MAX-PLANCK-INSTITUT FÜR PHYSIK

Recent results for LHC simulations matched with Parton Shower using MiNNLOPS

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Garching bei München, Germany

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LHC event

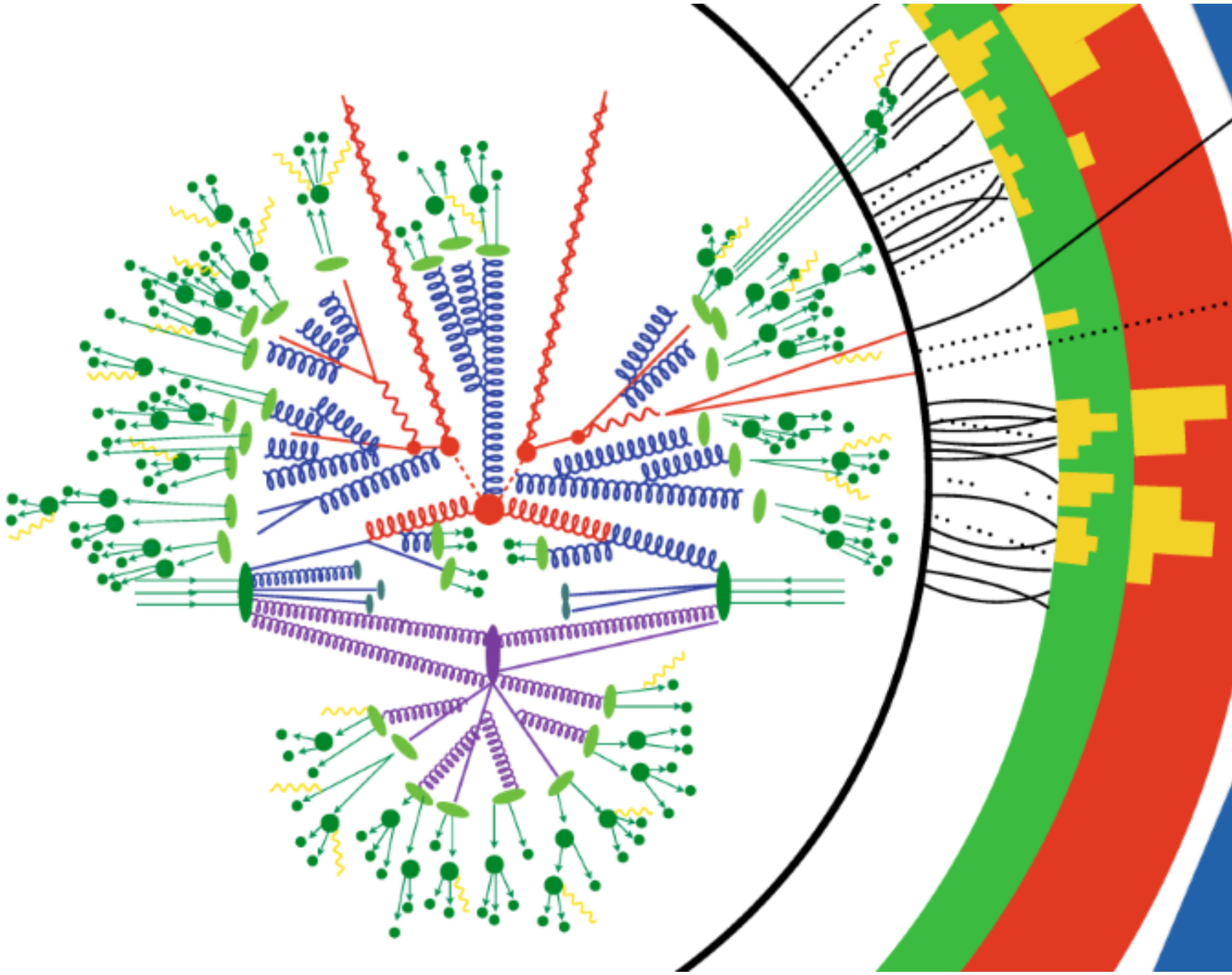

Image credit: Nature

LHC event

α_s^3 N^3LO

α_s^2 $NNLO$

α_s^1 NLO

α_s^0 LO

Hard Process N^xLO

☑ High precision

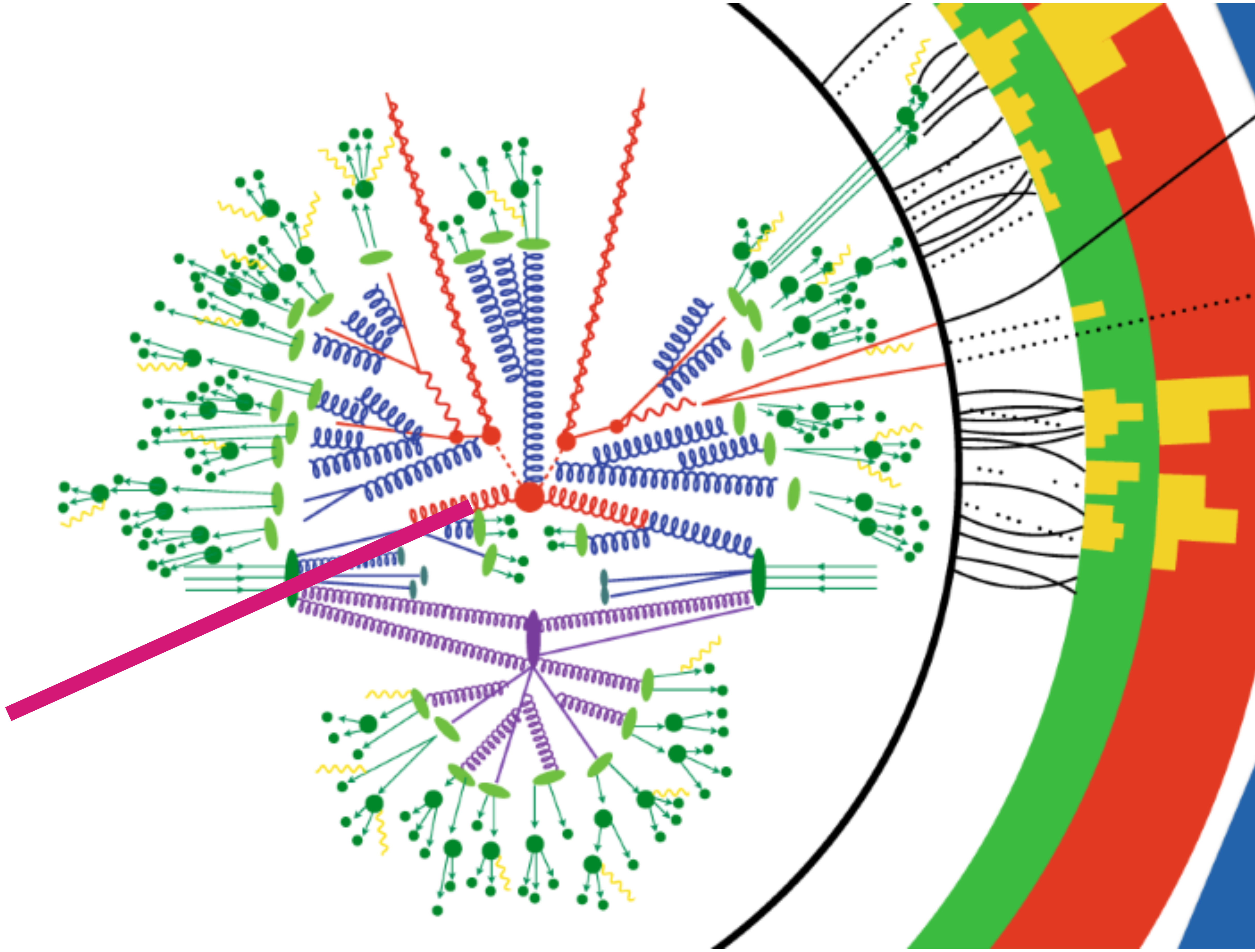

Image credit: Nature

LHC event

$\alpha_s^n \log^{n-1}$ — $NNLL$

$\alpha_s^n \log^n$ — NLL

$\alpha_s^n \log^{n+1}$ — LL

α_s^3 — N^3LO

α_s^2 — $NNLO$

α_s^1 — NLO

α_s^0 — LO

Parton shower PS_{N^yLL} and hadronisation

- ☑ Realistic description
- ☑ N^yLL resummation

Hard Process N^xLO

- ☑ High precision

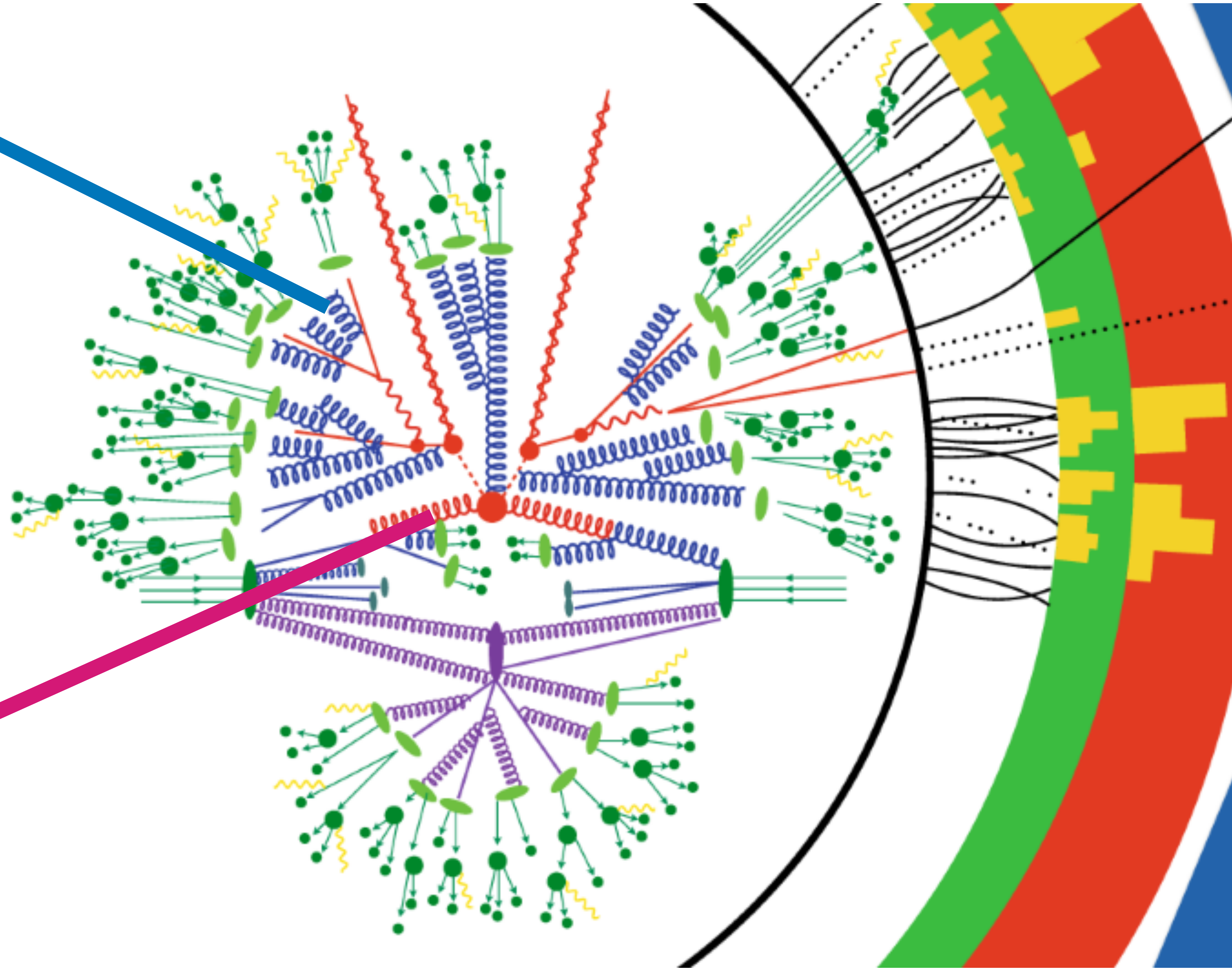

Image credit: Nature

LHC event

$\alpha_s^n \log^{n-1}$ — $NNLL$

$\alpha_s^n \log^{n}$ — NLL

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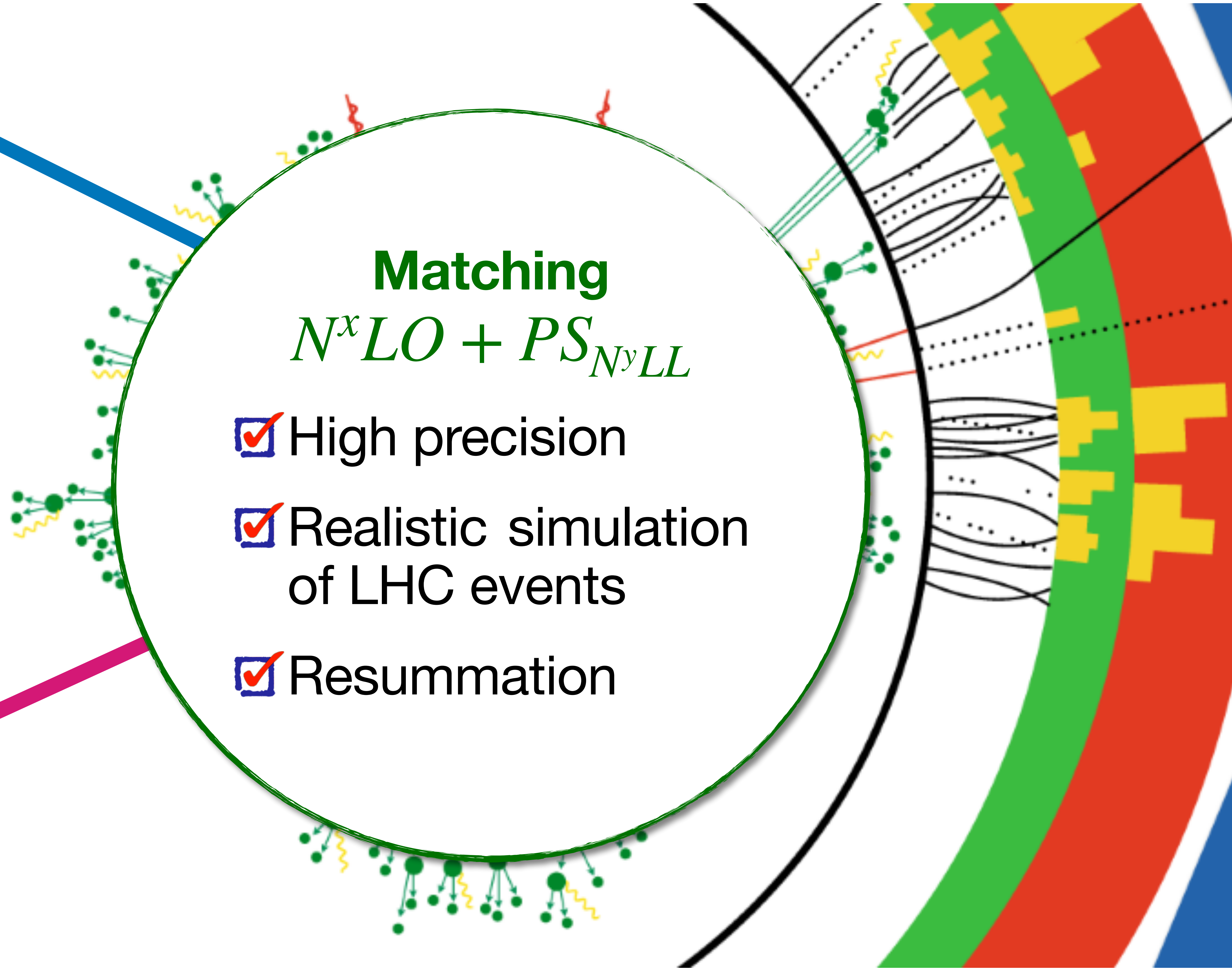


Matching

$N^xLO + PS_{N^yLL}$

- ☑ High precision
- ☑ Realistic simulation of LHC events
- ☑ Resummation

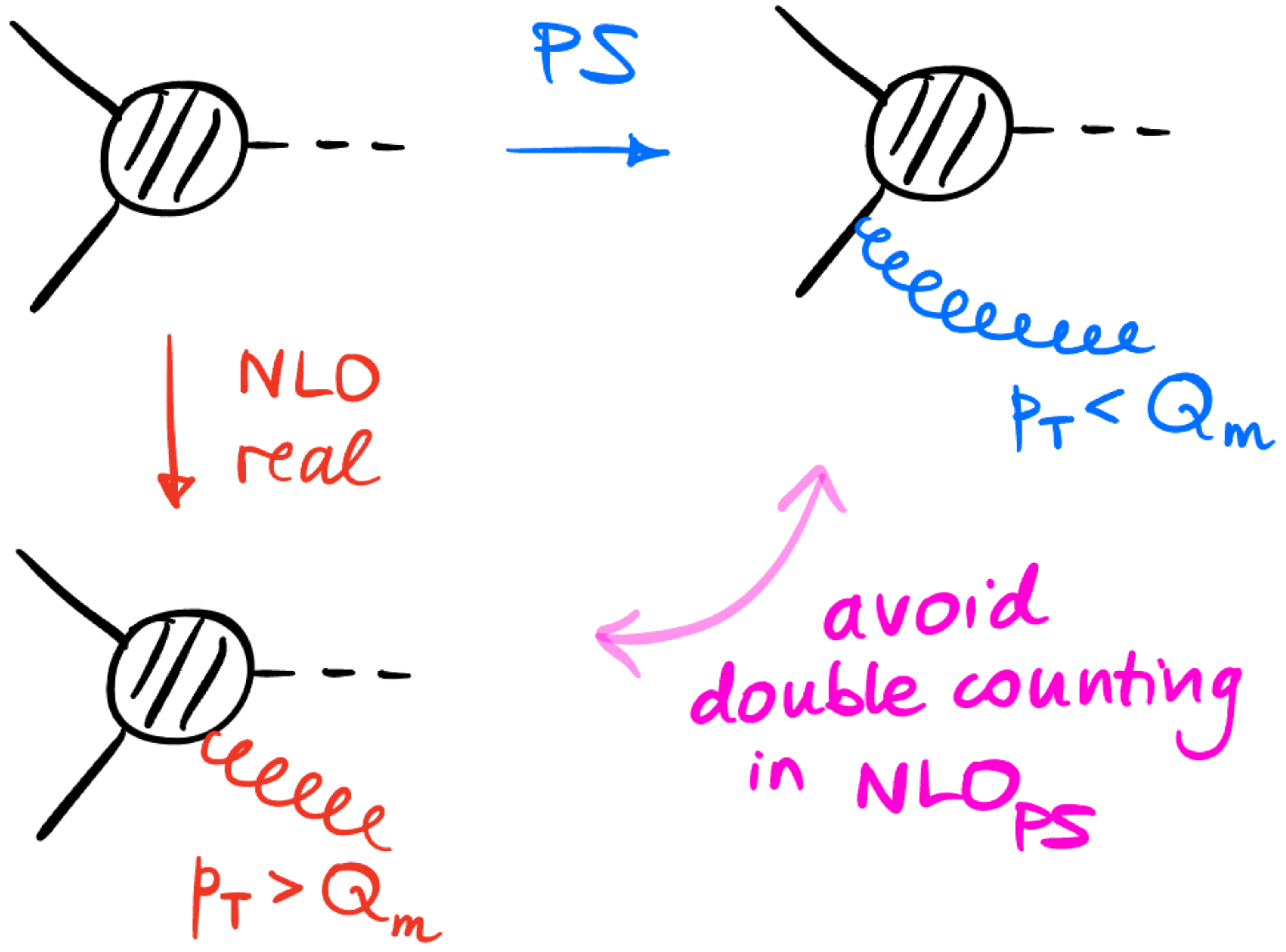
Image credit: Nature

NLO+PS$_{LL}$

Solved problem for long time.
Completely understood and fully automated.

Two main approaches:

- **POWHEG** [0409146, 0709.2092, 1002.2581]
- **MC@NLO** [0204244]



Problem: Match fixed-order predictions with Parton Shower avoiding an unphysical matching scale.

POWHEG idea: implement a Monte Carlo generator that produces just one emission (the hardest one) which alone gives the correct NLO result.

Nason [hep-ph/0409146]

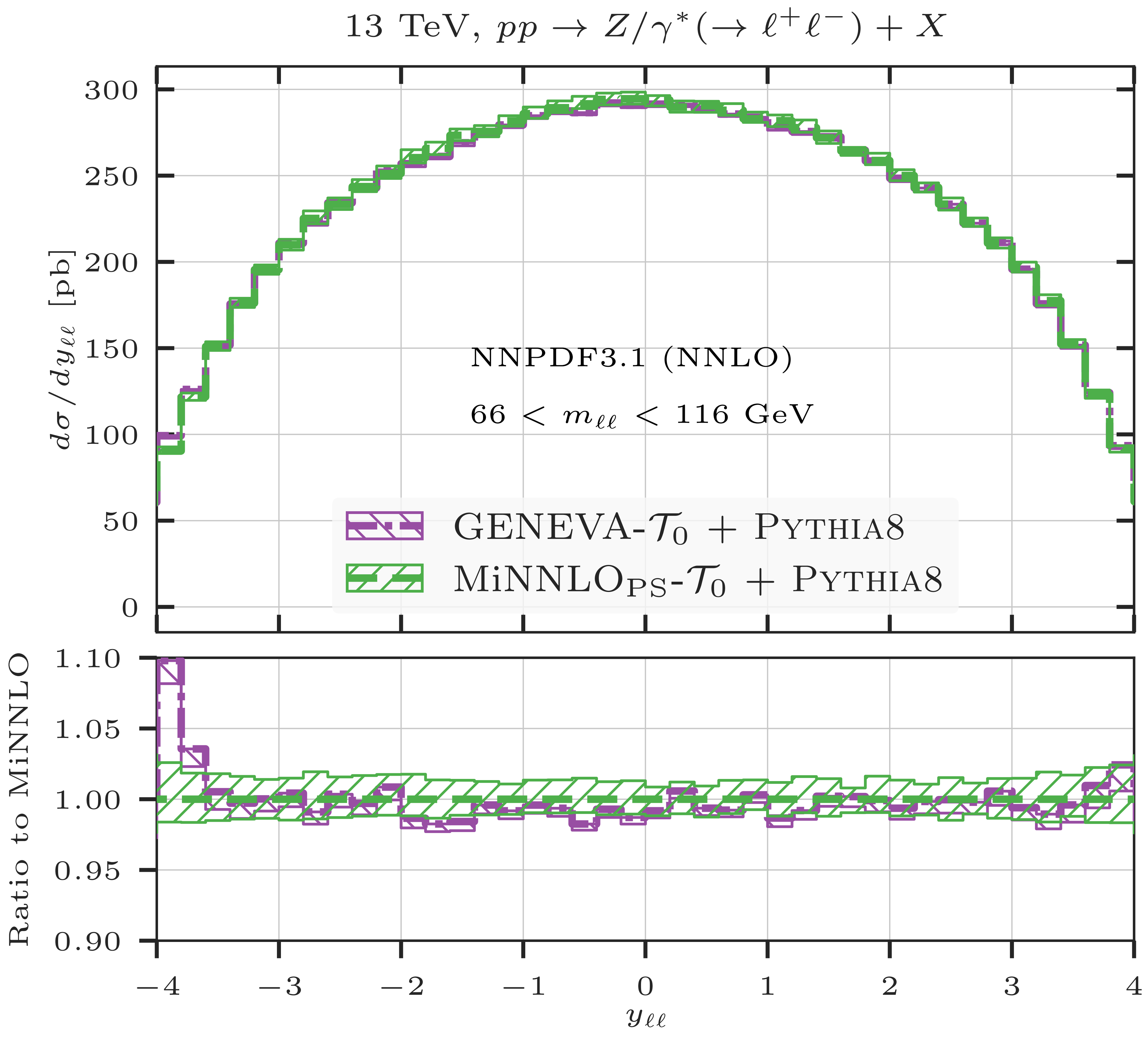
NNLO+PS$_{LL}$

State-of-the-art for precision LHC phenomenology.

Lots of ongoing efforts. **Many processes** already implemented, beyond the color-singlet production.

Two main approaches:

- **MiNNLOPS** [1908.06987]
  - in the POWHEG framework
- **GENEVA** [1311.0286]



Ebert, Rottoli, Wiesemann, Zanderighi, Zanoli [2402.00596]

2004 — POWHEG

2008 — NLO+PS for color singlet (F)

2010 — **NLO+PS** Fj

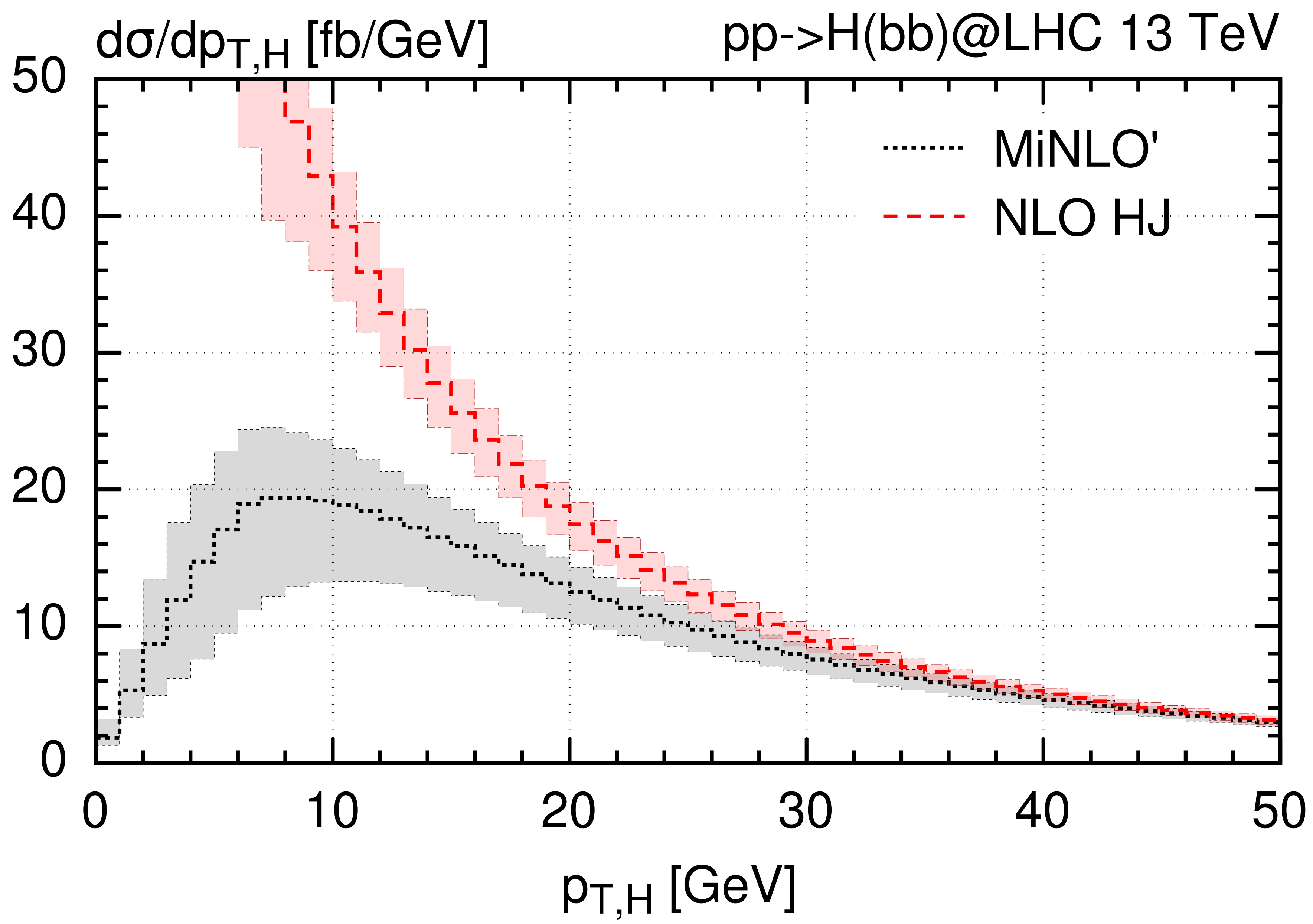
2012 — **MiNLO'**

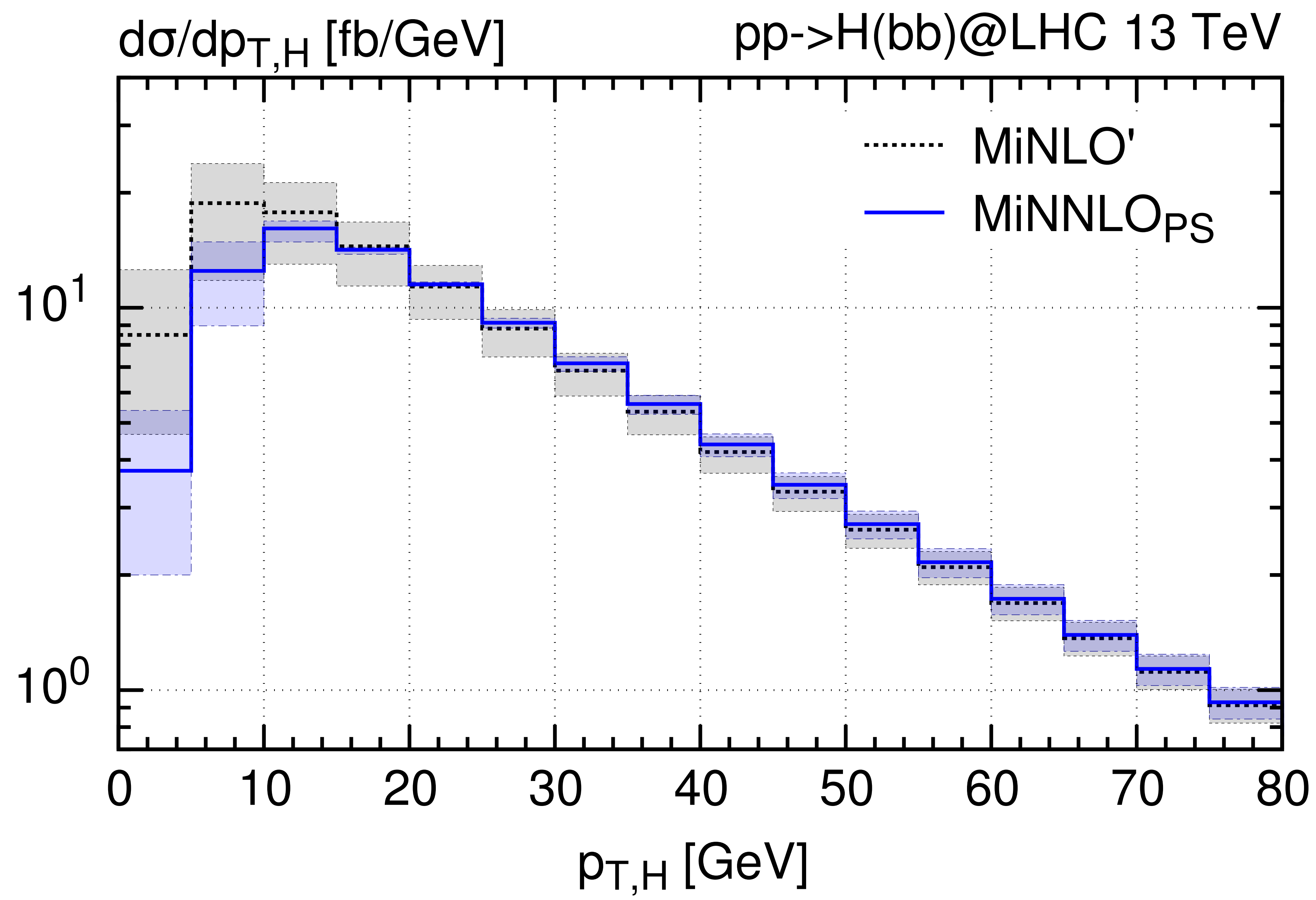
2013 — NNLO a posteriori reweighing of MiNLO'

2019 — **MiNNLOPS**

MiNLO'

Hamilton, Nason, Oleari, Zanderighi [1212.4504]

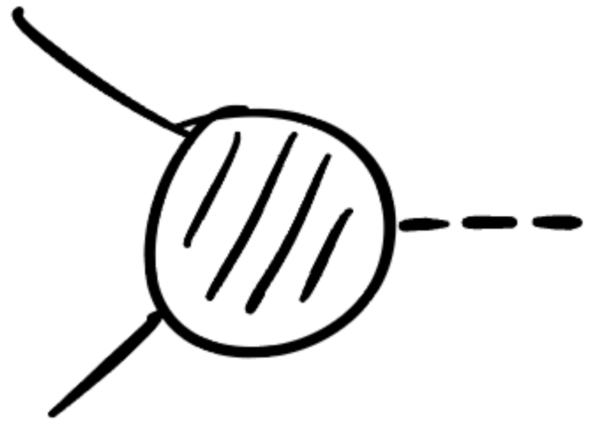




MiNNLOPS

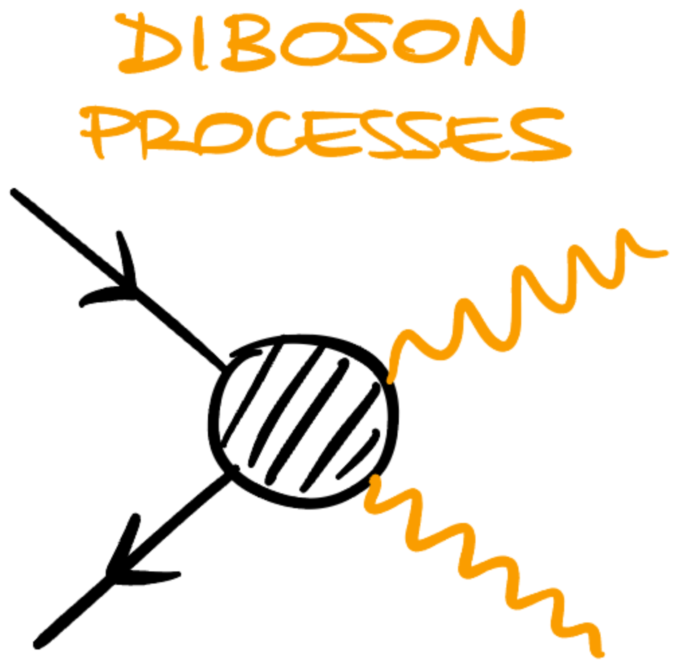
Monni, Nason, Re, Wiesemann, Zanderighi [1908.06987]

Classes of processes in MiNNLOPS



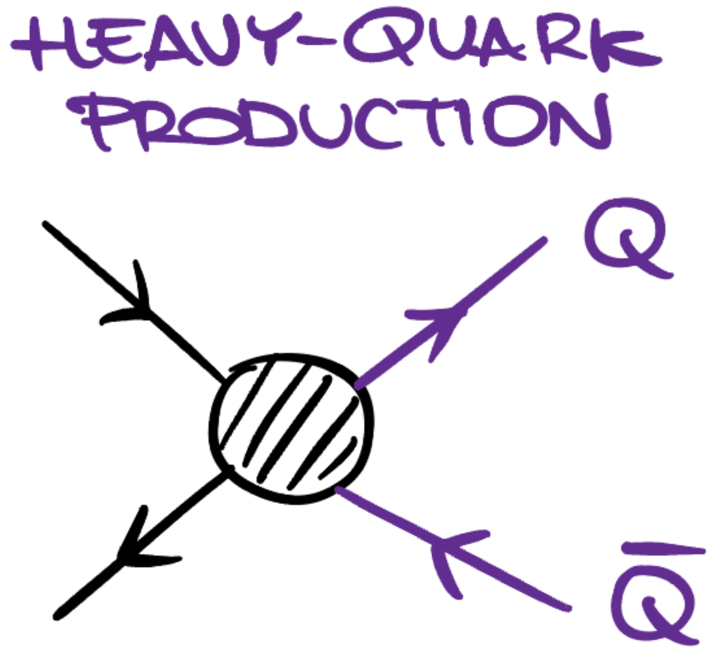
$gg \to H, W/Z$ [1908.06987, 2006.04133, 2402.00596, 2407.01354]

$b\bar{b} \to H$ [2402.04025]



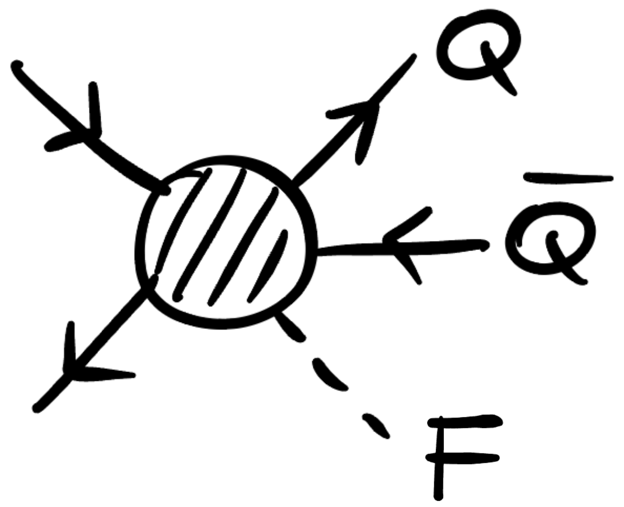
$Z\gamma$ [2010.10478, 2108.11315]
WW [2103.12077]
ZZ [2108.05337]
$WH/ZH(H \to b\bar{b})$ [2112.04168]
$\gamma\gamma$ [2204.12602]
WZ [2208.12660]
SMEFT studies [2204.00663, 2311.06107]

first (and currently only) NNLO+PS method for heavy-quark final states



$t\bar{t}$ [2012.14267,2112.12135]
$b\bar{b}$ [2302.01645, in progress]

$b\bar{b}Z$ [2404.08598]
$b\bar{b}H$ [in progress]



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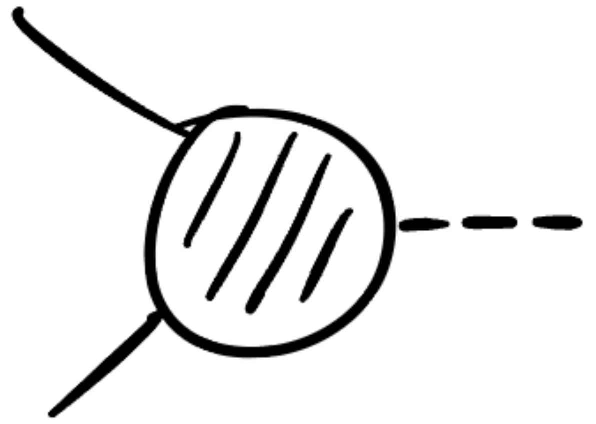

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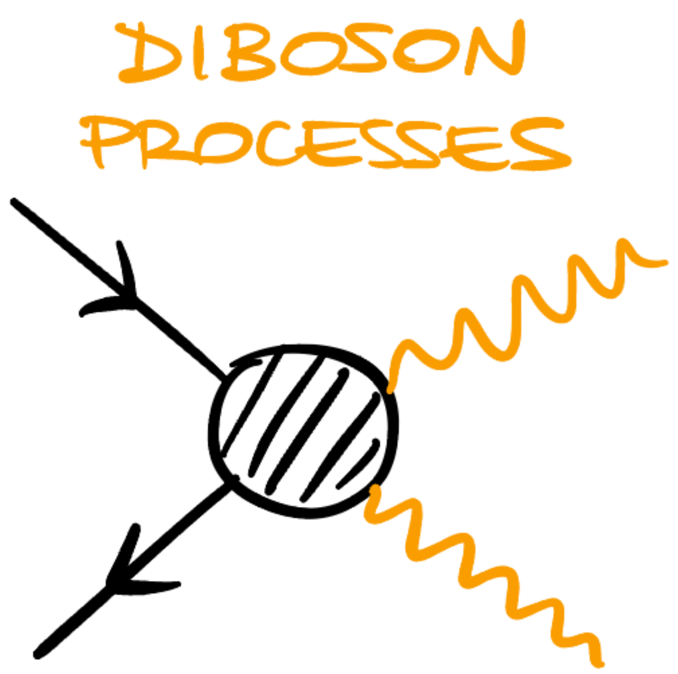

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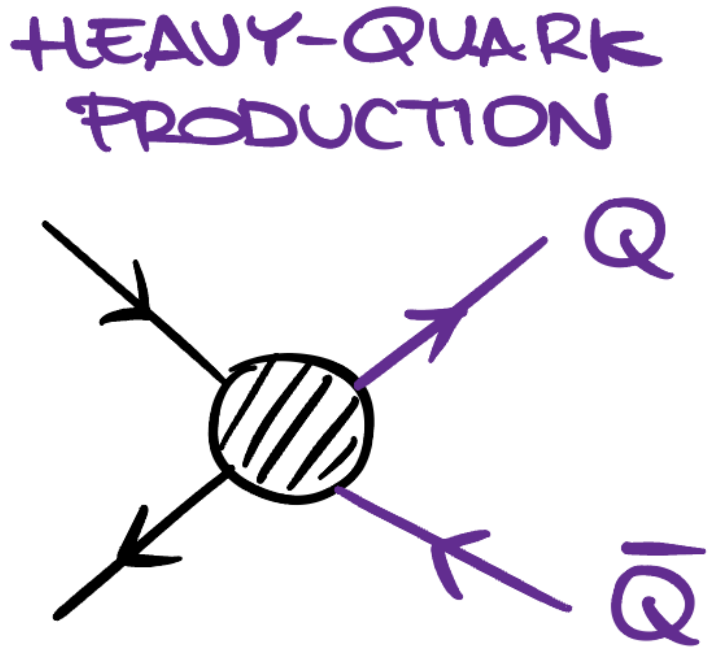

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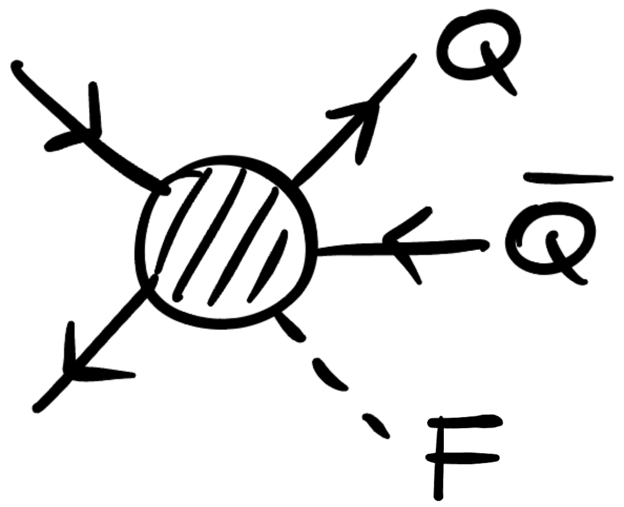


Recent results discussed in this talk

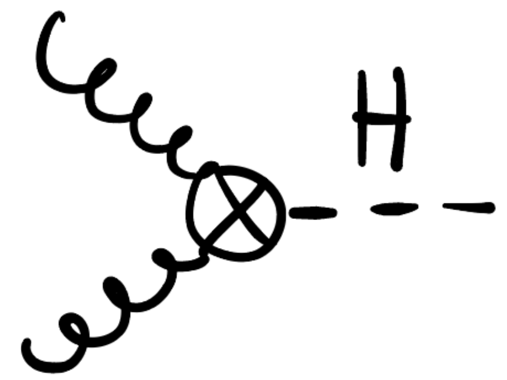
Full top dependence

ggF H

Niggetiedt, Wiesemann [2407.01354]

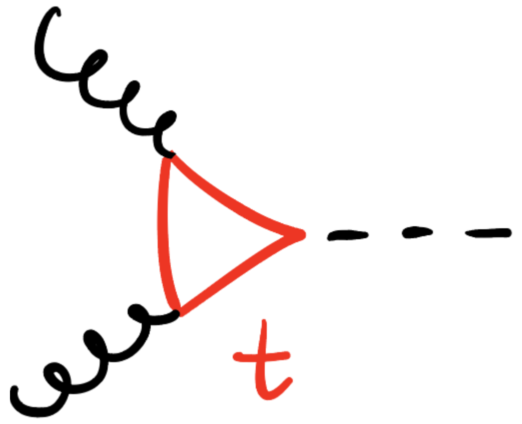
Why? Increasing precision calls for the inclusion of effects, like mass corrections!

The Higgs production via gluon fusion with **exact top-quark mass** dependence has been recently implemented in the MiNNLOPS generator.



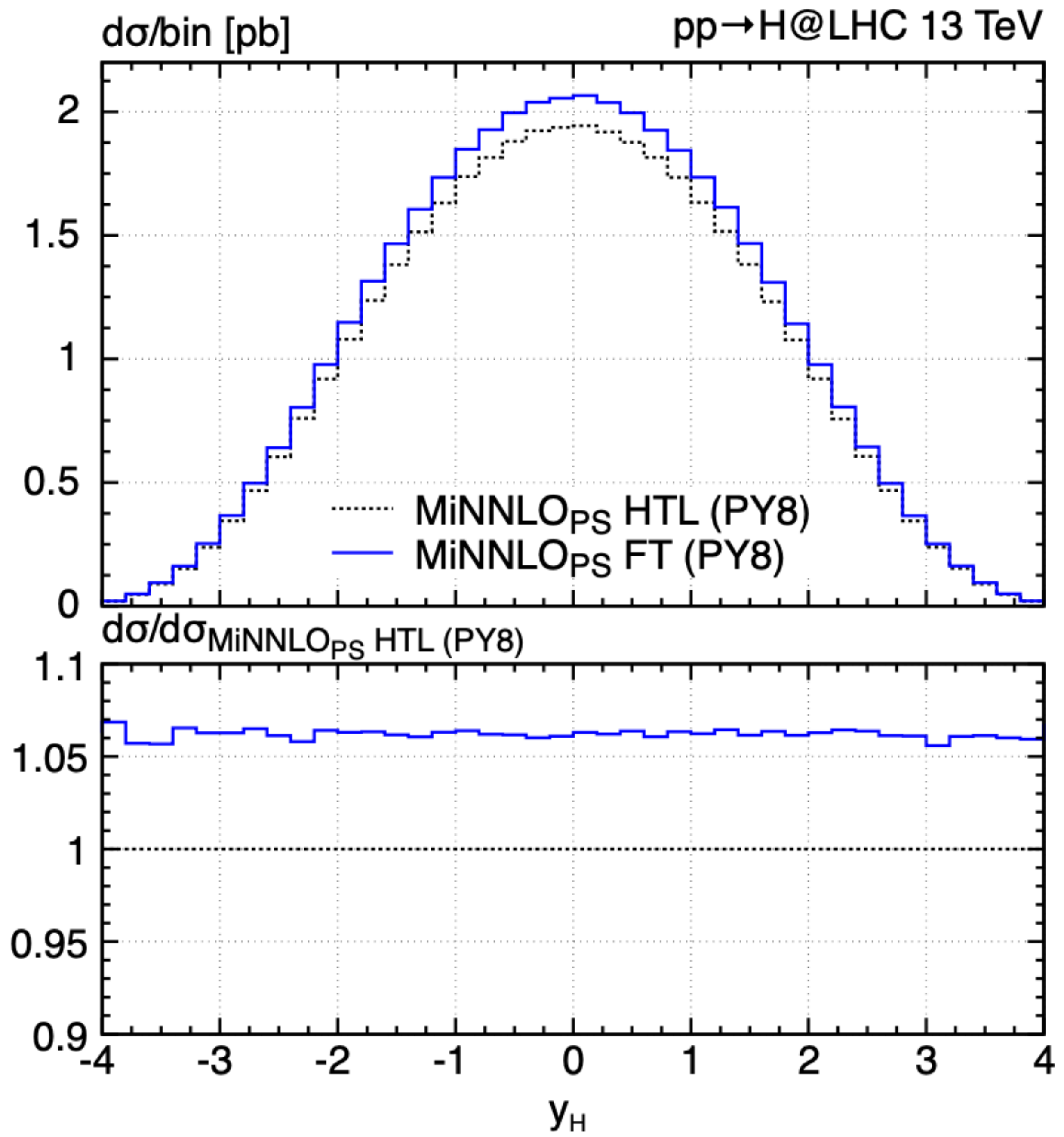
MiNNLO$_{PS}$ HTL

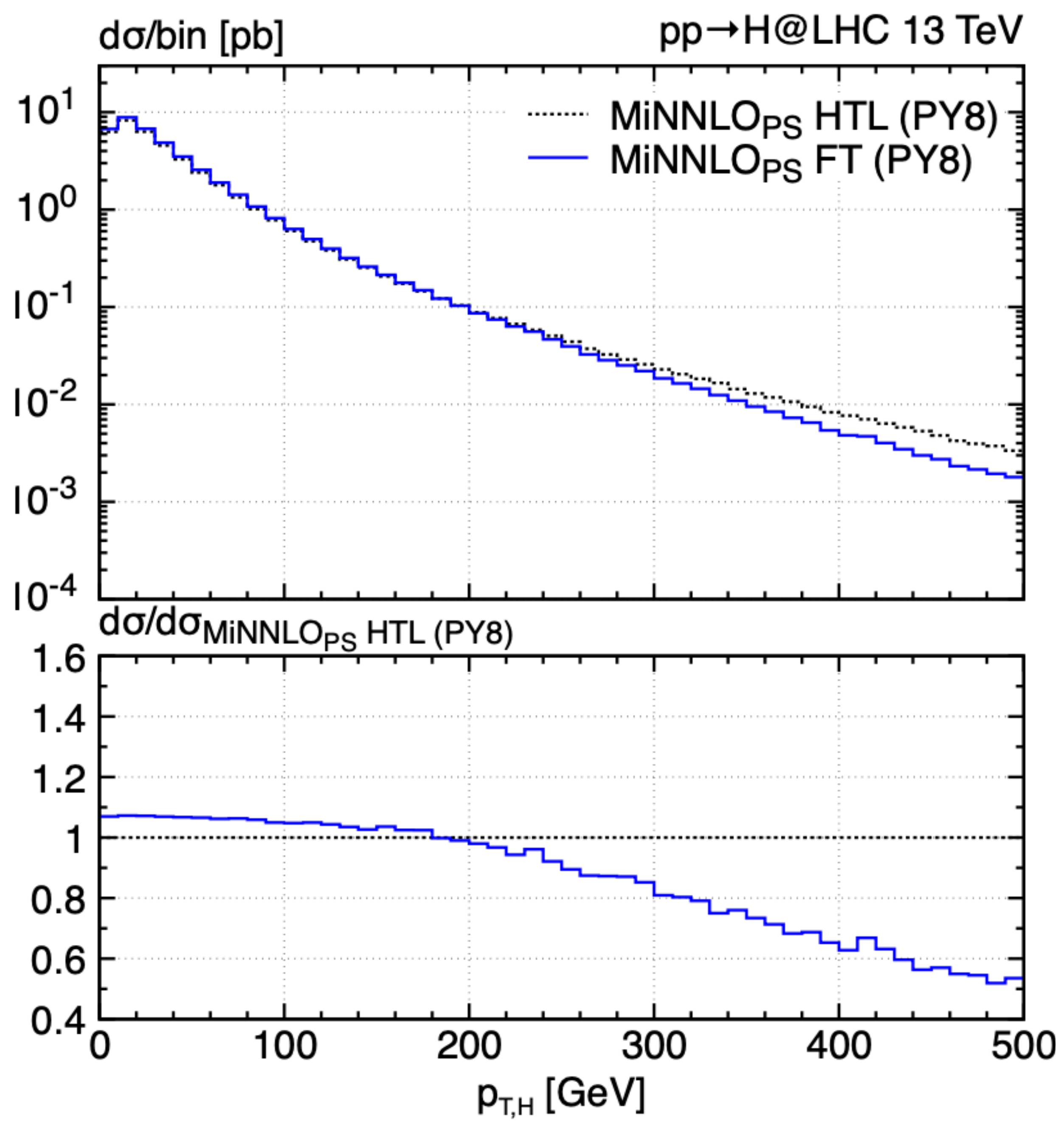
$$39.55(1)^{+11.0\%}_{-10.5\%}\,pb$$



MiNNLO$_{PS}$ FT

$$42.01(1)^{+11.2\%}_{-10.6\%}\,pb$$





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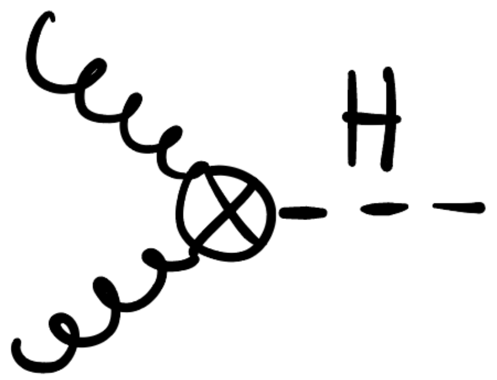

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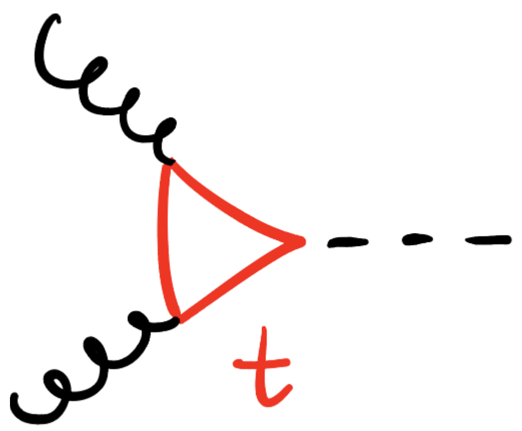

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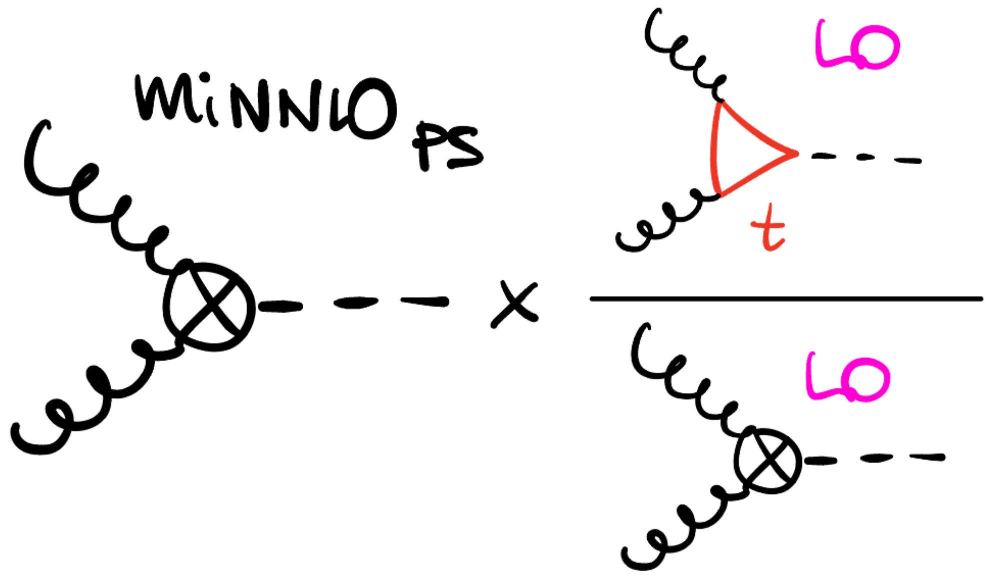
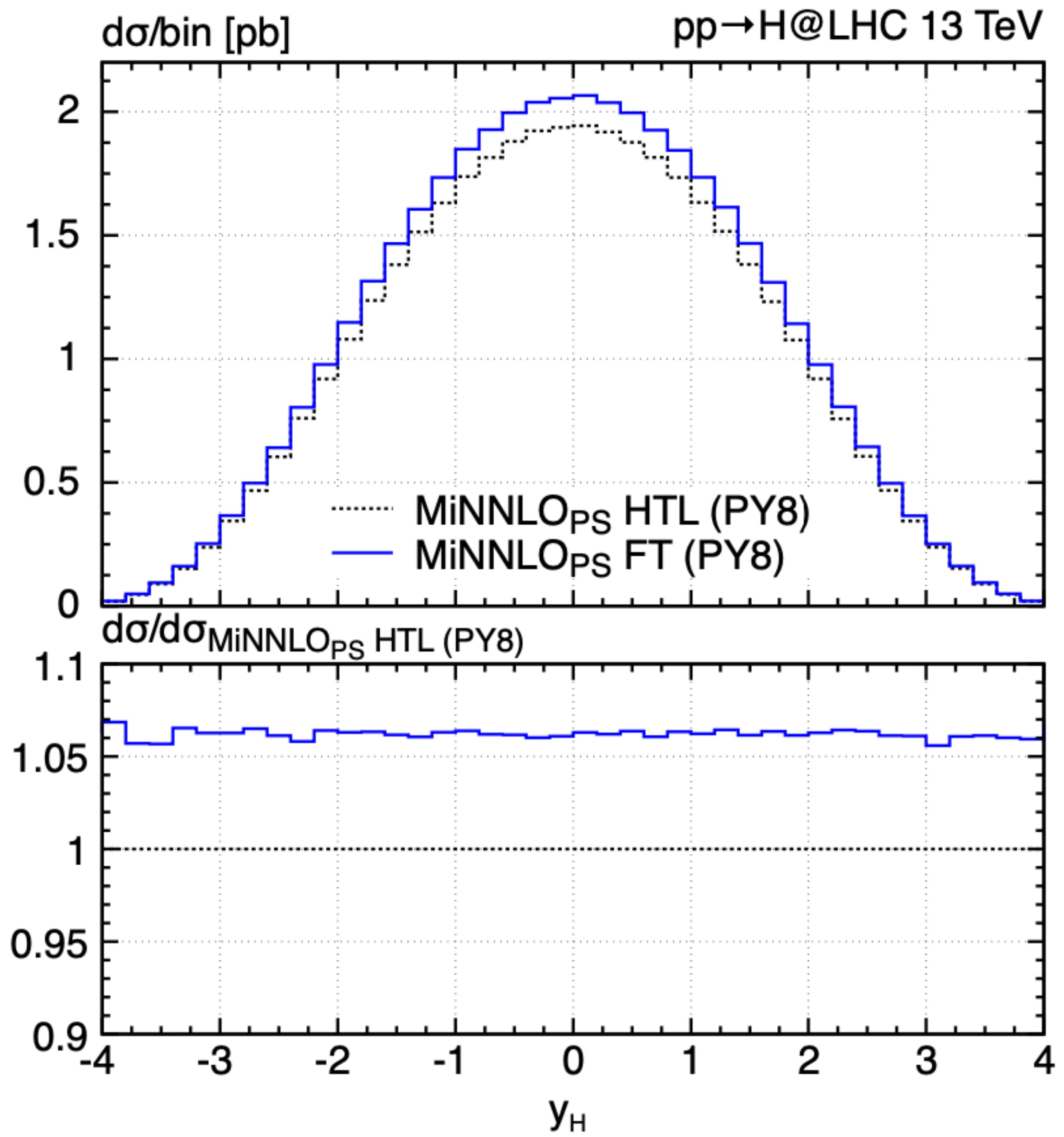
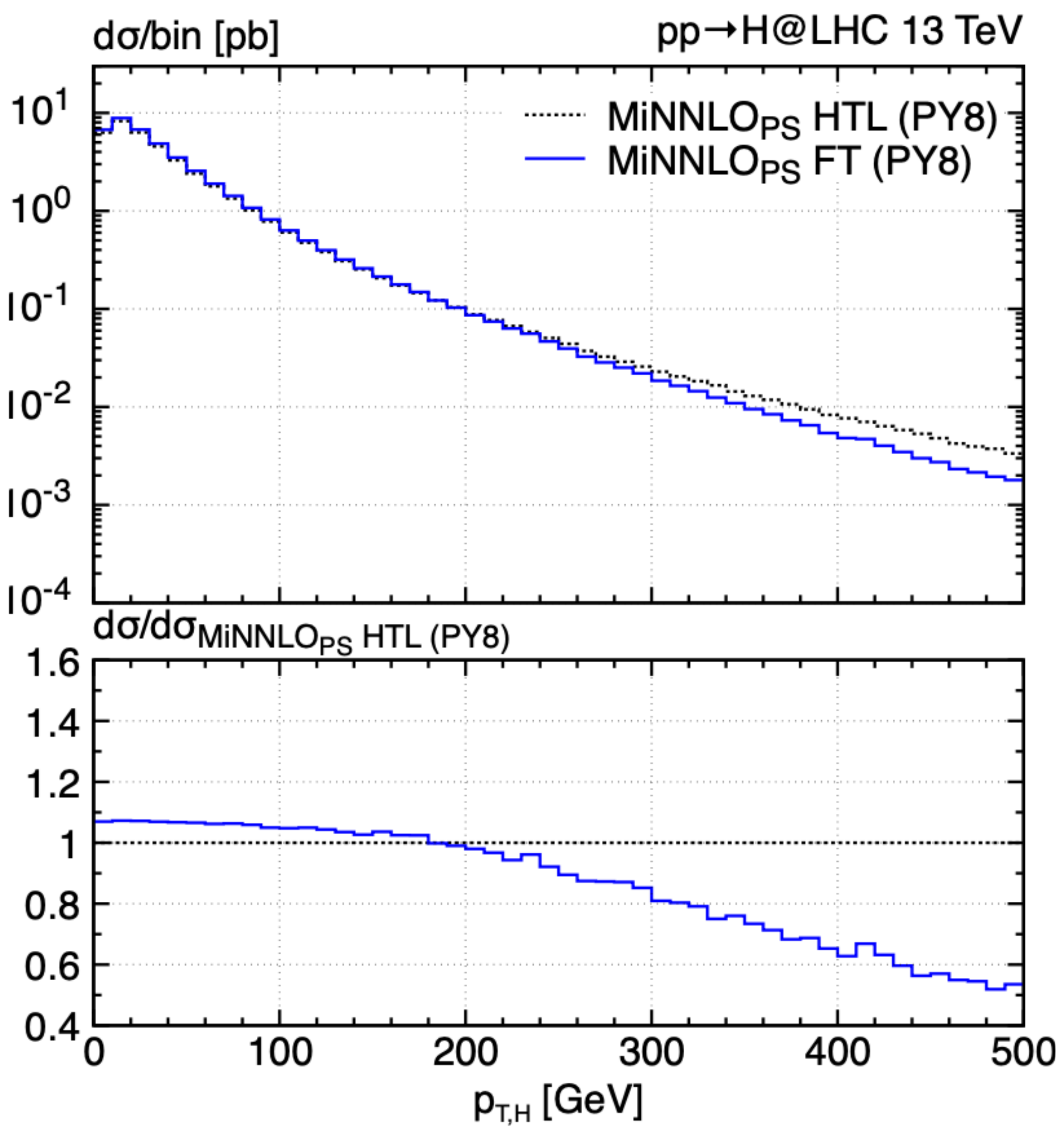


$$= 42.13(1)^{+11.0\%}_{-10.5\%}\,pb$$

Captures almost all mass effects





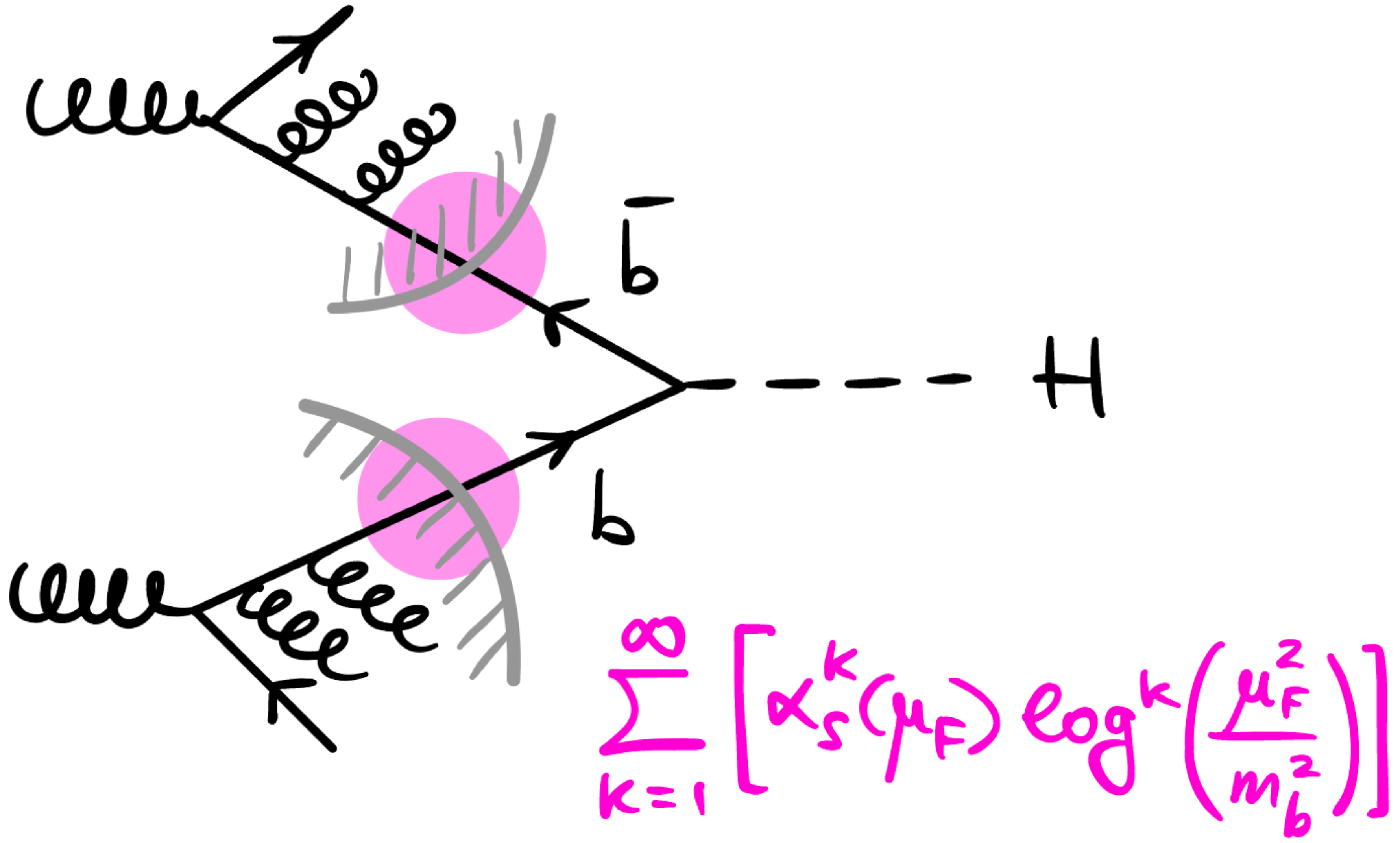
A rare but interesting channel

bb→H

CB, Sankar, Wiesemann, Zanderighi [2402.04025]

Why bbH? Higgs production via bottom fusion is a rare but crucial channel, **background of HH searches.**

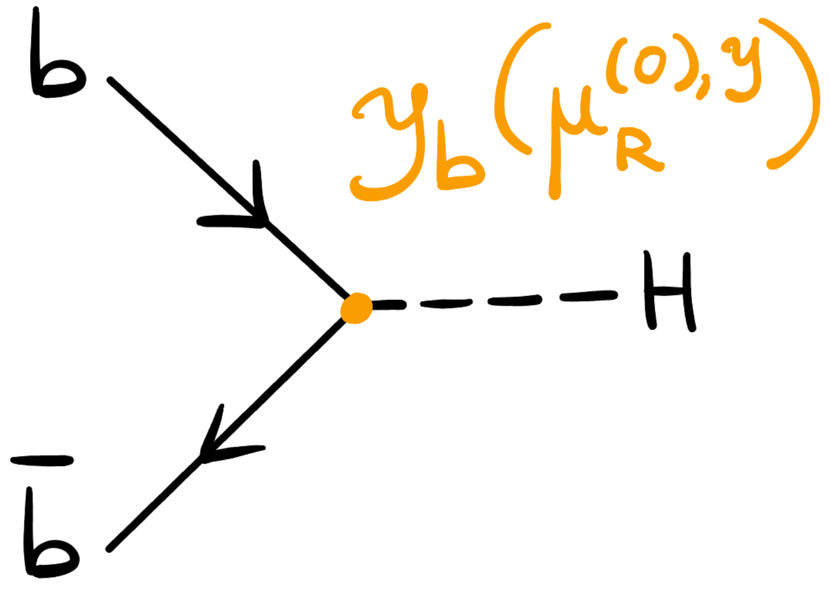
5FS



massless bottoms (5 flavour scheme)

- ✓ Collinear initial-state logs are resume into bottom PDFs
- \- $\mathcal{O}(m_b/m_H)$ are neglected: low accurate description of bottom kinematic distribution

Feature. Adaptation of the MiNNLOPS method to account for the extra scale dependence induced by an overall **Yukawa coupling** that is $\overline{\text{MS}}$ renormalised



See Moriond 2024

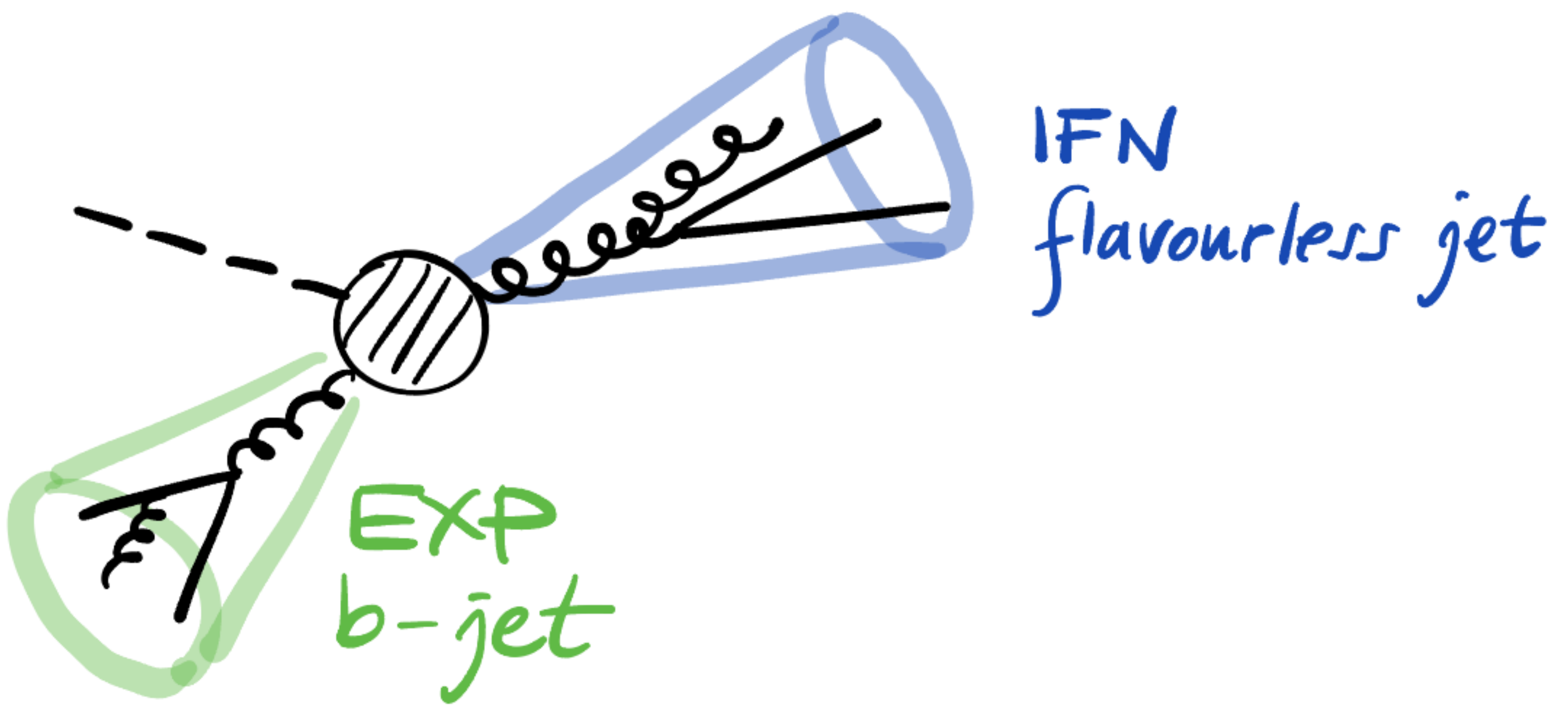
event generator → fully-exclusive results

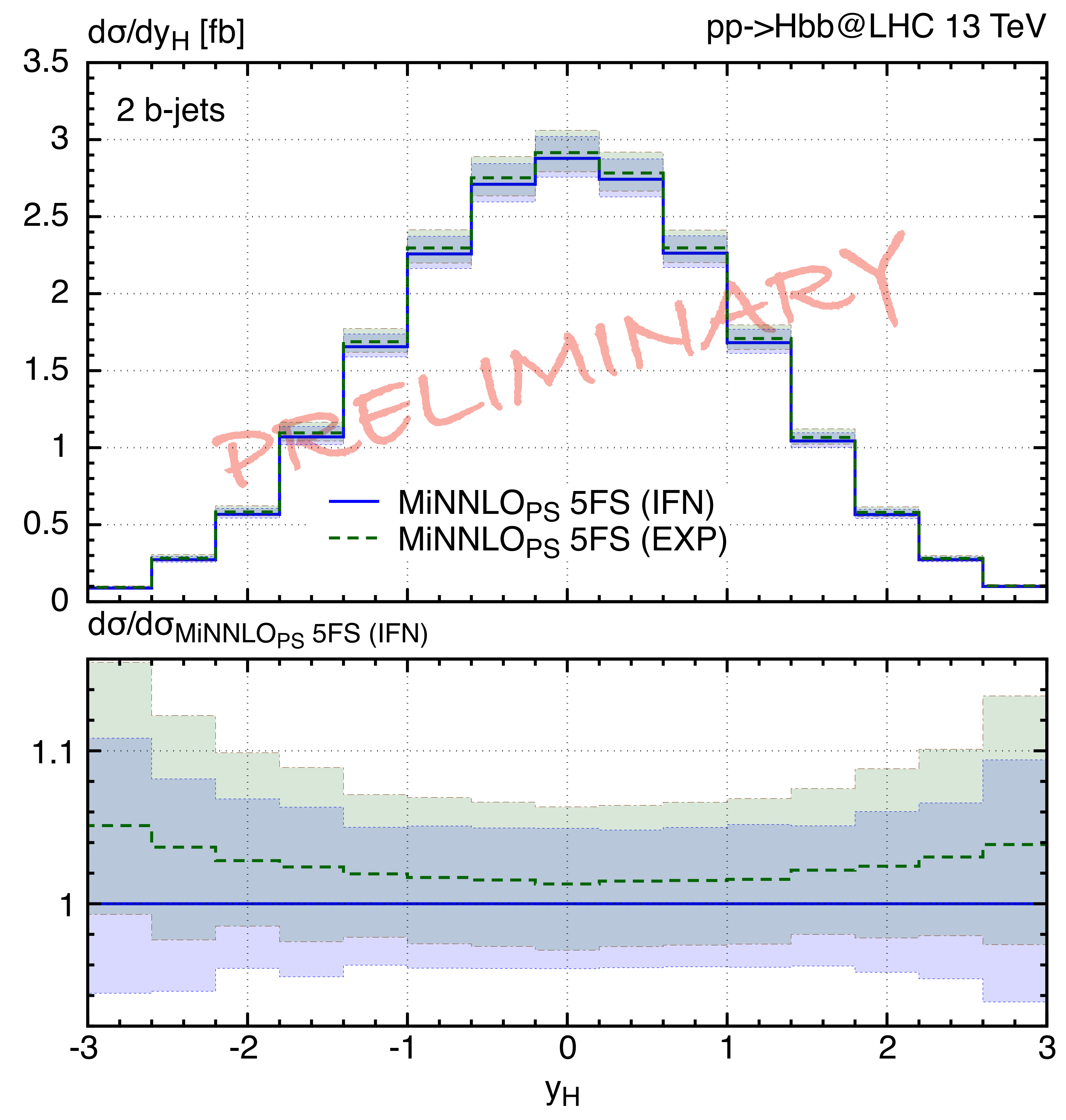
bb→H

CB, Sankar, Wiesemann, Zanderighi [in progress]

With the generated events, we have the opportunity to explore a lot of physics!

Several pheno studies can be conducted, such as the **b-tagging of jets**.





News. We have investigated the properties of the flavour jets in $bb \to H$

- **EXP**, a bjet contains at least a B-hadron
- **IFN**, IR-safe method called Interleaved Flavour Neutralisation
  Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler [2306.07314]

A new class of processes

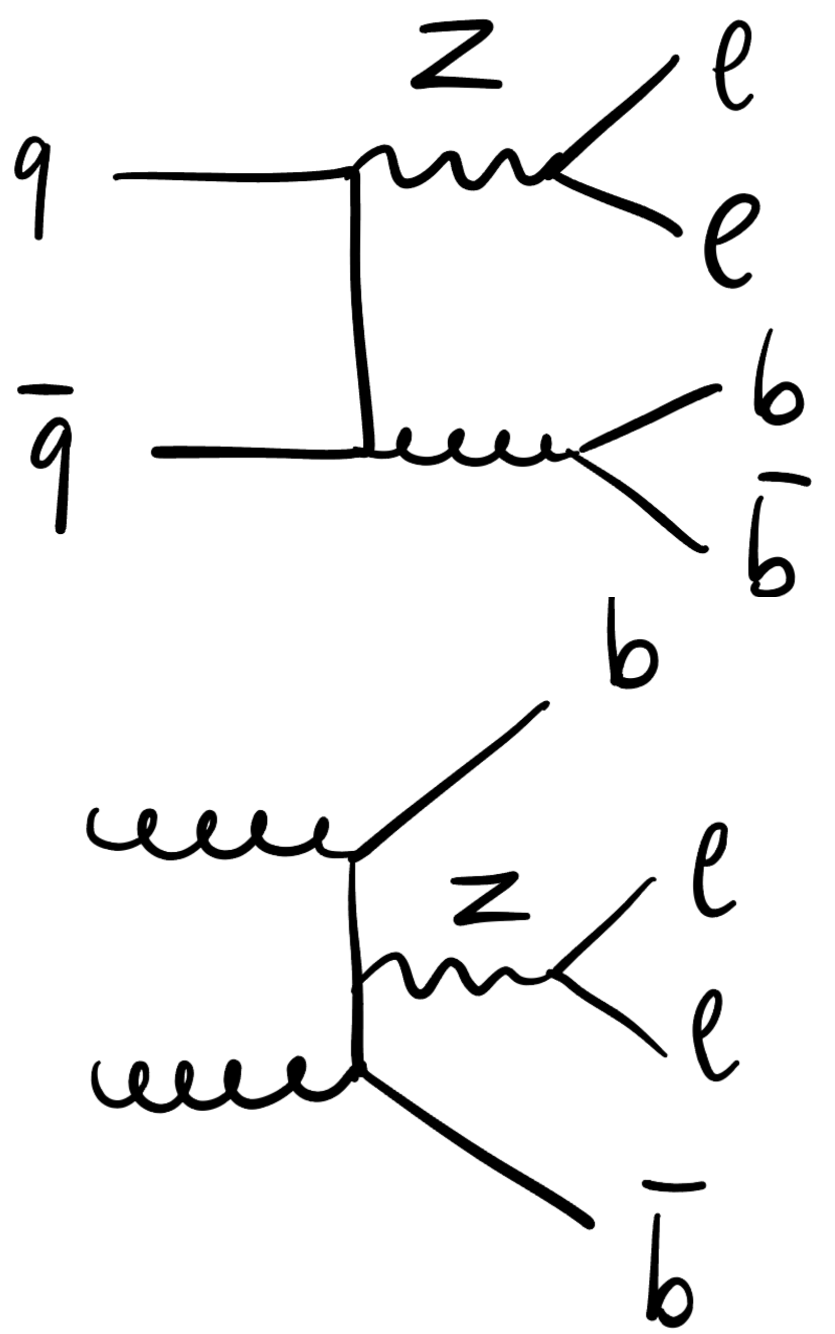
bbZ

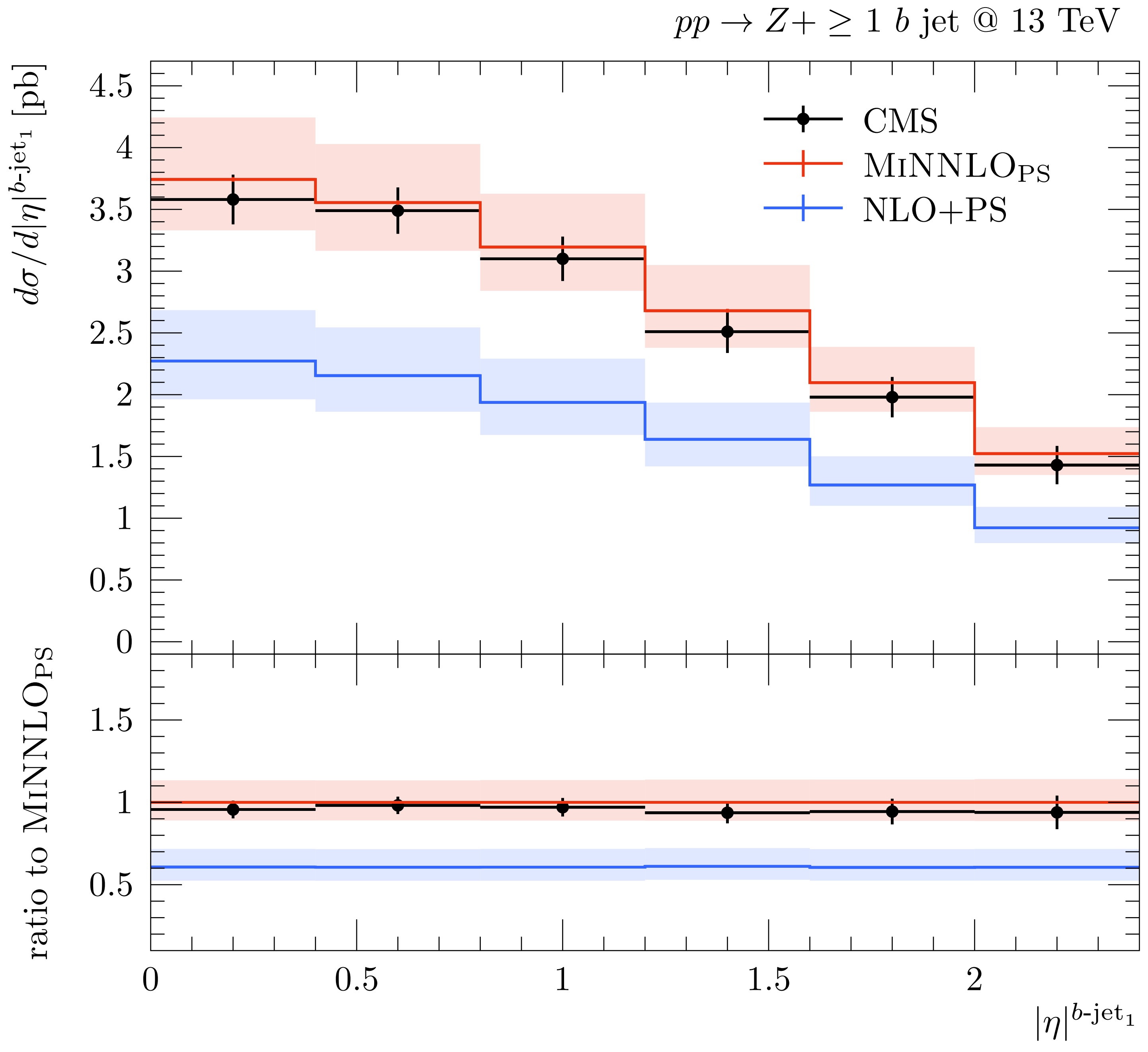
Mazzitelli, Sotnikov, Wiesmann [2404.08598]

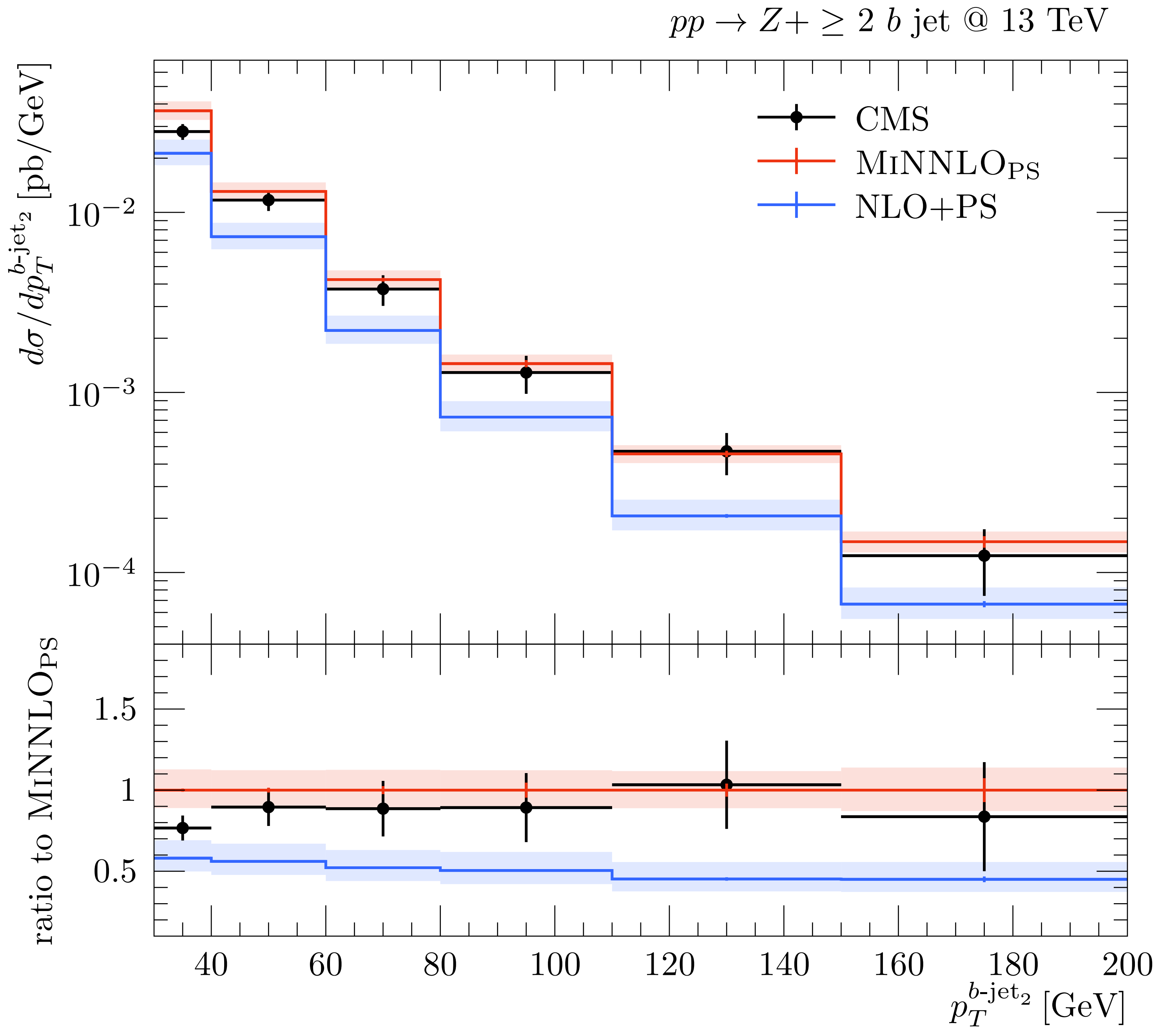
Why? Modelling high-multiplicity processes is mandatory for LHC studies. We must go beyond $2 \to 2$ processes.

MiNNLOPS now can perform predictions for **heavy-quark pair production in association to a color singlet.**

Feature. Treatment of the singular structure for heavy quarks in generic kinematics. Applied for the first time to $b\bar{b}\ell\ell$.







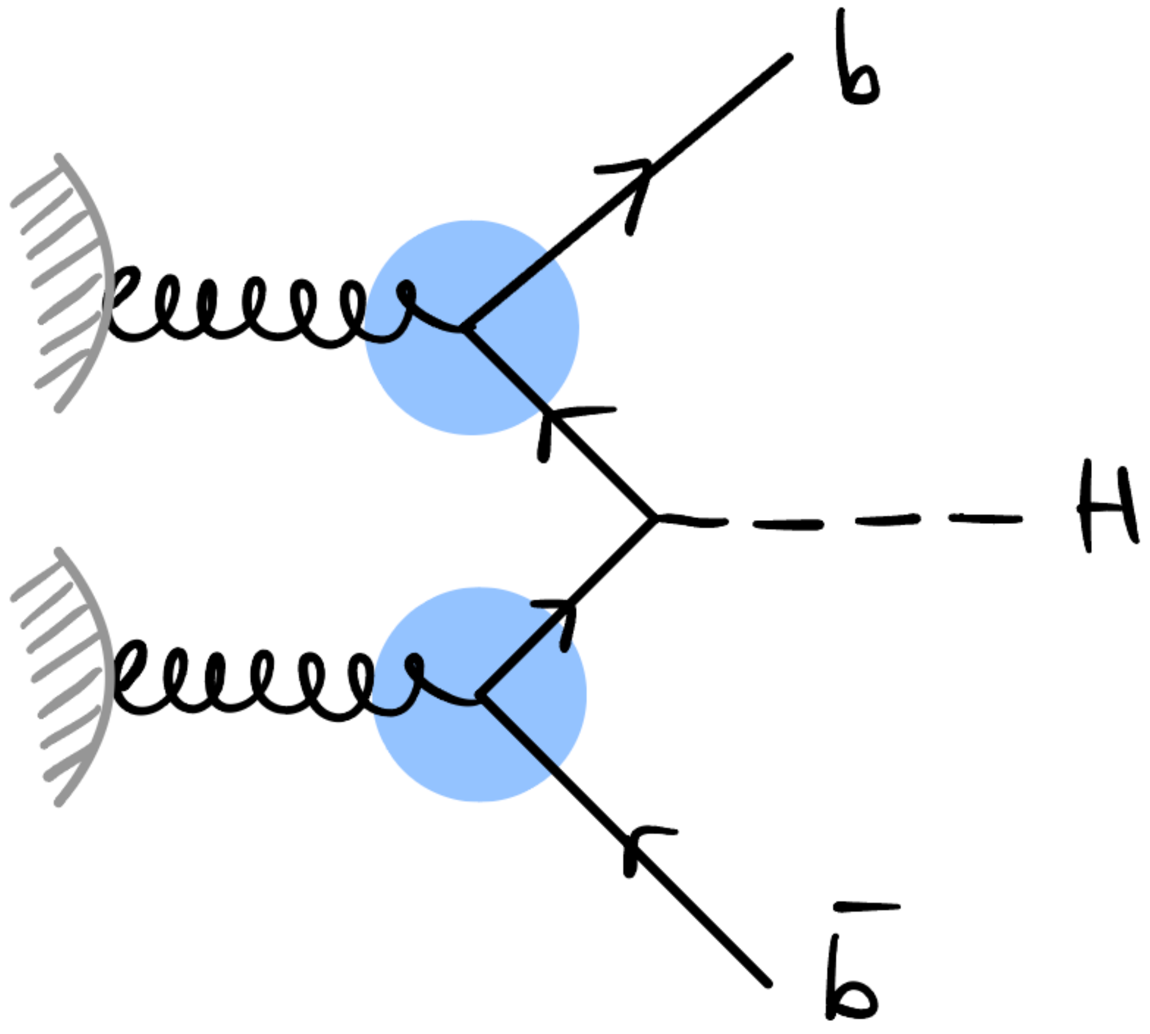
The massive calculation

bbH

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

Why bbH with massive quarks? The massless calculation is not accurate in some region of the phase-space and for B-hadron observables.

4FS



massive calculation (four-flavour scheme)

- Computing higher orders is extremely non-trivial due to higher multiplicity
- ✓ Mass effects $O(m_b/m_H)$ are present at any order

Feature. It requires both the MiNNLOPS extensions for Yukawa induced processes and heavy quarks in final state.

Theoretical bottleneck. Two-loop amplitude ⇝ implement a reliable and well-tested approximation

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

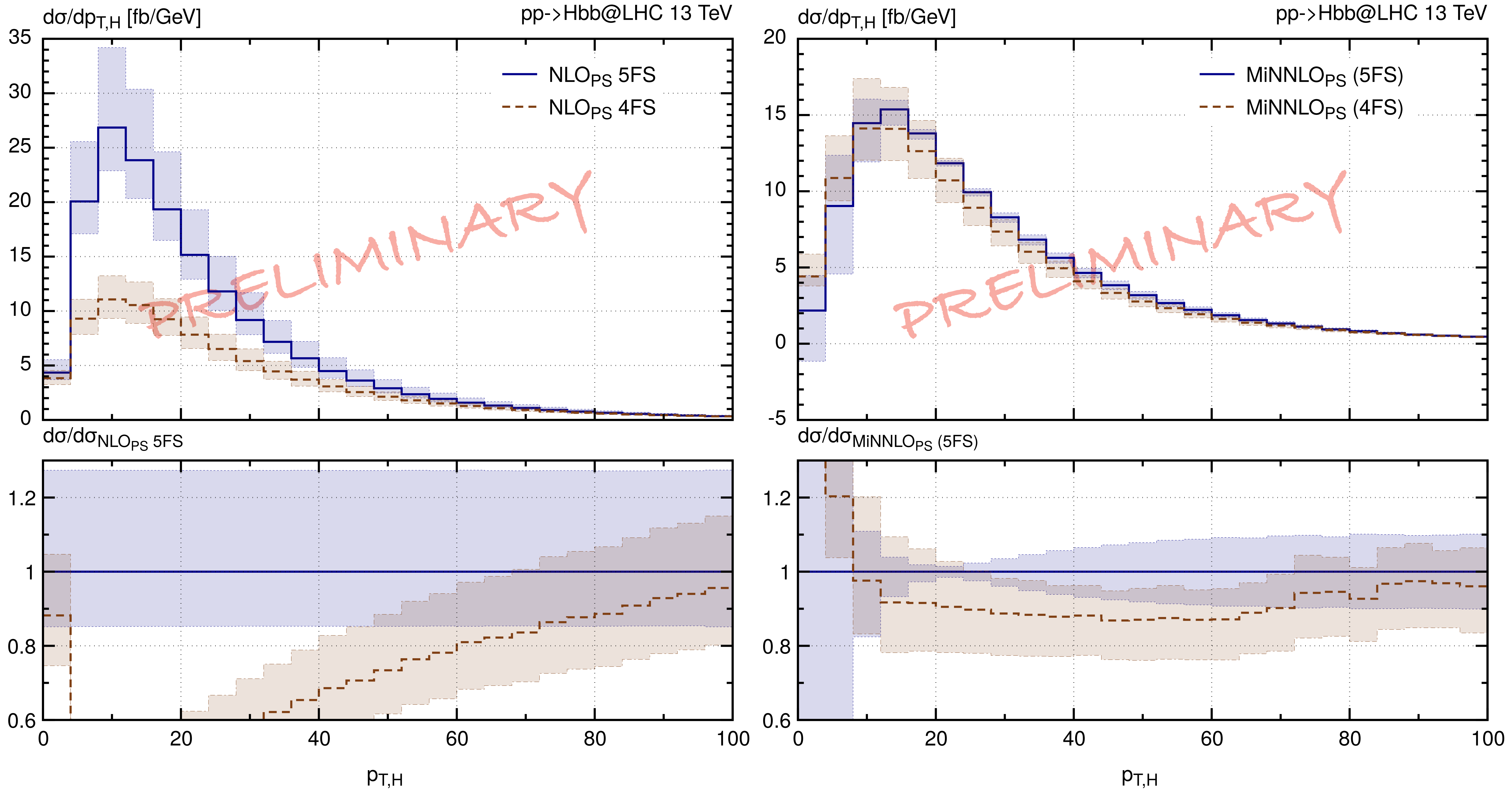
Massive vs massless

bbH

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

NNLO corrections in the 4FS solve the **long-standing issue of discrepancies** between the flavour-scheme predictions.

Higgs and one b-jet observables are in **agreement between the two MiNNLOPS** generators.



$\mathrm{NLO+PS}_{LL}$

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

$\mathrm{N}^{x}\mathrm{LO+PS}_{N^{y}LL}$

- NLO+PS are the standard of any analysis for a realistic modelling at colliders
- MiNNLOPS is a flexible and adaptive method to be applied to several processes with different features!
- Thanks to the accuracy of novel parton showers and the improvements in fixed-order calculations, we are in a promising period for the matching

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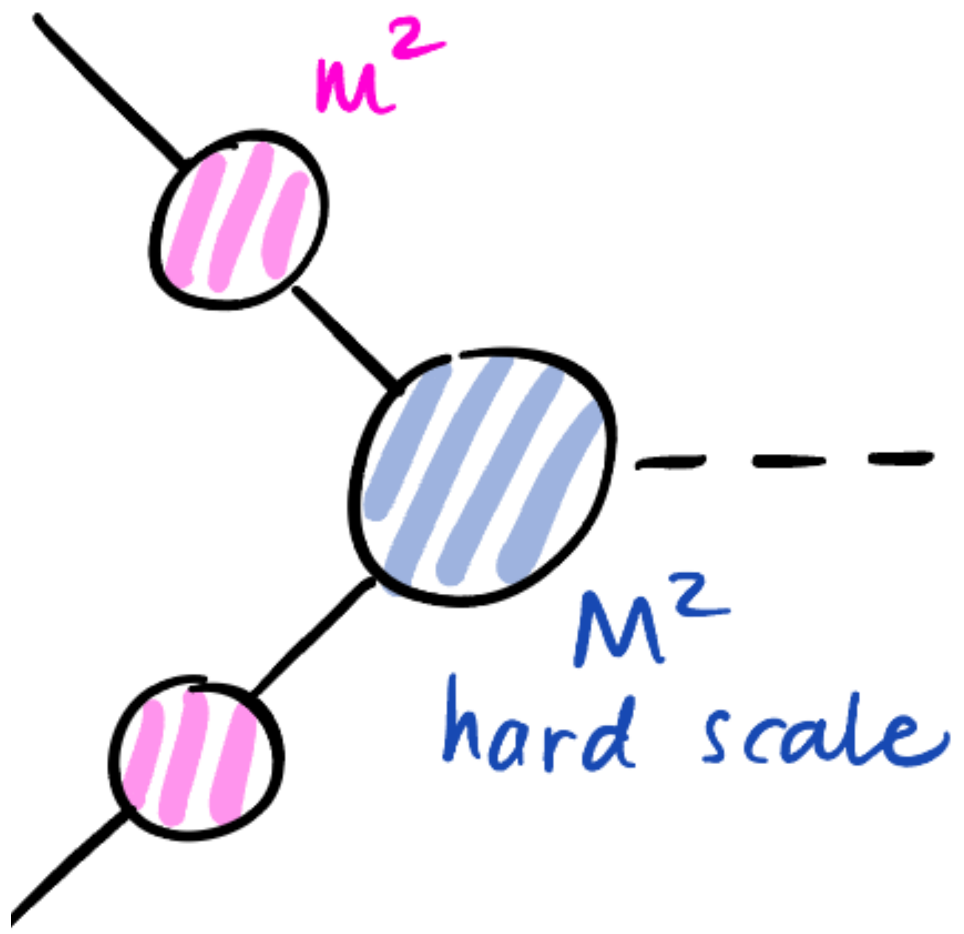
Thank you for the attention!

Backup slides

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 $\Rightarrow \dfrac{1}{H}\dfrac{d\ln H}{d\ln\mu^2} = -\dfrac{1}{S}\dfrac{d\ln S}{d\ln\mu^2} =: \gamma(\mu^2)$

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

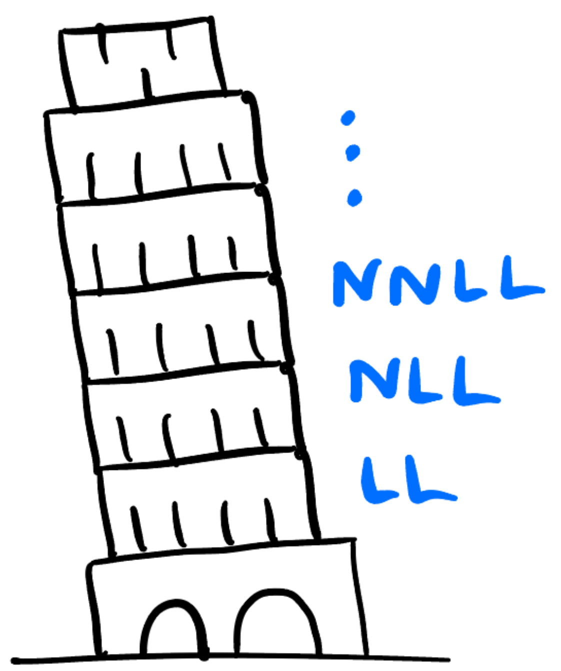
What is the probability that a Higgs boson is produced with transverse momentum $< p_T$?

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

for small p_T we need to sum up the logs

In general we have a tower of logs

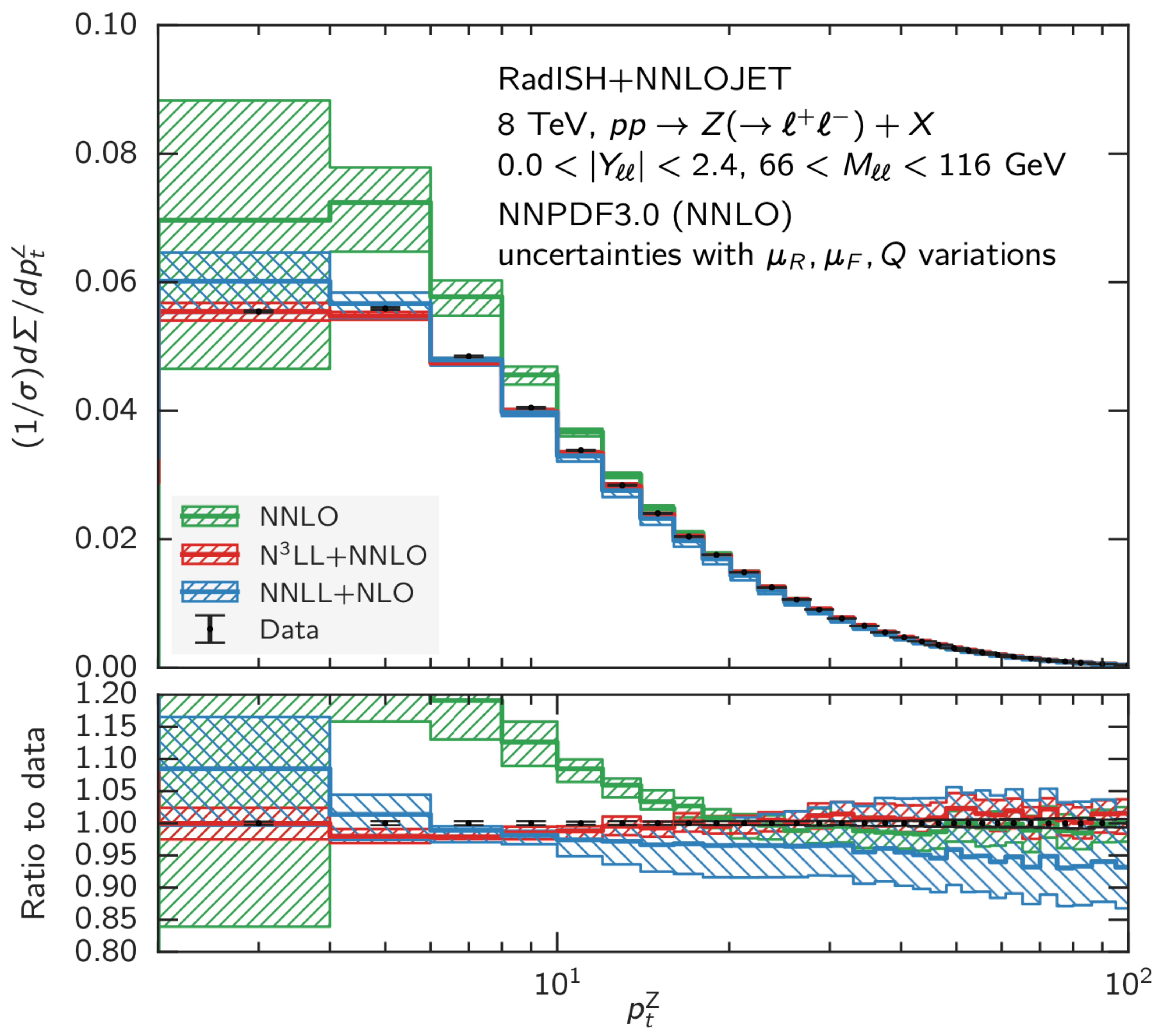
$$\exp\left[-\sum_{n,m} \alpha_s^n \ln^m \frac{m_H}{p_T}\right]$$



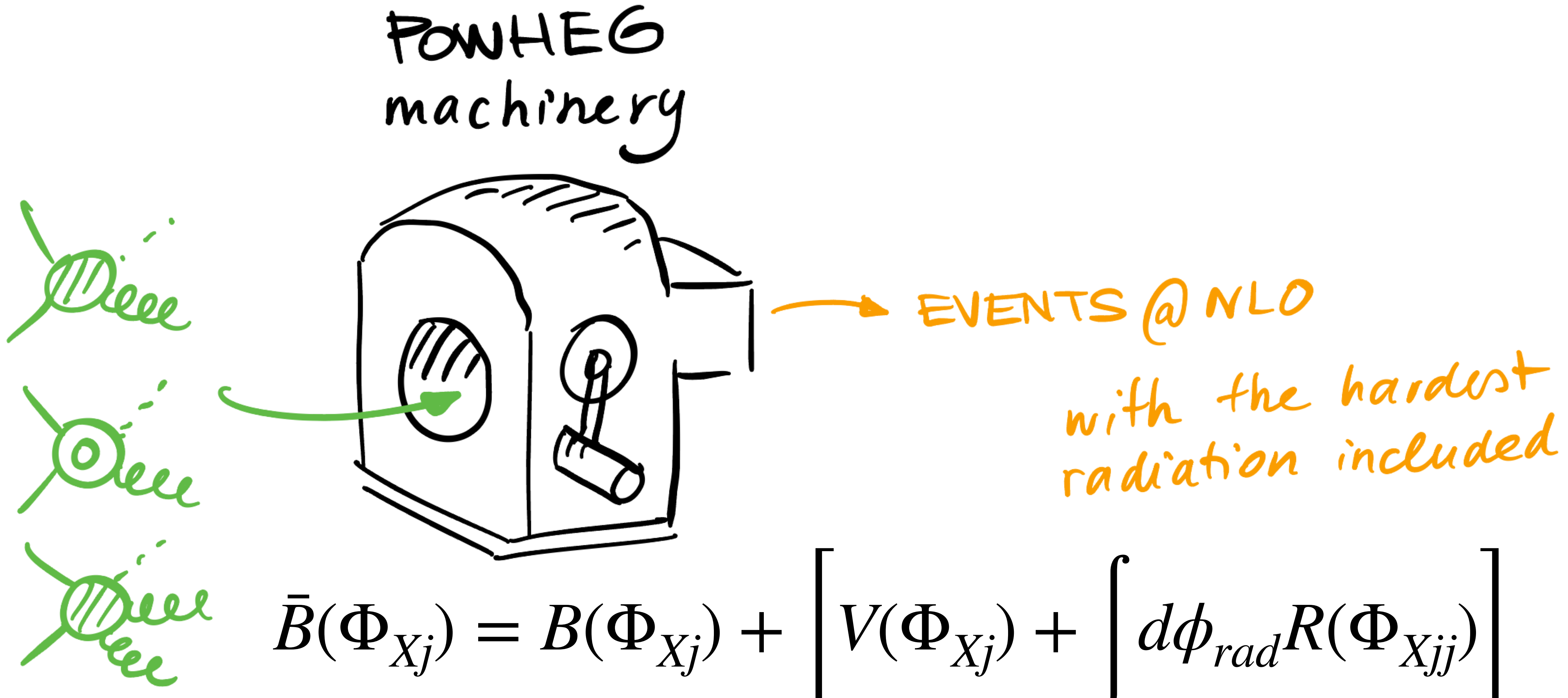
$m = n + 1$ → Leading Logs (LL)

$m = n$ → Next-To-LL (NLL)

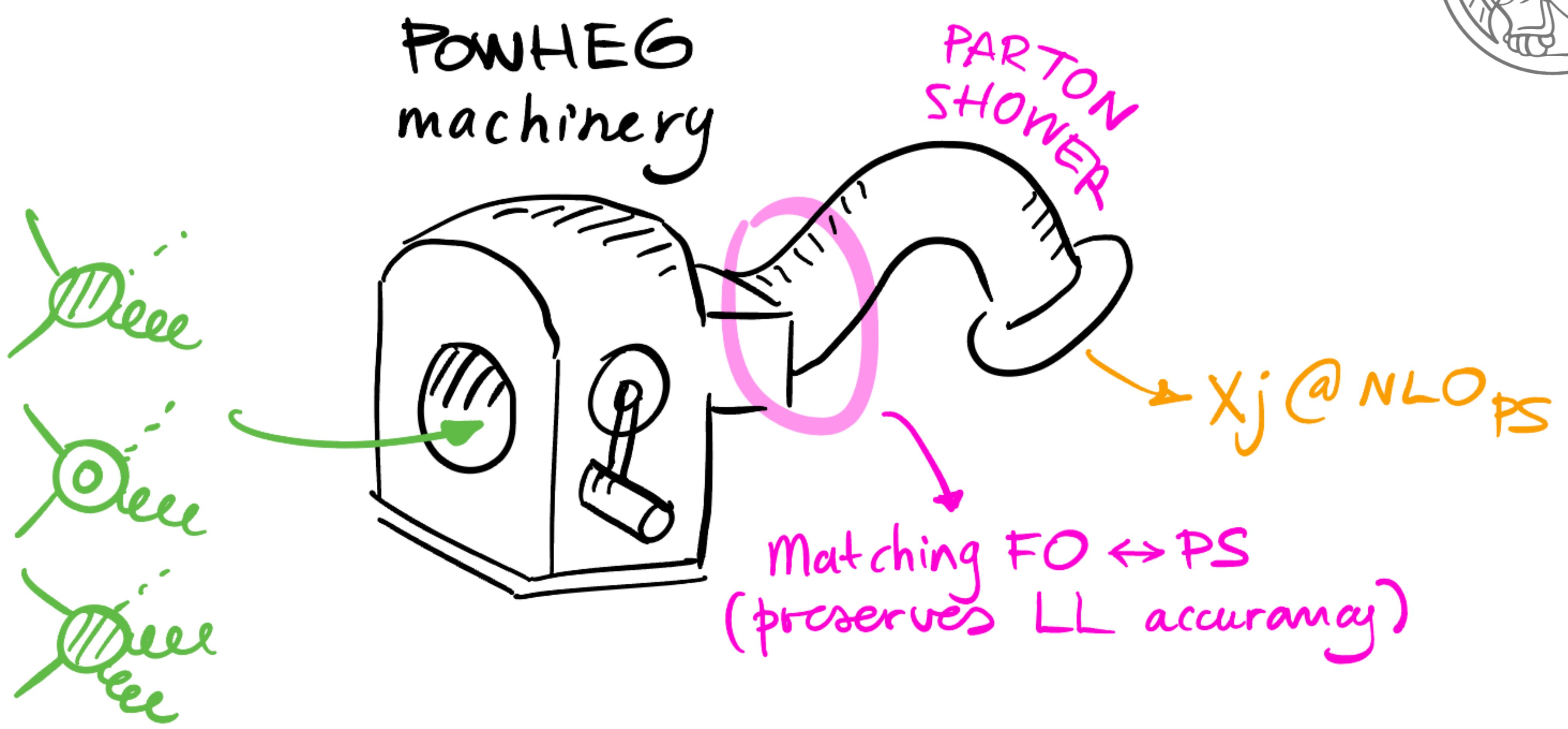
$m = n - 1$ → Next-To-NLL (NNLL) . . .



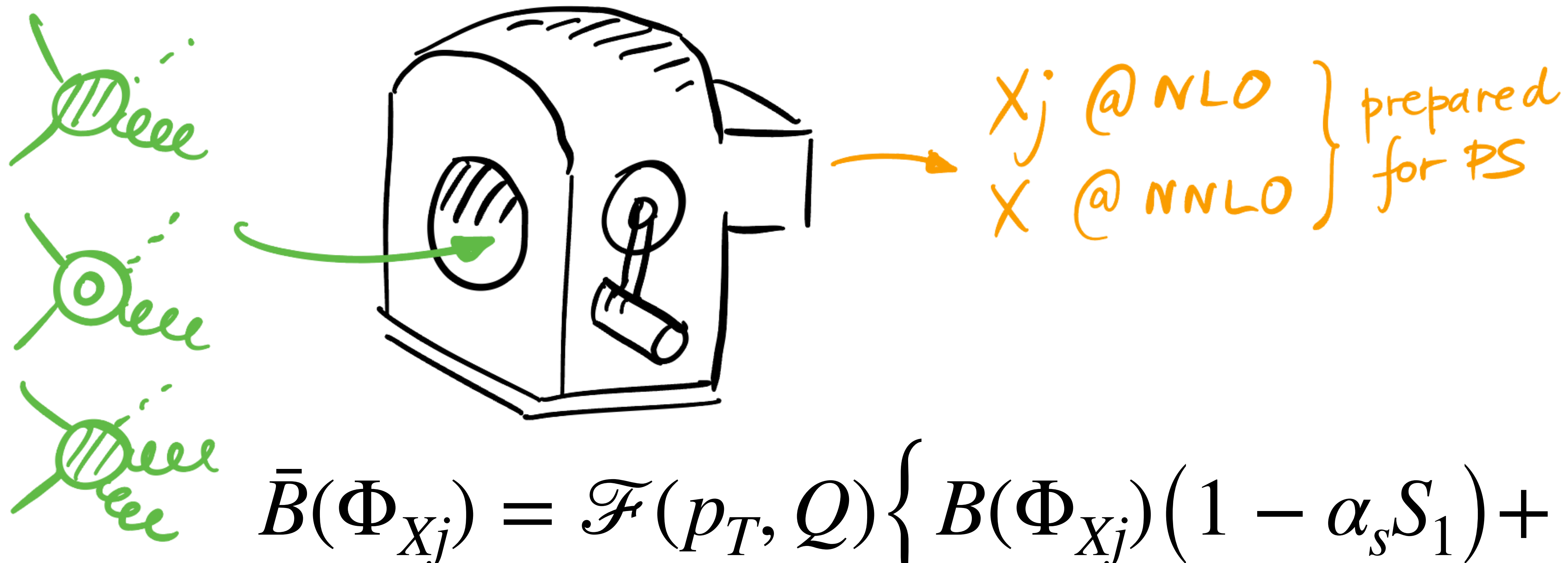
POWHEG



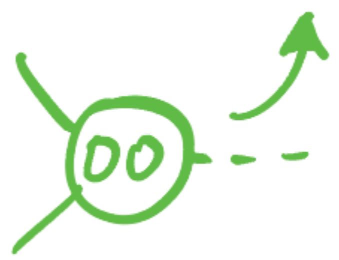
$$\bar{B}(\Phi_{Xj}) = B(\Phi_{Xj}) + \left[V(\Phi_{Xj}) + \int d\phi_{rad} R(\Phi_{Xjj})\right]$$

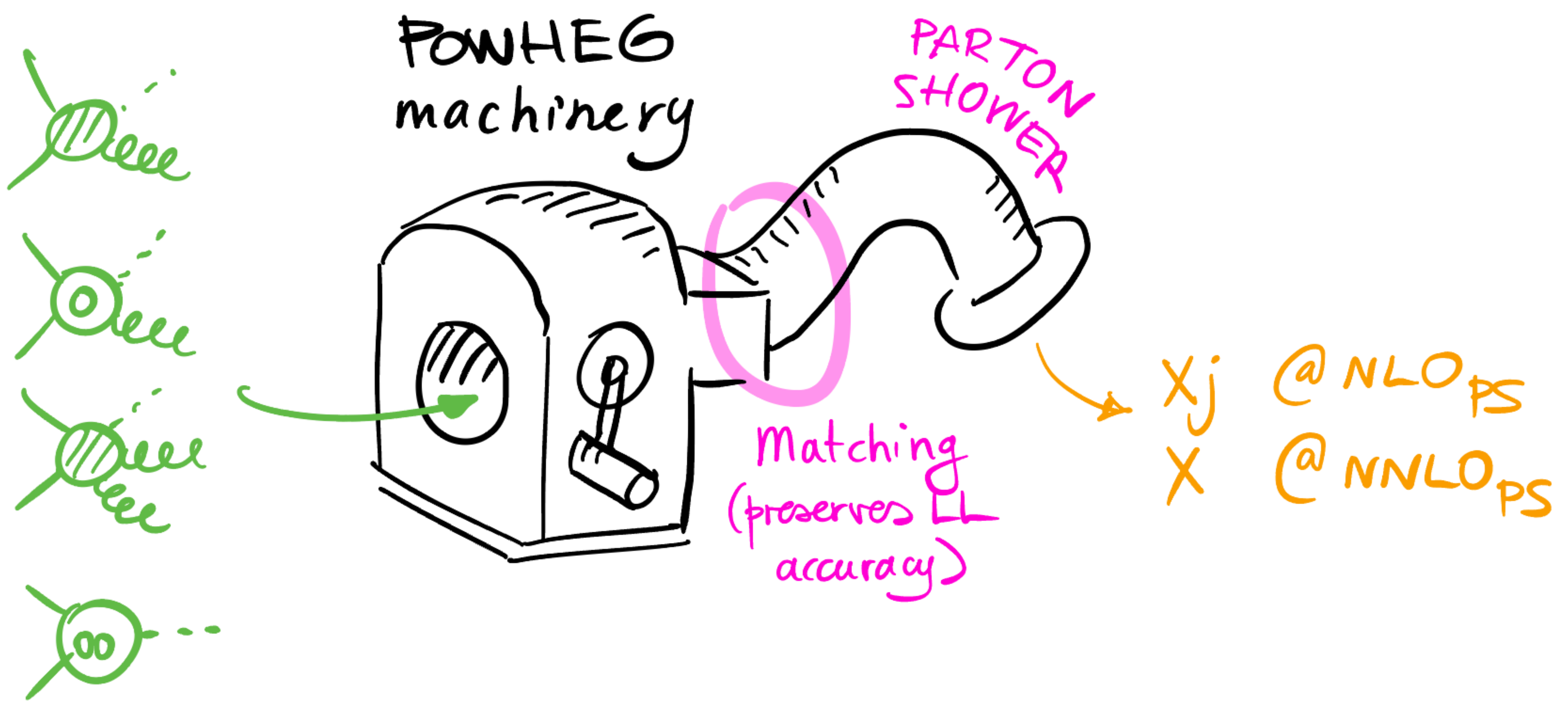


MiNNLO+POWHEG



$$\bar{B}(\Phi_{Xj}) = \mathscr{F}(p_T, Q)\Big\{ B(\Phi_{Xj})\big(1 - \alpha_s S_1\big) + \left[V(\Phi_{Xj}) + \int d\phi_{rad} R(\Phi_{Xjj})\right] + [D_3\text{-term}]\, F(\Phi_{Xj}) \Big\}$$





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 [1206.3572]

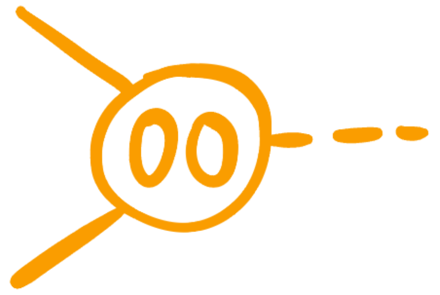
Split the differential inclusive cross-section into the singular and regular part in the small transverse momentum limit: $\mathrm{d}\sigma = \mathrm{d}\sigma^{sing} + \mathrm{d}\sigma^{reg}$.

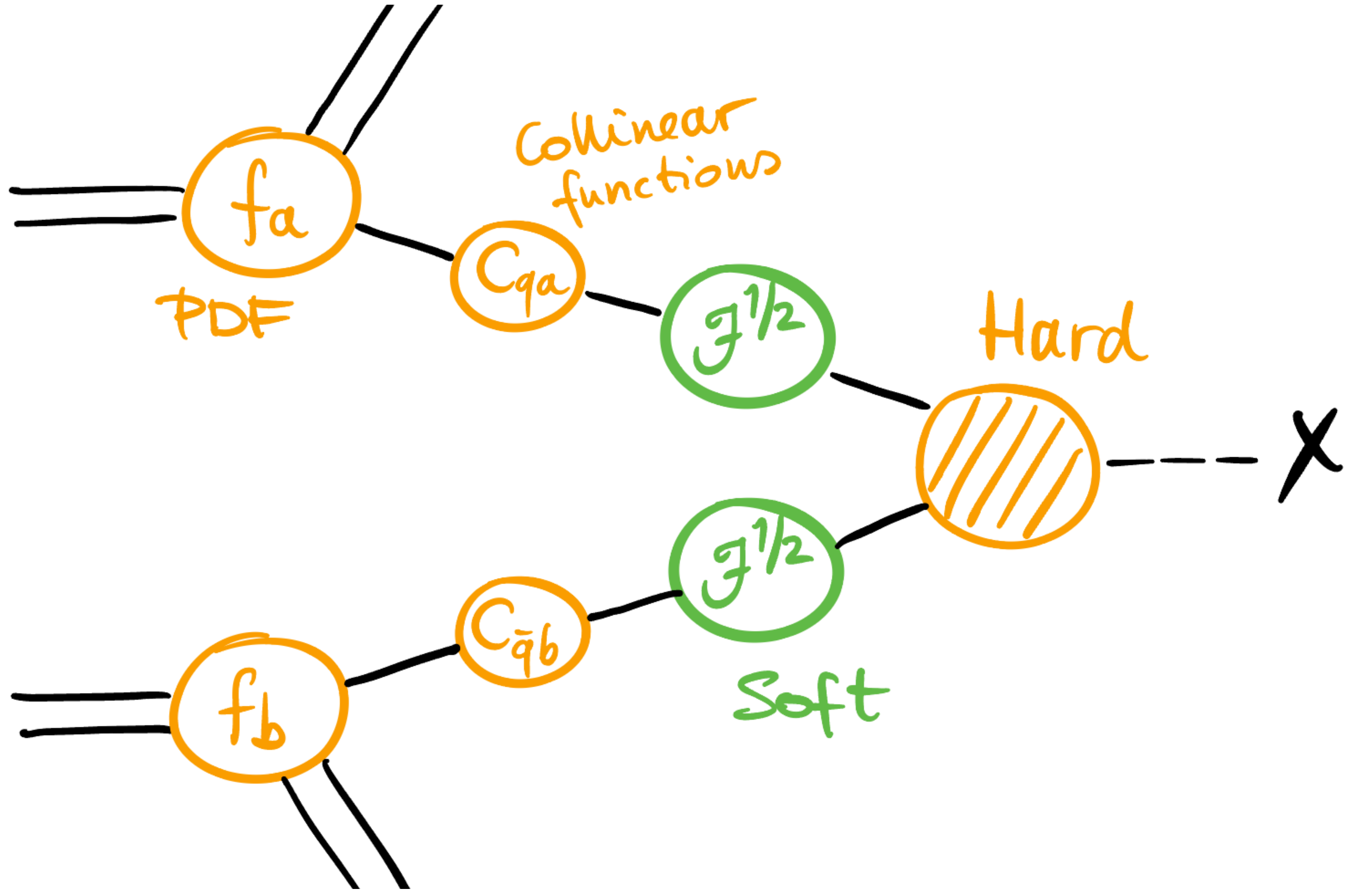
$$\frac{\mathrm{d}\sigma^{sing}}{\mathrm{d}p_T\,\mathrm{d}\Phi_X} = \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{\mathscr{F}(p_T)\,\mathscr{L}(p_T)\right\} =: \exp\left[-\tilde{S}(p_T)\right] D(p_T)$$

Sudakov form factor

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

Luminosity: it also contains





MiNNLOPS in a nutshell

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

The modified POWHEG function is

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

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]

5FS 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 $\mu_R = \mu_F = m_H$

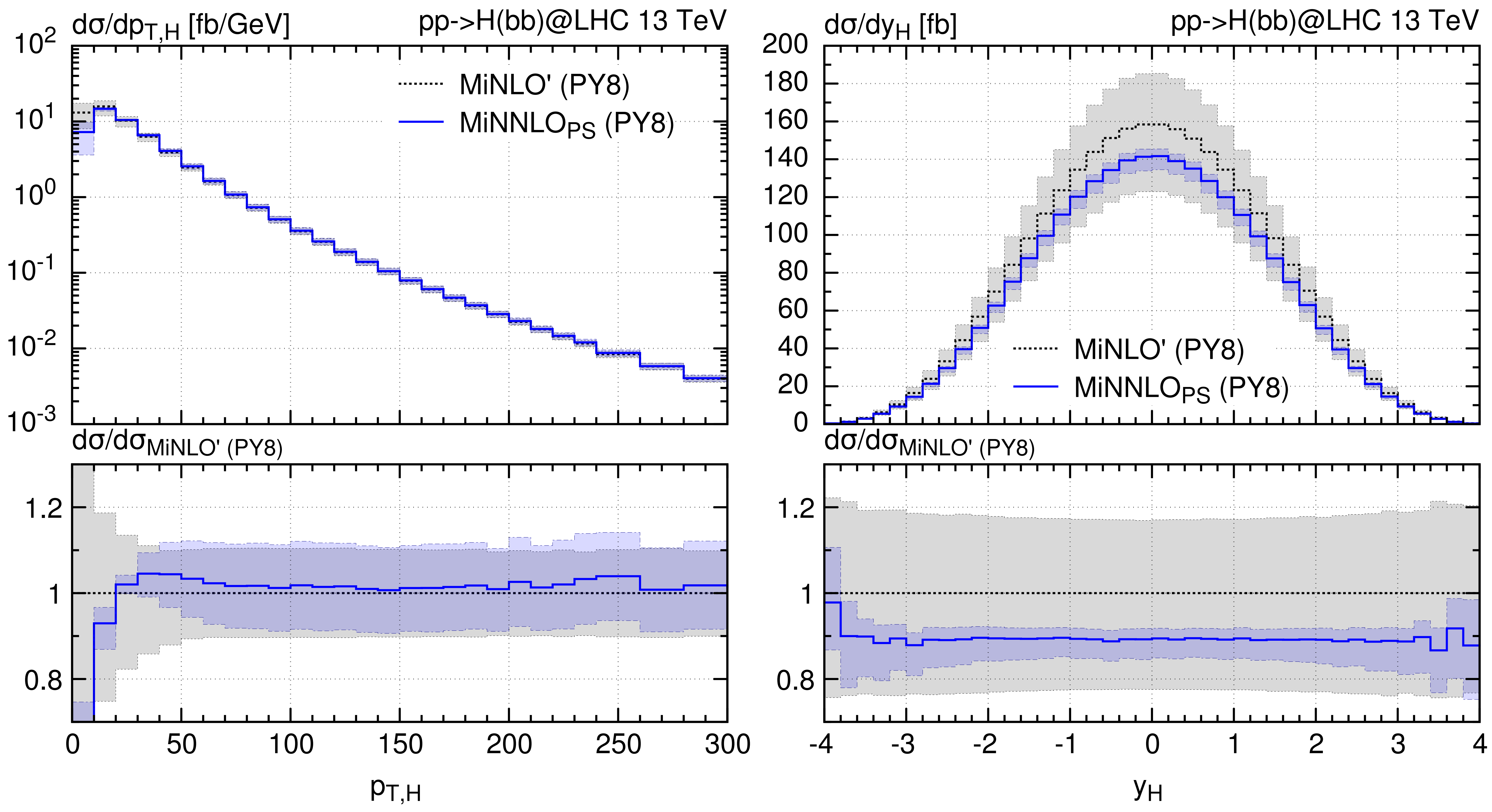
Harlander, Lieber, Mantel [1212.3249]

Process	NLO (SusHi)	NNLO (SusHi)	MiNLO′	MiNNLO$_{PS}$
$b\bar{b} \to H$	$0.646(0)^{+10.4\%}_{-10.9\%}$ 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

- 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

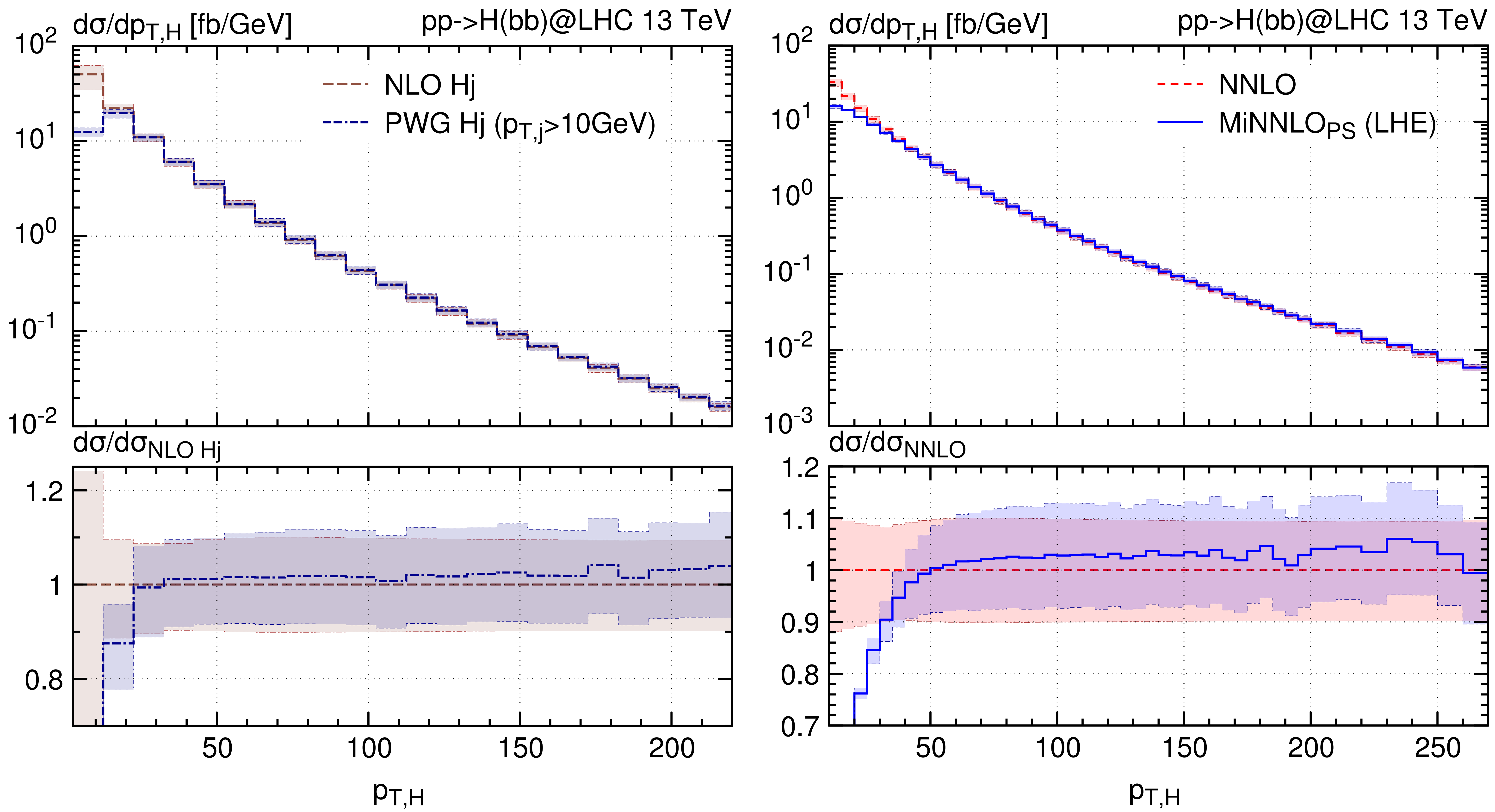
Transverse momentum spectrum of the Higgs boson | **Rapidity distribution of the Higgs boson**



- At small $p_{T,H}$, MiNNLOPS significantly damps 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 with FO results

Transverse momentum spectrum of the Higgs

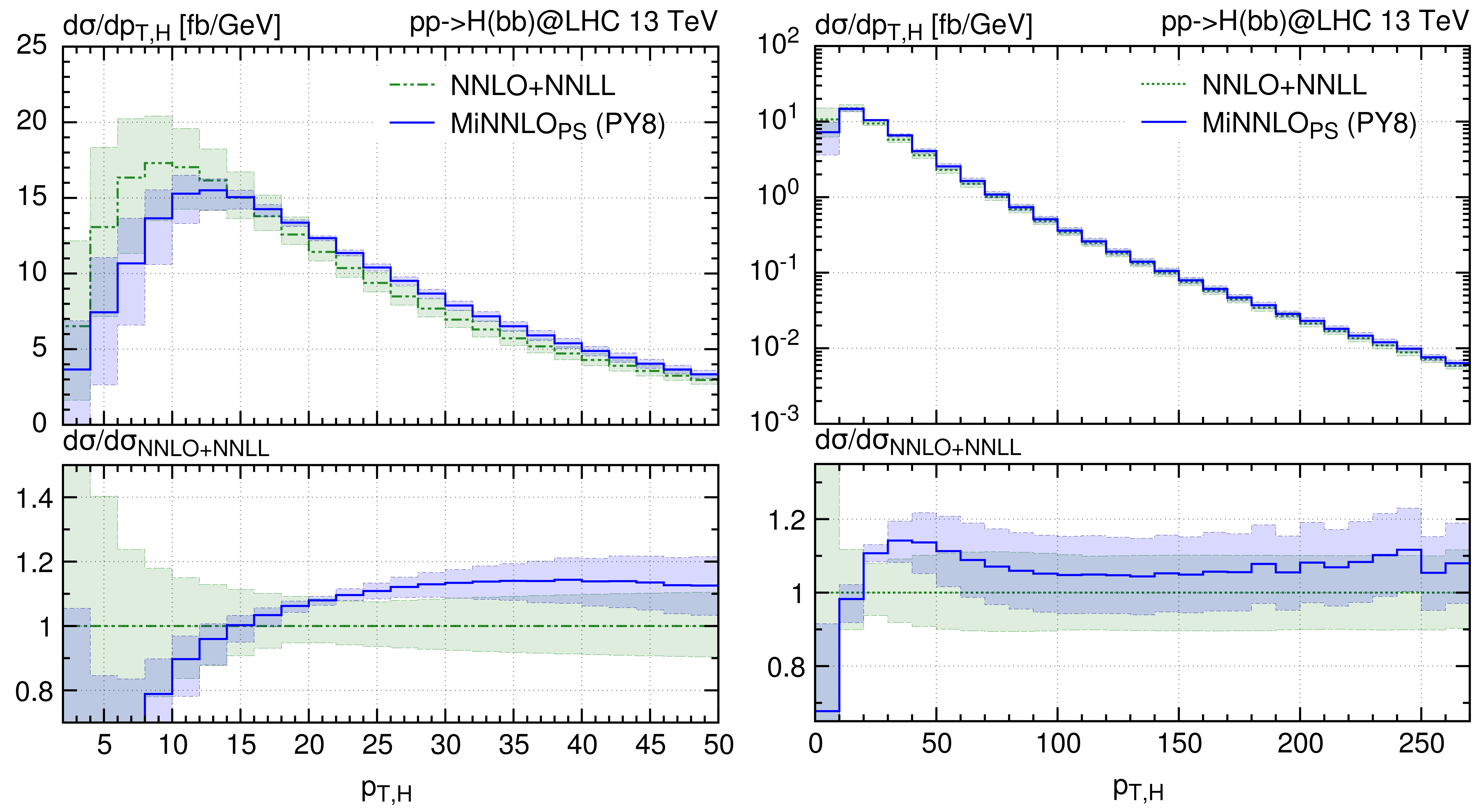


Full **agreement** at large transverse momenta $p_{T,H}$ with analytic **fixed-order predictions**

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

Comparison with 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]

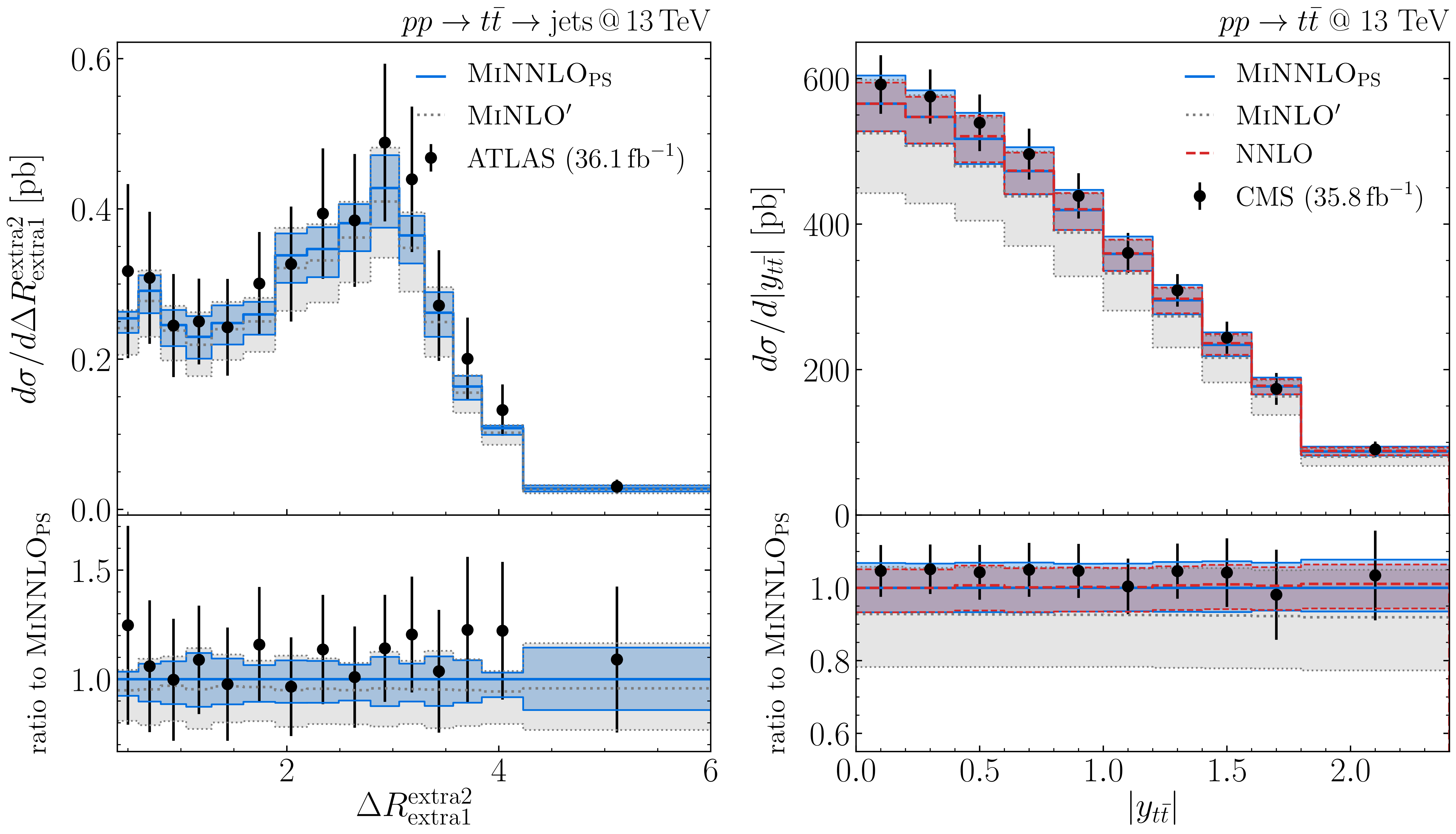
Mazzitelli, Monni, Nason,
Re, Wiesemann, Zanderighi
[2012.14267]

Heavy-quark pair production

The method was generalised for coloured final states with an **intensive phenomenological comparison** against ATLAS, CMS and LHCb data.

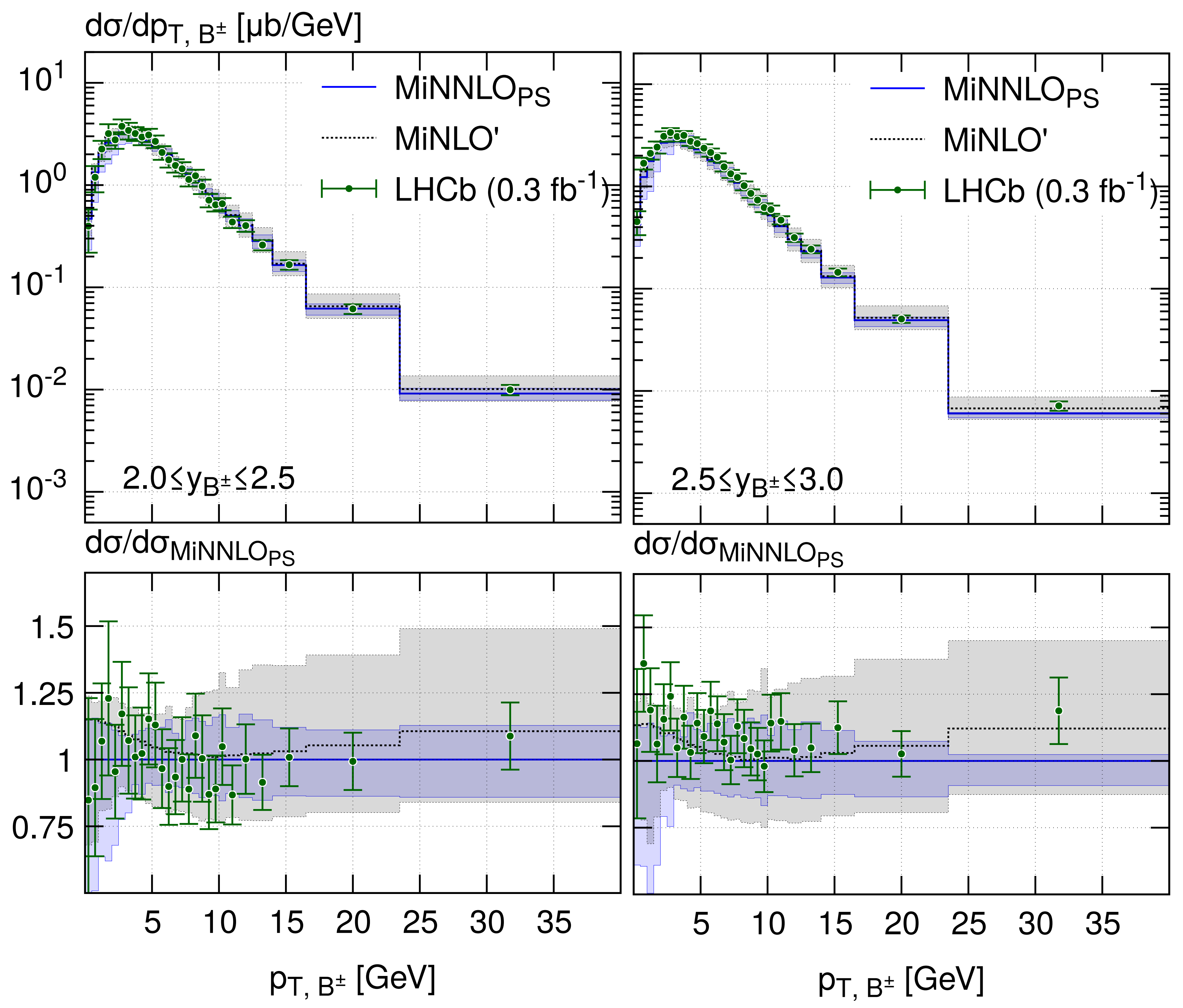
$t\bar{t}$

Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi [2112.12135]



$b\bar{b}$

Mazzitelli, Ratti, Wiesmann, Zanderighi [2302.01645]



Massification

bbH

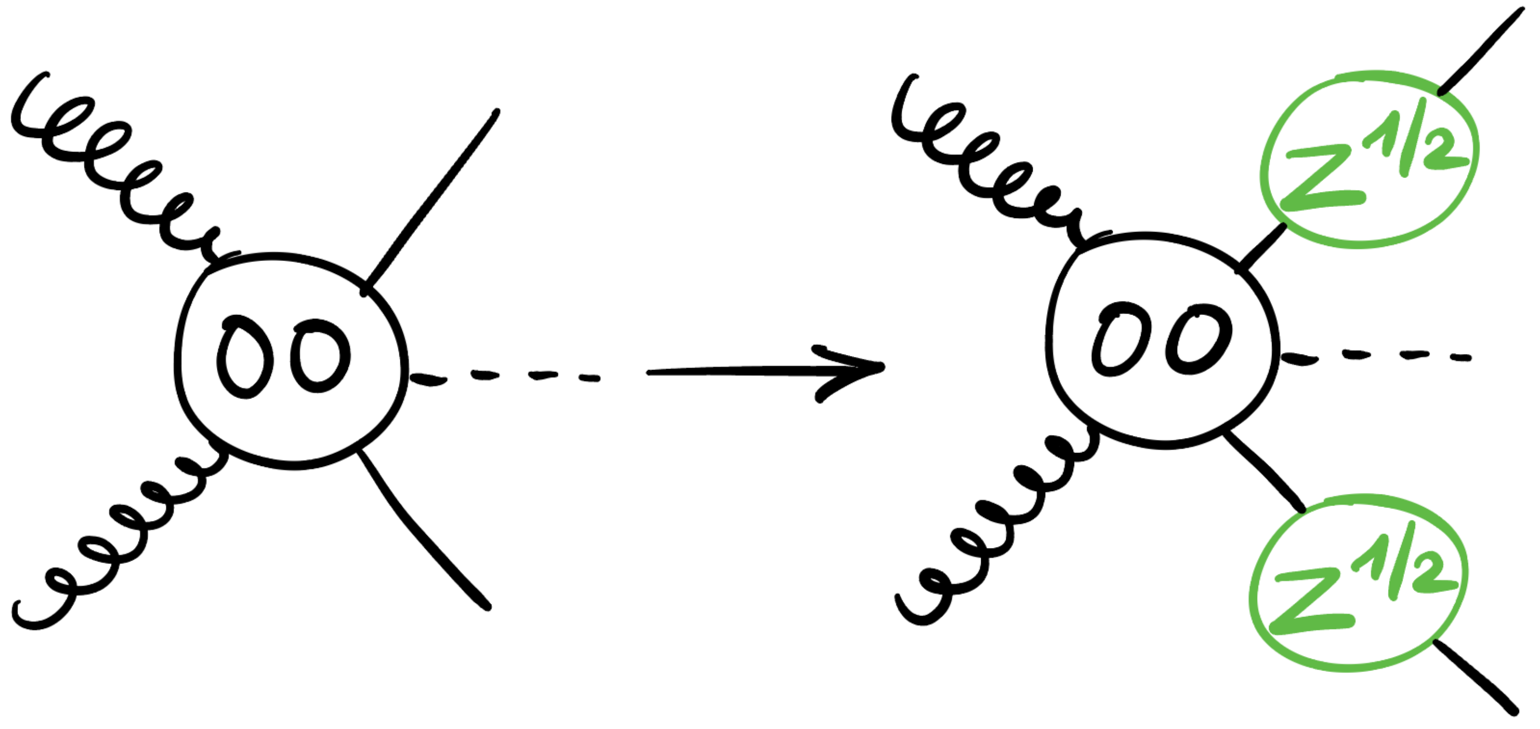
Biello, Mazzitelli, Sankar, Wiesemann, Zanderighi [in progress]

First two-loop massification in Bhabha scattering

Penin [hep-ph/0508127]

Extension for non-abelian theories from factorisation principles

Mitov, Moch [hep-ph/0612149]



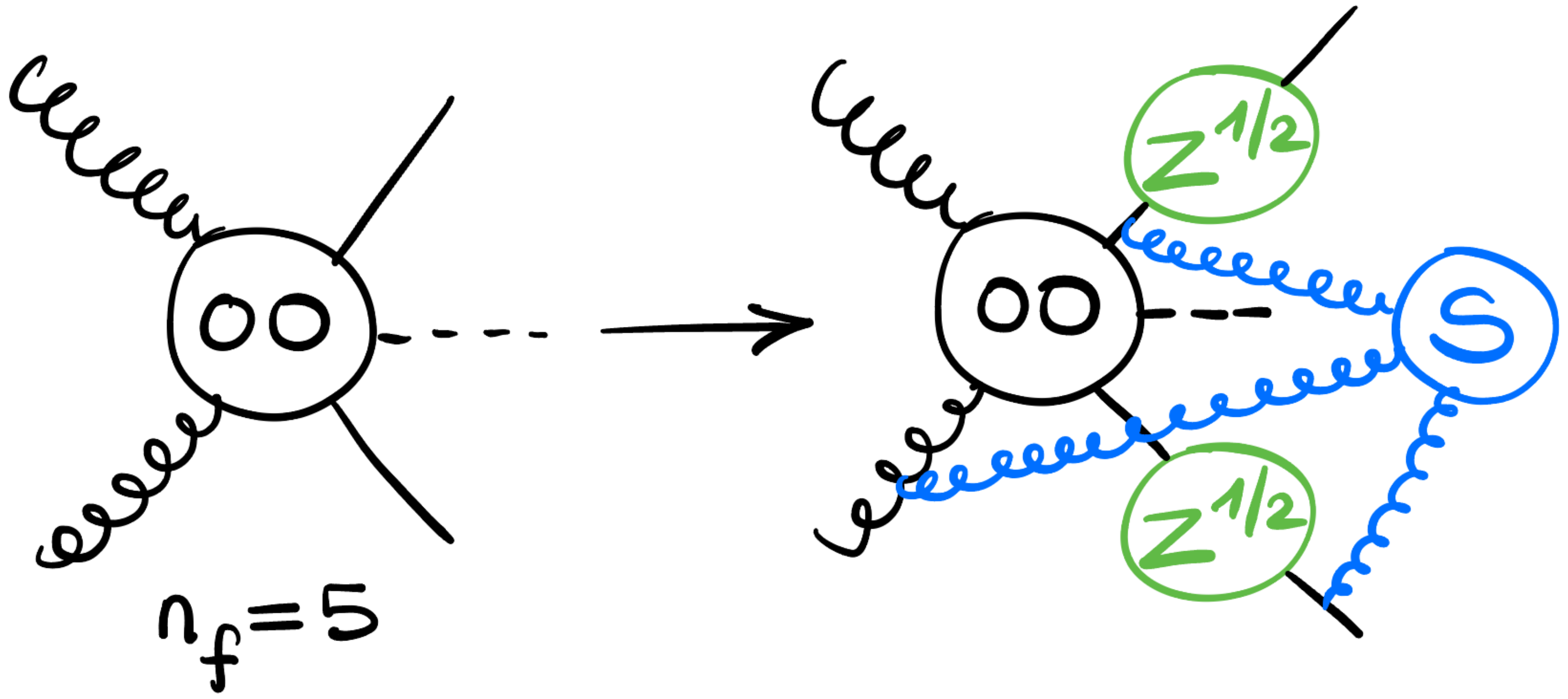
First massification of internal loops in Bhabha using the SCET formalism

Becher, Melnikov [0704.3582]

Recent application for QCD amplitudes

Wang, Xia, Yang, Ye [2312.12242]

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



Cross-checks with the independent implementation of Chiara Savoini