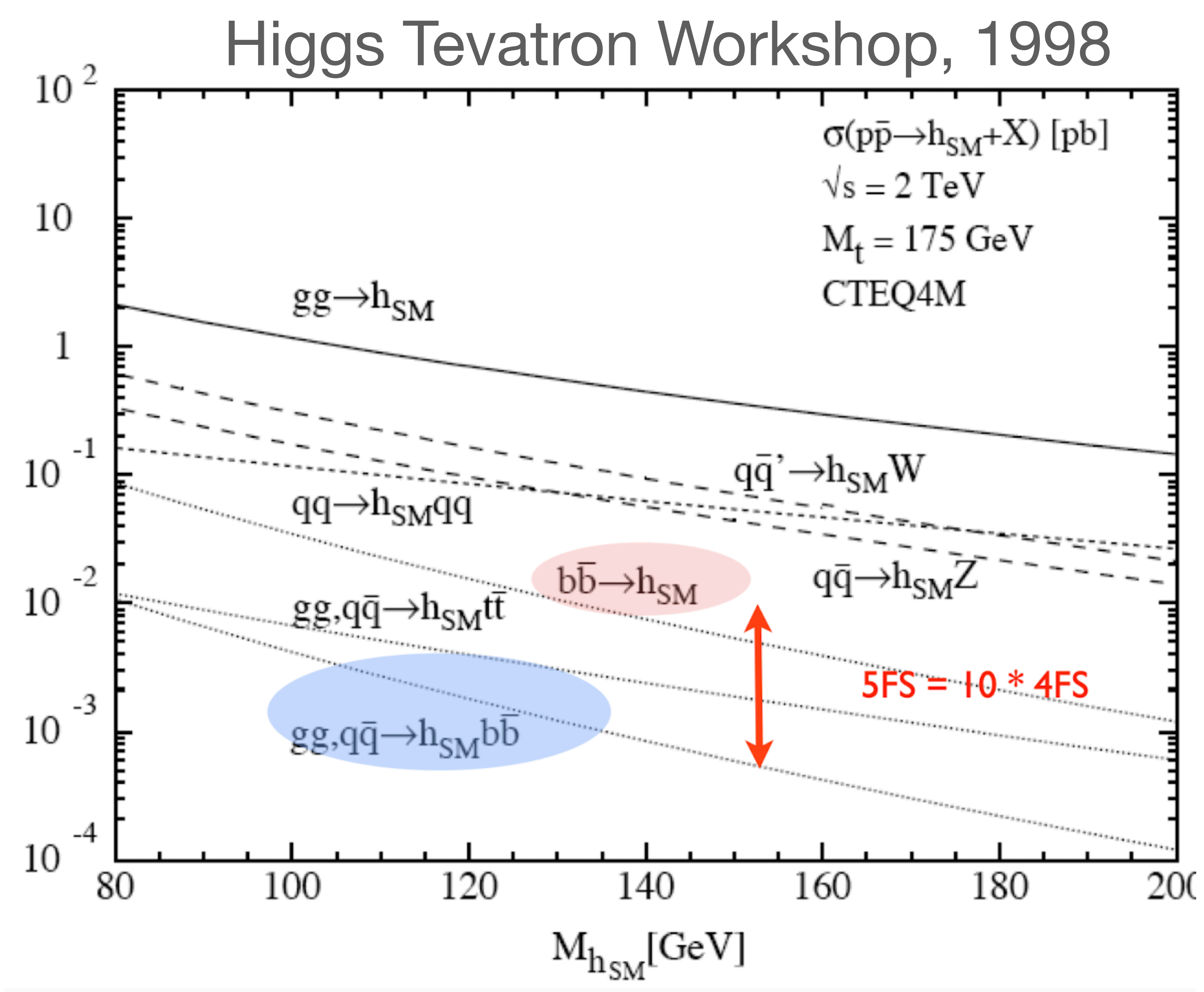


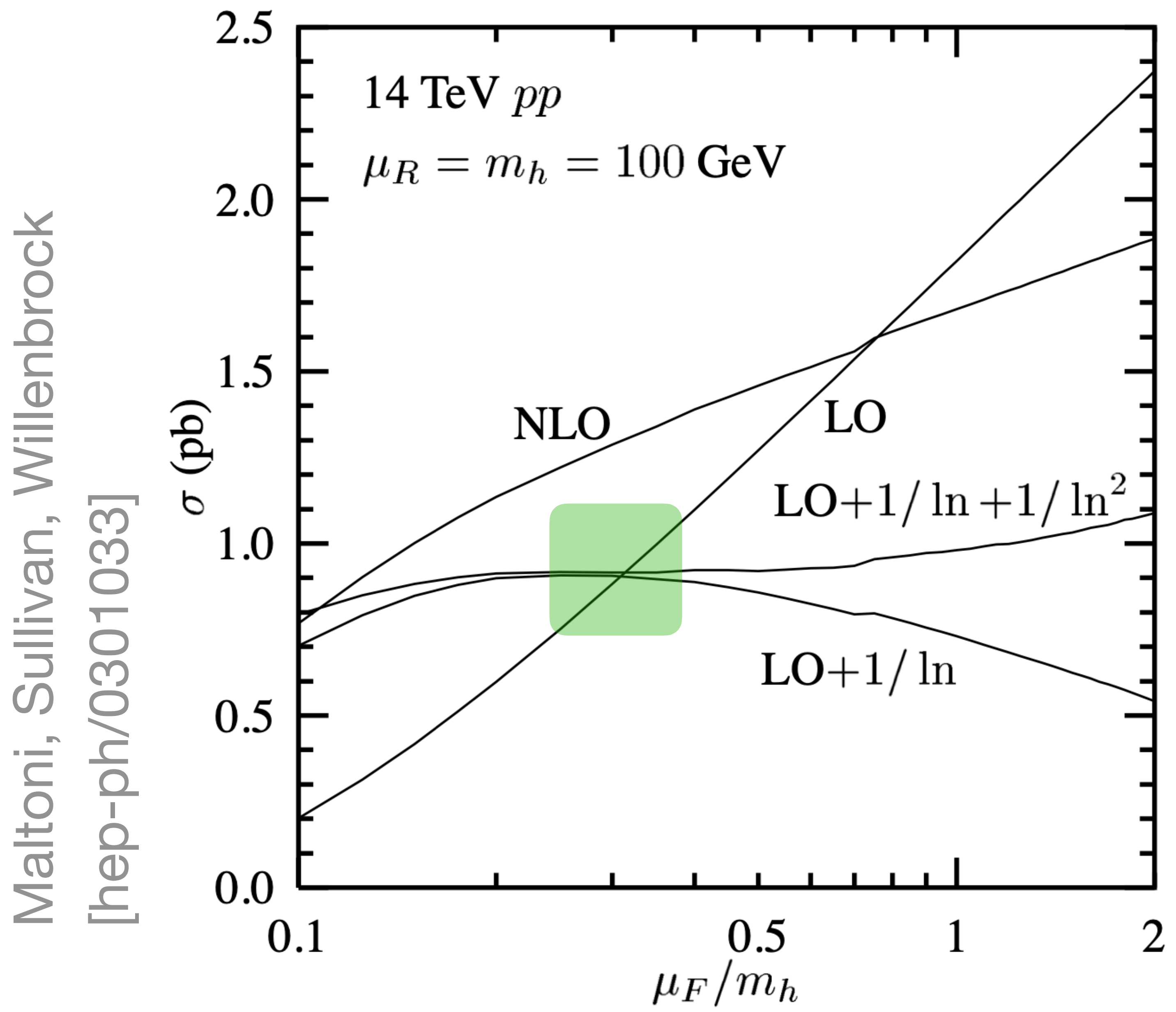




Historical LO comparisons

Large differences in the predictions were first observed at the leading order: the effect of collinear resummation is extremely large.





For $\mu_F = m_H/4$, FO computations in the different schemes become compatible, indeed the collinear logs have a small effect. This also improved the convergence of the perturbation series.

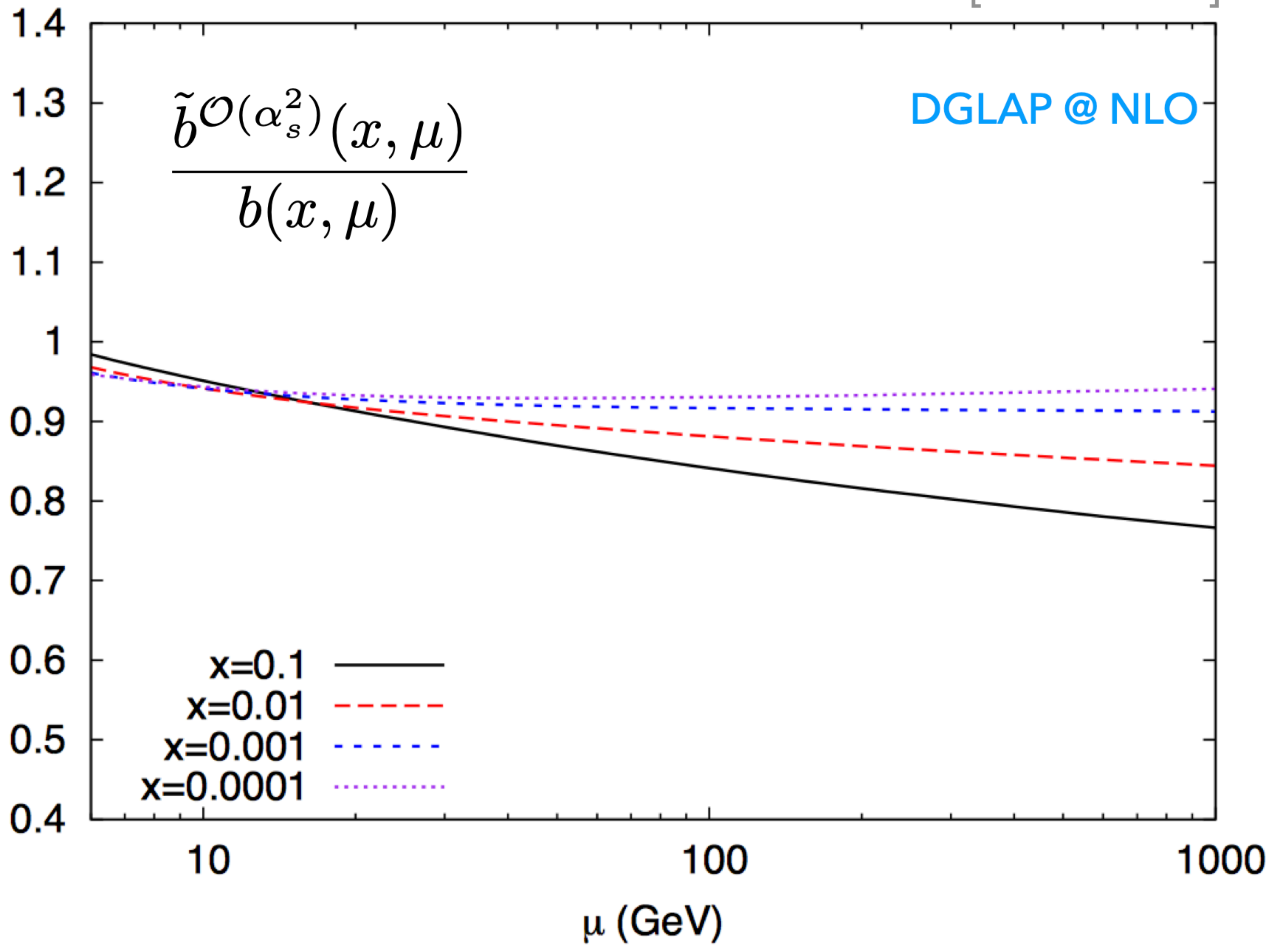
The improvement of the compatibility opens the possibility to match together the predictions at least at the inclusive level (Santander matching, FONLL…)

Differences between schemes

Maltoni, Ridolfi, Ubiali [1203.6393]
Thorne [1402.3536]
Olness, Schienbein [0812.3371]

Lot of progress in understanding the origin of the differences. The predictions can be merged into a consistent picture by taking into account two main results.

[1203.6393]



1. At NLO, the resummation effects of collinear logs are important only at high Bjorken-x
2. The possibly large ratios m_H^2/m_b^2 are always accompanied by universal phase space factors f

$$\ln^2 \frac{m_H^2 f}{m_b^2} = \ln^2 \frac{\tilde{\mu}^2}{m_b^2}, \quad \tilde{\mu} < m_H$$

FONLL

Forte, Napoletano, Ubiali [1508.01529]
Forte, Napoletano, Ubiali [1607.00389]

- FONLL matches the flavour schemes

  $\sigma^{FONNL} = \sigma^{4FS} + \sigma^{5FS}$ – double couting.

  For a consistent subtraction, we have to express the two cross-sections in terms of the same α_s and PDFs.

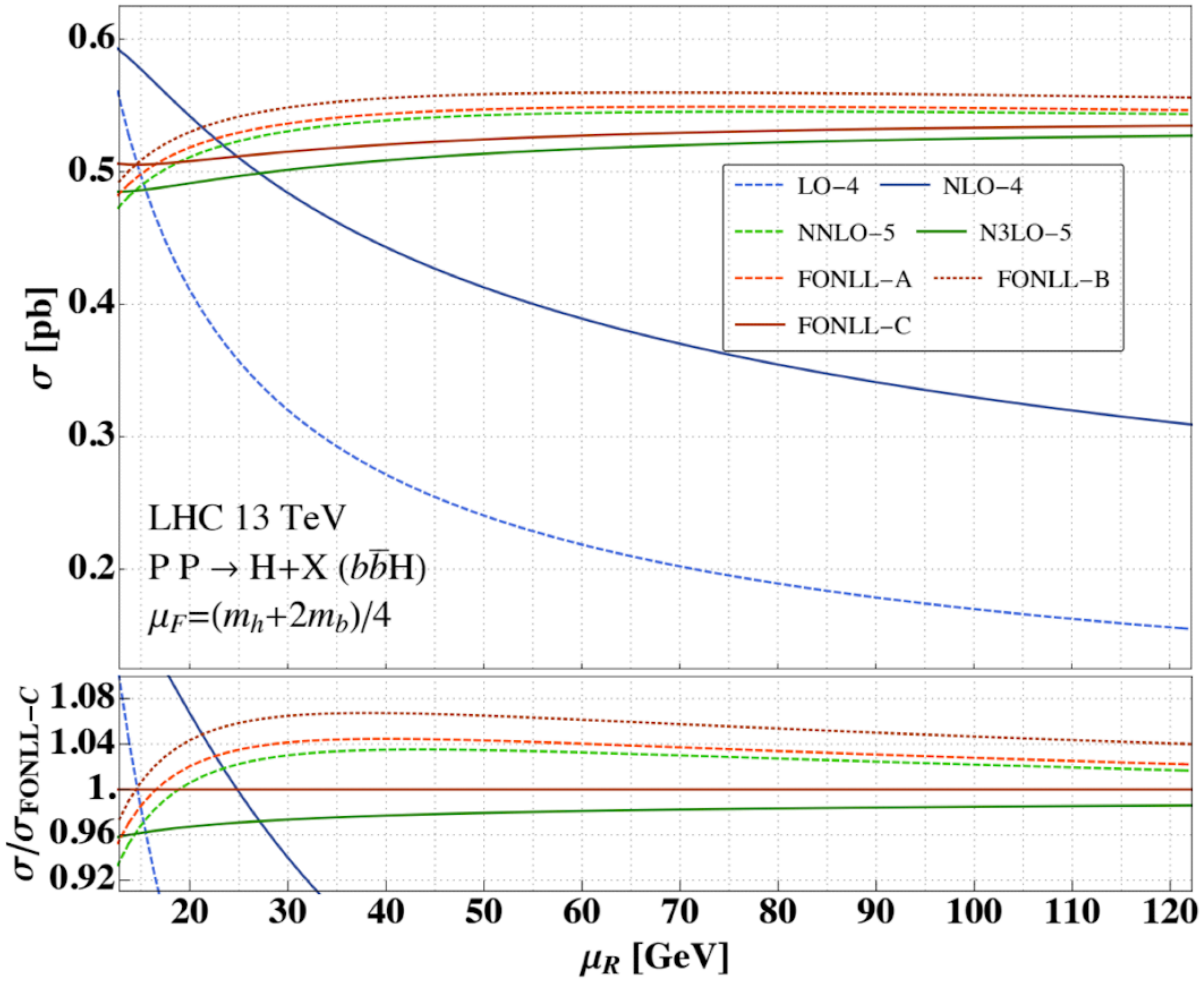
- Currently, the flavour matching for bbH is performed at

  $$\text{FONNL}_C := \text{N}^3\text{LO}_{5FS} \oplus \text{NLO}_{4FS}.$$

- Differential FONLL applied for Z+b-jet

  $$d\sigma^{FONLL} = d\sigma^{5FS} + \left(d\sigma^{4FS}_{m_b} - d\sigma^{4FS}_{m_b \to 0}\right)$$

Duhr, Dulat, Hirschi, Mistlberger [2004.04752]



[Gauld, Gehrmann-De Ridder, Glover, Huss, Majer, 2005.03016]