Combining NNLO QCD corrections with parton showers for Higgs production in bottom-quark fusion

Aparna Sankar

In collaboration with

C. Biello, M. Wiesemann, G. Zanderighi

based on [2402.04025]

MAX-PLANCK-INSTITUT FÜR PHYSIK

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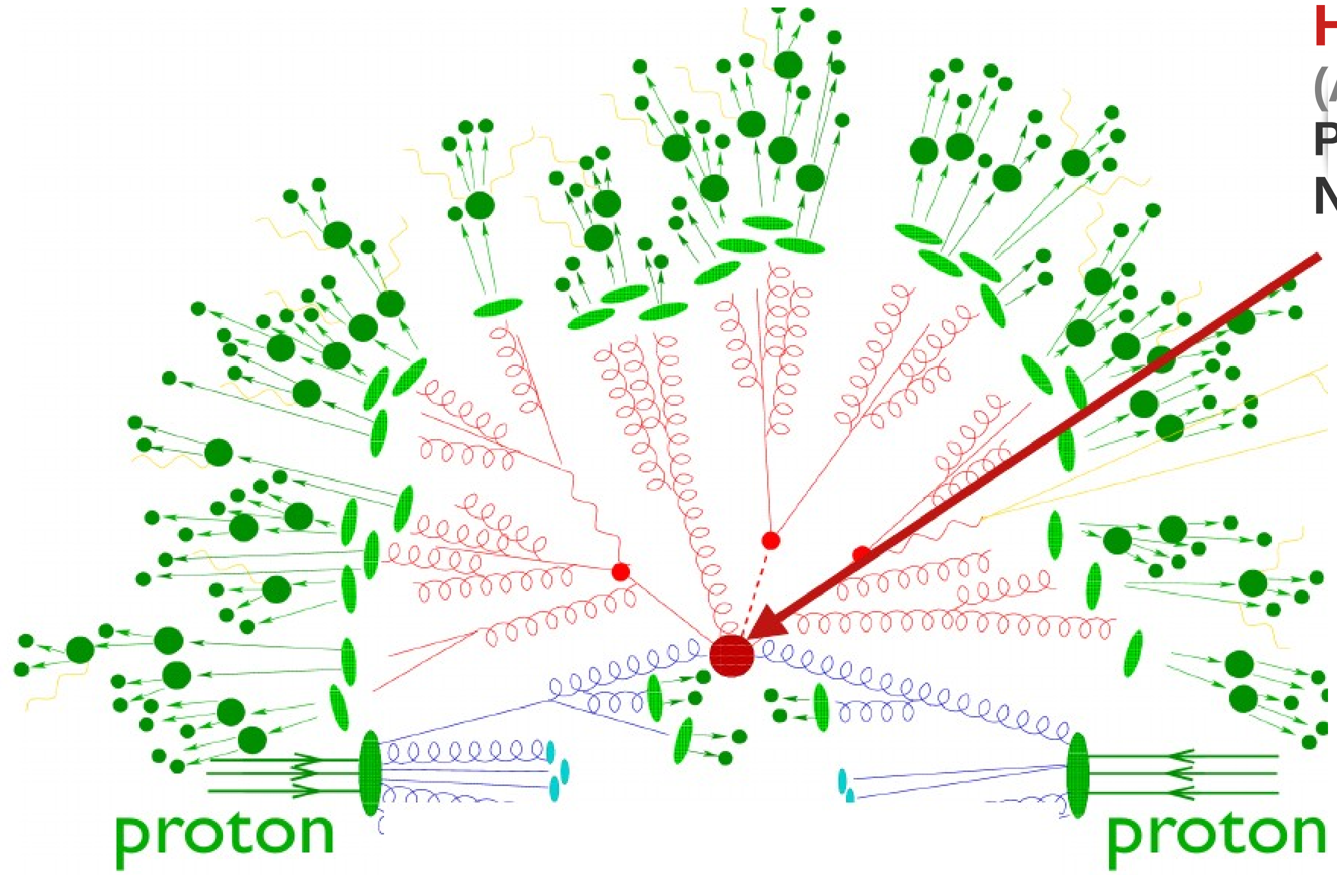
Grenoble, 10 April 2024

Events at LHC: theoretical perspective



Hard scattering
($\Lambda_{QCD} << \mu \approx Q$)
Perturbation theory
NNLO is the frontier!

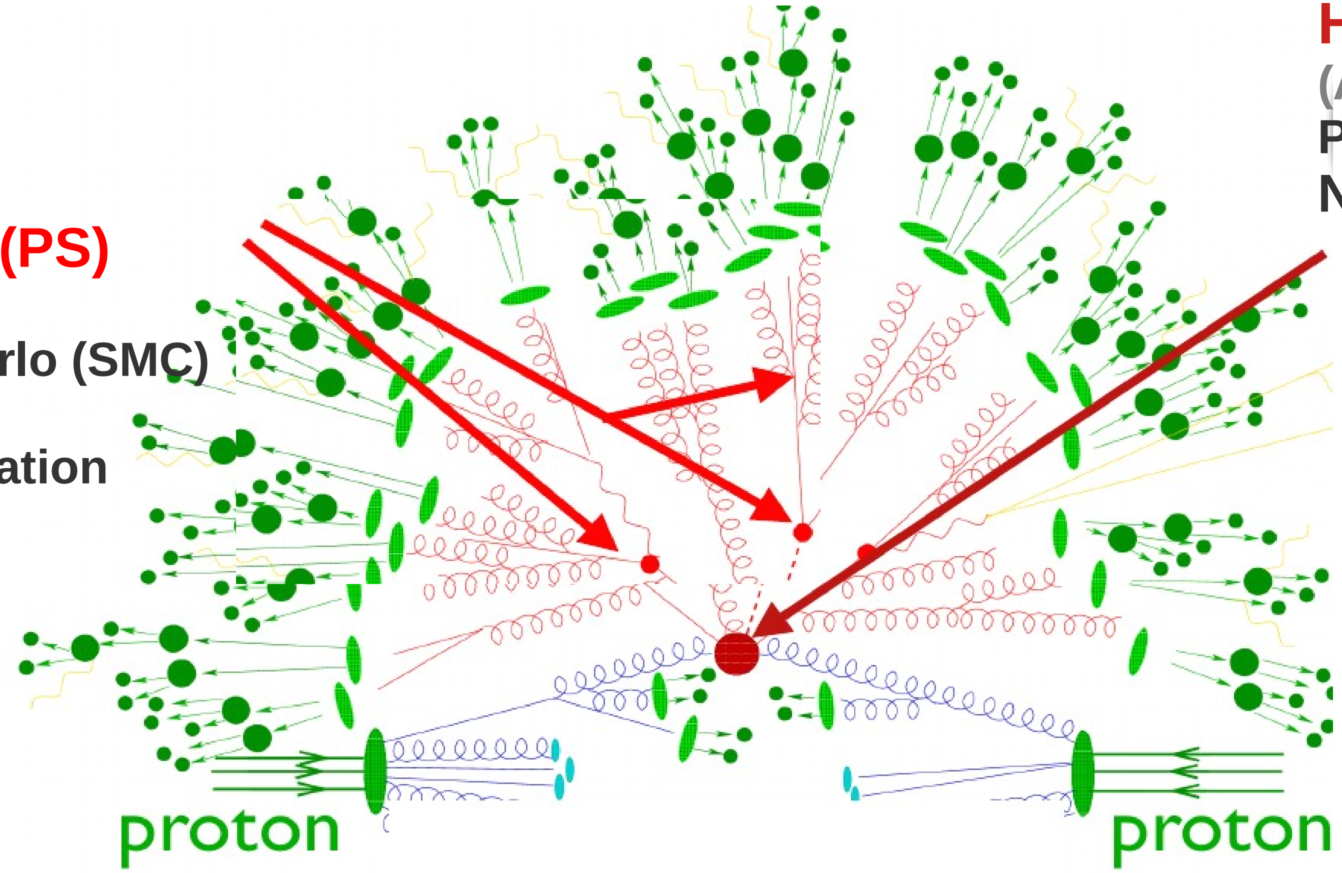
[Sherpa's artistic view]

Events at LHC: theoretical perspective

Parton shower (PS)

$\Lambda_{QCD} < \mu < Q$

Shower Monte Carlo (SMC)
Resummation of soft/collinear radiation
Less accurate



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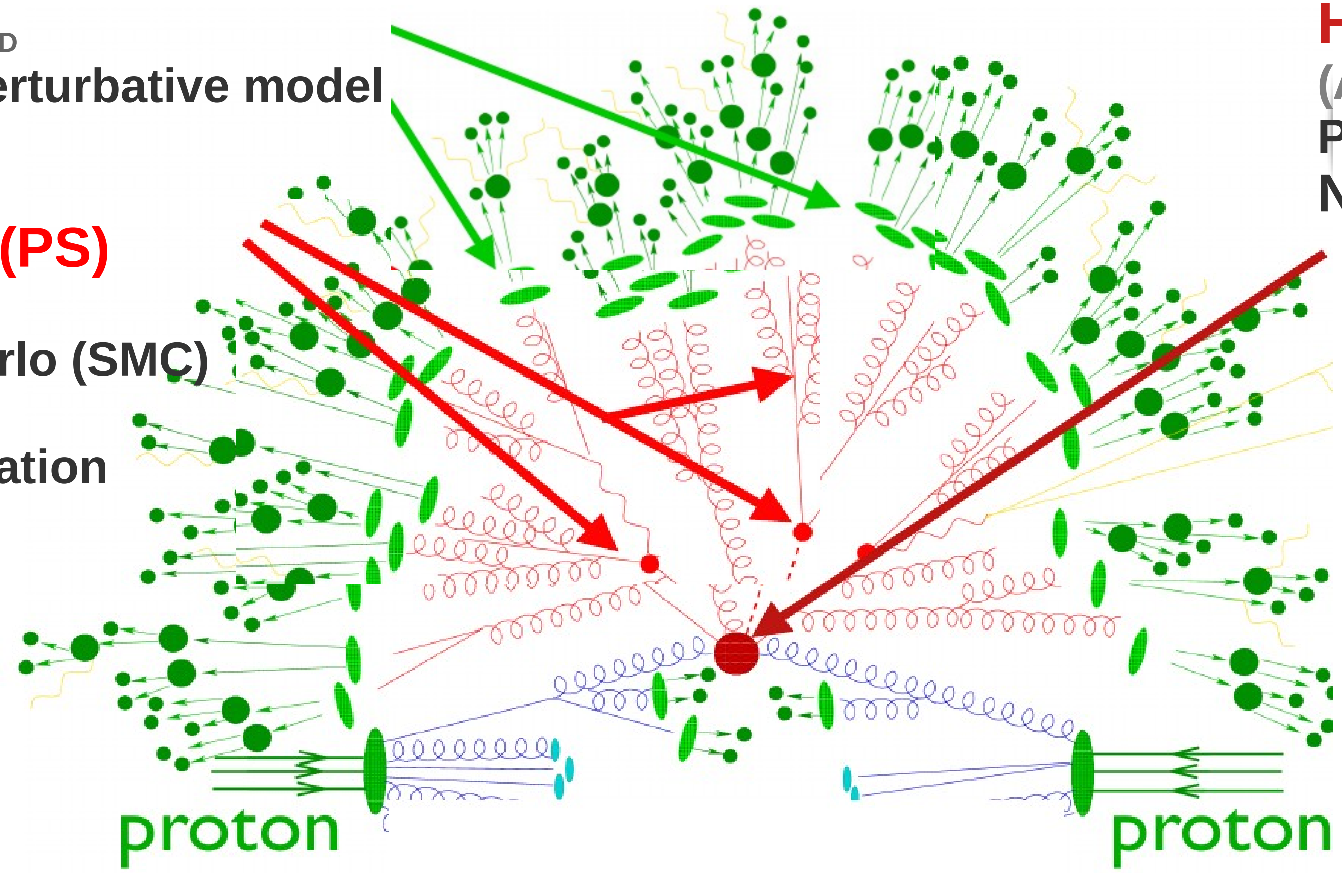

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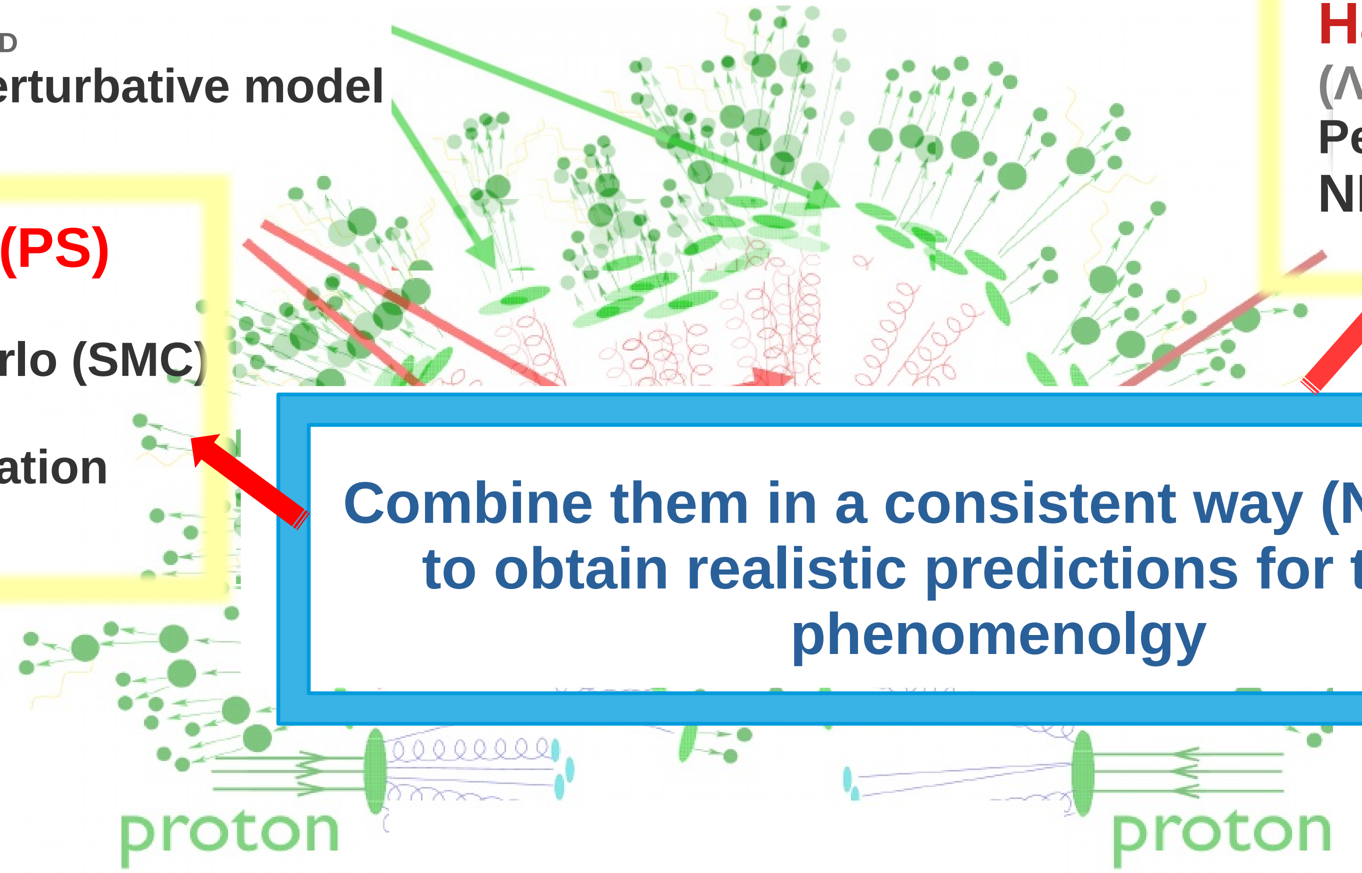

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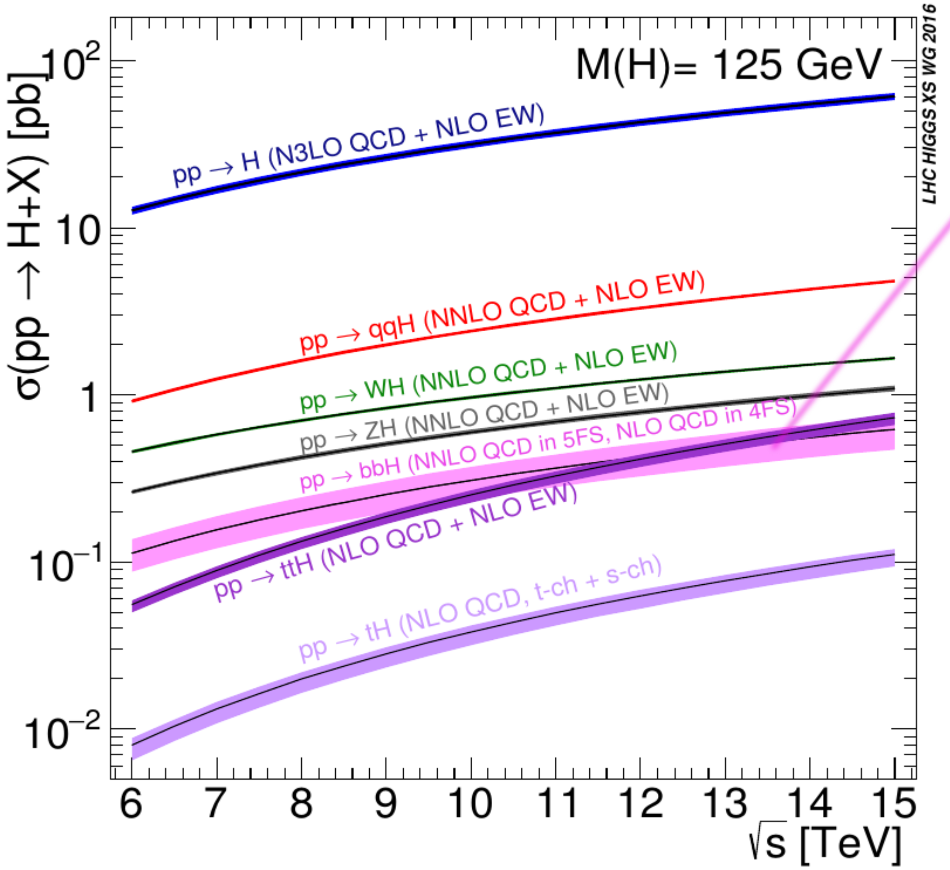
Combine them in a consistent way (NNLO+PS) to obtain realistic predictions for the LHC phenomenolgy

[Sherpa's artistic view]

Higgs in bottom fusion ($b\bar{b}H$)



[LHC HIGGS XS WG 2016]

- Although it is a **subdominant channel,** its cross section is **large enough.**
- **Bottom Yukawa coupling**: Important due to its **enhancement in New Physics models** like minimal supersymmetric extensions of the SM
- $b\bar{b}H$ enters as a **background** in other **Higgs searches** (notably HH)
- Also interesting on **how bottom quark is treated**

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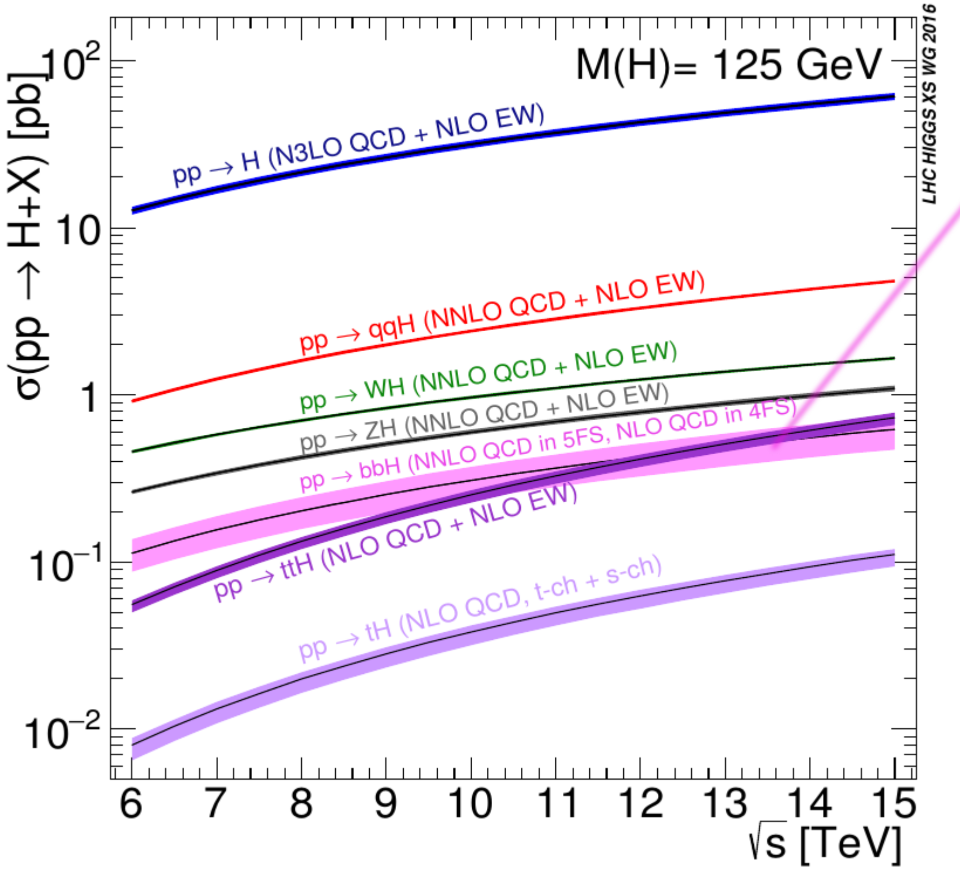

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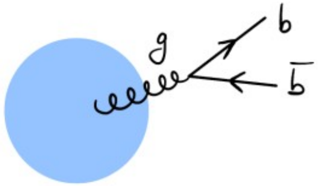
5 flavor scheme (5FS)

$$\mathbf{m_b = 0}$$
$$\mathbf{f_b \neq 0}$$

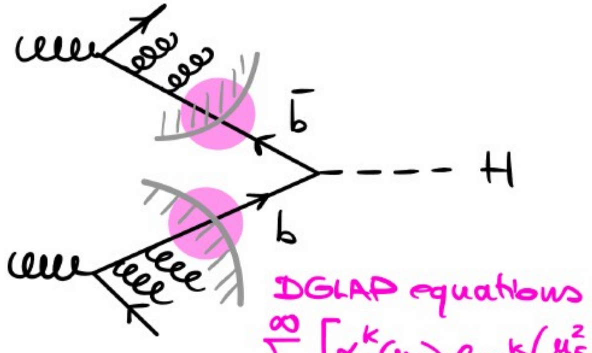
4 flavor scheme (4FS)

$$\mathbf{m_b} \neq 0$$
$$\mathbf{f_b} = 0$$



Higgs in bottom fusion ($b\bar{b}H$)

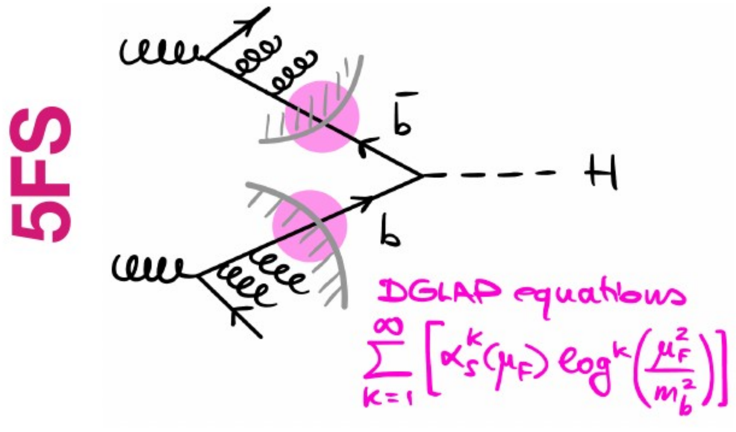
5FS

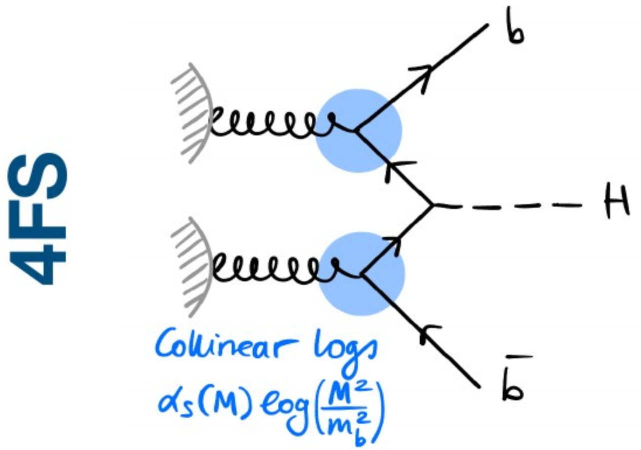


$$\sum_{k=1}^{\infty}\left[\alpha_s^k(\mu_F)\log^k\left(\frac{\mu_F^2}{m_b^2}\right)\right]$$

- ✔ Computing **higher orders** is **easier**
- ✔ The **DGLAP** evolution **resums** initial state collinear **logs** into the bottom PDFs
- Neglecting $O(m_b/m_H)$, it yields **less accurate** description of bottom kinematic distribution

Higgs in bottom fusion ($b\bar{b}H$)





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- Computing **higher orders** is more **difficult** due to higher multiplicity & also due to the massive bottom
- It **does not resum** possibly large **collinear logs**
- **Mass effects** $O(m_b/m_H)$ are present

Higgs in bottom fusion ($b\bar{b}H$)

STATE OF THE ART:

- **N3LO** for the total cross section in the **5FS** [Duhr, Dulat, Mistlberger (1904.09990)]
- **N3LO matched** to **NLO** in the **4FS** by a prescription, namely, **FONLL** [Duhr, Dulat, Hirschi, Mistlberger (2004.04752)] [Forte, Napoletano, Ubiali [1508.01529, (1607.00389)]
- **NLO+PS** in the **4FS** [Wiesemann, Frederix, Frixione, Hirschi, Maltoni, Torrielli (1409.5301)]
- **NLO-QCD** (matched to **parton showers**) combined with **NLO-EW** in the **4FS** [Pagani, Shao, Zaro (2005.10277)]

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THIS TALK:

We discuss the **first fully-differential** calculation of **NNLO QCD** matched to **parton showers** (**NNLO+PS**) for **$b\bar{b}H$** in the **5FS.**

NNLO+PS accuracy

- **MiNLO'** + reweighting [Hamilton, Nason, Zanderighi (1212.4504)]
- **Geneva** [Alioli, Bauer, Berggren, Tackmann,Walsh, Zuberi (1211.7049)]
- **UNNLOPS** [Höche, Prestel (1507.05325)]

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$\text{MiNNLO}_{\text{PS}}$

	F	F+J	F+JJ
$\text{F@MiNNLO}_{\text{PS}}$	NNLO	NLO	LO

[Monni, Nason, Re, Wisemann, Zanderighi (1908.06987)]

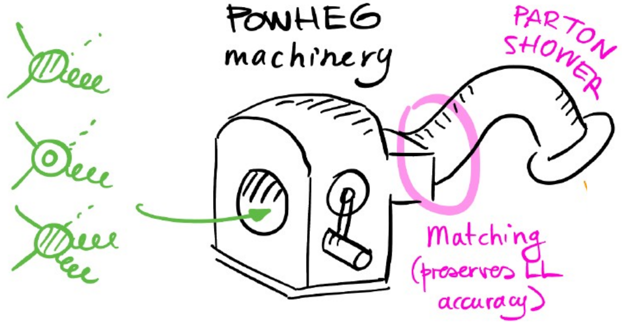
An extension of the MiNLO' procedure

	F	F+J	F+JJ
FJ@MiNLO'	NLO	NLO	LO

- ✓ No computationally intense reweighting
- ✓ No unphysical merging scale
- ✓ Leading-log (LL) accuracy of the shower preserved
- ✓ Numerically efficient

MiNNLO$_{PS}$ in a Nutshell

- The matching to the parton shower is performed according to the **POWHEG** method [P. Nason (0409146)]
- The **POWHEG** approach: we generate the **hardest radiation** (i.e. the largest p_T) **first** with **NLO** accuracy, then attaching a **parton shower** with **softer** emissions.



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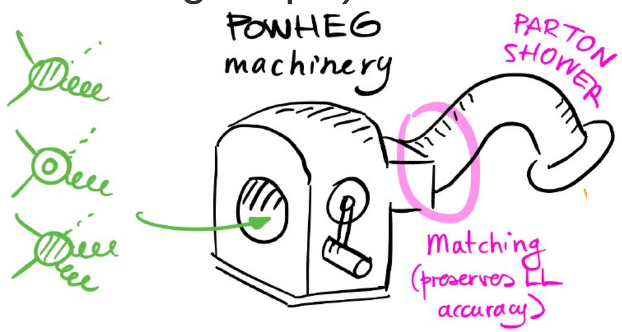
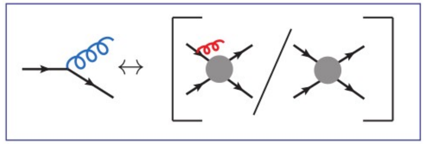


- **MiNNLO$_{PS}$** in **POWHEG** framework: we start from a differential description of the production of the colour singlet and a jet (**pp → F + J**).

$$d\sigma_F^{\mathrm{MiNNLO_{PS}}} = d\Phi_{FJ}\bar{B}^{\mathrm{MiNNLO_{PS}}} \times \left\{ \Delta_{pwg}(\Lambda_{pwg}) + \int d\Phi_{rad}\Delta_{pwg}(p_{T,rad})\frac{R_{FJ}}{B_{FJ}} \right\}$$



Describes the generation of the 1st radiation

Describes the generation of the 2nd radiation according to the **POWHEG** method

MiNNLO$_{\text{PS}}$ in a Nutshell

Central ingredient of MiNNLO$_{\text{PS}}$

Very simplified notation!

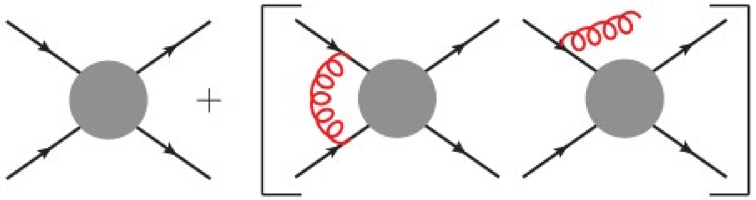
MiNLO′ structure

$\mu_R = \mu_F = p_T$

$$\bar{\text{B}}^{\text{MiNNLO}_{\text{PS}}} \sim e^{-\tilde{\text{S}}} \left\{ d\sigma_{\text{FJ}}^{(1)} \left(1 + \tilde{\text{S}}^{(1)}\right) + d\sigma_{\text{FJ}}^{(2)} + \left(\text{D} - \text{D}^{(1)} - \text{D}^{(2)}\right) \right\}$$

Sudakov form factor
suppresses $\bar{B}$ at low p_T

FO differential cross sections

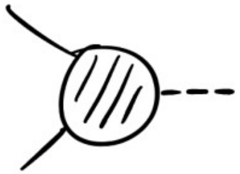


Luminosity

$$D(p_T) = -\frac{d\tilde{S}(p_T)}{dp_T}\mathcal{L}(p_T) + \frac{d\mathcal{L}(p_T)}{dp_T}$$

Additional terms to reach **NNLO** accuracy

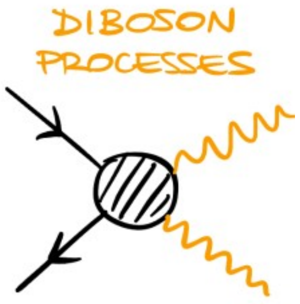
Phenomenology with MiNNLO$_{PS}$



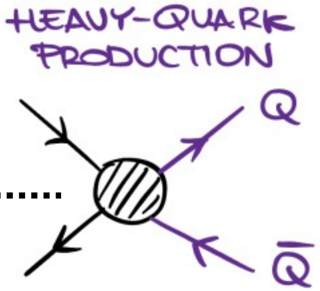
$gg \rightarrow H, W/Z$ [1908.06987,2006.04133, 2402.00596]

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

5FS



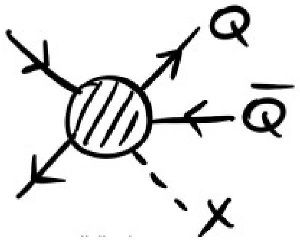
$Z\gamma$ [2010.10478, 2108.11315]
WW [2103.12077]
ZZ [2108.05337]
WH/ZH($H \rightarrow b\bar{b}$) [2112.04168]
$\gamma\gamma$ [2204.12602]
WZ [2208.12660]
SMEFT studies [2204.00663, 2311.06107]



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

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

4FS



Talk by J. Mazzitelli

Phenomenology of $b\bar{b}H$

Comparison of the total inclusive cross section of **MiNLO′** and **MiNNLO$_{PS}$** predictions with fixed-order results at NLO and NNLO obtained with the public code **SusHi** [with μ_R and μ_F set to m_H]

[Harlander, Liebler, Mantler (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

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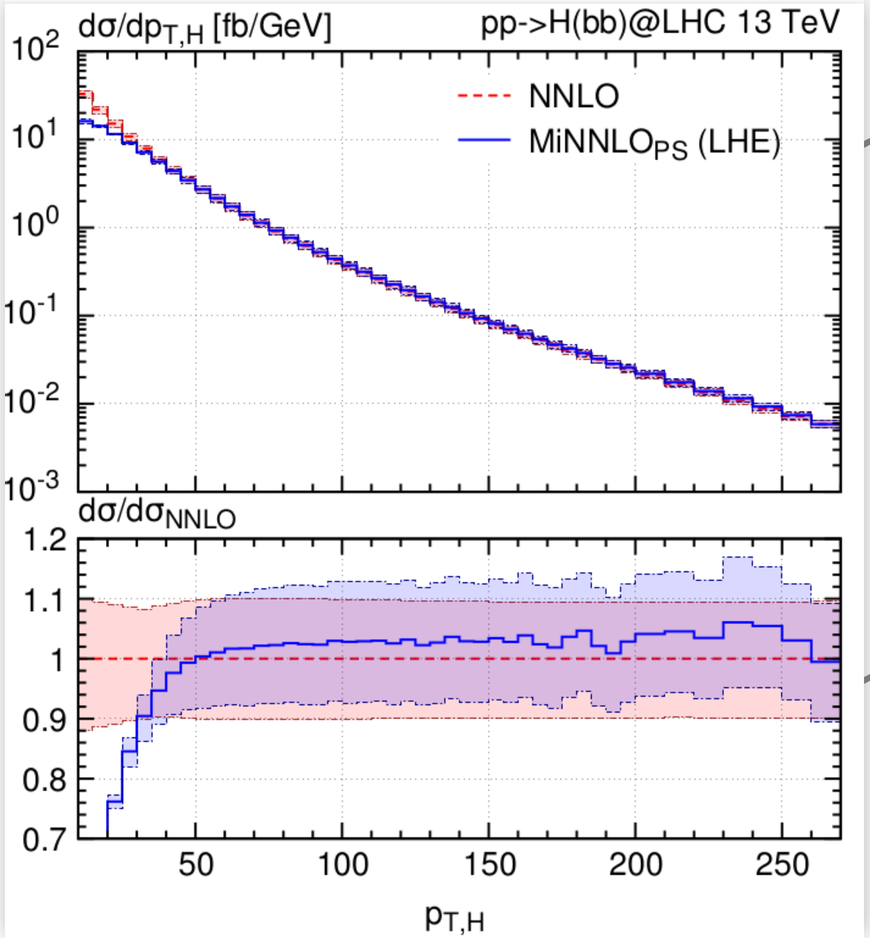
- NNLO QCD corrections **reduce cross section** by > 10%
- Scale **uncertainities** significantly **reduced** with NNLO QCD corrections
- Our **MiNNLO$_{PS}$** predictions are in **agreement with NNLO** QCD cross section within quoted uncertainties

Comparison to fixed-order results

Transverse-momentum spectrum of the Higgs boson ($p_{T,H}$)

Les Houches level (LHE)



$d\sigma/dp_{T,H}$ [fb/GeV]

$d\sigma/d\sigma_{NNLO}$

NNLO [Harlander, Tripathi, Wiesemann (1403.7196)]

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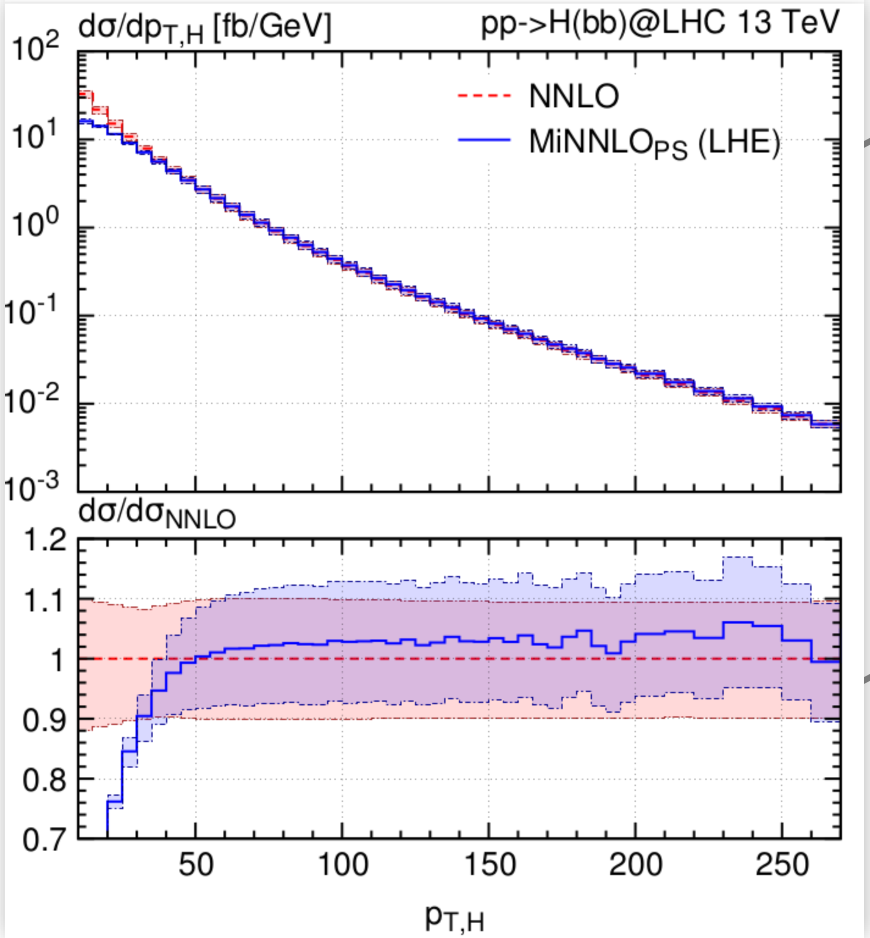


$d\sigma/dp_{T,H}$ [fb/GeV]

$d\sigma/d\sigma_{NNLO}$

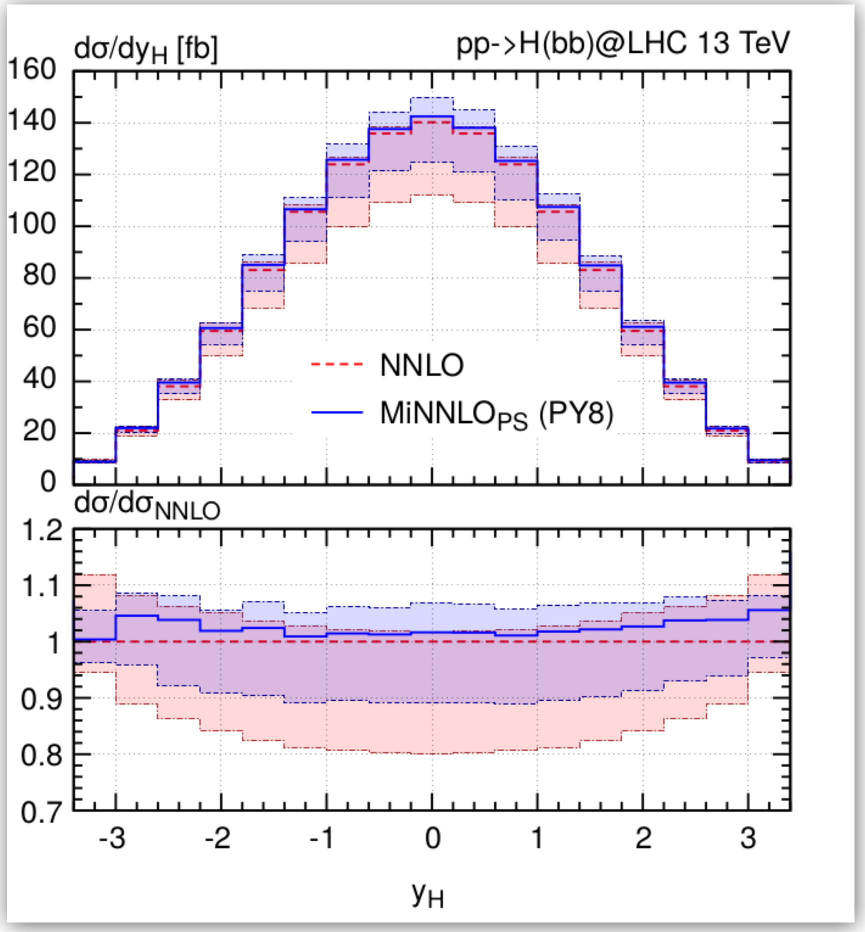
- **Full agreement** in **large $p_{T,H}$** regime with fixed-order predictions within quoted uncertainities
- Fixed-order calculations diverge for $p_{T,H} \to 0$ **MiNNLO$_{PS}$** prediction remains **finite**

NNLO [Harlander, Tripathi, Wiesemann (1403.7196)]

Comparison to fixed-order results

Rapidity distribution of the Higgs boson (y_H)

PY8 level



NNLO [Mondini, Williams (2102.05487)]

Comparison to fixed-order results

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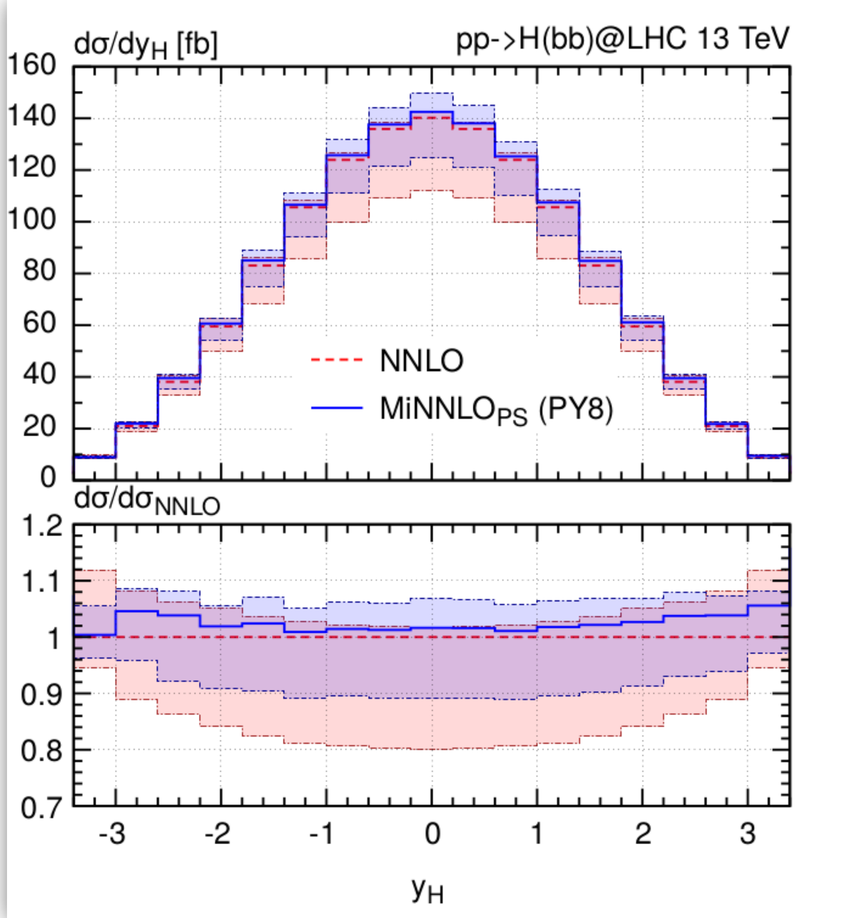
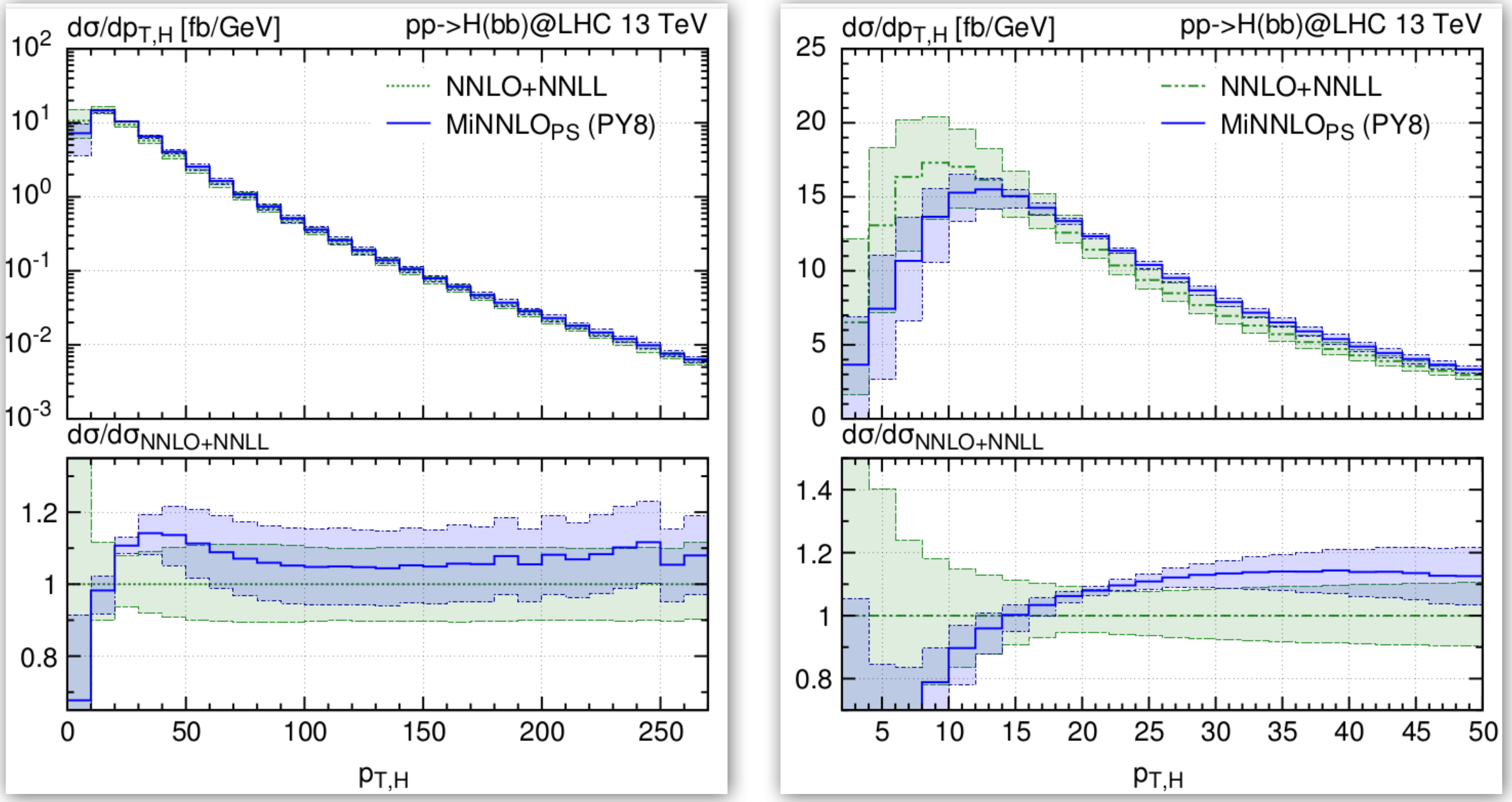


- A **good agreement**, both in terms of normalization and in terms of shape, between the two central predictions.
- The **bands** of **MiNNLO$_{PS}$** result are **more symmetric** & slightly **smaller** than the **NNLO** ones.
- Apart from that, impact of the parton shower is very moderate.

NNLO [Mondini, Williams (2102.05487)]

Comparison to NNLO+NNLL



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

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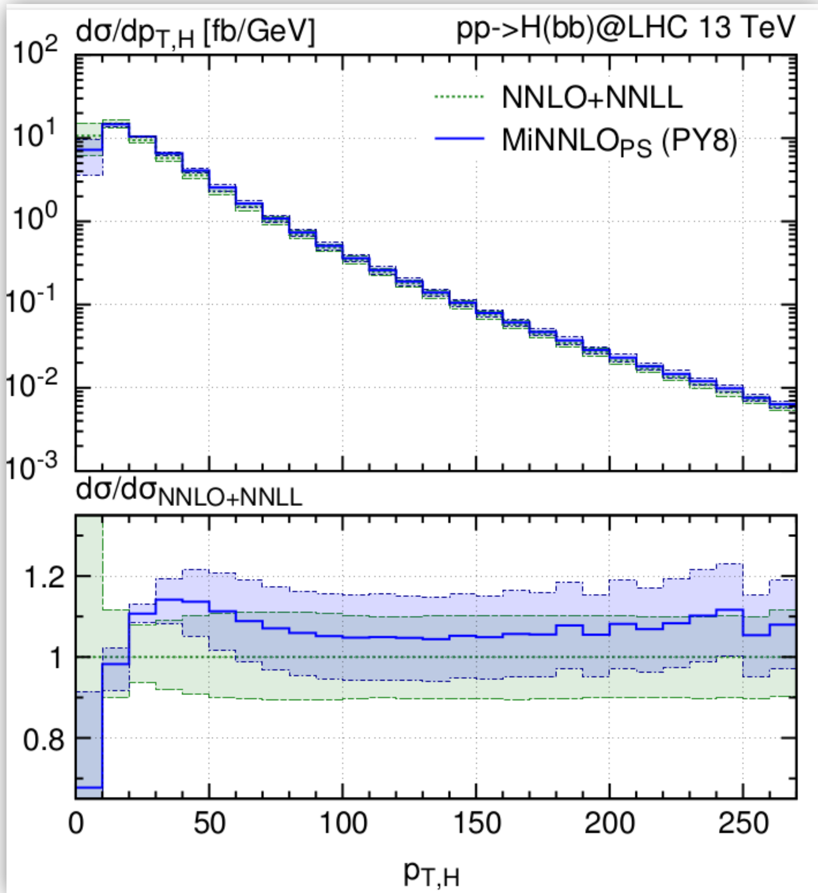
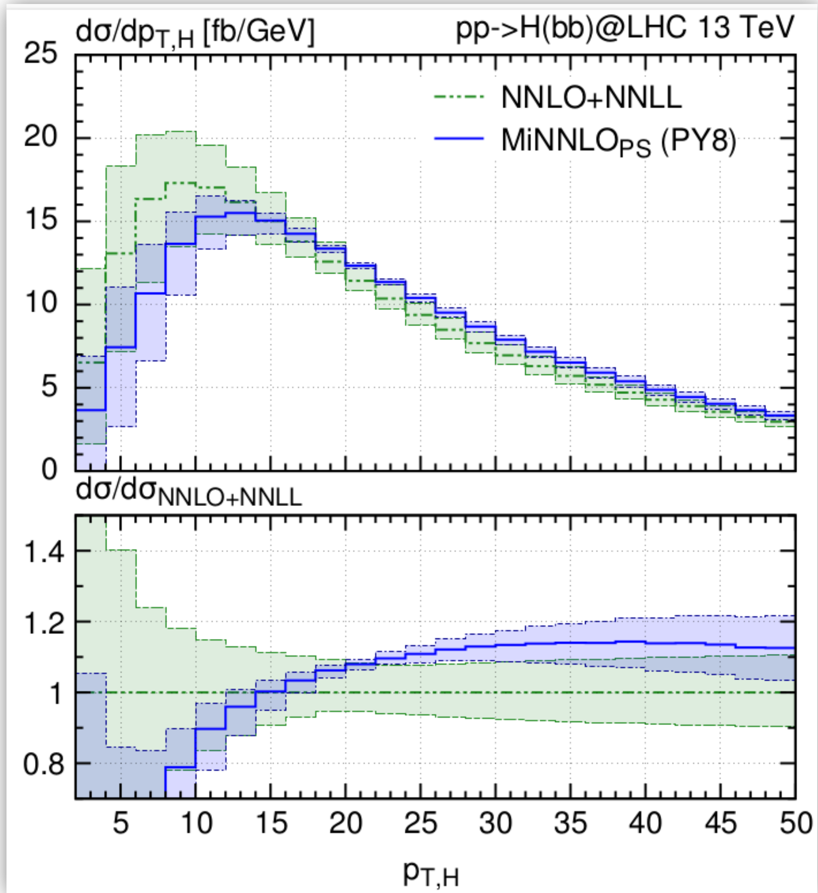


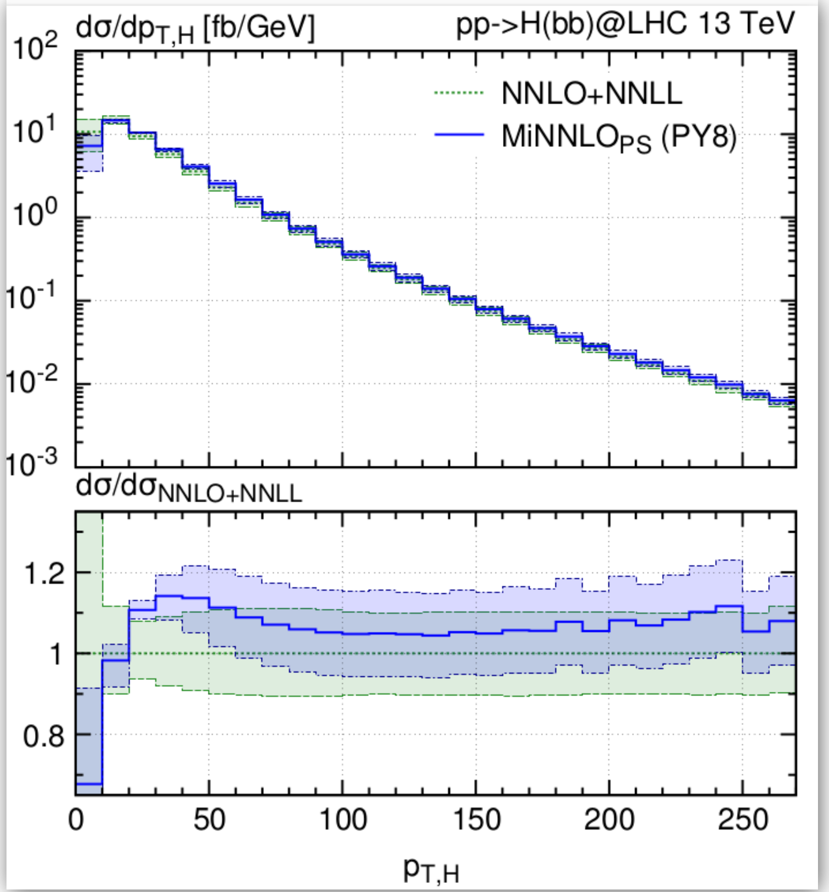


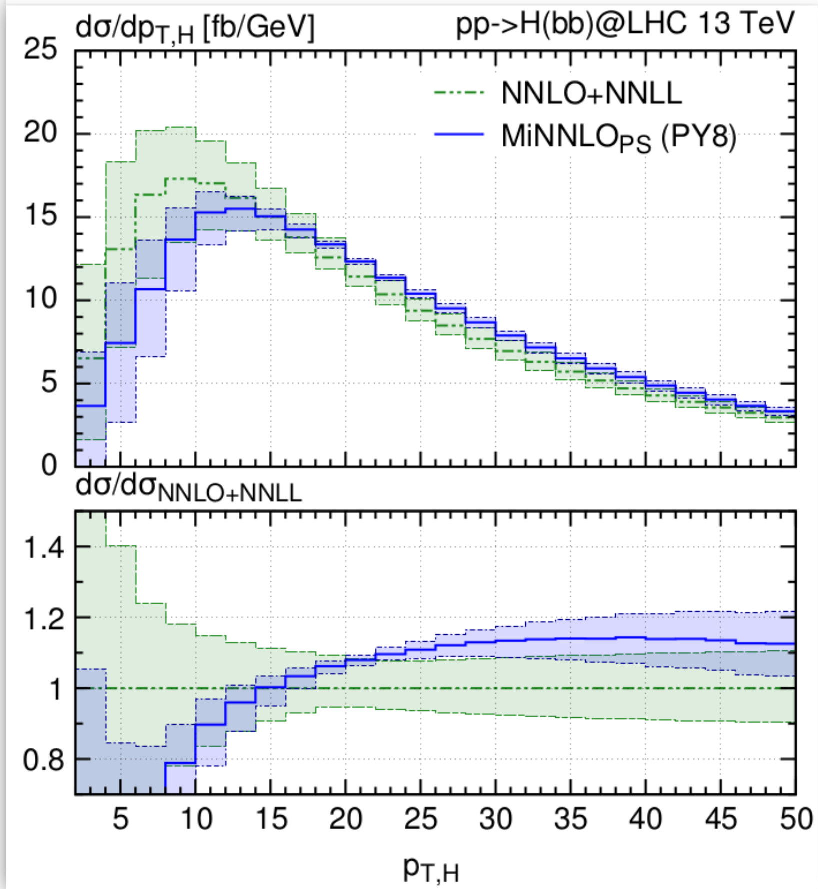
NNLO+NNLL [Harlander, Tripathi, Wiesemann (1403.7196)]

Parton showering effects

- **At large $p_{T,H}$**: MiNNLO$_{PS}$ shifted 10% up, well within the given scale-uncertainty bands.

Comparison to NNLO+NNLL



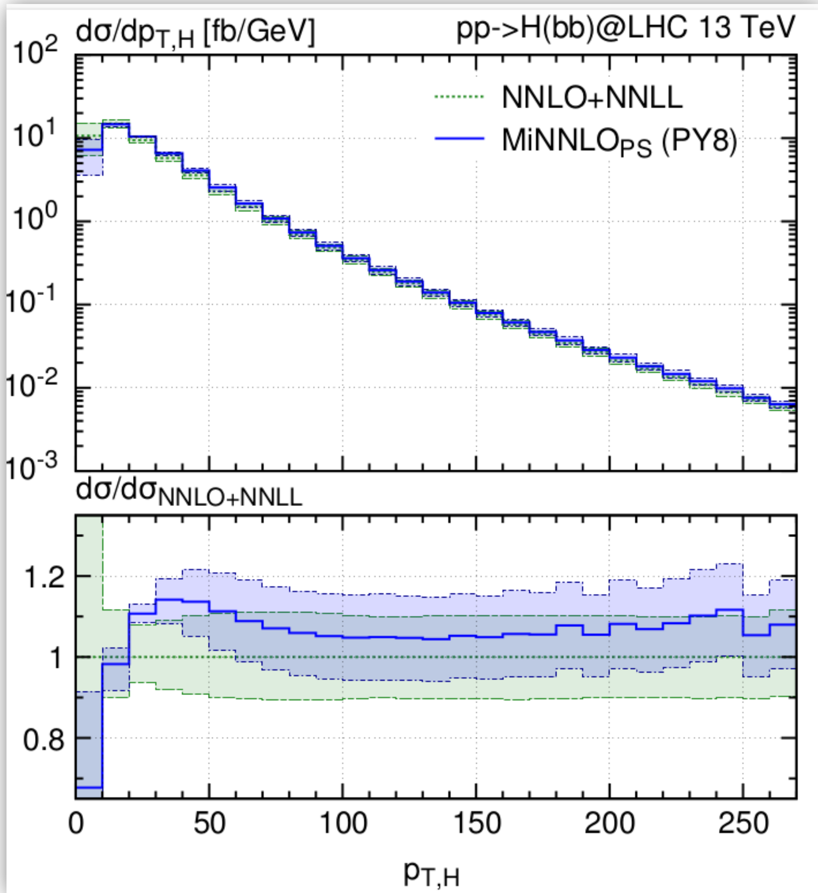


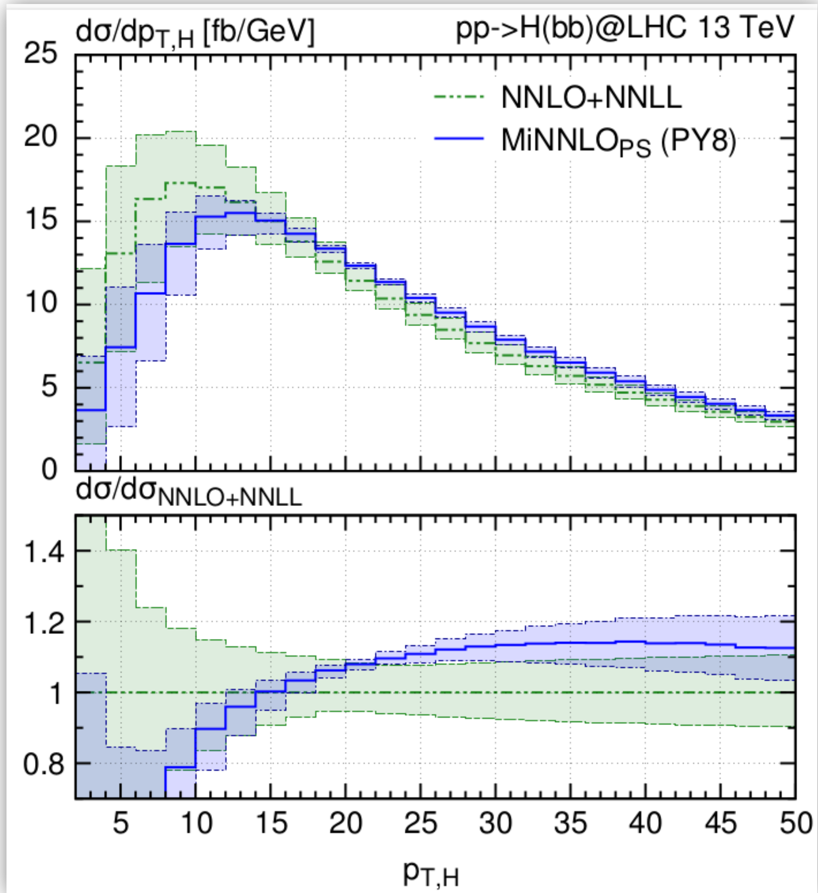
NNLO+NNLL [Harlander, Tripathi, Wiesemann (1403.7196)]

Parton showering effects

- **At large $p_{T,H}$:** MiNNLO$_{PS}$ shifted 10% up, well within the given scale-uncertainty bands.
- **At small $p_{T,H}$:** slightly worsen the agreement. MiNNLO$_{PS}$ uncertainities are **underestimated.** Require additional variations within the shower settings.

Comparison to NNLO+NNLL





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- **At small $p_{T,H}$**: slightly worsen the agreement. **MiNNLO$_{PS}$** uncertainities are **underestimated.** Require additional variations within the shower settings.
- **Massless** approximation **misses** potentially **relevant mass effects at small p_T**, need to **combine** with for **massive 4FS** calculation.

$b\bar{b}H$ in 4FS with MiNNLO$_{PS}$

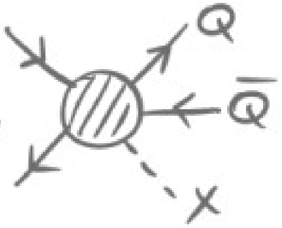
- Start from the **POWHEG** ***Hb$\bar{b}$j*** generator
- Produce **NNLO+PS** predictions using the framework of MiNNLO$_{PS}$

Mazzitelli, Wiesemann [in progress]

$b\bar{b}H$ in 4FS with MiNNLO$_{PS}$

- Start from the **POWHEG** ***Hbb̄j*** generator

- Produce **NNLO+PS** predictions using the framework of MiNNLO$_{PS}$



Mazzitelli, Wiesemann [in progress]

- The **double virtual correction** for a **massive bottom** pair and Higgs production is not known: approximate it with the **massification procedure**

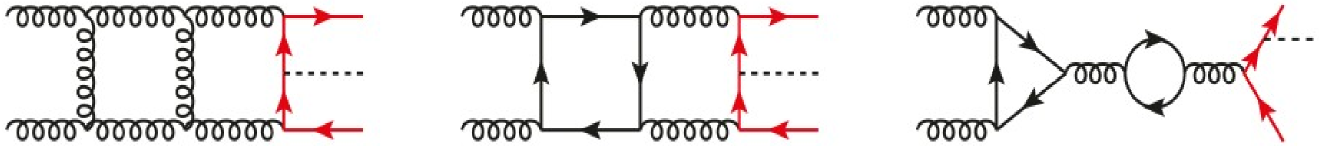
Talk by L. Buonocore

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

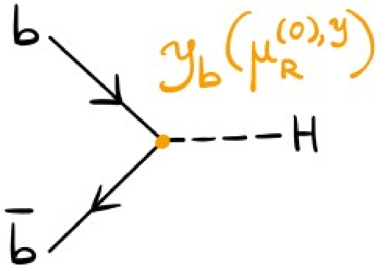
Mitov, Moch [0612149]

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

Badger, Hartanto, Kryś, Zoia [2107.14733]

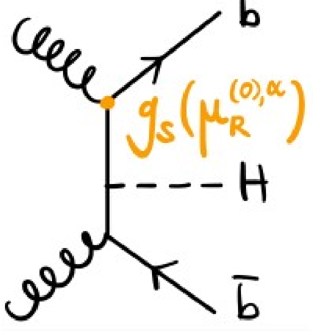


$b\bar{b}H$: scheme comparison



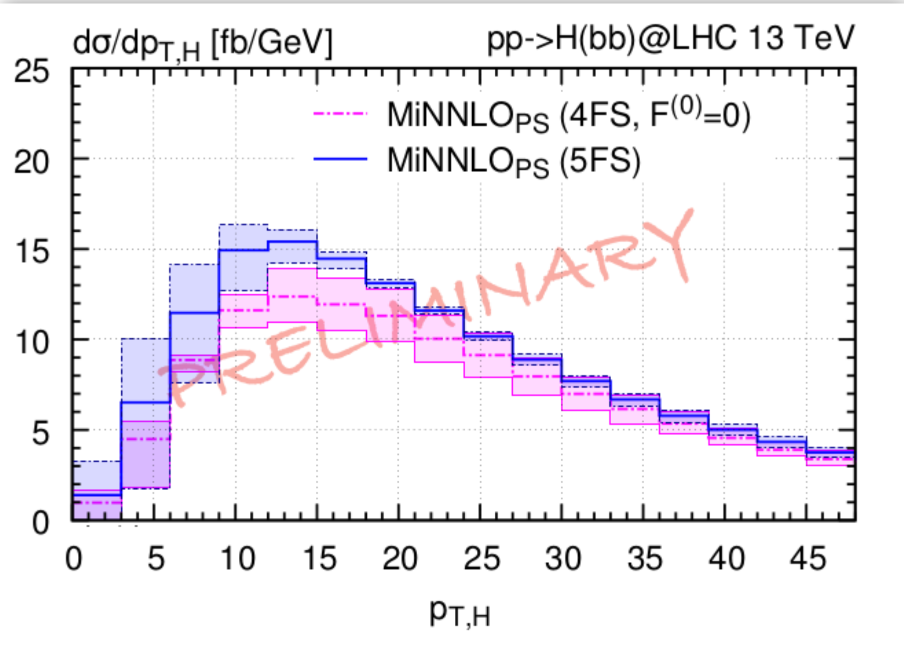
40% 14%

$(\mu_R^{(0),\alpha}, \mu_R^{(0),y})$	NLOPS (5FS)	NLOPS (4FS)	MiNNLOPS (5FS)	MiNNLOPS (4FS, $\mathscr{F}^{(0)} = 0$)
$(\frac{1}{4}H_T, m_H)$	$0.646(0)^{+10.4\%}_{-10.9\%}$ pb	$0.381(2)^{+20.2\%}_{-15.9\%}$ pb	$0.509(8)^{+2.9\%}_{-5.3\%}$ pb	$0.434(1)^{+6.4\%}_{-10.0\%}$ pb



$$\frac{H_T}{4} = \frac{1}{4} \sum_{i \in \text{final}} \sqrt{m^2(i) + p_T^2(i)}$$

PDF: NNPDF40_nnlo_as_01180
with different active flavours



Summary & Outlook

- **First presentation** of **NNLO+PS** computation for **$b\bar{b} \rightarrow$ H (5FS)** production at the LHC by using **MiNNLO$_{PS}$** method.

- **Extensive validation** against fixed-order results from literature, showcasing consistency in relevant kinematical regions.

- **Initial step** towards a complete NNLO+PS description of $b\bar{b}$H production.

- **Future directions** include the completion of **4FS $b\bar{b}$H** with massive bottom quarks and the combination of full **4FS–5FS at NNLO+PS** accuracy.

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THANK YOU !

Backup slides

MiNNLO$_{PS}$ in a Nutshell

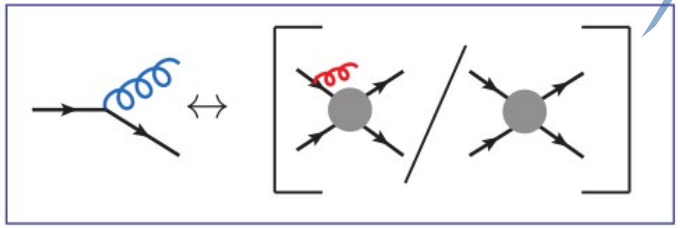
MiNNLO$_{PS}$ in **POWHEG** framework: we start from a differential description of the production of the colour singlet and a jet (**pp → F + J**) with phase space **Φ_{FJ}**.

POWHEG sudakov form factor

$$d\sigma_F^{\text{MiNNLO}_{PS}} = d\Phi_{FJ}\bar{B}^{\text{MiNNLO}_{PS}} \times \left\{ \Delta_{pwg}(\Lambda_{pwg}) + \int d\Phi_{rad}\Delta_{pwg}(p_{T,rad})\frac{R_{FJ}}{B_{FJ}} \right\}$$

Describes the generation of the 1st radiation

Describes the generation of the 2nd radiation according to the **POWHEG** method above the infrared cutoff Λ_{pwg} = 0.89 GeV



Φ_{rad} : The phase space of the 2nd radiation.

$p_{T,rad}$: Transverse momentum of the 2nd radiation.

B_{FJ} & ***R_{FJ}*** are the squared tree-level matrix elements for ***FJ*** & ***FJJ*** production, respectively.

MiNNLO$_{PS}$ in a Nutshell

Central ingredient of MiNNLO$_{PS}$

Very simplified notation!

MiNLO' structure

$\mu_R = \mu_F = p_T$

$$\bar{B}^{\mathrm{MiNNLO_{PS}}} \sim e^{-\tilde{S}} \left\{ d\sigma_{FJ}^{(1)} \left(1 + \tilde{S}^{(1)}\right) + d\sigma_{FJ}^{(2)} + \left(D - D^{(1)} - D^{(2)}\right) \right\}$$

Sudakov form factor

suppresses $\bar{B}$ at low p_T

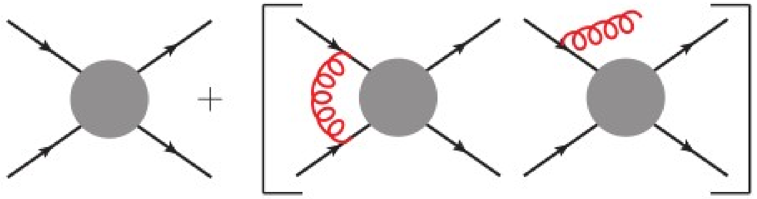
$$\int_{p_t^2}^{Q^2} \frac{dq^2}{q^2} \left[A(\alpha_s(q^2)) \log \frac{Q^2}{q^2} + \tilde{B}(\alpha_s(q^2)) \right]$$

$$A(\alpha_S) = \left(\frac{\alpha_S}{2\pi}\right) A^{(1)} + \left(\frac{\alpha_S}{2\pi}\right)^2 A^{(2)} + \left(\frac{\alpha_S}{2\pi}\right)^3 A^{(3)}$$

$$\tilde{B}(\alpha_S) = \left(\frac{\alpha_S}{2\pi}\right) B^{(1)} + \left(\frac{\alpha_S}{2\pi}\right)^2 \tilde{B}^{(2)}$$

$$\tilde{B}^{(2)} = B^{(2)} + 2\zeta_3 (A^{(1)})^2 + 2\pi\beta_0 H^{(1)}$$

FO differential cross sections



Luminosity

$$D(p_T) = -\frac{d\tilde{S}(p_T)}{dp_T} \mathcal{L}(p_T) + \frac{d\mathcal{L}(p_T)}{dp_T}$$

Additional terms to reach **NNLO** accuracy for inclusive distributions in F.
contains double virtual correction to pp -> F

Phenomenology of $b\bar{b}H$ - Setup

- **Inputs:**
  - Center-of-mass energy: **13 TeV** at LHC.
  - Higgs boson mass (mH): **125 GeV**, ΓH (decay width): 0 GeV.
  - PDFs: **NNPDF40_nnlo_as_01180** with 5 active flavours.
  - Central μR and μF scales set via **MiNNLO$_{PS}$** method [$\mu_R = \mu_F \sim p_T$].
  - **Yukawa coupling** renormalized in **$\overline{\text{MS}}$ scheme** [Yb(mb=4.18 GeV) -> Yb(mH) = 2.79].

- **Scale Settings and Uncertainties:**
  - Scale uncertainitities assessed through customary **7-point μ_R and μ_F variation.**

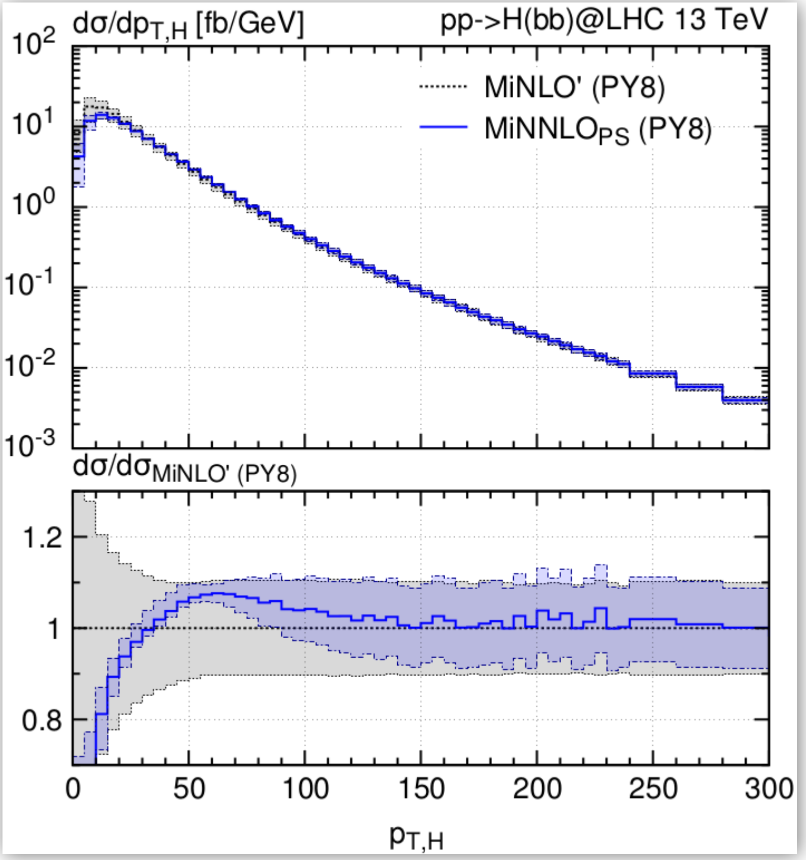
- **Matching to Parton Shower:**
  - Predictions matched to parton shower using **Pythia8** with **leading-log (LL)** accuracy.

- **Exclusion of Effects:**
  - **Hadronization**, multi-parton interactions (**MPI**), and **QED** radiation effects are **switched off**.

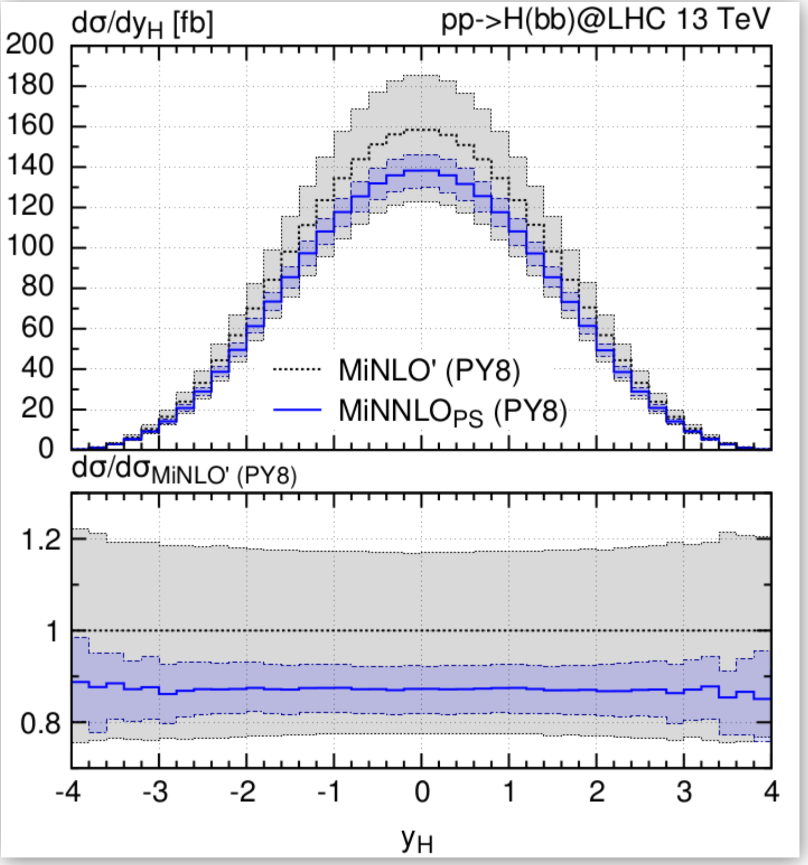
Comparison of MiNLO' & MiNNLO$_{PS}$

PY8 level

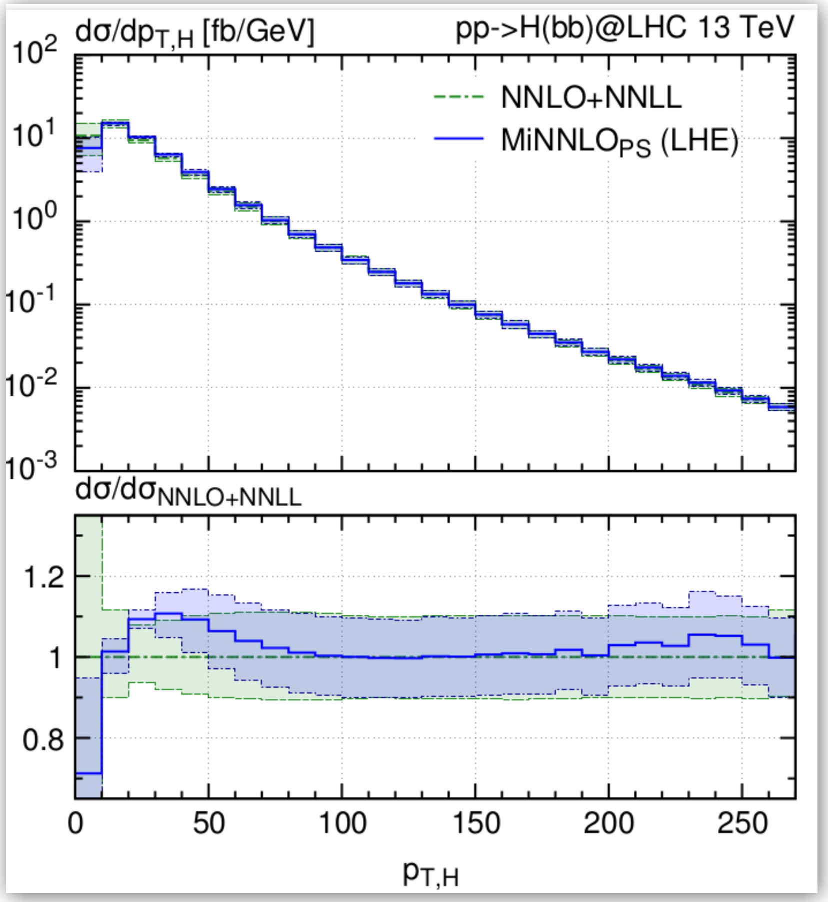
Transverse-momentum spectrum of the Higgs boson ($p_{T,H}$)

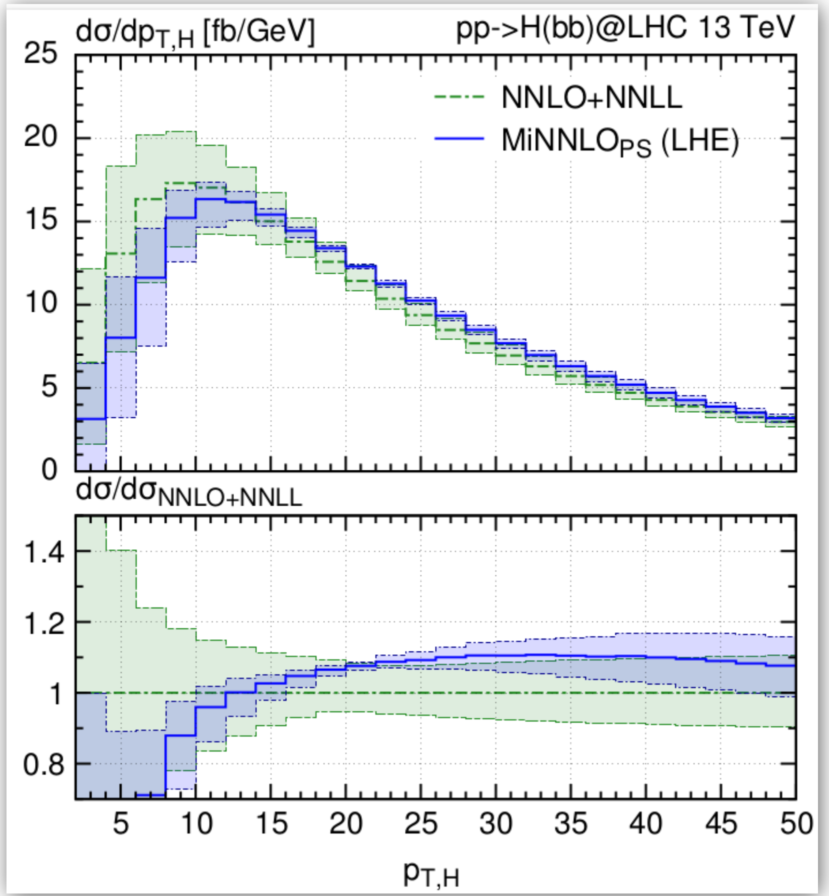


Rapidity distribution of the Higgs (y_H)



- At small p_T, MiNNLO$_{PS}$ **significantly dampens** distributions, **reduces scale uncertainties.**
- At large p_T, MiNLO' & MiNNLO$_{PS}$ predictions **coincide**, both **NLO** accurate.
- y_H distribution: MiNNLO$_{PS}$ introduces a flat 14% negative correction, **reduces scale uncertainties.**





Les Houches level (LHE)

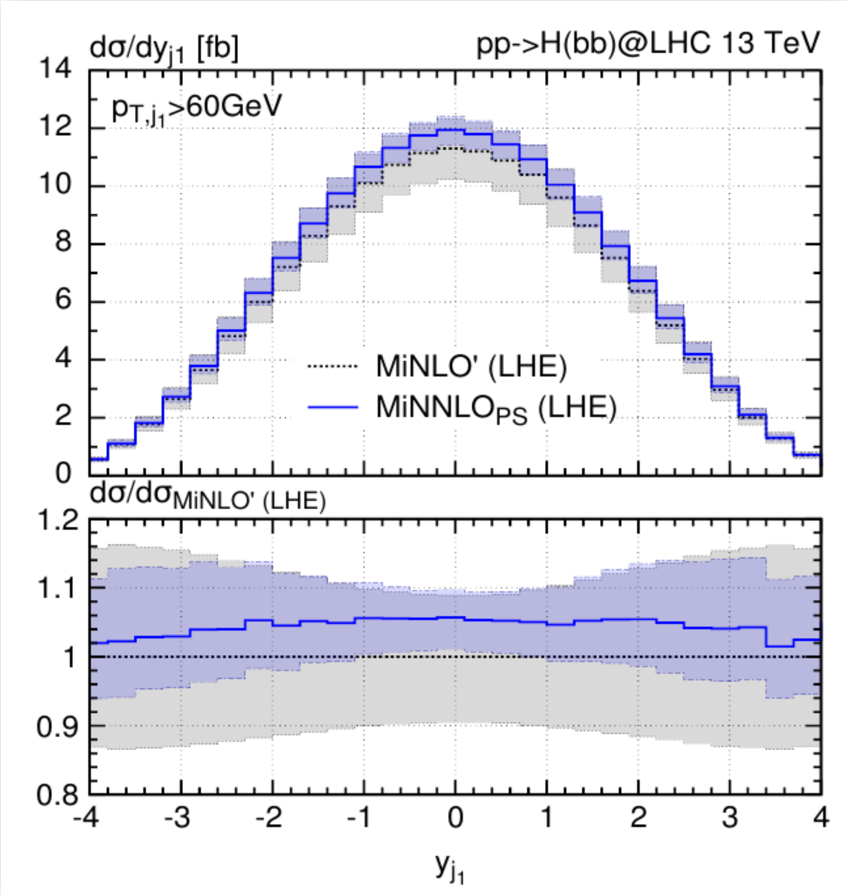
At high $p_{T,H}$:
they coincide again

At small $p_{T,H}$:
Acceptable agreement

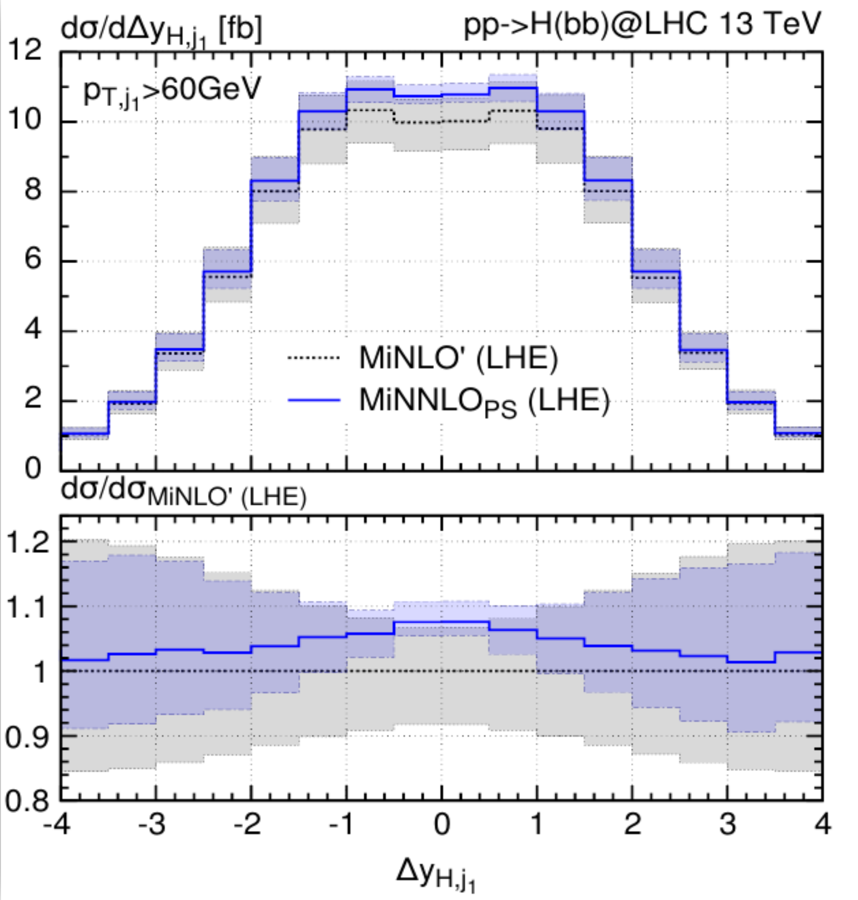
NNLO+NNLL [Harlander, Tripathi, Wiesemann (1403.7196)]

Comparison of MiNLO′ & MiNNLO$_{PS}$

Rapidity distribution of the leading jet (y_{j1})

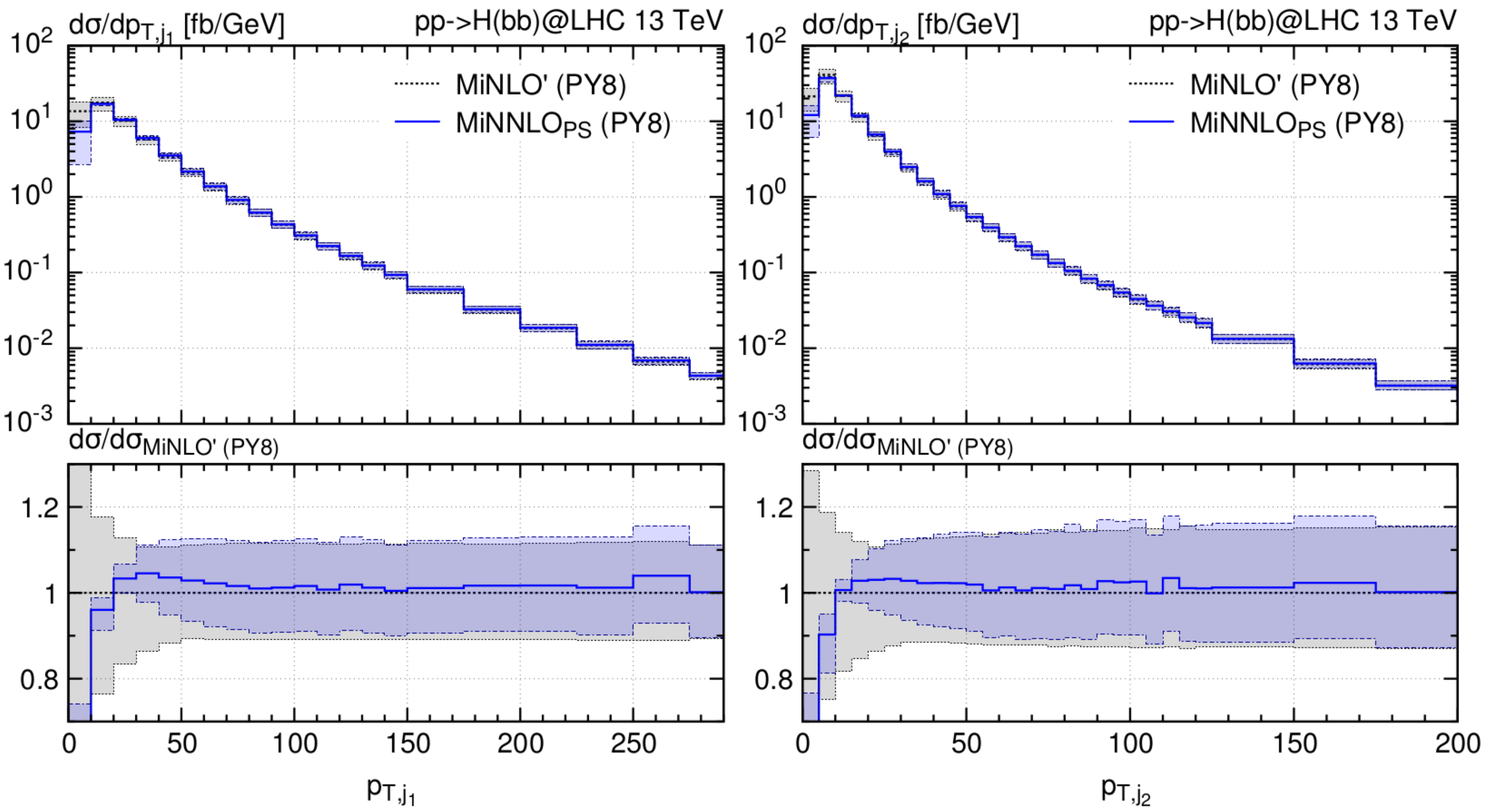


Rapidity difference between the Higgs boson & the leading jet ($\Delta y_{H,j1}$)



- Very similar shapes for MiNLO′ & MiNNLO$_{PS}$ results
- MiNLO′ & MiNNLO$_{PS}$: fully consistent within the quoted scale uncertainties

Comparison of MiNLO' & MiNNLO_{PS}



FONLL

- 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

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