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FÜR PHYSIK

Higgs production via bottom fusion in MiNNLOPS

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in collaboration with
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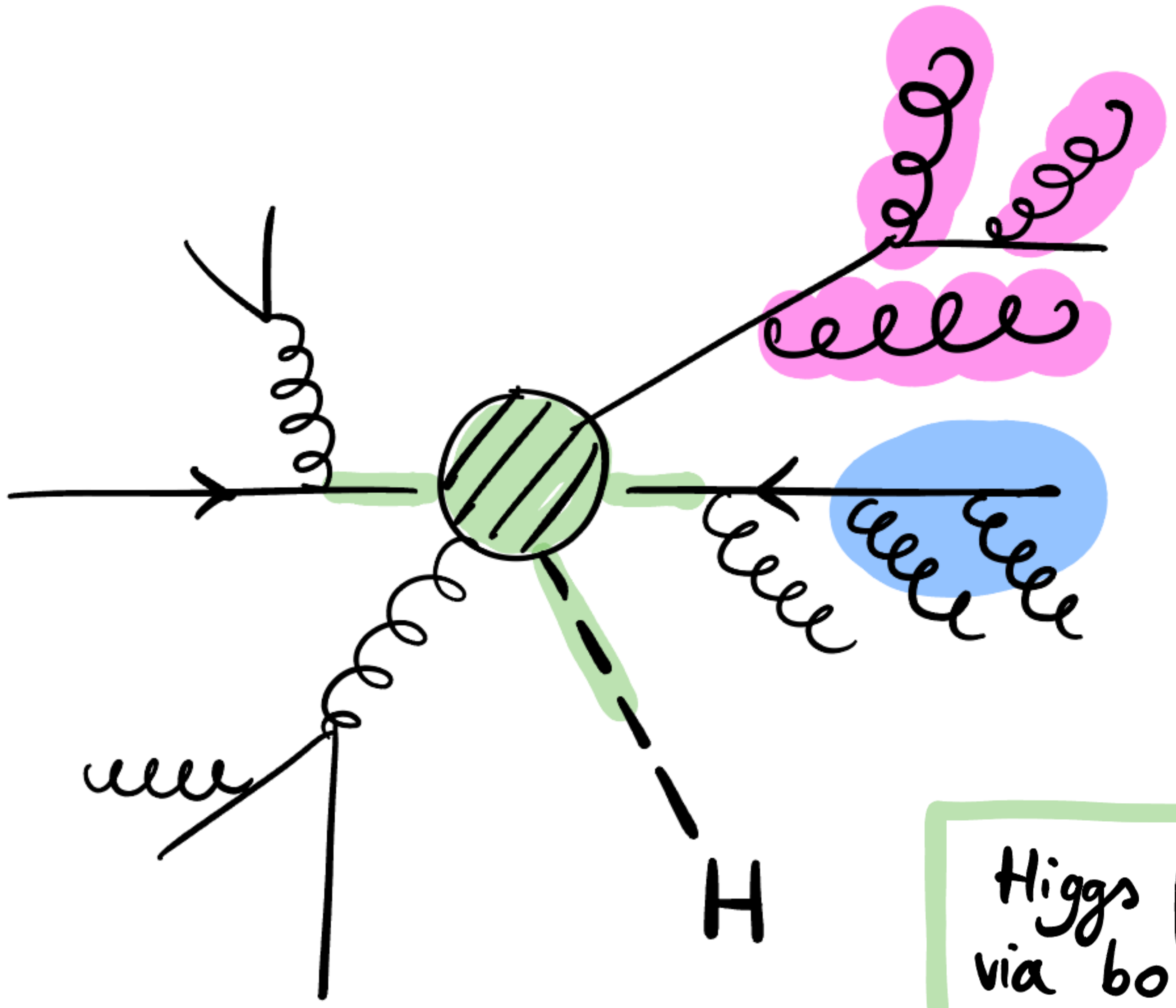
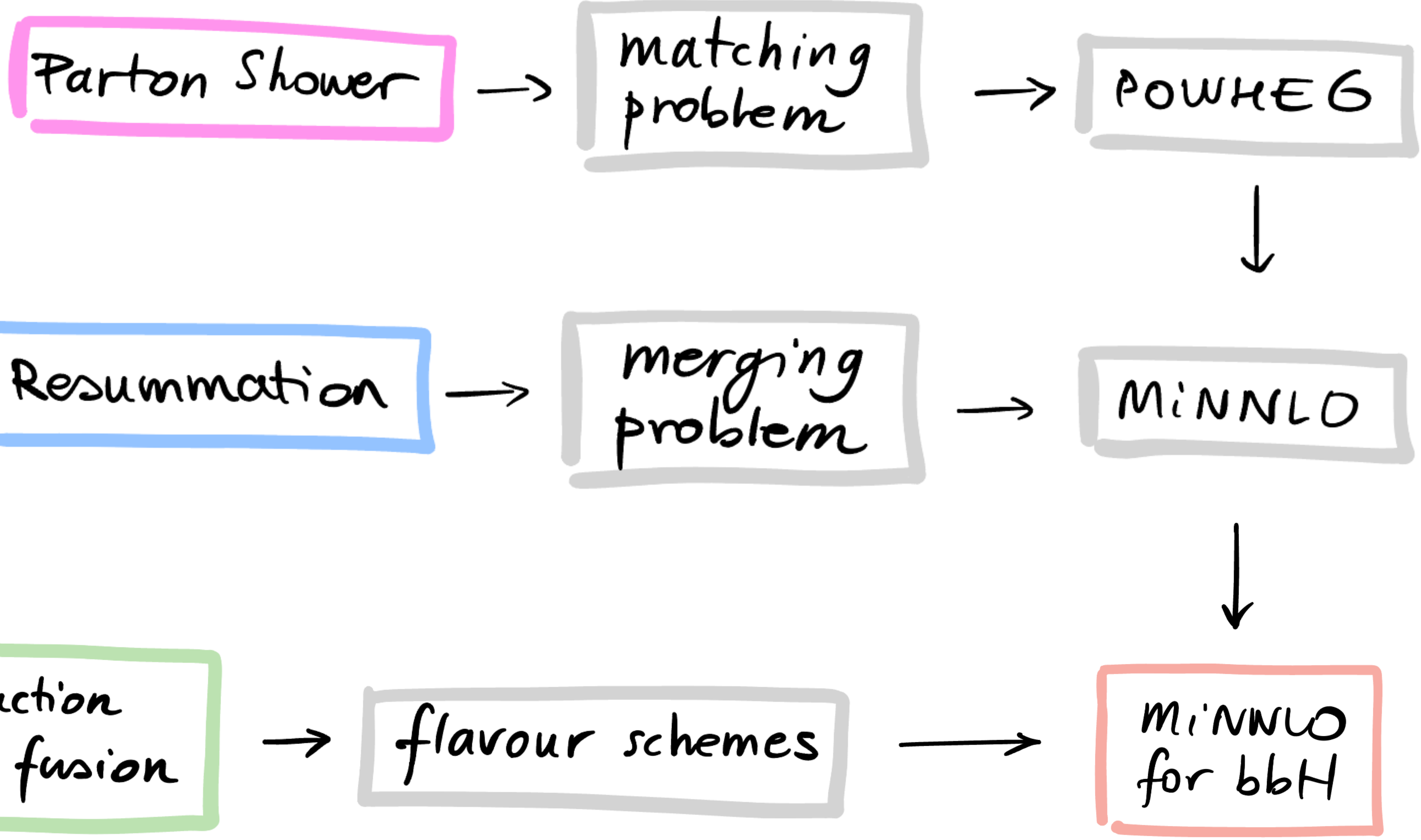
Milan Christmas Meeting
Università degli Studi di Milano and INFN
December 22nd, 2023

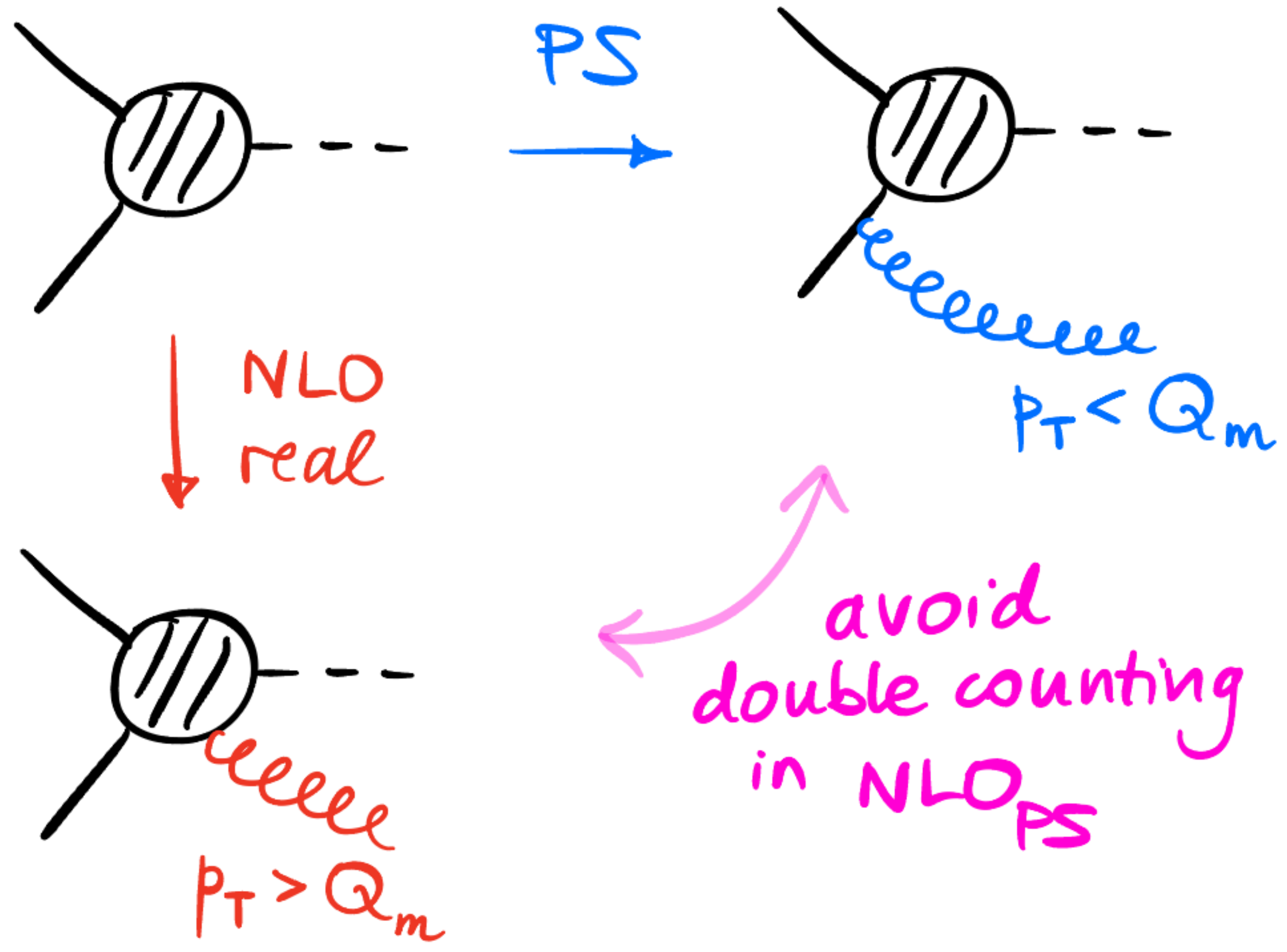
Outline


H


Parton Shower
matching problem
POWHEG
Resummation
merging problem
MiNNLO
Higgs production via bottom fusion
flavour schemes
MiNNLO for bbH

The method

Matching problem



NLO predictions contain real corrections that also the Shower Monte Carlo produces.

POWHEG solution: Write a simplified Monte Carlo that generates just one emission (the hardest one) which alone gives the correct NLO result.

Nason [hep-ph/0409146]

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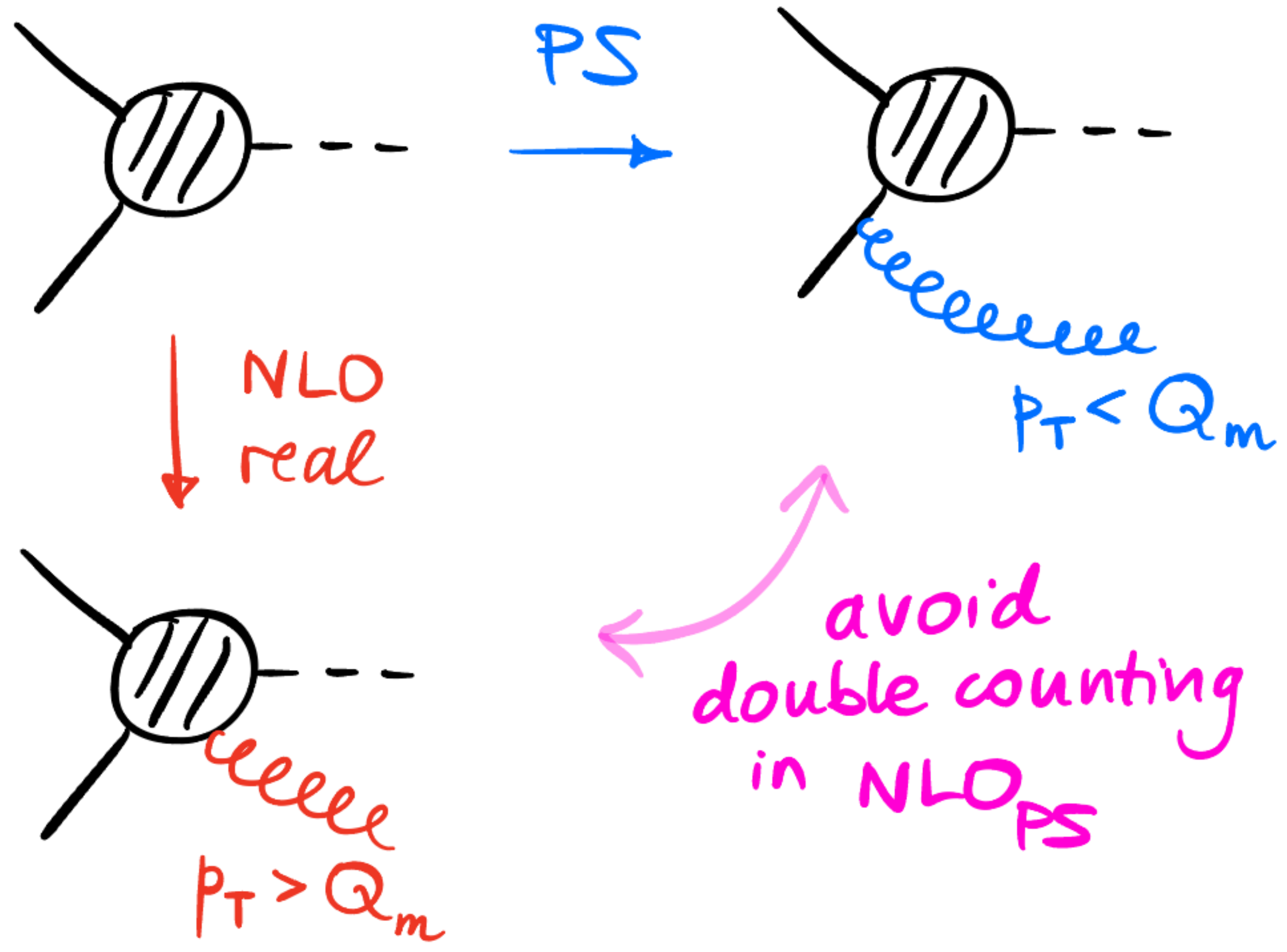

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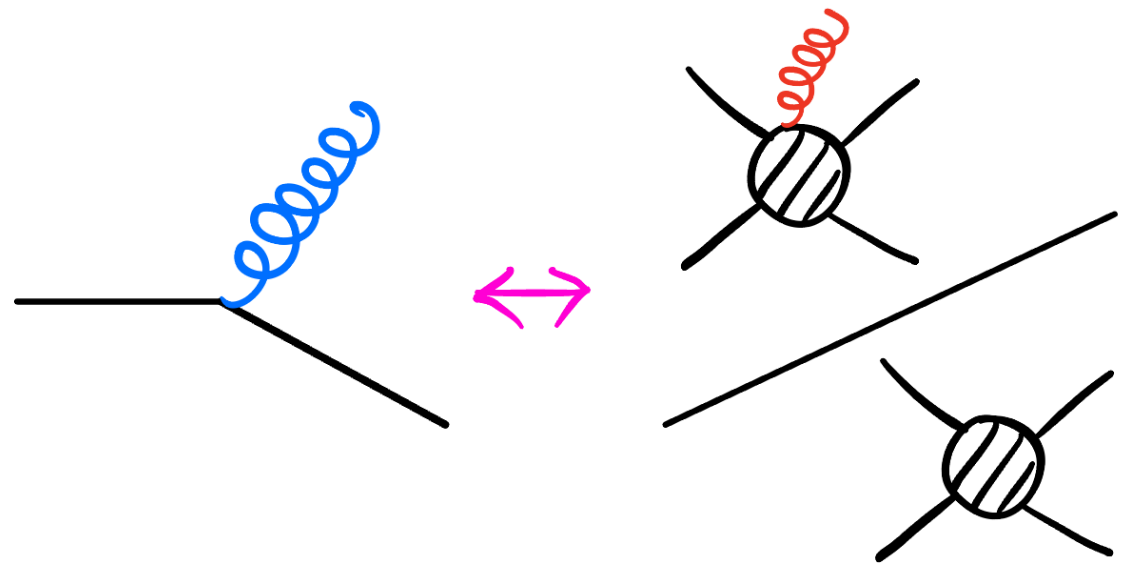
POWHEG master formula

$$d\sigma = d\Phi\, \bar{B}(\Phi) \left[\Delta_{t_0}^{pwg} + d\phi_{rad}\, \Delta_t^{pwg} \frac{R(\Phi_n, \phi_{rad})}{B(\Phi)} \right]$$

with

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

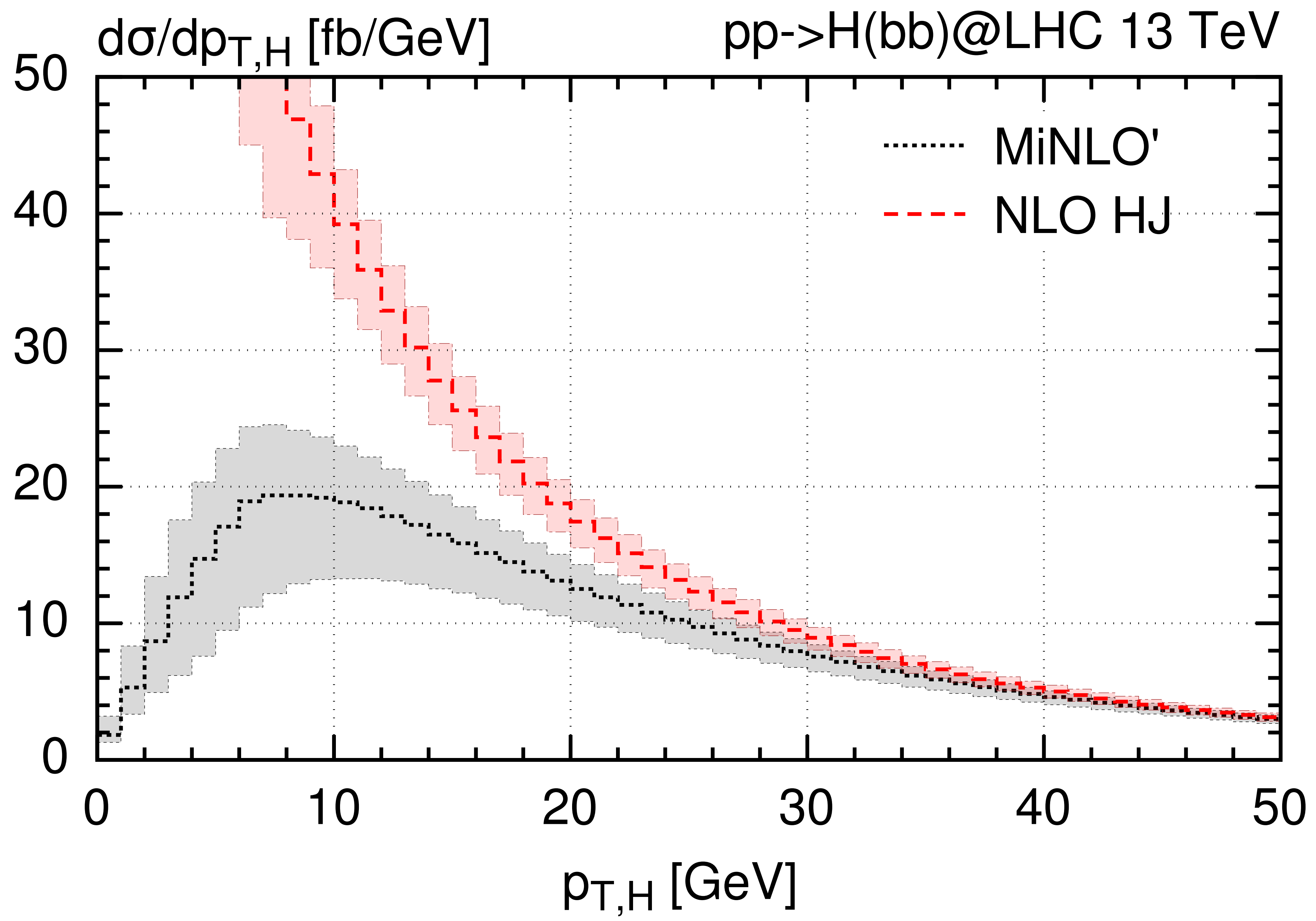


Merging problem

How can we achieve NLO accuracy for inclusive X predictions from the XJ generator?

The idea of MiNLO' is to merge different multijet calculations using the techniques of transverse momentum resummation.

Hamilton, Nason, Zanderighi [1206.3572]
Hamilton, Nason, Oleari, Zanderighi [1212.4504]



The merging procedure takes the advantages of two methods:

- Flexibility of FO and matching with PS
- All-order control of the resummation

with particular scale choices and without an unphysical merging scale.

MiNNLOPS in a nutshell

NLO Xj $\longrightarrow$ NNLO X

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

Monni, Nason, Re, Wiesemann, Zanderighi [1206.3572]

Split the differential inclusive cross-section into the singular and regular part in the small transverse momentum limit: $\mathrm{d}\sigma = \mathrm{d}\sigma^{sing} + \mathrm{d}\sigma^{reg}$.

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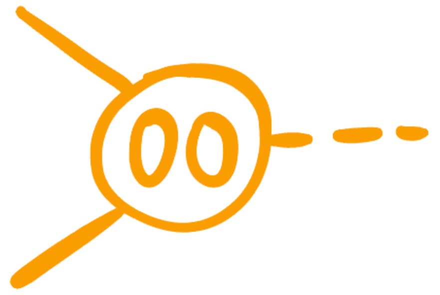
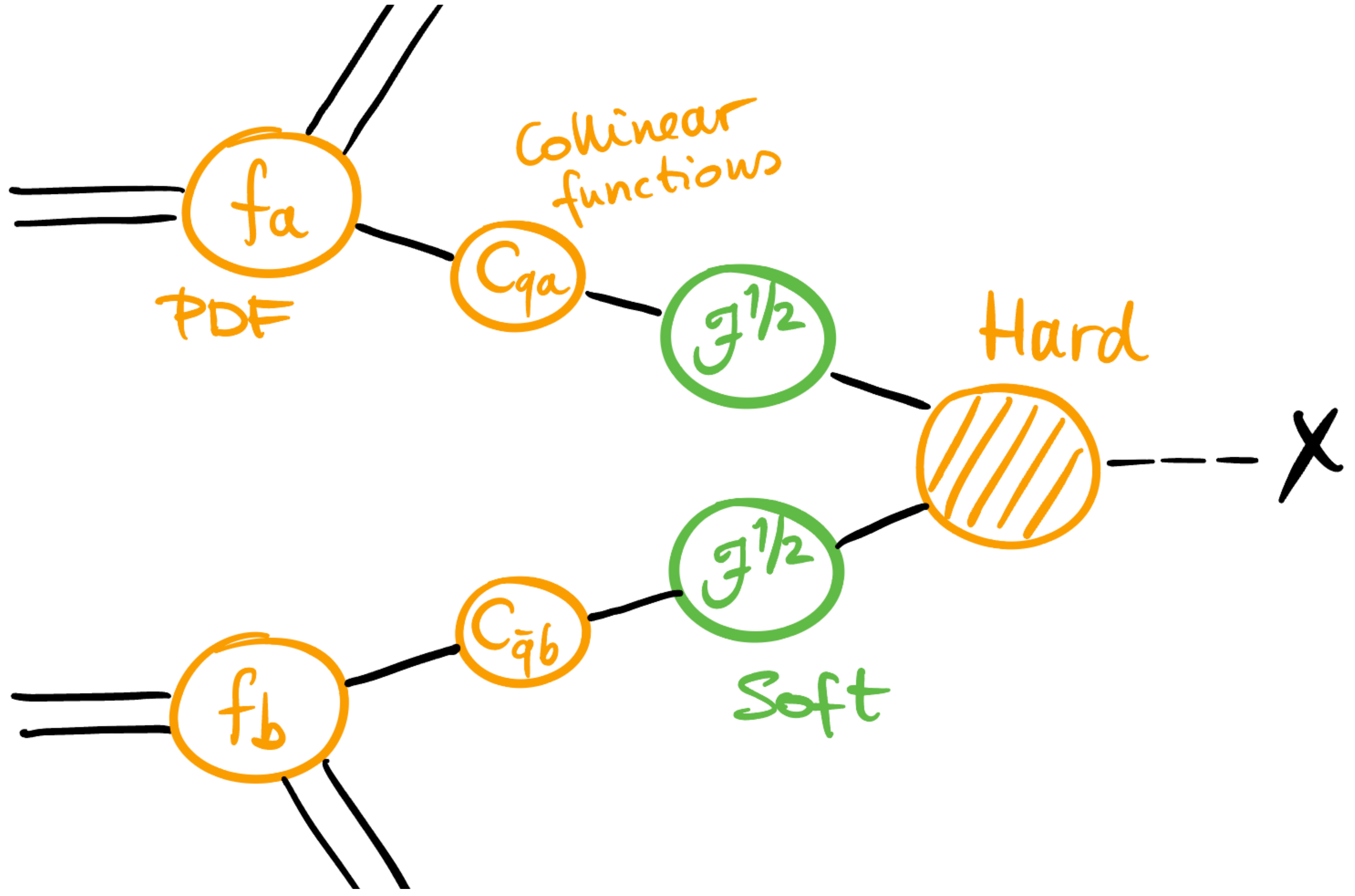
$$\frac{\mathrm{d}\sigma^{sing}}{\mathrm{d}p_T\,\mathrm{d}\Phi_X} = \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{\mathcal{F}(p_T)\,\mathcal{L}(p_T)\right\} =: \exp\left[-\tilde{S}(p_T)\right] D(p_T)$$

Sudakov form factor

$$\mathcal{F}(p_T) = \exp\left[-\tilde{S}(p_T)\right]$$

Luminosity: it also contains





MiNNLOPS in a nutshell

$$\mathrm{d}\sigma = \mathrm{d}\sigma^{sing} + \mathrm{d}\sigma^{reg}$$

The modified POWHEG function is

$$\bar{B}(\Phi_{XJ}) = e^{-\tilde{S}(p_T)} \left\{ B\left(1 - \alpha_s(p_T)\,\tilde{S}^{(1)}\right) + V + \int \mathrm{d}\phi_{rad}\, R + \left[D(p_T) - D^{(1)} - D^{(2)}\right] \times F^{corr} \right\}$$

MiNLO' structure

Extra term: it ensures NNLO accuracy.

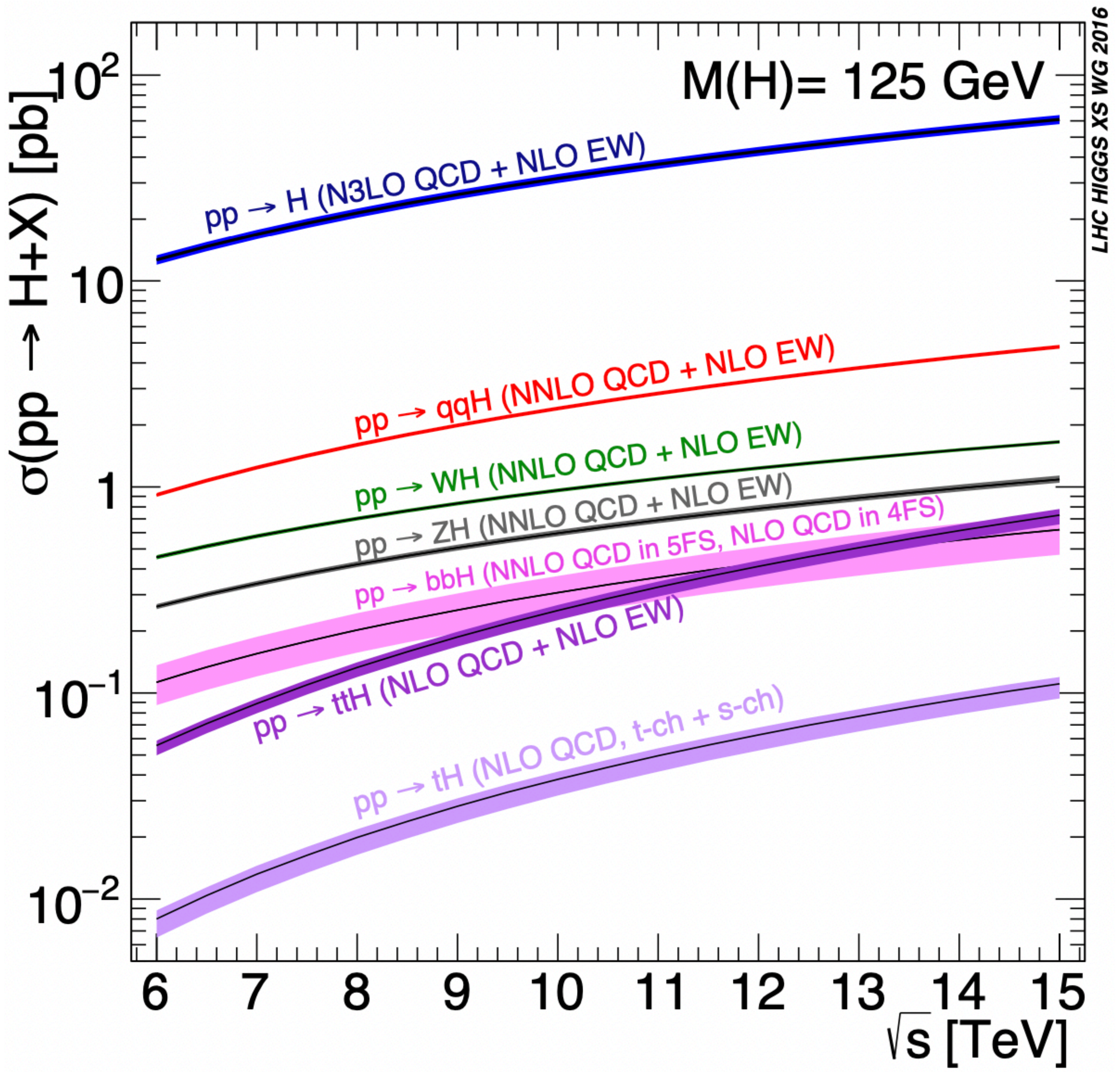
F^{corr} encodes the spreading of the D-terms upon the full Φ_{XJ}.

- In the singular part, the QCD scales must be $\mu_F \sim \mu_R \sim p_T$.
- For the regular part, different scale choices can be performed:
  - the transverse momentum p_T (original choice)
  - the hard scale Q (`FOatQ=1`)

Gavardi, Oleari, Re [2204.12602]

The process

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**

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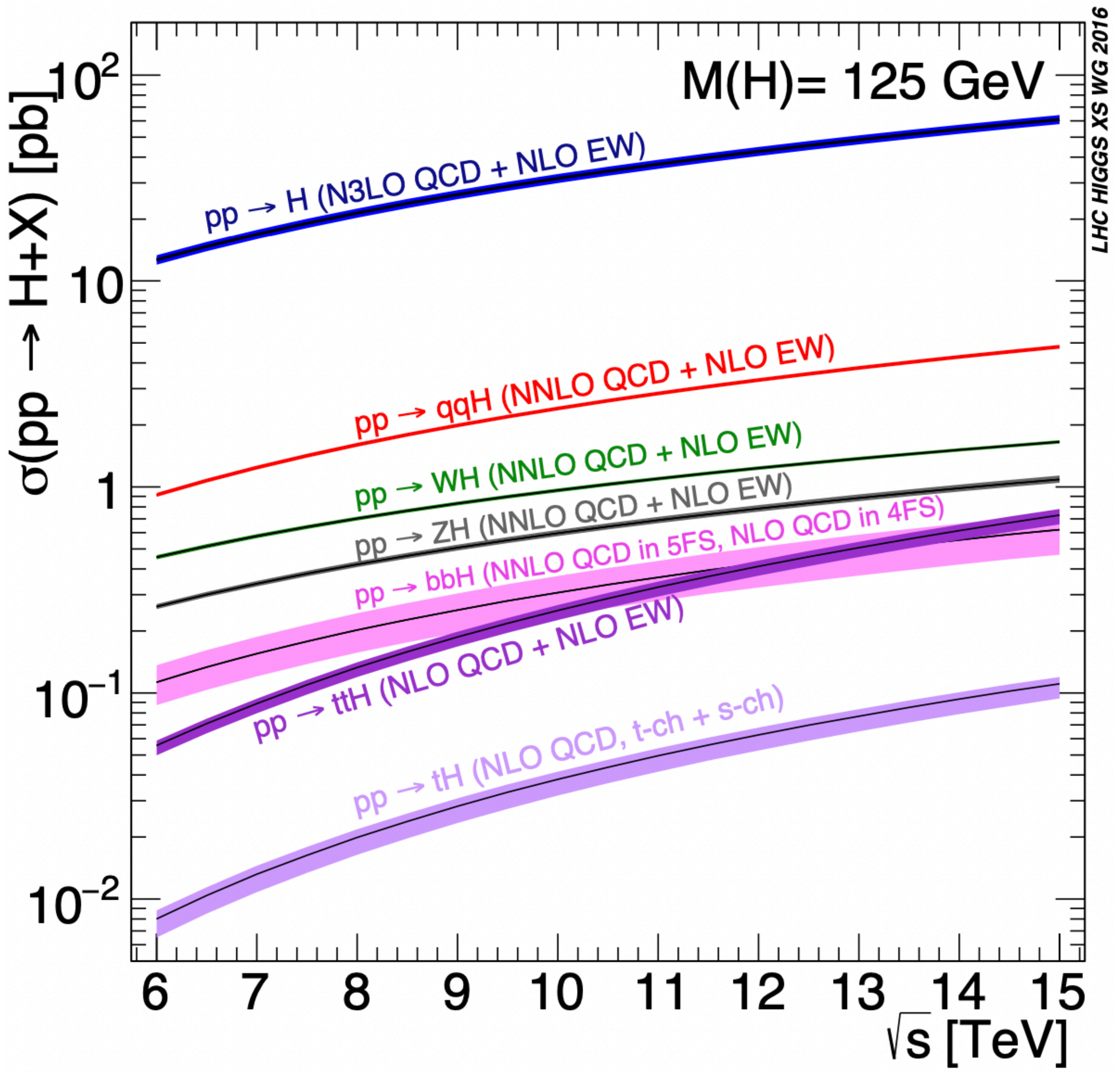

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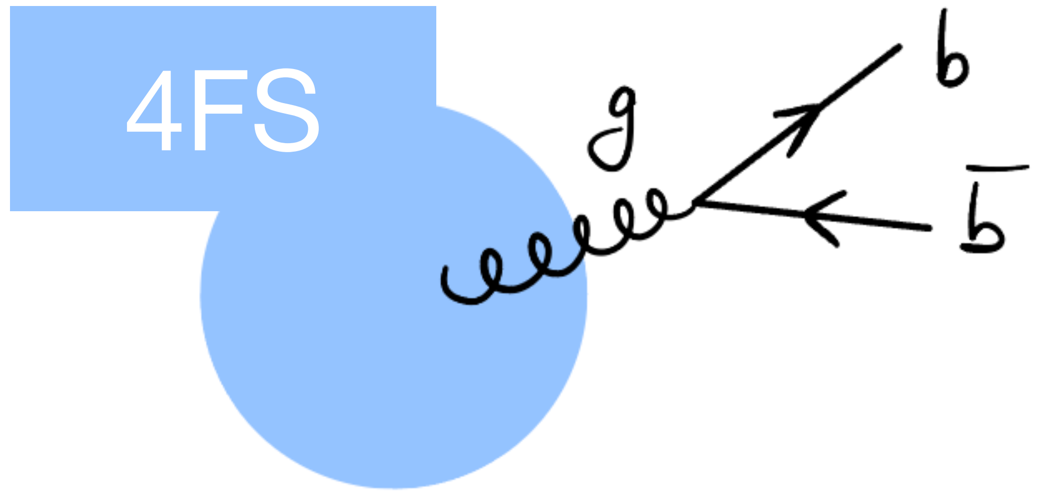
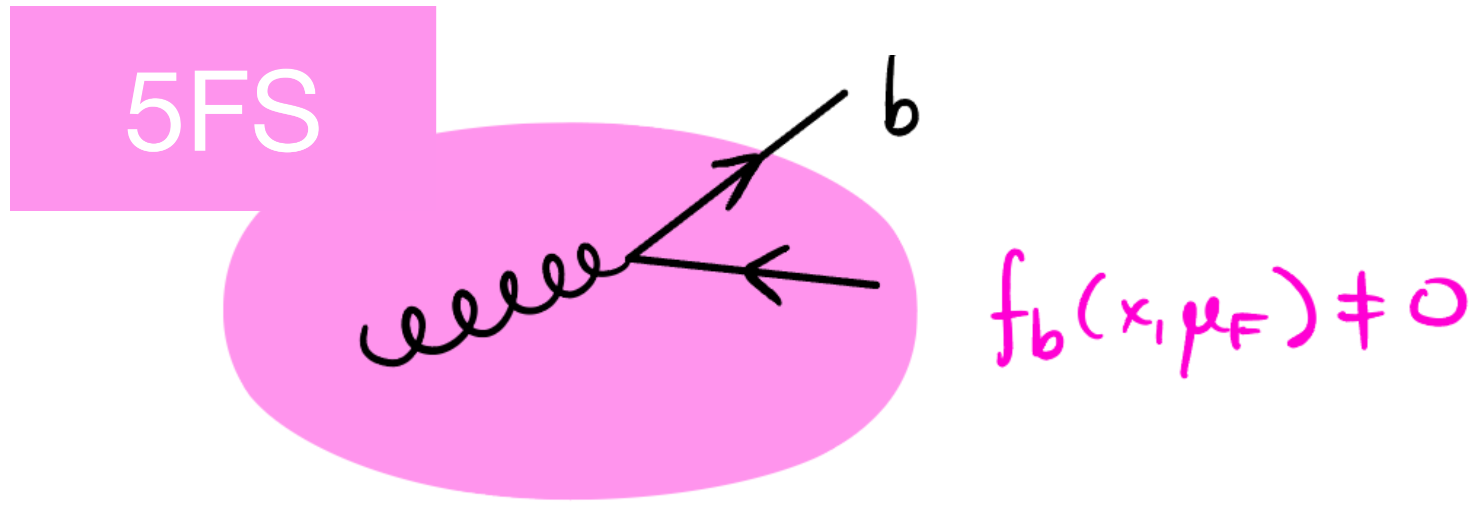
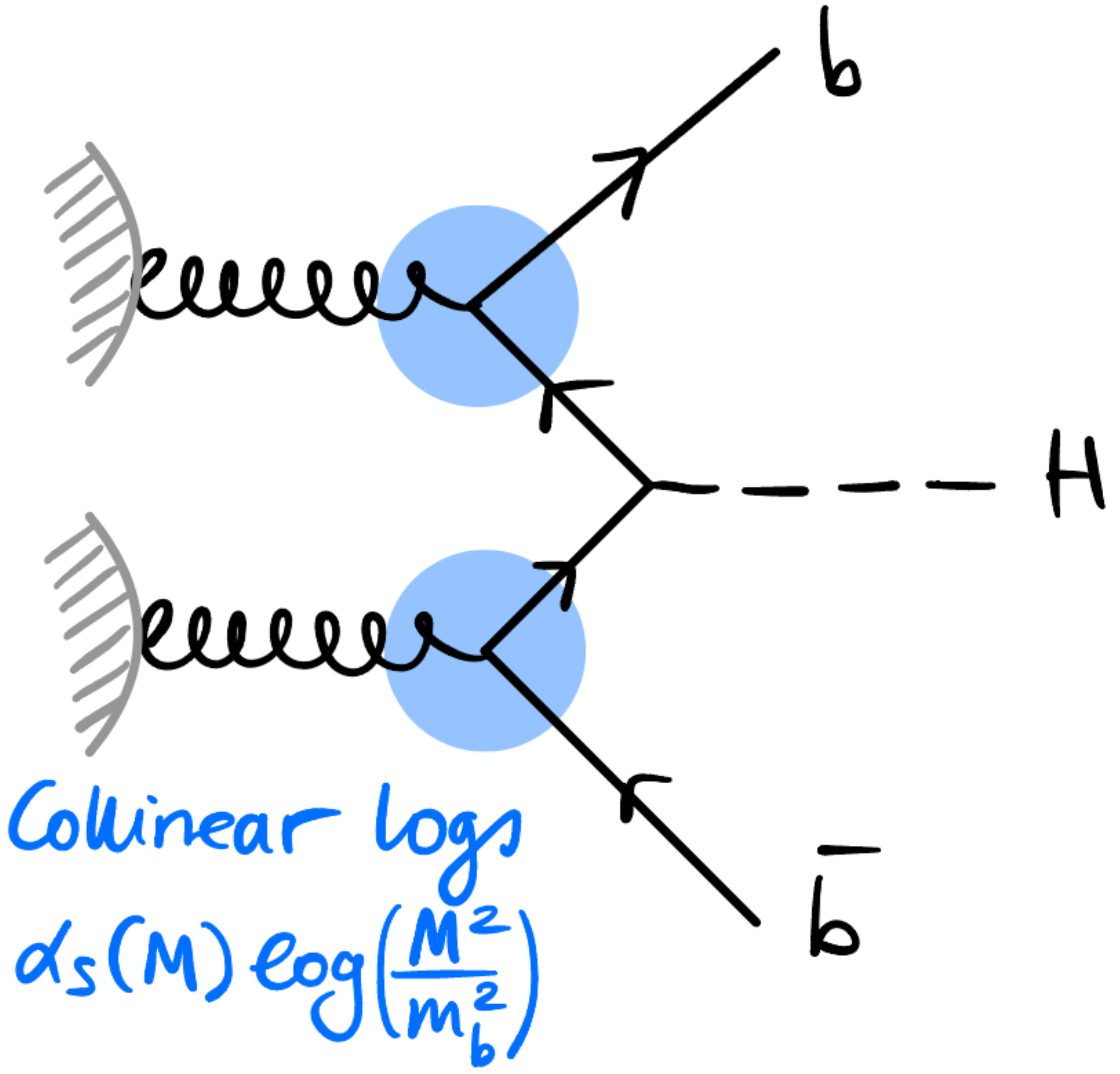
$b\bar{b}H$ is also of theoretical interest for the **different schemes** of calculations that can be used





4FS

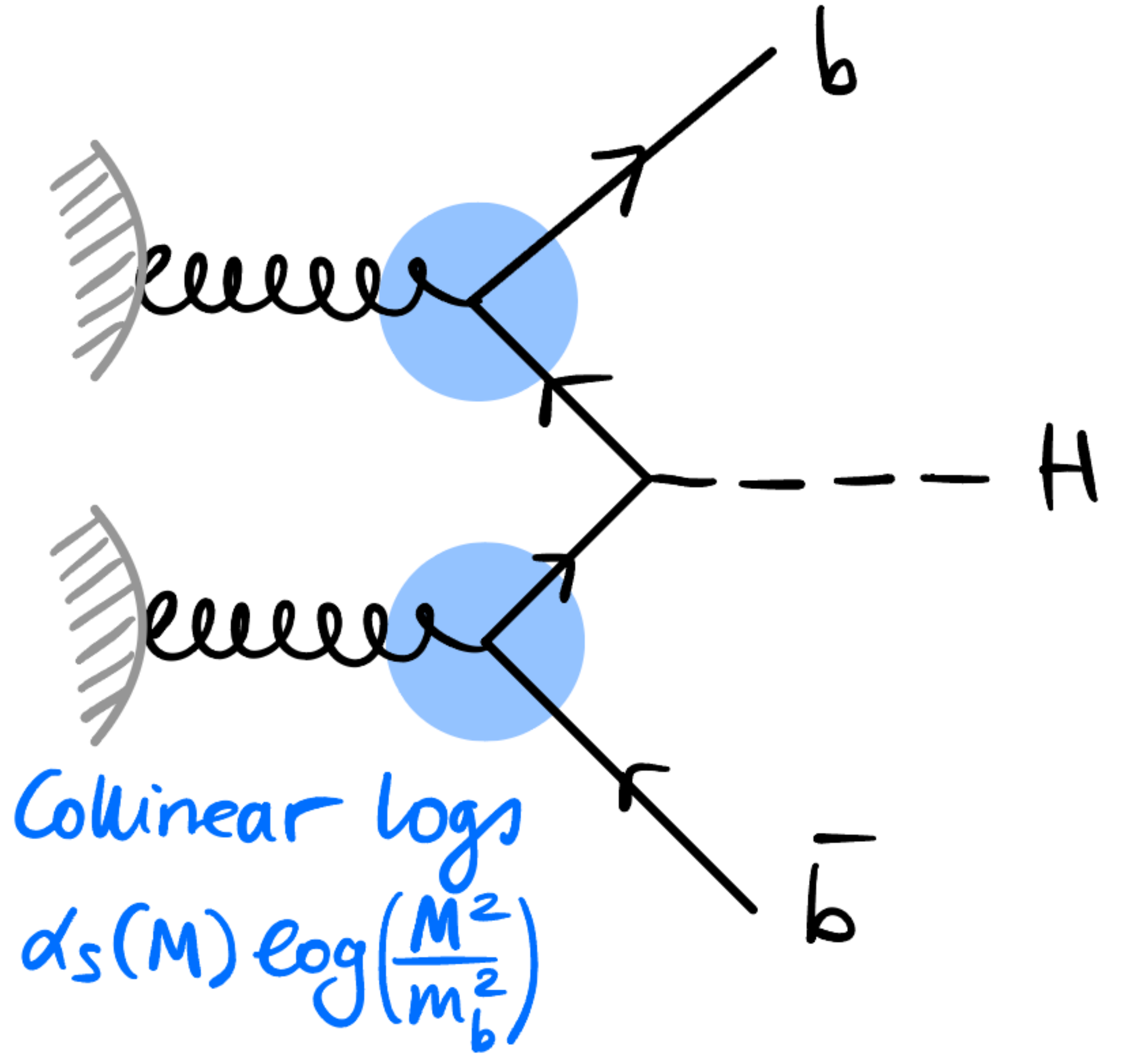


decoupling/massive scheme

- 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

4FS



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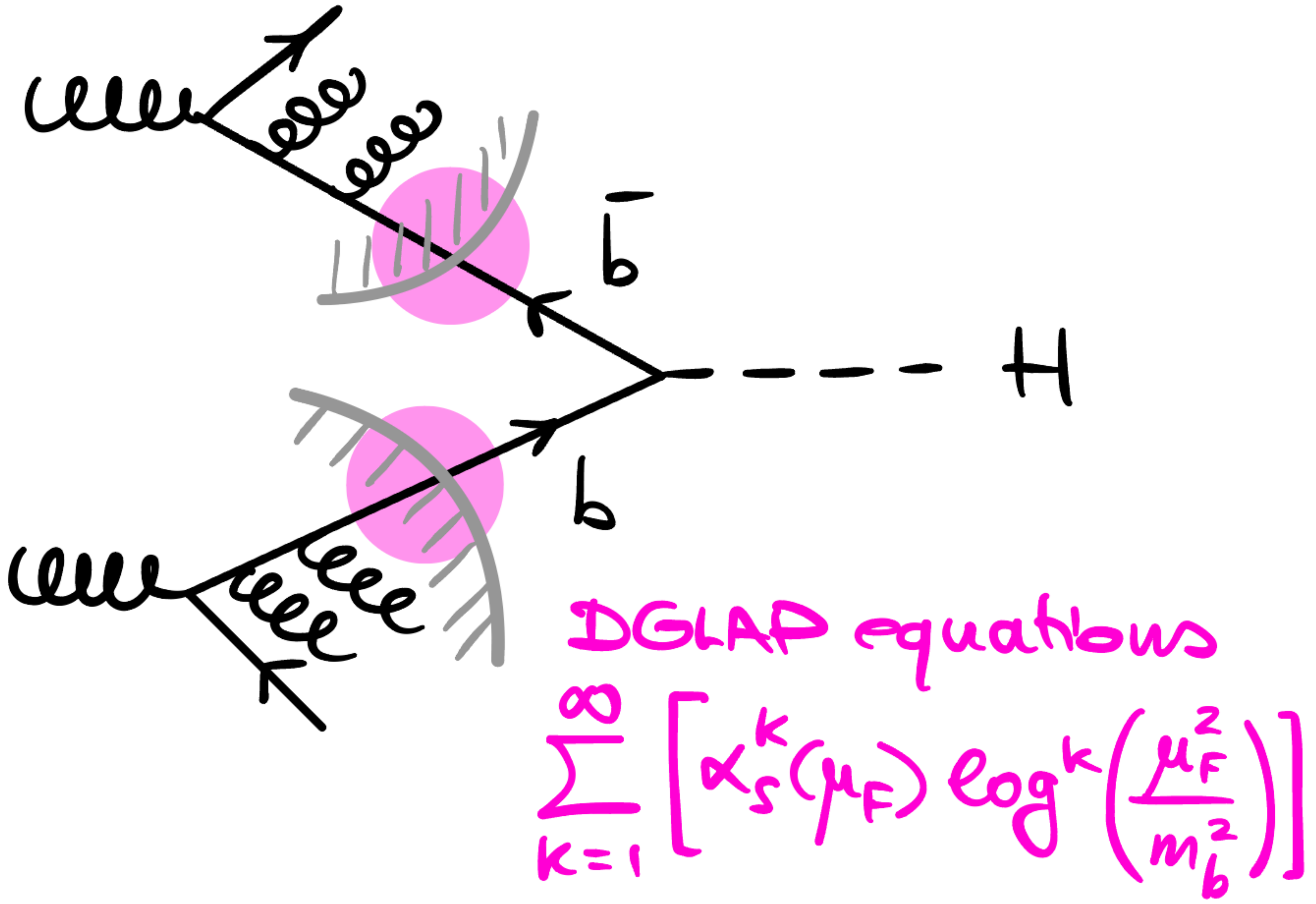
5FS



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

Current state of the art

- N^3LO for the total cross section in the 5FS — Duhr, Dulat, Mistlberger [1904.09990]
- N^3LO^{5FS} matched to NLO^{4FS} using the FONLL matching

Duhr, Dulat, Hirschi, Mistlberger [2004.04752]
Forte, Napoletano, Ubiali [1508.01529, 1607.00389]

- NLO^{4FS} matched to parton shower — Wiesemann, Frederix, Frixione, Hirschi, Maltoni, Torrielli [1409.5301]; Jäger, Reina, Wackeroth [1509.05843]

- NLO^{4FS}_{QCD} + PS combined with NLO^{4FS}_{EW} — Pagani, Shao, Zaro [2005.10277]

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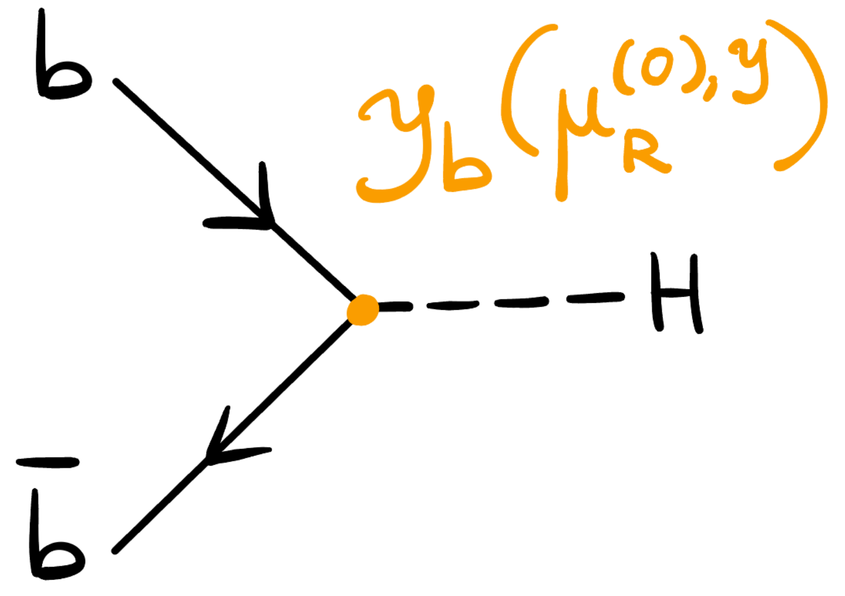
This talk:

We focus on the 5FS calculation of the $b\bar{b}H$ process and we perform the **first fully-differential** calculation of **NNLO QCD** matched to **parton shower** (NNLO^{5FS} + PS)

MiNNLOPS for Yukawa induced processes

The Yukawa coupling is renormalised in $\overline{\text{MS}}$ scheme.



The running of this Born coupling requires some adaptations of the MiNNLOPS method to take account the extra scale dependence.

$$H^{(1,2)} \to H^{(1,2)}\left(\log \frac{\mu_R^{(0),y}}{m_H}\right)$$

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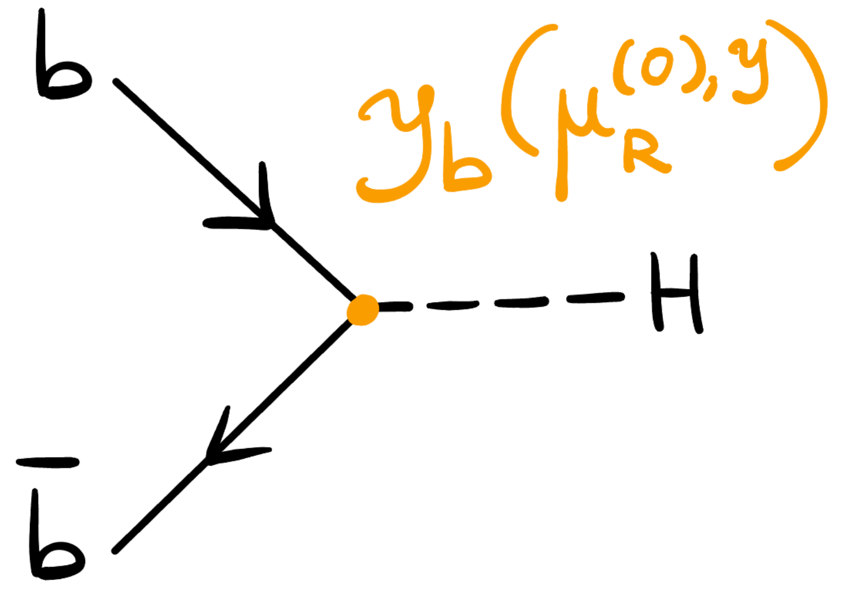

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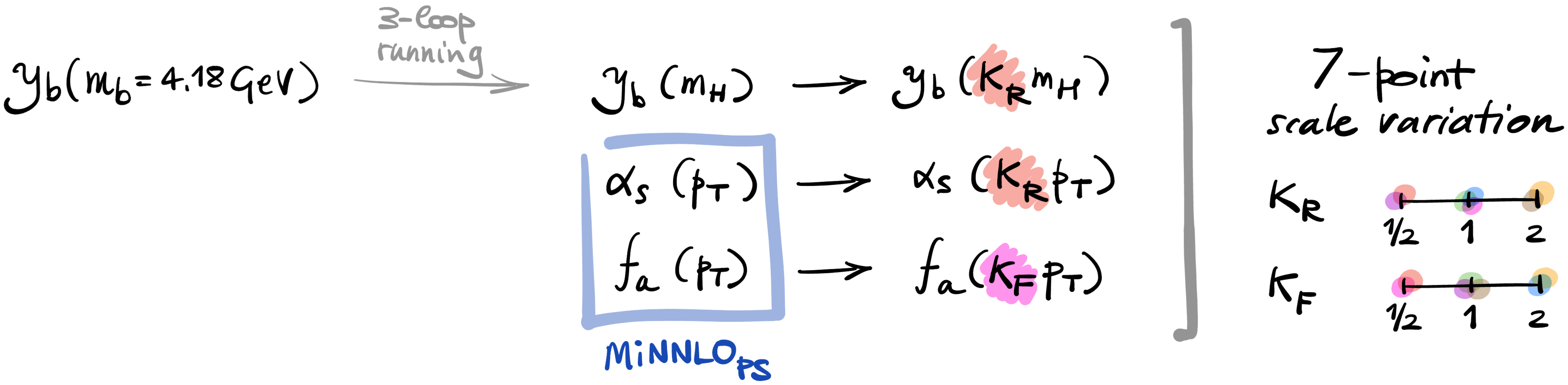


Cross-section results

Same PDFs:
NNPDF40_nnlo_as_01180
with 5 active flavours

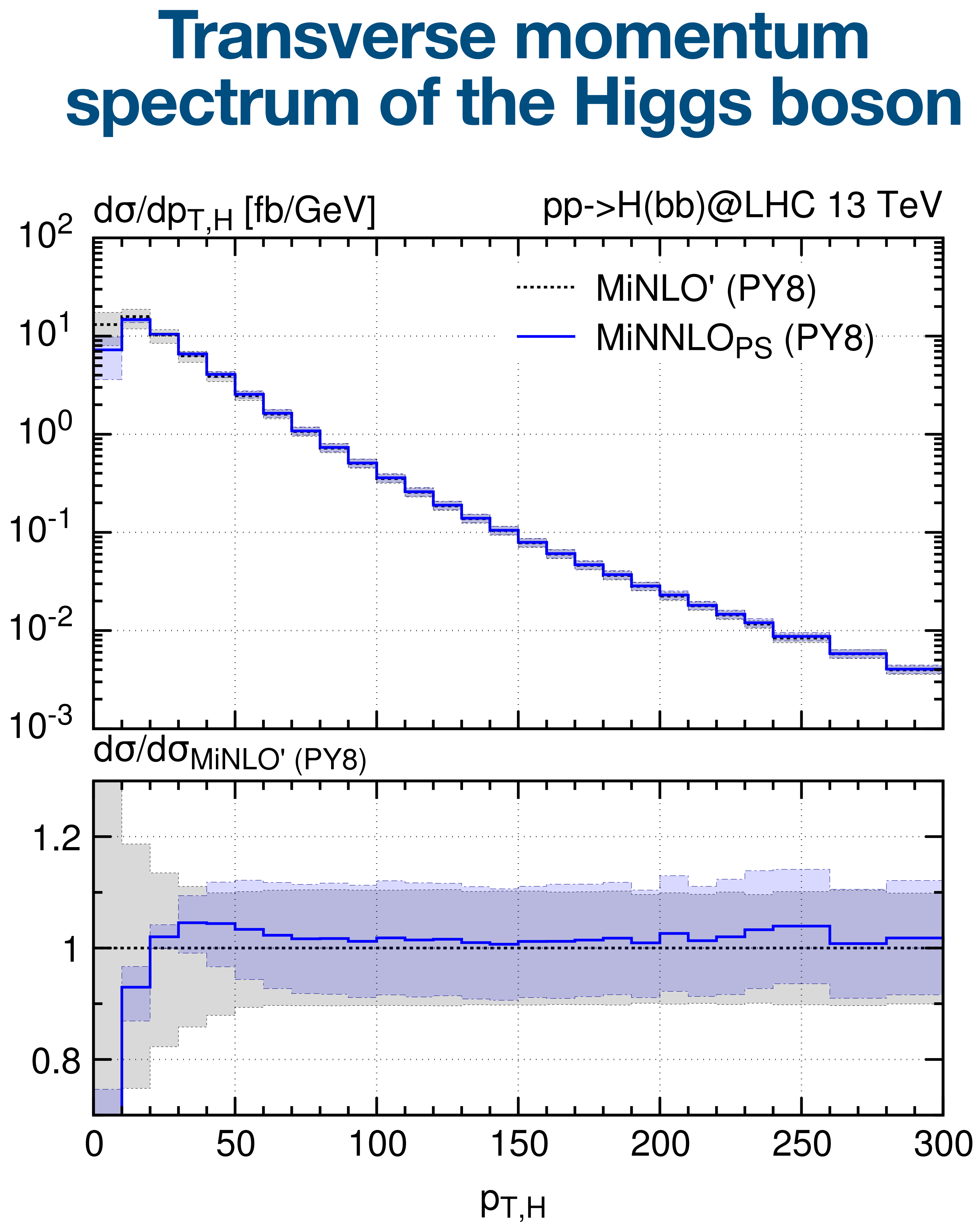
Comparison of the total inclusive cross section with FO results obtained with the public code **SusHi** with $\mu_R = \mu_F = m_H$

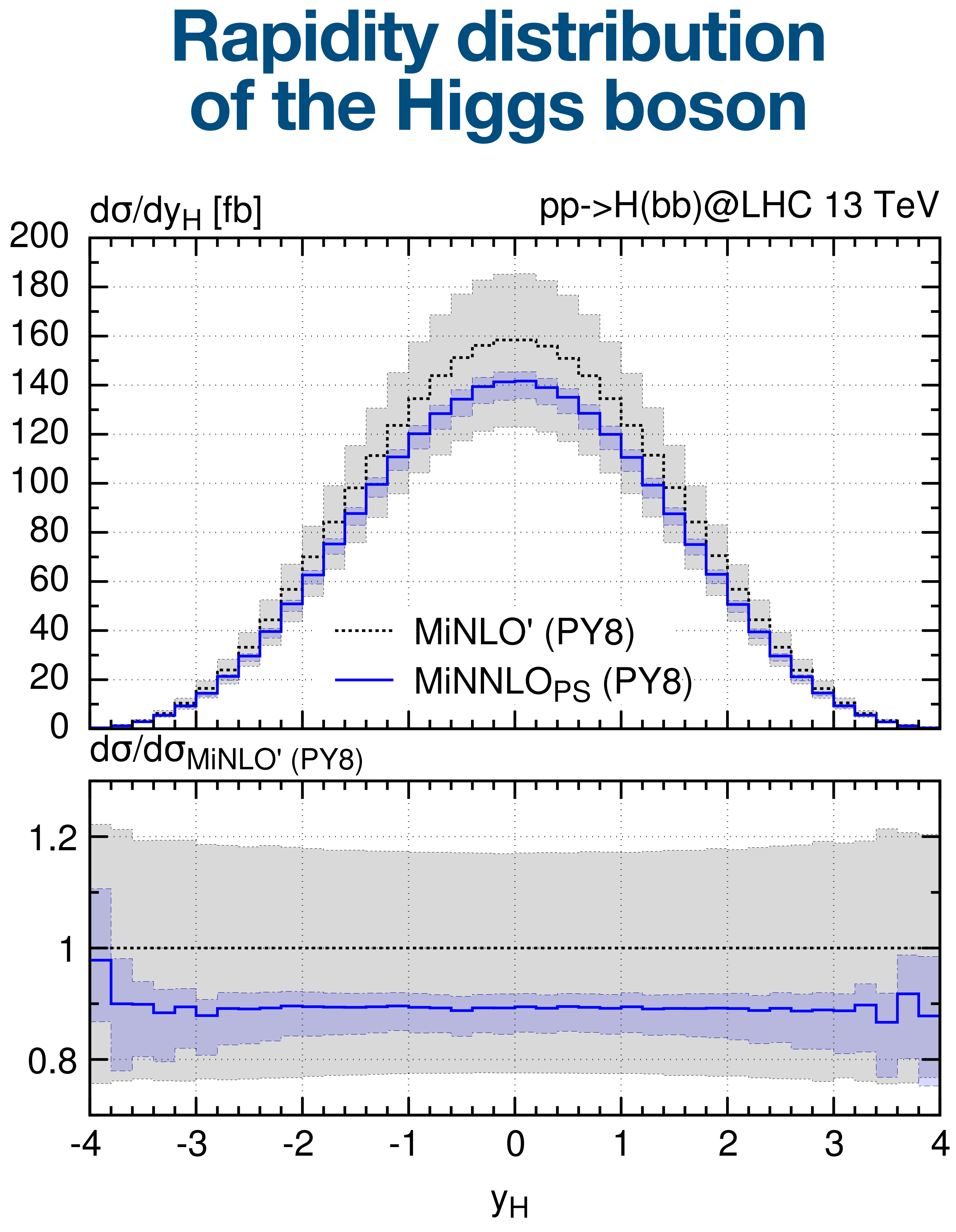
Harlander, Lieber, Mantel [1212.3249]

Process	NLO (SusHi)	NNLO (SusHi)	MiNLO′	MiNNLOPS	MiNNLOPS (FOatQ 1)
$b\bar{b} \to H$	$0.646(0)^{+10.4\%}_{-10.9\%}$ pb	$0.518(2)^{+7.2\%}_{-7.5\%}$ pb	$0.571(1)^{+17.4\%}_{-22.7\%}$ pb	$0.509(8)^{+2.9\%}_{-5.3\%}$ pb	$0.508(4)^{+3.6\%}_{-4.3\%}$ pb

- NNLO cross section is reduced by $\sim 20\,\%$
- Scale uncertainties significantly reduced at NNLO
- Our MiNNLOPS predictions are in agreement with **SusHi** within the uncertainties

Comparison of MiNLO' and MiNNLOPS

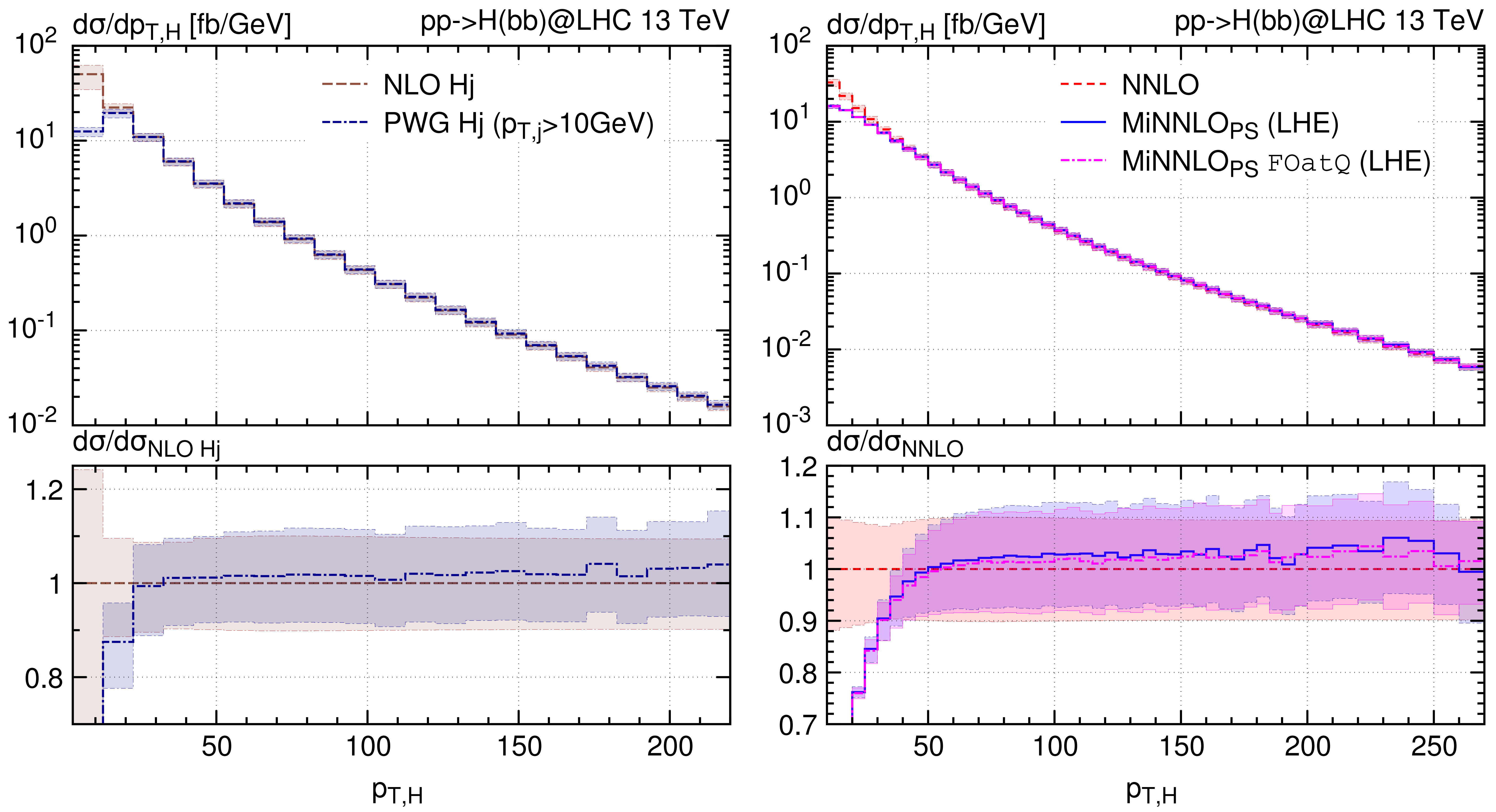




- At small $p_{T,H}$, MiNNLOPS significantly dampens the distribution.
- At high $p_{T,H}$, MiNNLOPS and MiNLO' coincide, both NLO accurate
- MiNNLOPS has a flat negative correction in the rapidity y_H distribution

Comparison to FO results

Transverse momentum spectrum of the Higgs



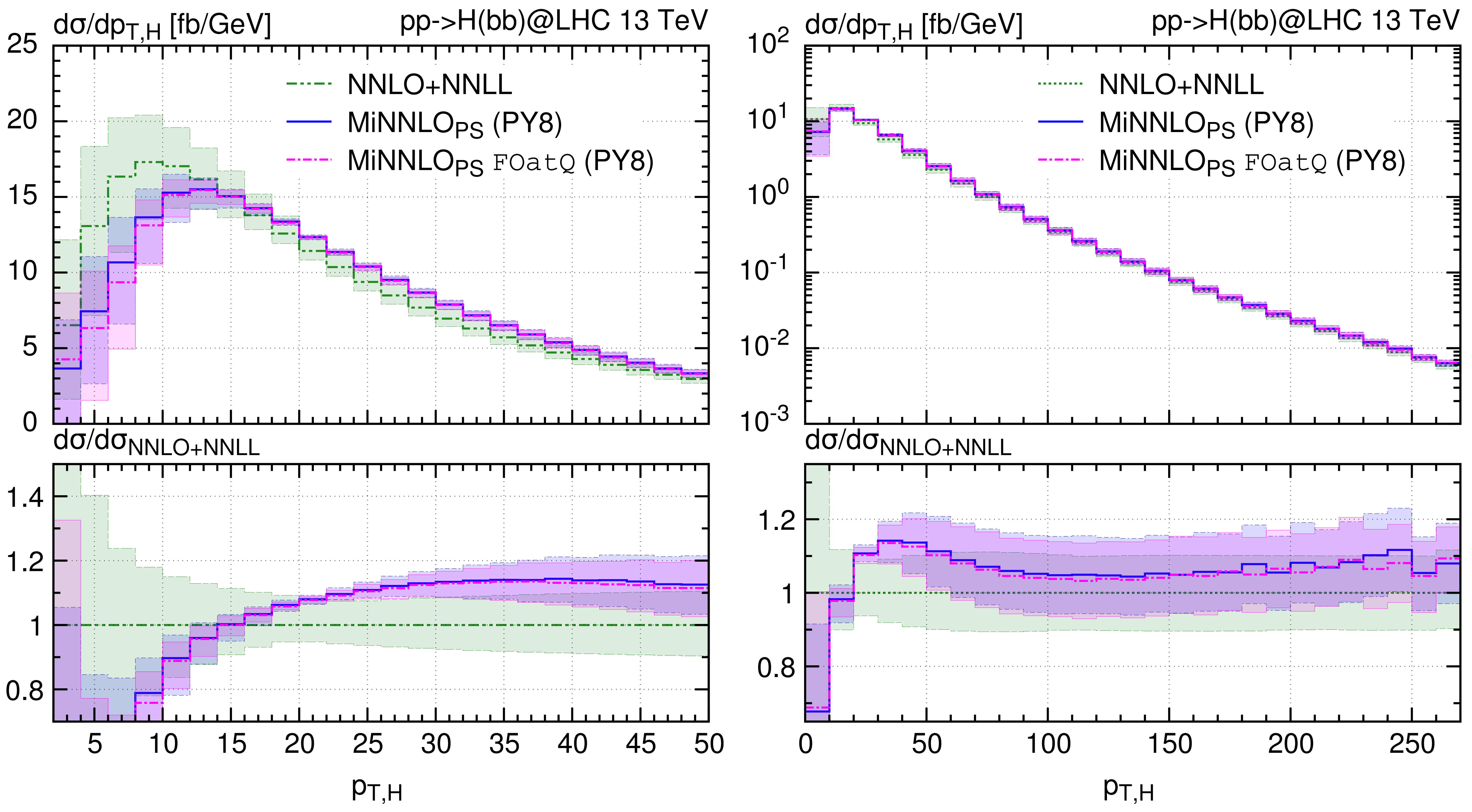
We tested our POWHEG generator before and after the MiNNLO implementation.

Full **agreement** at large transverse momenta $p_{T,H}$ with analytic **Fixed-Order predictions**

NLO Hj Harlander, Ozeren, Wiesemann [1007.5411]
NNLO Harlander, Tripathi, Wiesemann [1403.7196]

Comparison to resummed results

Transverse momentum spectrum of the Higgs



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

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

NNLO+NNLL Harlander, Tripathi, Wiesemann [1403.7196]

Summary and outlook

- Presentation of **NNLO+PS predictions** for Higgs production via bottom fusion **in 5FS** which are in **agreement with fixed-order** results from literature.
- It is an **initial step** towards a complete NNLO+PS description of $b\bar{b}H$.

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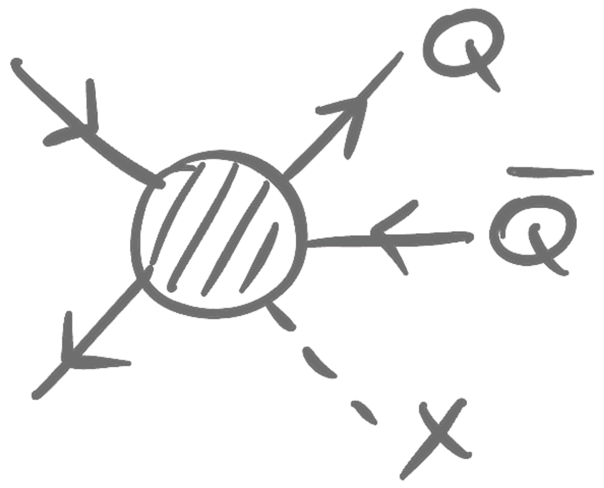
- We are working on the NNLO+PS implementation in **4FS**.

MiNNLO$_{PS}$ 

$+$ massification of $H^{(2)}$ $+$ two-loop finite reminder

Badger, Hartanto, Kryś, Zoia [2107.14733]

- With the 4FS generator, one could perform a differential **FONLL combination** of the NNLOPS results in the **two schemes**.

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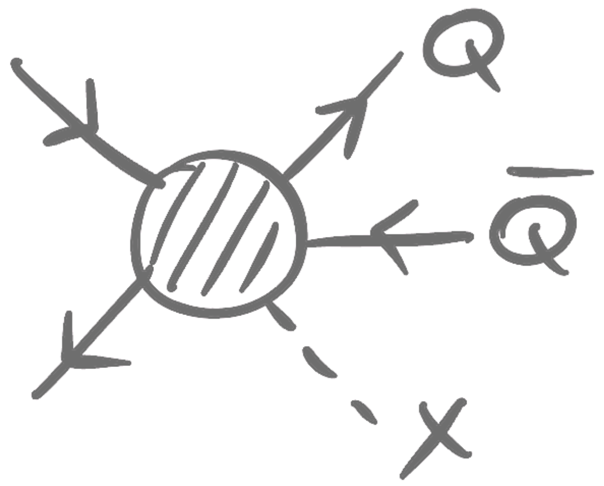
MiNNLO$_{PS}$



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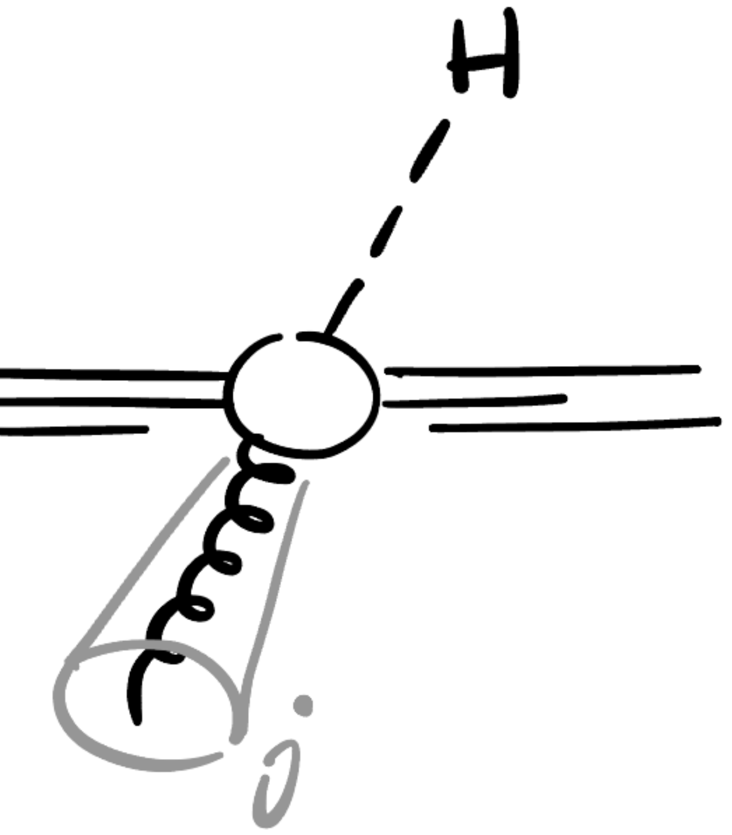
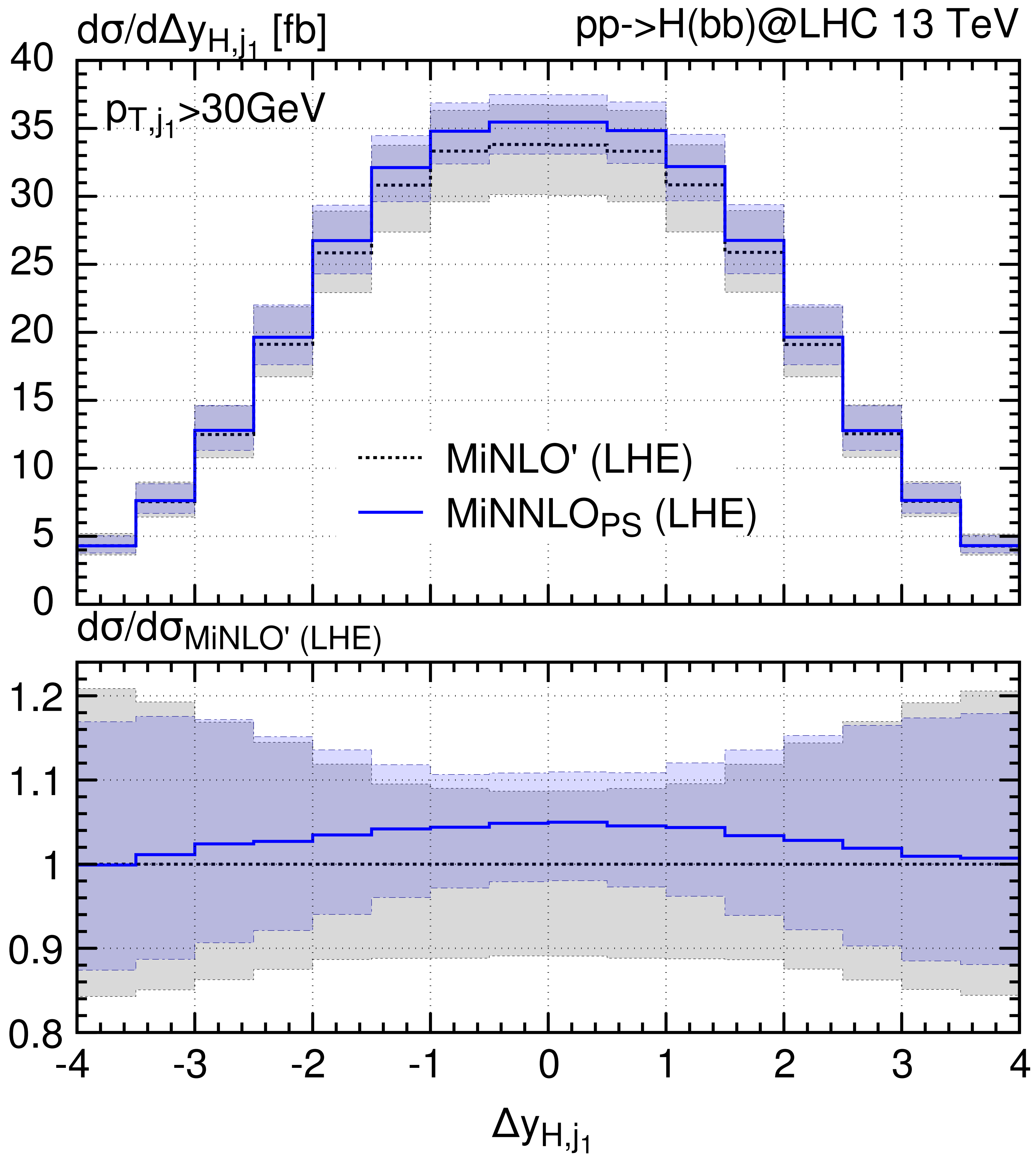
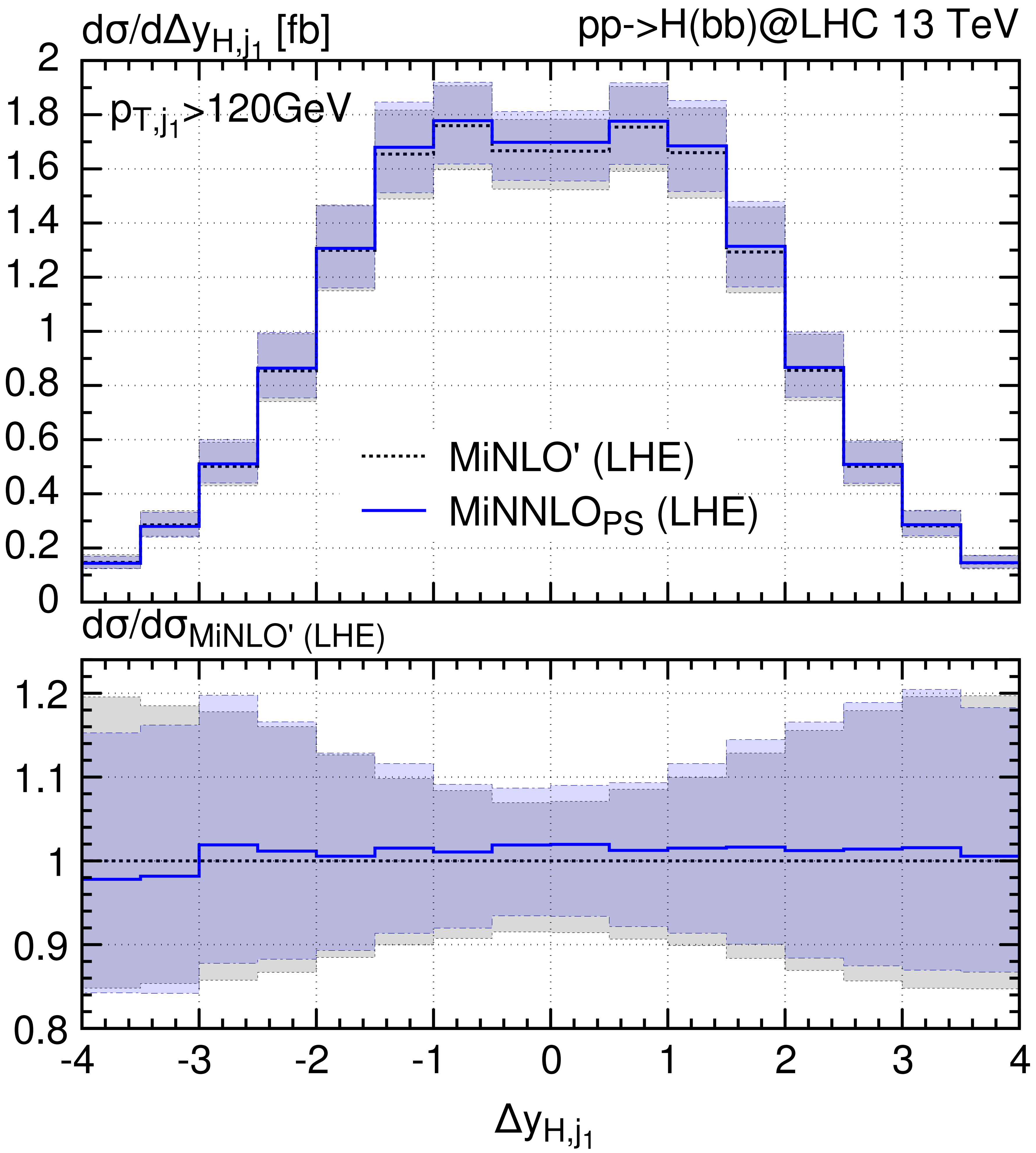
Thank you for your attention
and Happy Christmas!

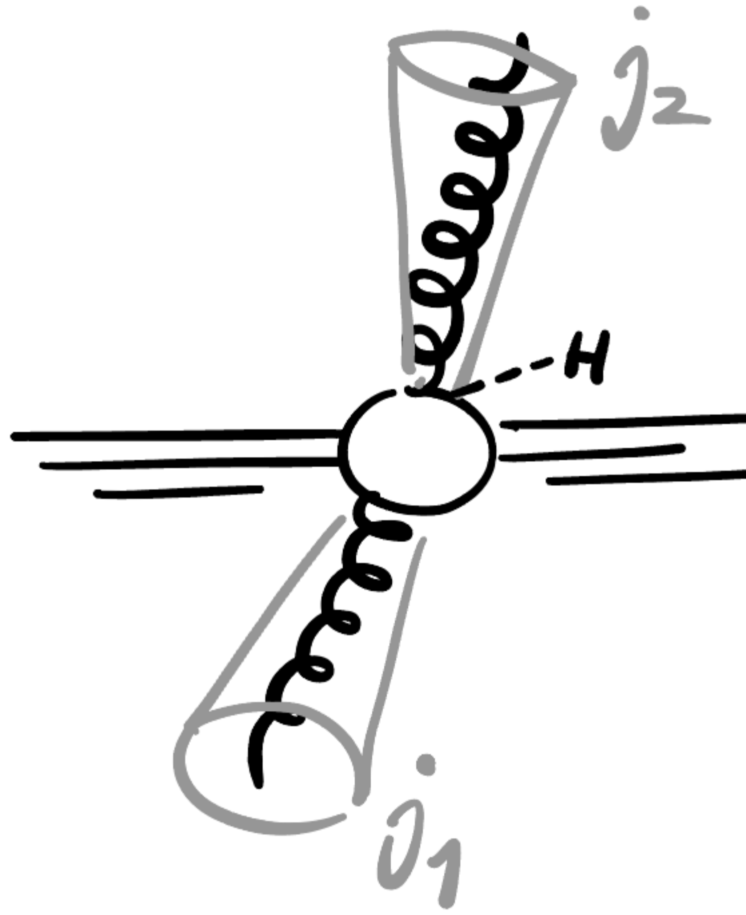
Backup slides

Jet-observables: difference of rapidity

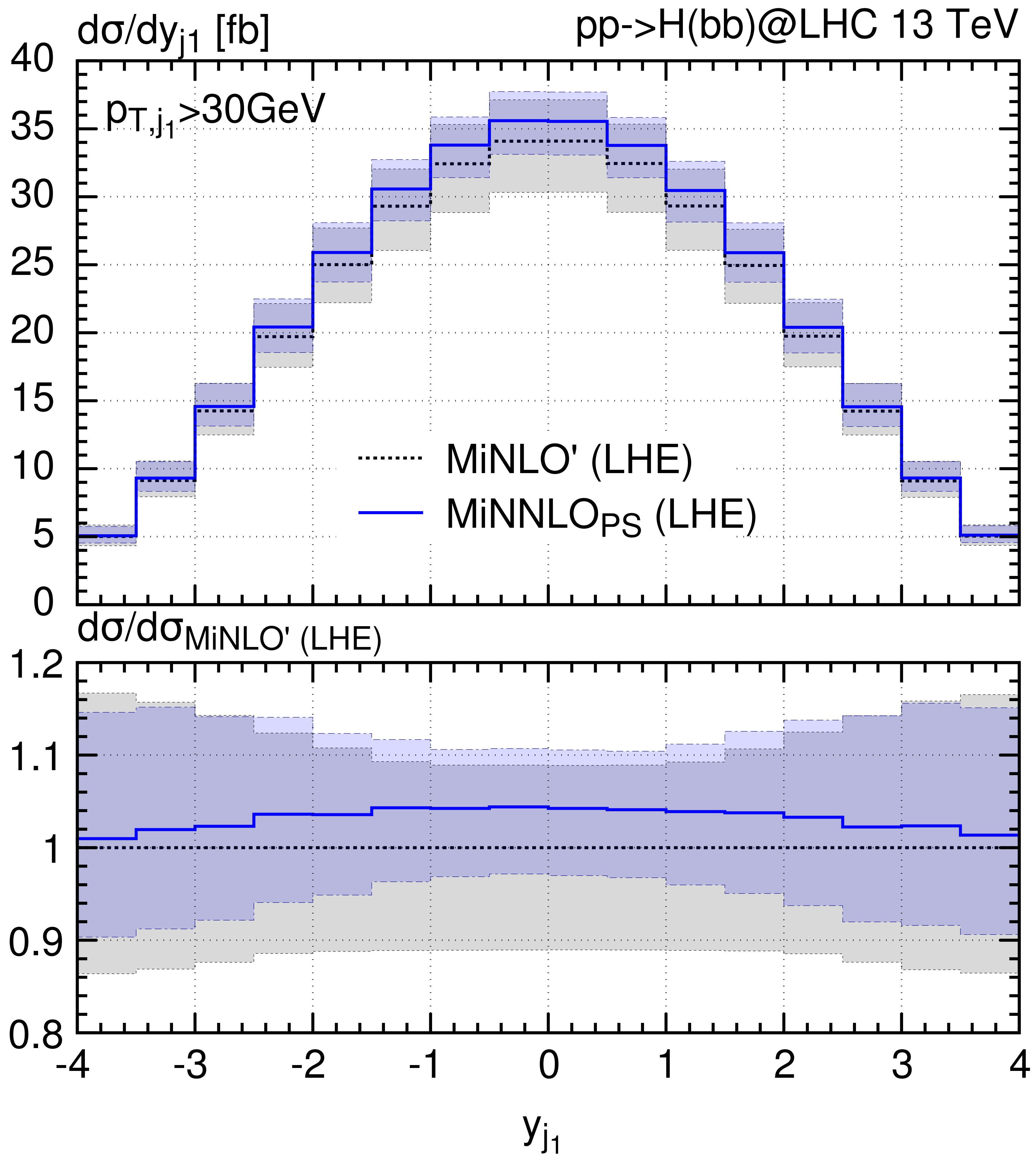


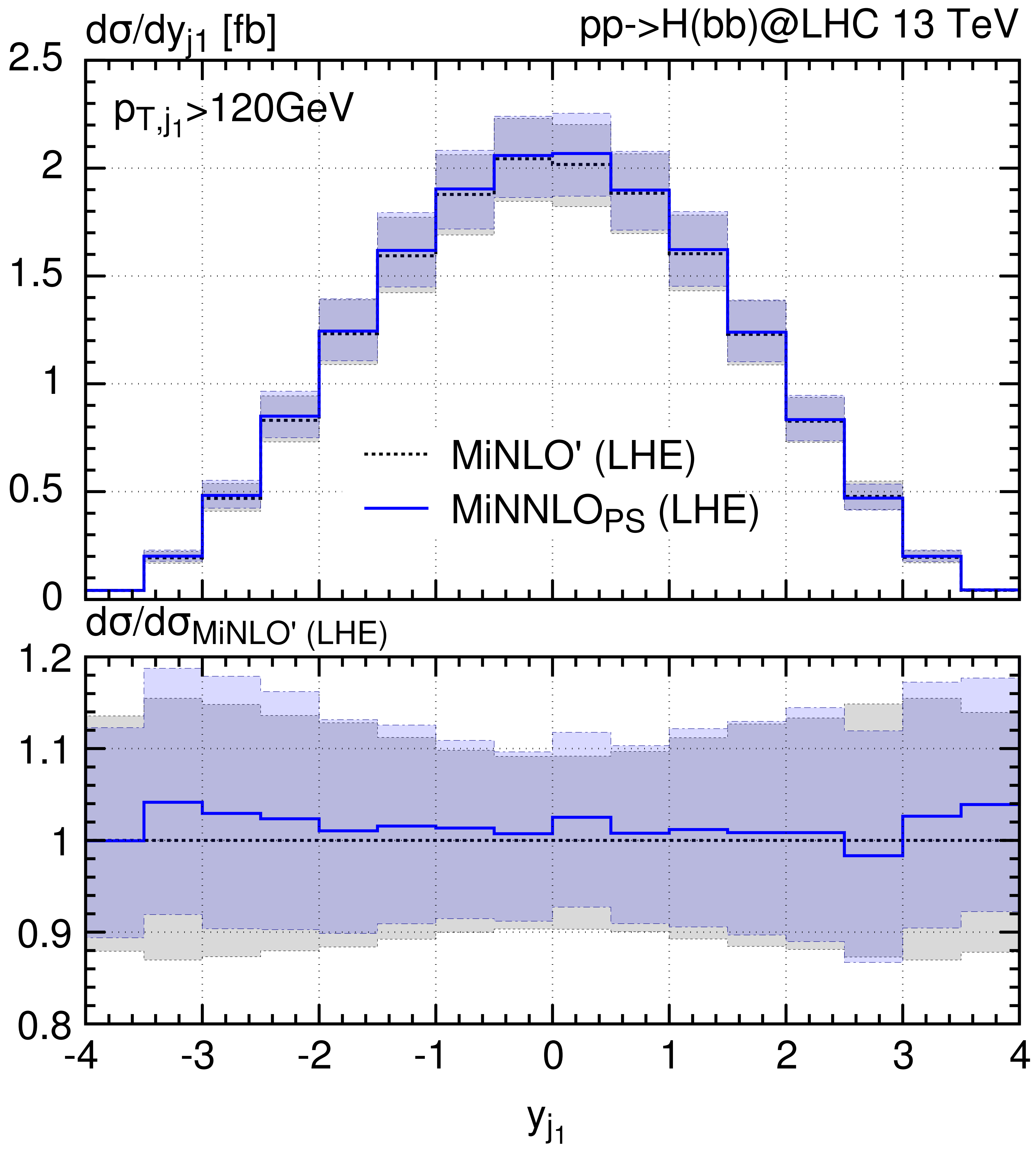






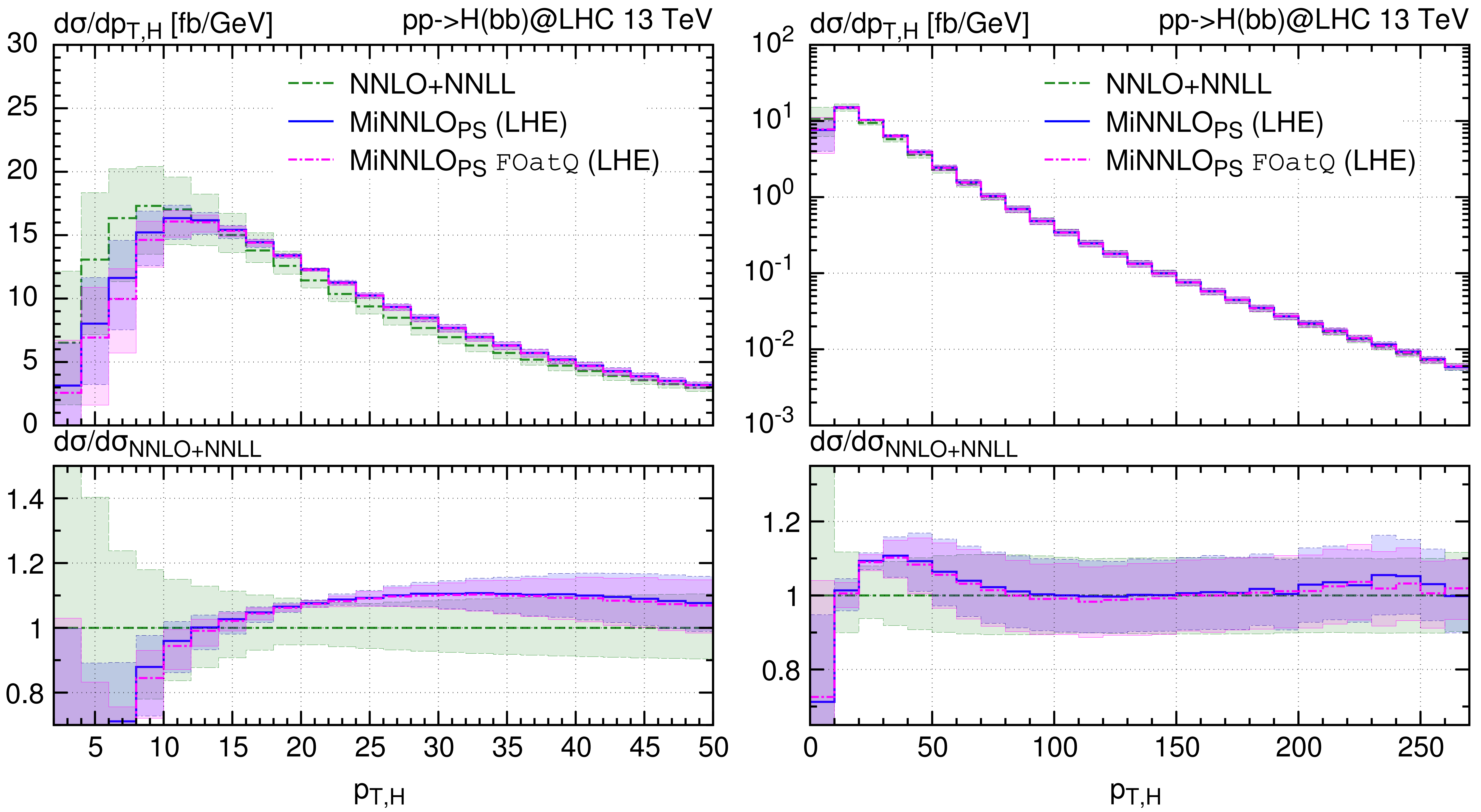
Jet-observables: jet rapidity





Resummed results vs LHE

Transverse momentum spectrum of the Higgs

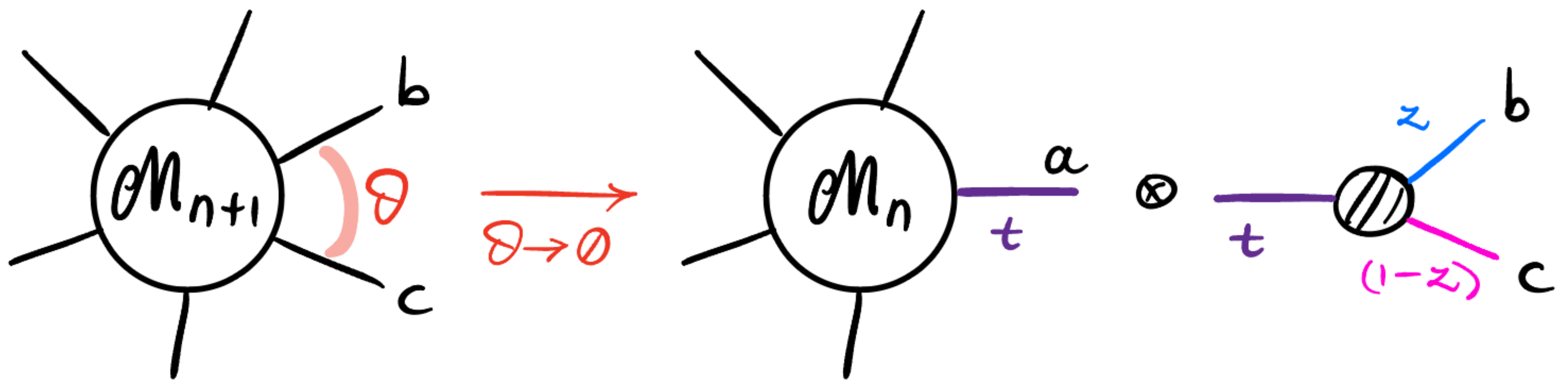


- The agreement is better before the Parton Shower
- In the case of LHE events, there is a perfect agreement at high $p_{T,H}$ between the analytic and MiNNLOPS distributions

Marchesini, Webber [NPB238(1984)1]
Sjostrand [PLB157(1985)321]
Altarelli, Parisi [NPB126(1977)298]

Shower Monte Carlo

The Parton Shower formalism is based on **collinear factorisation** with a probabilistic description of the splitting process.



Similarly to a radioactive decay, the probability of evolving between two scales and emitting no gluons is

$$\Delta_t = \exp\left[-\int_t \frac{dt'}{t'} dz' d\varphi' \frac{\alpha_s}{2\pi} P(z')\right]$$

exp(−λt) = non-radiation probability

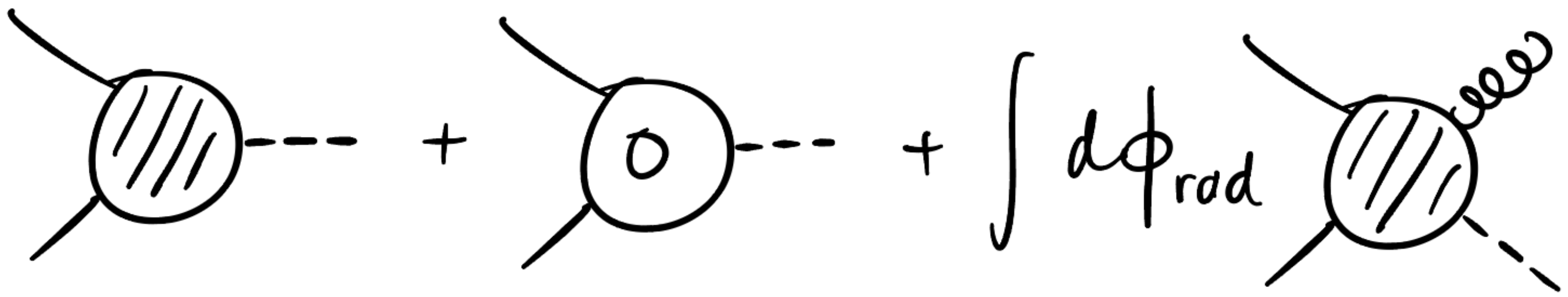
Using this form factor we can deduce the SMC prediction with the first emission

$$\langle \mathcal{O} \rangle = \int d\Phi_n B(\Phi_n) \left[\mathcal{O}(\Phi_n)\Delta_{t_0} + \int_{t_0} \frac{dt}{t} dz d\varphi \mathcal{O}(\Phi_n, \phi_r) \Delta_t \frac{\alpha}{2\pi} P(z) \right]$$

exp(−λt) λδt = probability of the 1st radiation

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

NLO



- ✓ NLO accuracy for inclusive observables
- ✓ Reduced theoretical uncertainty
- ✓ Correct quantum interference
- Wrong shape for small-p_T region
- Description only at the parton level
- Computationally expensive

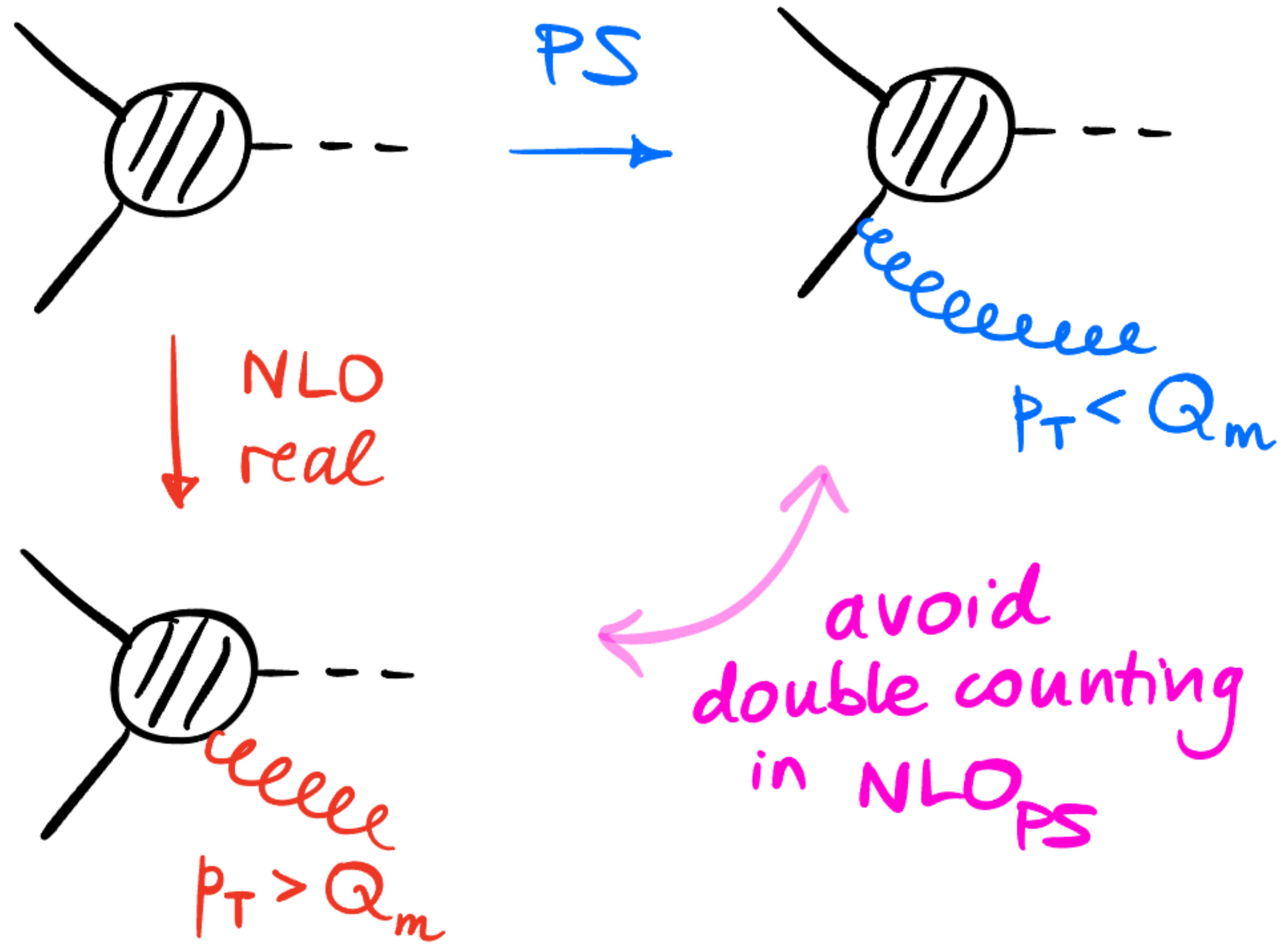
SMC (LOPS)

- Total normalisation accurate only at LO
- Poor description at high-p_T
- Partial interference through shower ordering
- ✓ Sudakov suppression of small-p_T emissions (LL resummation)
- ✓ Simulate high-multiplicity events at the hadron level
- ✓ Computationally cheap

HERWIG, SHERPA, PYTHIA, …

Approaches are complementary: combine them in a consistent way

Matching problem



Double counting can be easily solved by applying a cut in phase space:

- **Reject hard jets** produced by PS with $p_T > Q_m$

But how can we obtain smooth distributions without a critical dependence on the matching scale Q_m?

MC@NLO [Frixione, Webber, 2002] and POWHEG [Nason, 2004] are two fully tested solutions.

POWHEG Idea

Write a simplified Monte Carlo that generates just one emission (the hardest one) which alone gives the correct NLO result.

$$\Delta^{pwg} = \exp\left[-\int \text{exact real-radiation probability above } p_T\right]$$

POWHEG in a nutshell

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

The exact NLO prediction is

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

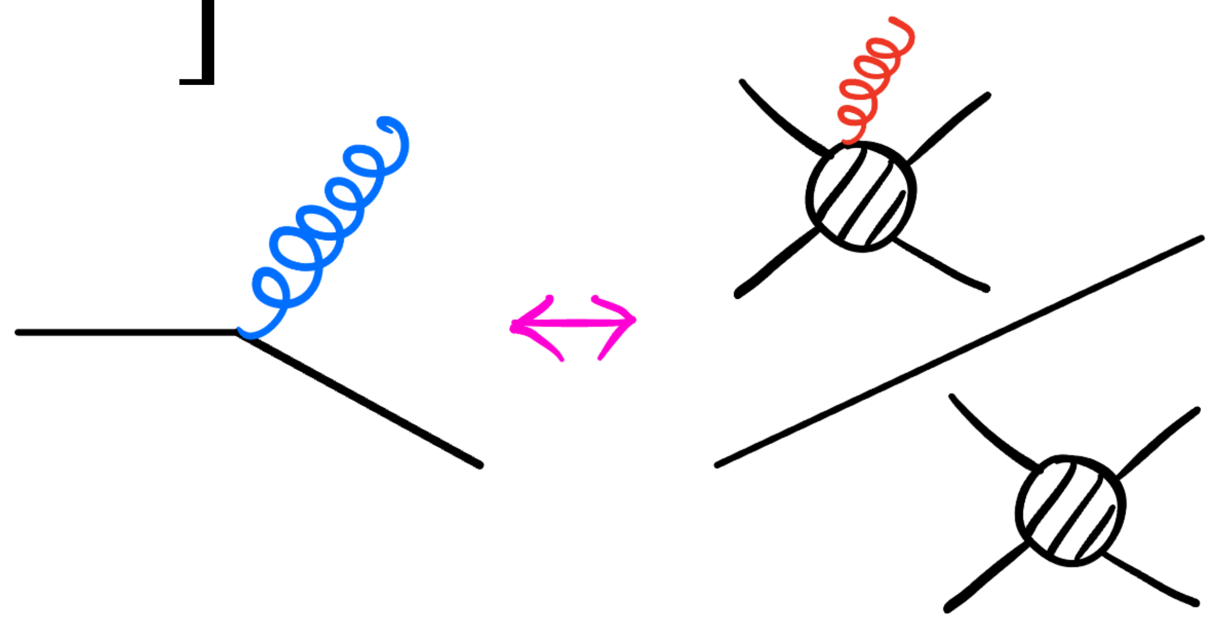
Comparing with the SMC

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

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

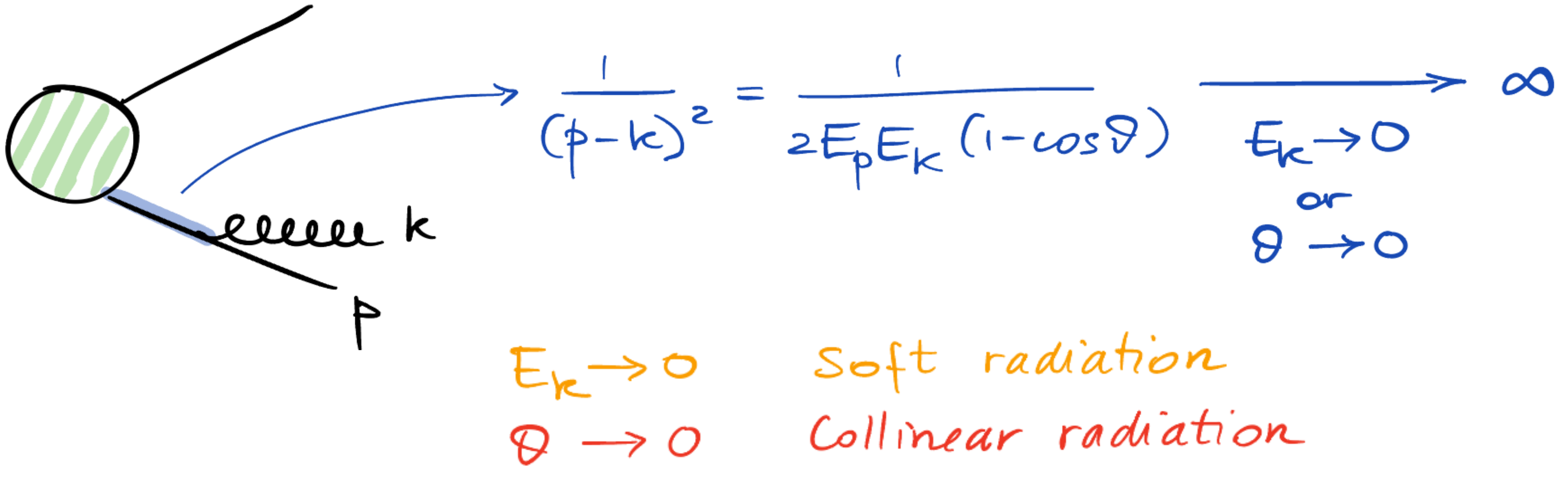
$$\langle \mathcal{O} \rangle = \int d\Phi_n \, \bar{B}(\Phi_n) \left[\mathcal{O}(\Phi_n) \, \Delta_{t_0}^{pwg} + \int d\phi_{rad} \, \mathcal{O}(\Phi_n, \phi_{rad}) \, \Delta_t^{pwg} \frac{R(\Phi_n, \phi_{rad})}{B(\Phi_n)}) \right]$$

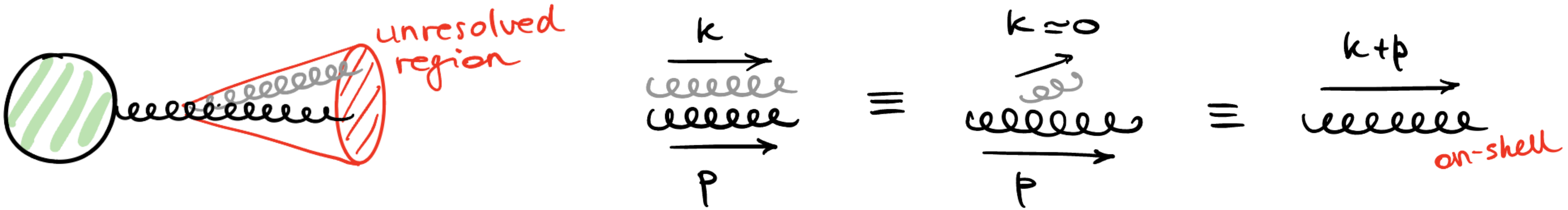
with $\Delta_t^{pwg} = \exp \left[- \int d\phi'_{rad} \frac{R(\Phi_n, \phi'_{rad})}{B(\Phi_n)} \Theta(t' - t) \right]$



IR divergences

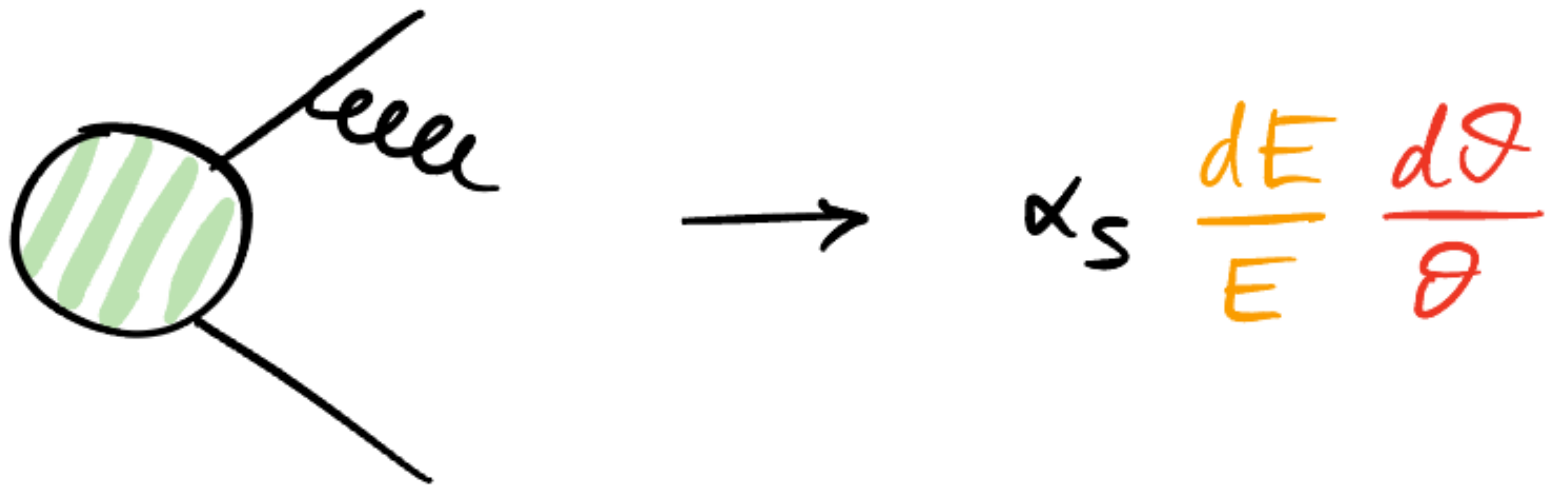
The radiation of a *massless* particle produces divergences: a manifestation of the degeneration of these states

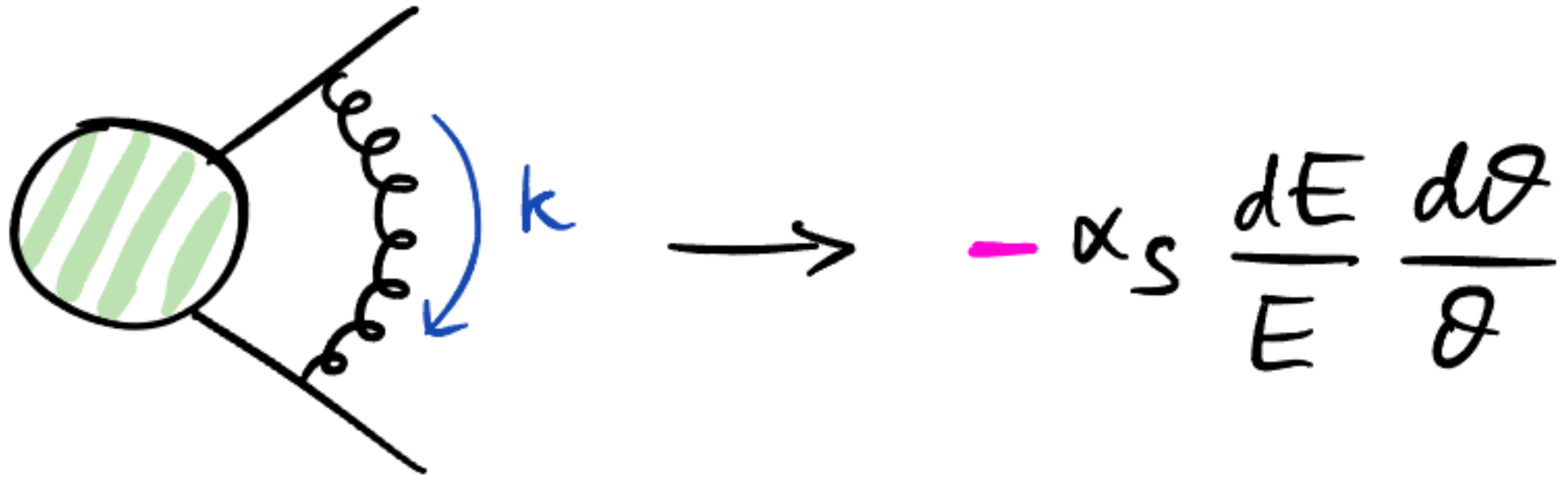




Logs as residues of IR divergences

A divergent structure is also present in the virtual contribution.
The **IR divergences cancel out** order by order in perturbation theory!

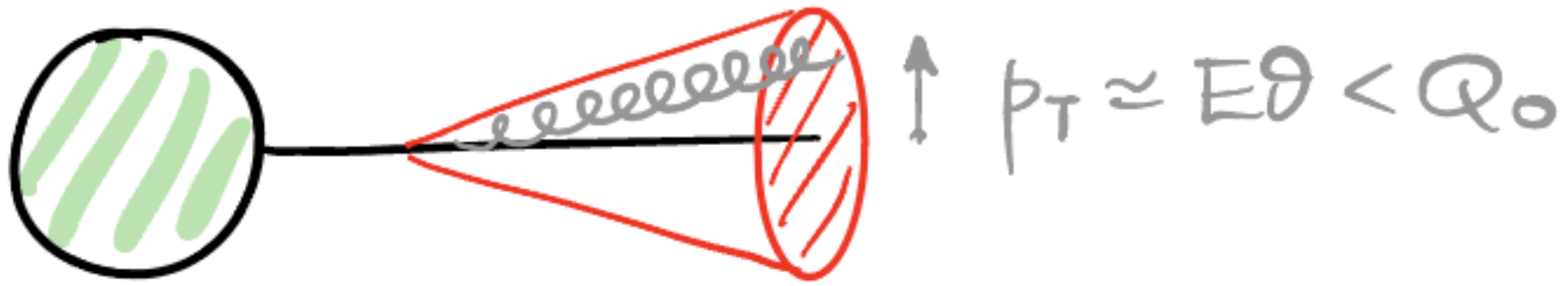




The IR divergences are cancelled, but if we are exclusive…

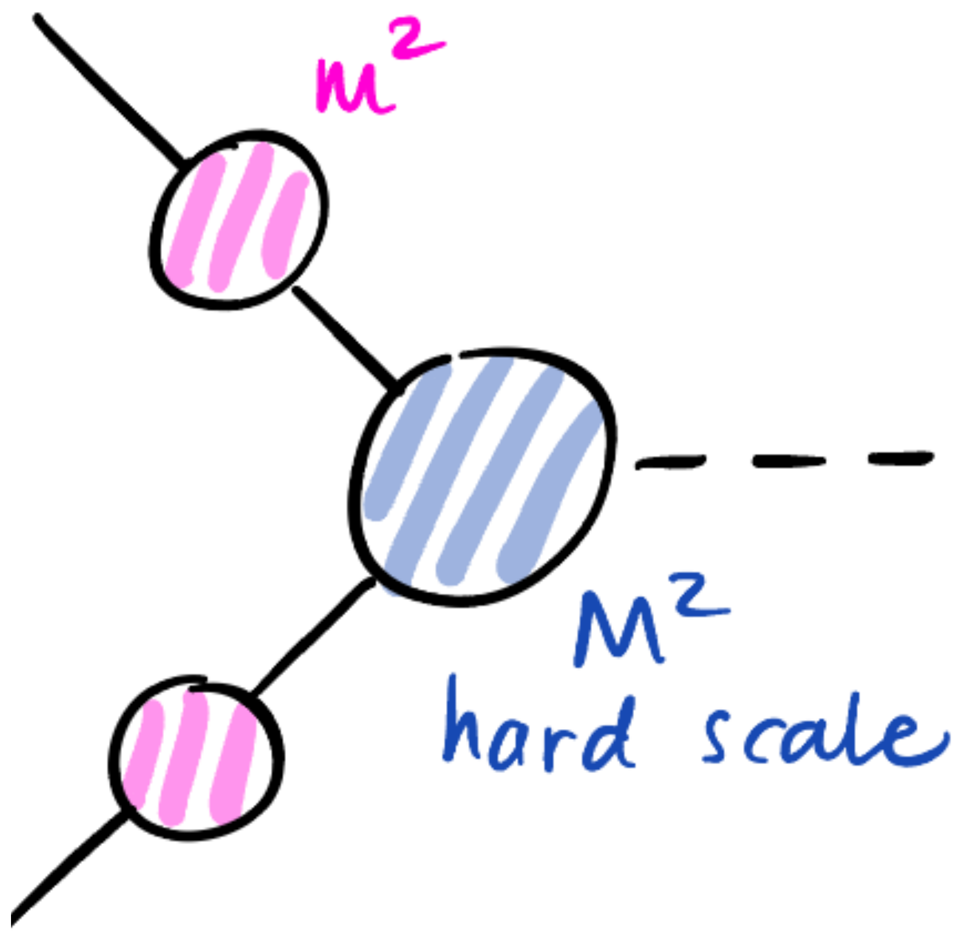
$$-\alpha_s \int_0^Q \frac{dE}{E}\frac{d\theta}{\theta}\,\Theta\left(E\theta < Q_0\right)\Big|_{\text{real}} + \alpha_s \int_0^Q \frac{dE}{E}\frac{d\theta}{\theta}\Big|_{\text{virt}} = \alpha_s \ln^2 \frac{Q}{Q_0}$$

Double Log



Resummation from factorisation

Consider a physical quantity $\mathcal{O}(M^2, m^2)$ in which m^2 measures the distance from the IR region.



If $m^2 \ll M^2$, $\quad \mathcal{O}(M^2, m^2) = \underbrace{H\left(\frac{M^2}{\mu^2}\right)}_{\text{Hard}} \underbrace{S\left(\frac{m^2}{\mu^2}\right)}_{\text{Soft}}$

$\mathcal{O}$ is μ − independent $\Rightarrow \frac{1}{H}\frac{d\ln H}{d\ln\mu^2} = -\frac{1}{S}\frac{d\ln S}{d\ln\mu^2} =: \gamma(\mu^2)$

Solving the differential equation,

$$\mathcal{O}(M^2, m^2) = H(1)\, S(1) \exp\left[-\int_{m^2}^{M^2} \frac{dq^2}{q^2}\gamma(q^2)\right]$$

for $m^2 \to 0$

Sudakov form factor: it captures at *all order* the log-enhanced terms

Transverse momentum resummation

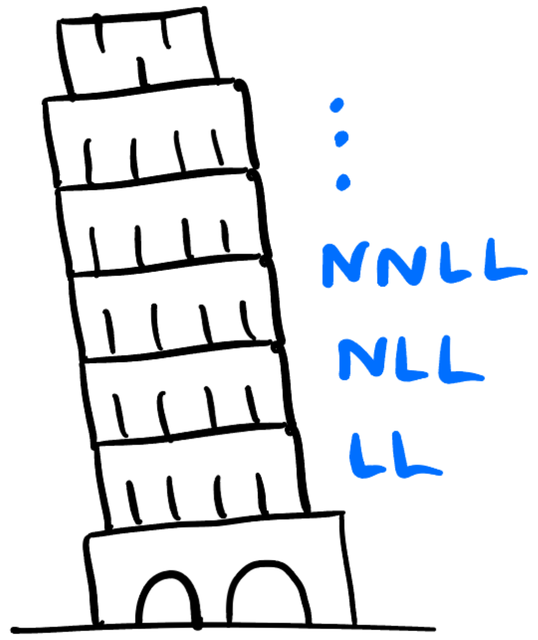
What is the probability that a boson is produced with transverse momentum $< p_T$?

$$\mathscr{P} \simeq -\#\alpha_s \ln^2 \frac{Q}{p_T} + \mathcal{O}(\alpha_s^2) \rightarrow \exp\left[-\#\alpha_s \ln^2 \frac{Q}{p_T}\right]$$

for small p_T we need to sum up the logs

In general we have a tower of logs

$$\exp\left[-\sum_{n,m} \alpha_s^n \ln^m \frac{Q}{p_T}\right]$$

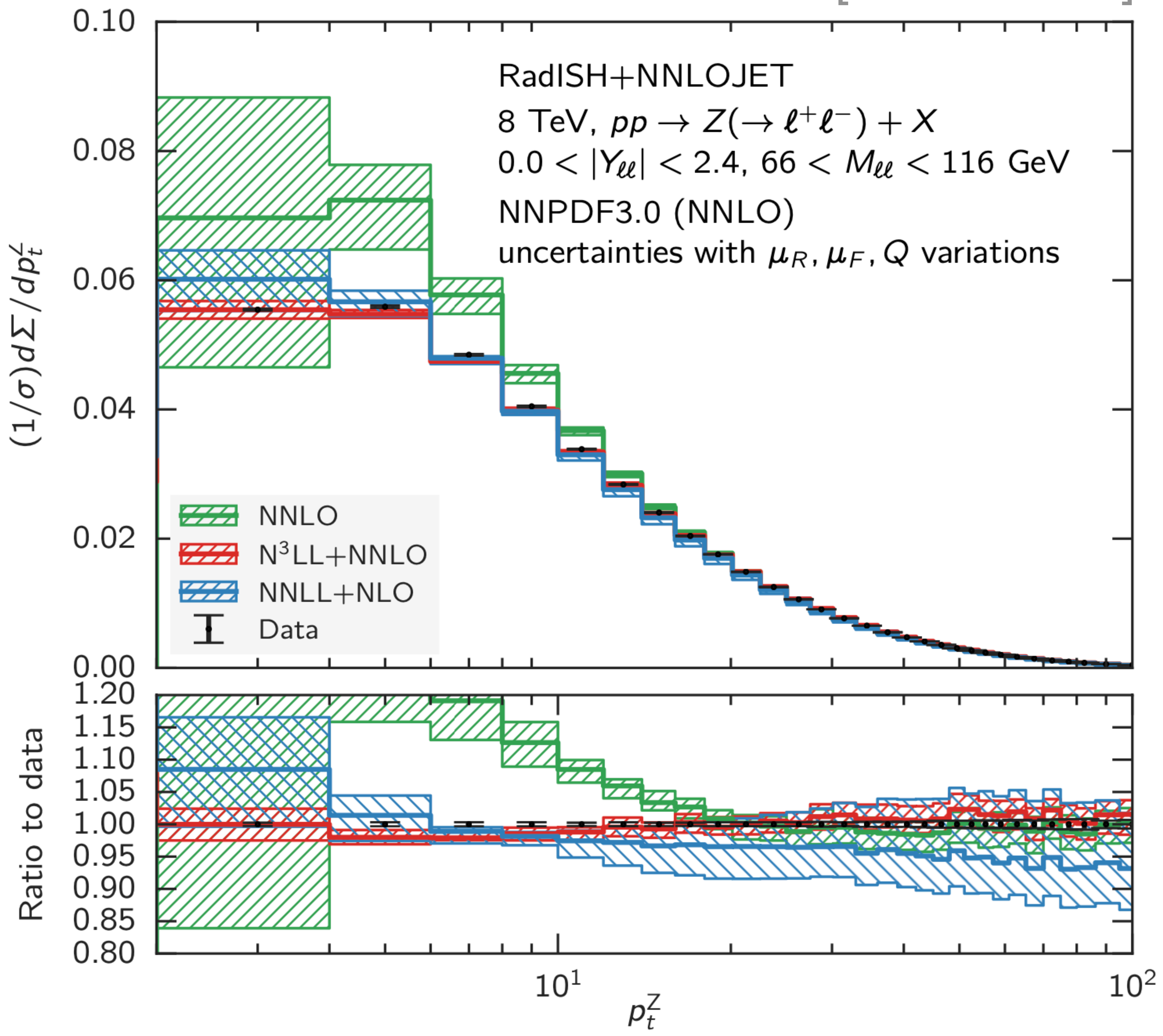


$m = n + 1$ → Leading Logs (LL)

$m = n$ → Next-To-LL (NLL)

$m = n - 1$ → Next-To-NLL (NNLL) . . .

Brizon et al. [1805.05916]



MiLO

$$\sigma^{FO}_{Xj} = \sigma_1 + \alpha_s \sigma_2 + \ldots$$ FO cross section

$$\mathcal{F} = \exp[\ldots] = 1 + \alpha_s S_1 + \alpha_s^2 S_2 + \ldots$$ Sudakov form factor

We introduce the MiLO cross section

$$\sigma_{MiLO} := \mathcal{F}\sigma_1 = \sigma^{FO}_{Xj}\left(1 + \mathcal{O}(\alpha_s)\right)$$

We want to fix $\mathcal{F}$ in order to obtain

$$\frac{d\sigma_{MiLO}}{dp_T^2 dy} \sim \frac{d}{dp_T^2}\left\{\mathcal{F}(p_T, Q) f_a(x_a, p_T) f_b(x_b, p_T)\right\}$$

PDF $f_i(x_i, \mu_F)$

such that

$$\frac{d\sigma}{dy} = \int_0^Q dp_T^2 \frac{d\sigma_{MiLO}}{dp_T^2 dy} \sim f_a(x_a, Q) f_b(x_b, Q)$$

X cross section at fixed rapidity y

$\mathcal{F}(Q, Q) = e^0 = 1$

$\mathcal{F}(0, Q) = e^{-\infty} = 0$

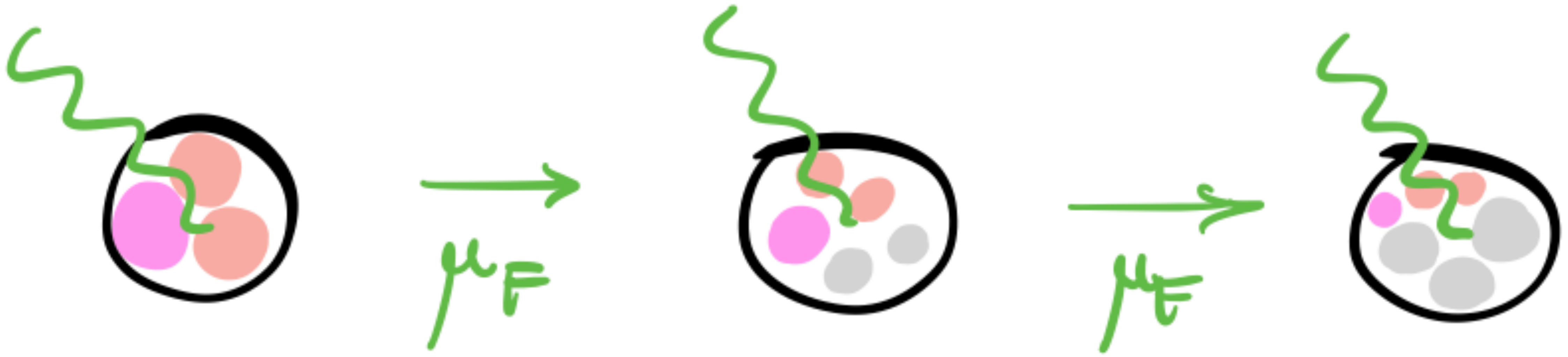
In the singular part of the Xj cross section,

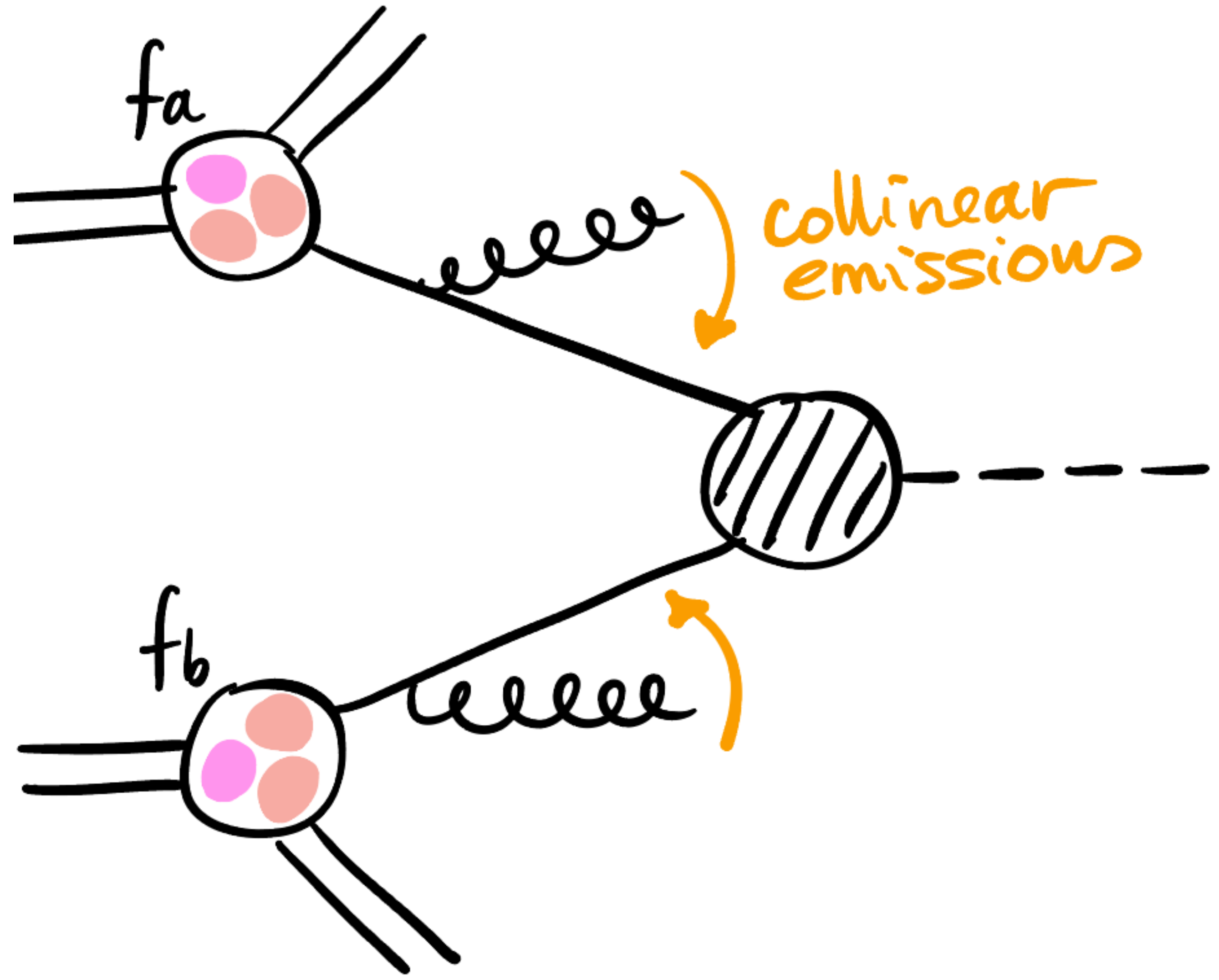
$$\frac{d\sigma^{sing}_{Xj}}{dp_T^2 dy} = \frac{1}{p_T^2}\sum_{nm} \alpha_s^n(\mu_R)\,\mathscr{C}_{nm}\ln^m\frac{p_T^2}{Q^2} = \frac{1}{p_T^2}\alpha_s(\mu_R)\left(\mathscr{C}_{11}\ln\frac{p_T^2}{Q^2} + \mathscr{C}_{10} + \ldots\right),$$

where $\mathscr{C}_{10} \supset \frac{1}{\alpha_s(\mu_F)}\mu_F^2\frac{d}{d\mu_F^2}(f_a f_b)$

This contribution is related to DGLAP evolution

The collinear divergences of initial states can be reabsorbed in PDFs causing their running



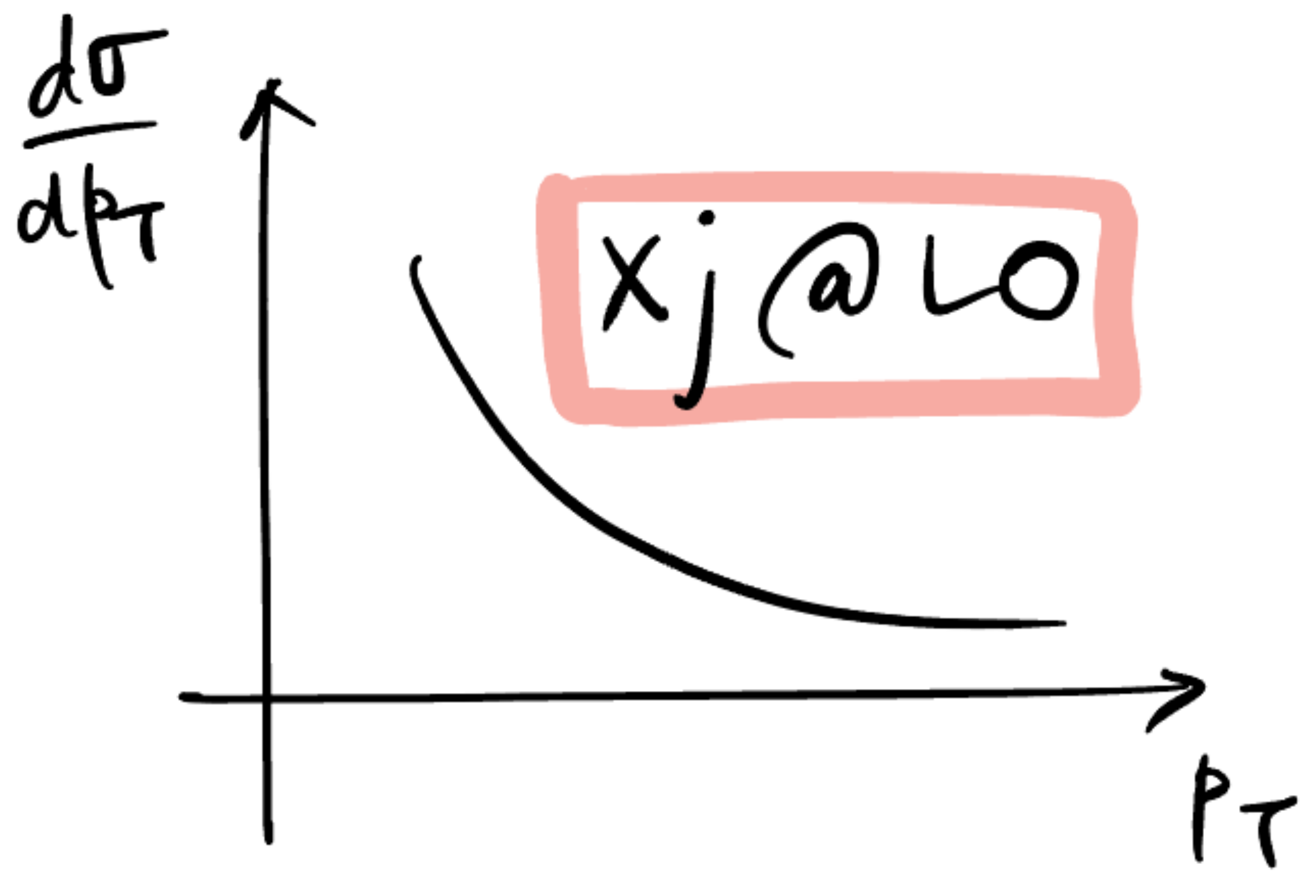


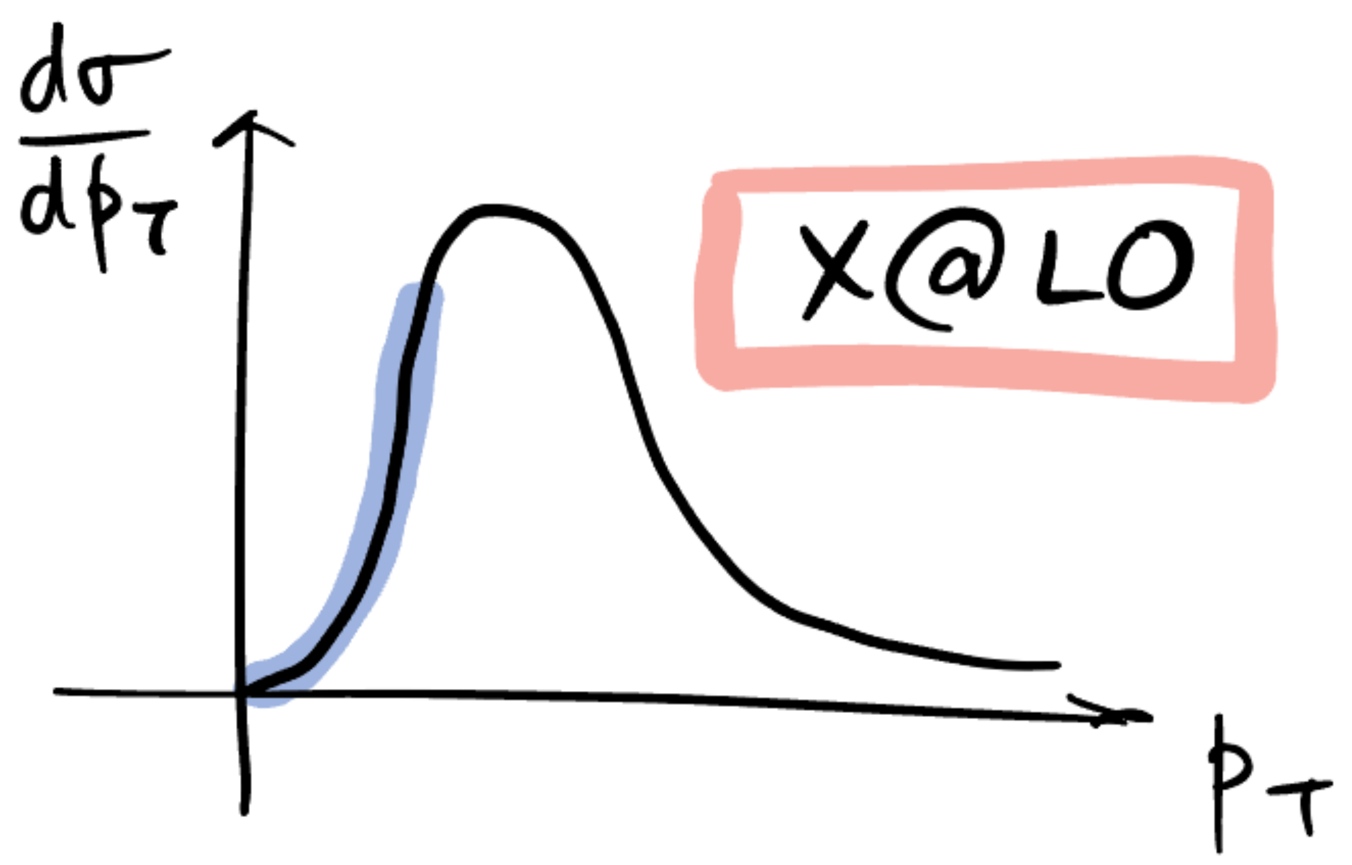
If we set $\mu_R = p_T$ and $\mu_F = p_T$, the resumed cross section becomes

$$\frac{d\sigma_{MiLO}}{dp_T^2 dy} = \mathcal{F}(p_T, Q) \frac{d\sigma_{Xj}^{LO}}{dp_T^2 dy} = \frac{d}{dp_T^2} \left\{ \mathcal{F}(p_T, Q)\, f_a(x_a, p_T) f_b(x_b, p_T) \right\}$$

<u>iff</u> $\mathcal{F}(p_T, Q) = \exp\left[- \int_{p_T}^{Q} \frac{d\mu^2}{\mu^2} \alpha_s(\mu^2) \left(A_1 \ln \frac{Q^2}{\mu^2} + B_1 \right) \right]$

MiLO Sudakov:
essential to capture the logs at low p_T



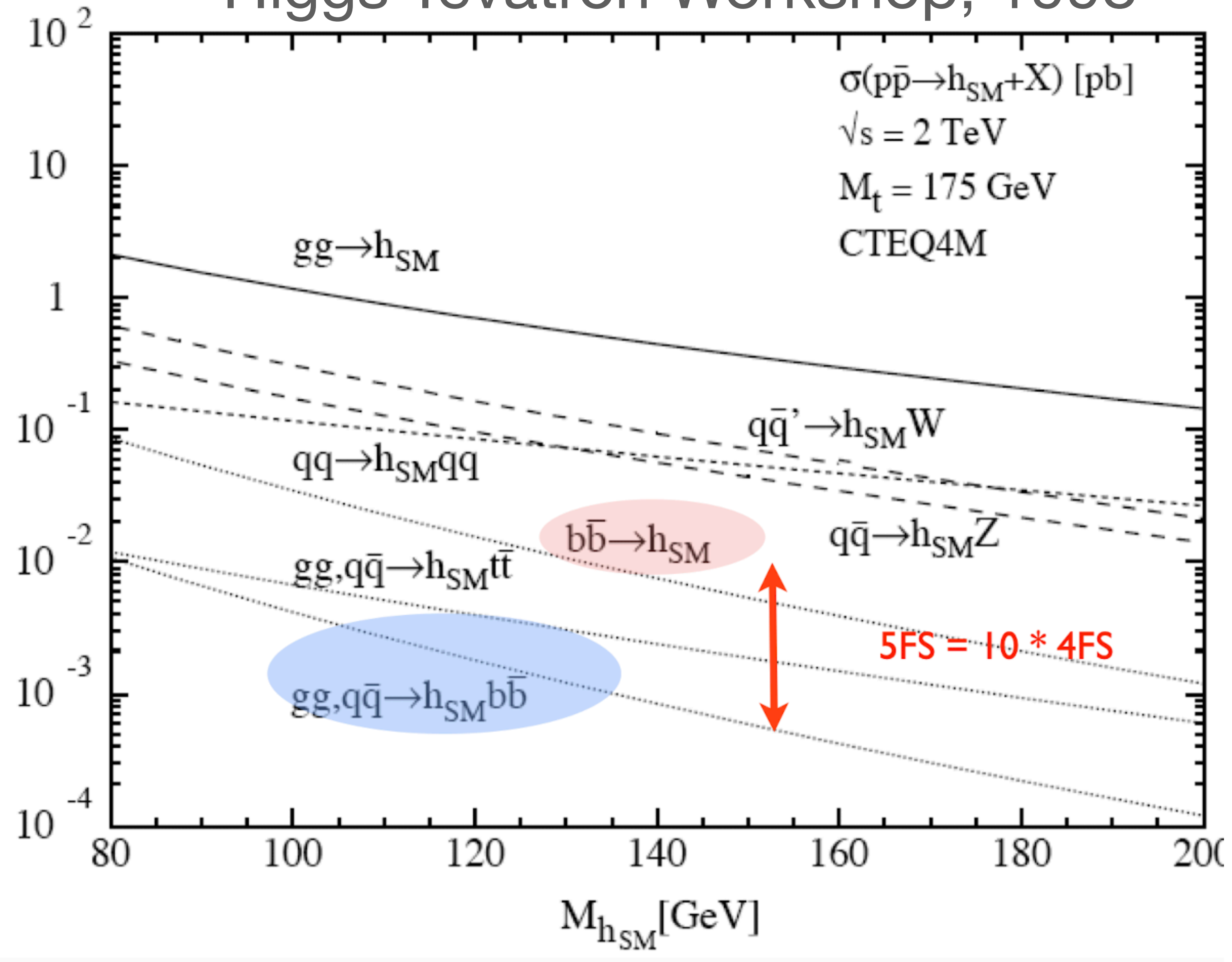


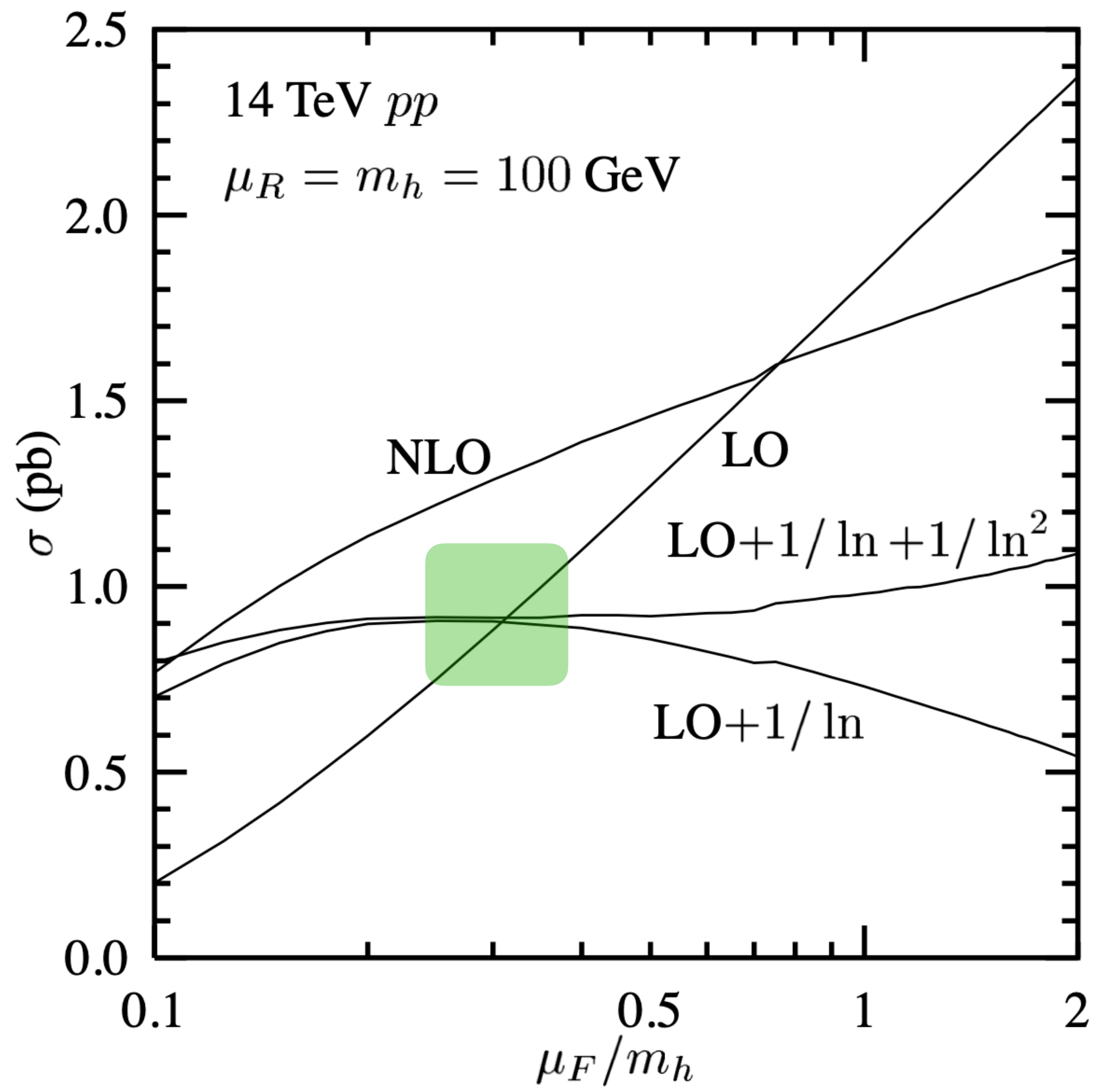
From a manipulation of FO Xj cross section, we obtained inclusive predictions.

Historical LO comparisons

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

Higgs Tevatron Workshop, 1998





Maltoni, Sullivan, Willenbrock [hep-ph/0301033]

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.

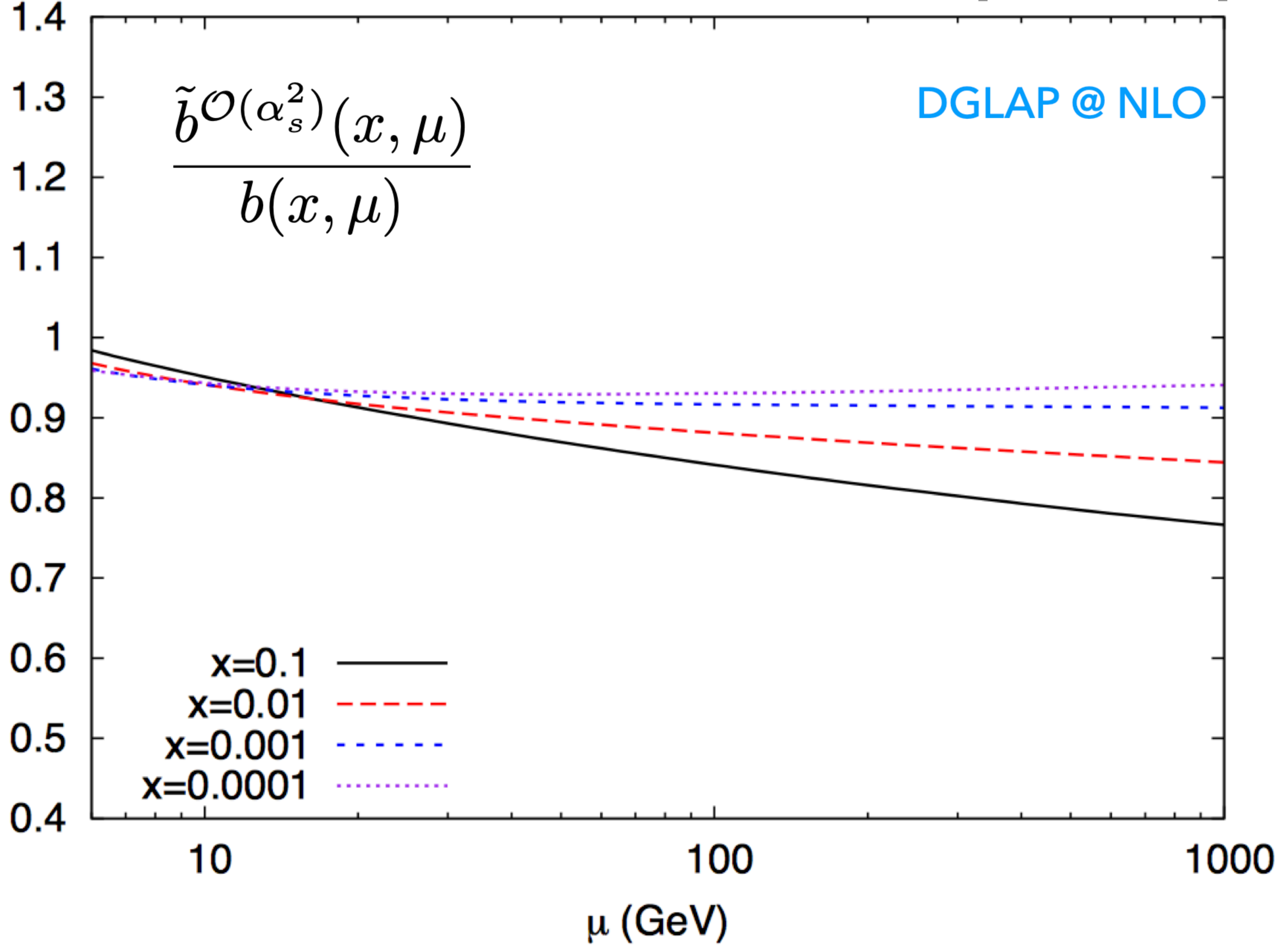
The improvement of the compatibility opens the possibility to match together the predictions at least at the inclusive level (Santander matching, FONLL…)

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

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

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.

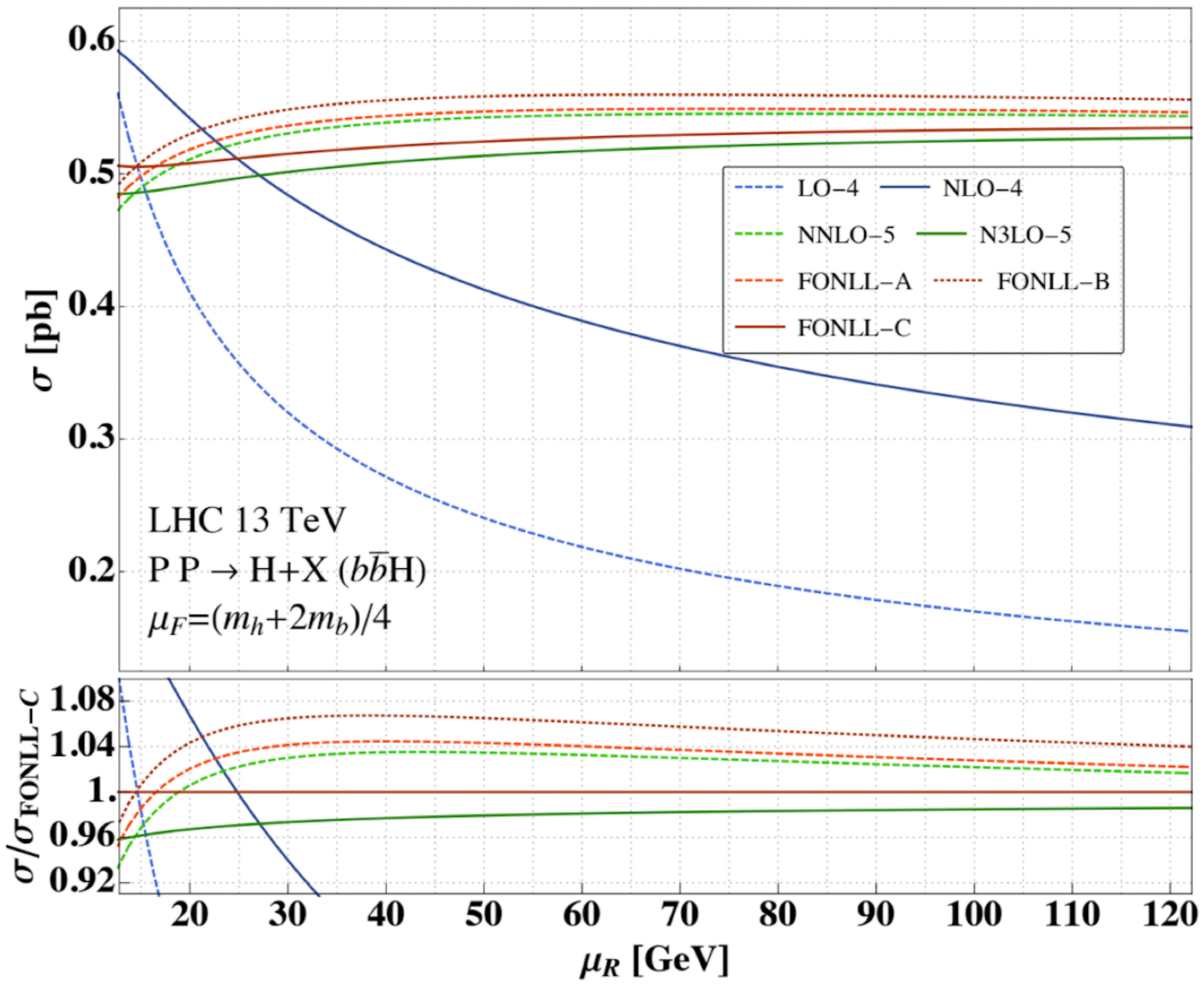
- Currently, the flavour matching for bbH is performed at

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

- 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]

Exclusive observables

Recent developments in fully differential calculations, for example:

1. Introduce an unphysical scale μ_b in order to switch from 4FS to 5FS in a region where mass effects and collinear logs are not crucial [Bertone, Glazov, Mitov, Papanastasiou, Ubiali, 1711.03355]
2. Massive 5FS at NLO [Krauss, Napoletano, 1712.06832]
3. Differential FONLL applied for Z+b-jet [Gauld, Gehrmann-De Ridder, Glover, Huss, Majer, 2005.03016]

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