Higgs production through bottom annihilation in the 5FS with MiNNLO$_{PS}$

Aparna Sankar

In collaboration with

C. Biello, M. Wiesemann, G. Zanderighi

based on [EPJC 84, 479 (2024)]

MAX-PLANCK-INSTITUT
FÜR PHYSIK

Technische Universität München

2nd Workshop on Tools for High Precision LHC Simulations

Castle Ringberg | May 9, 2024

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

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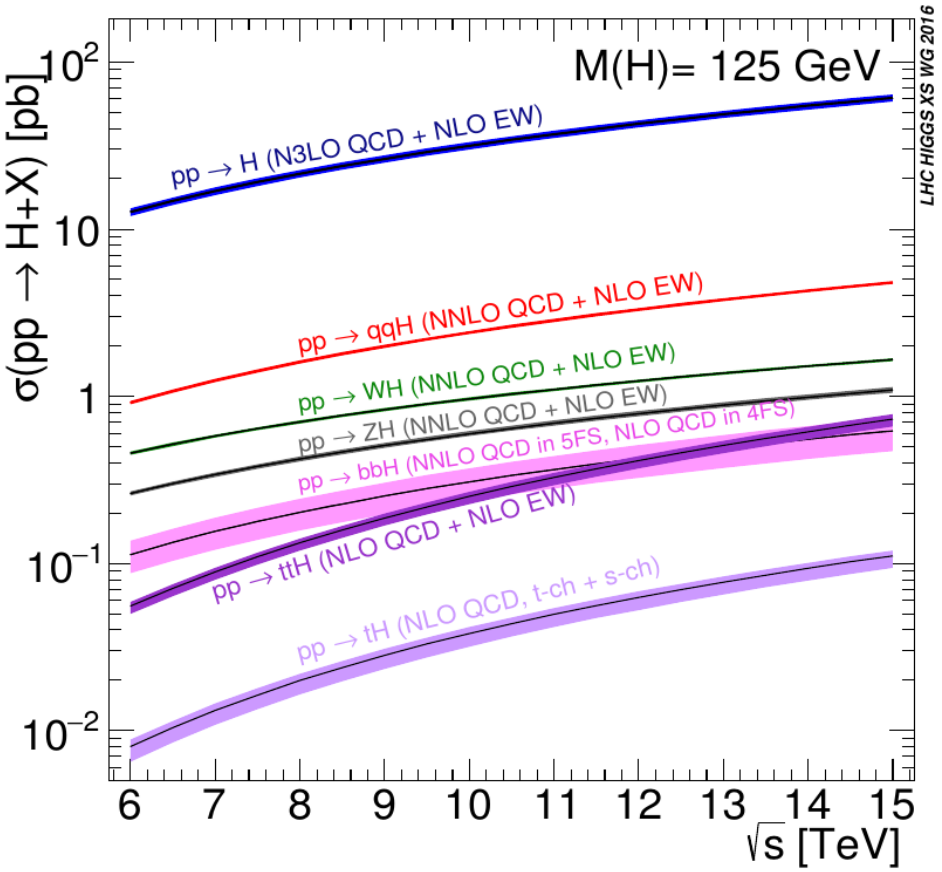

[LHC HIGGS XS WG 2016]

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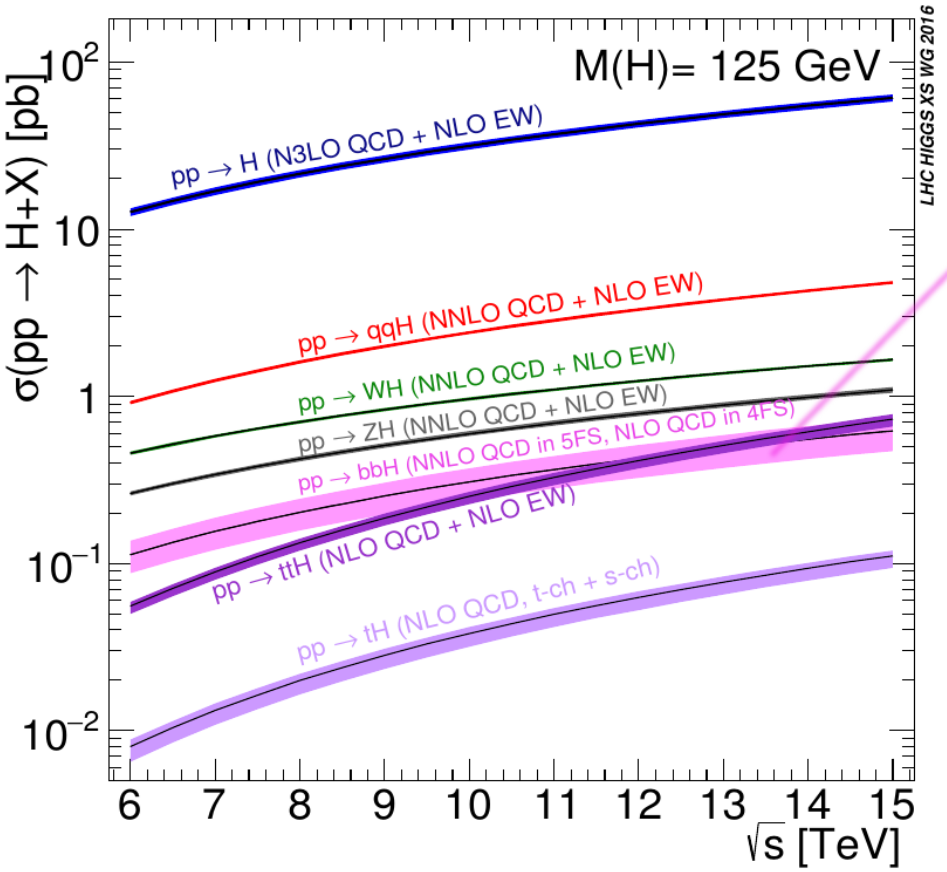

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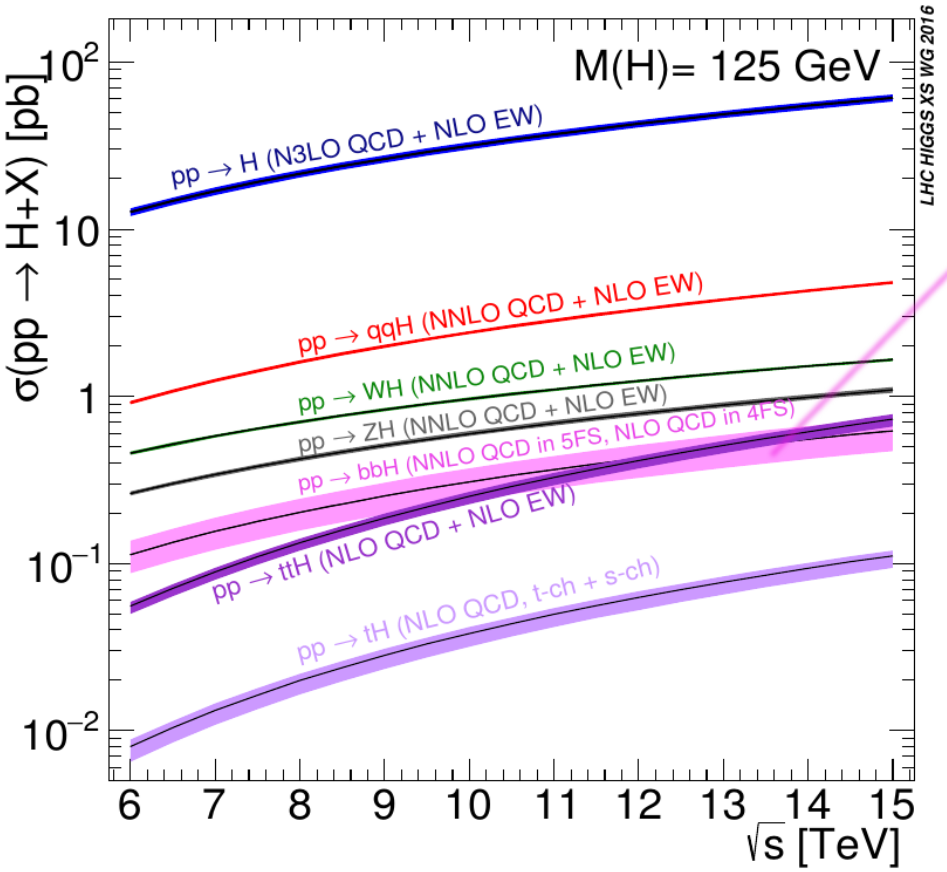

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- Direct probe of **Higgs couplings to the bottom quark** ($\mathbf{y_b}$) in production
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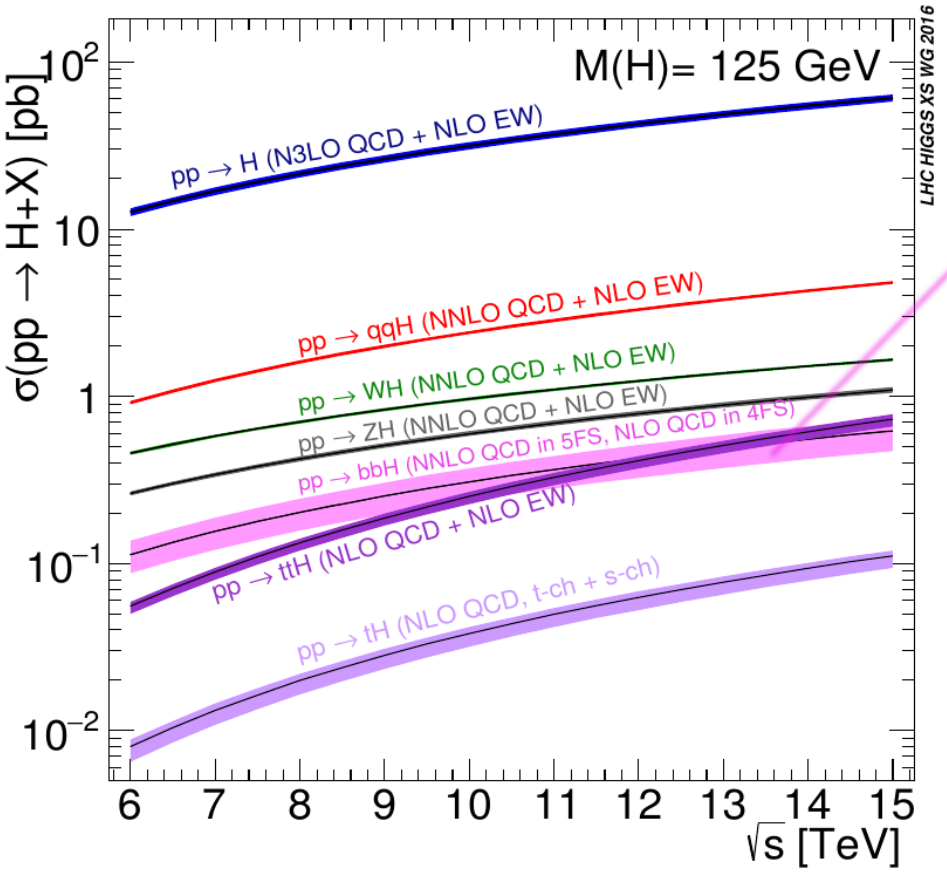

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- Direct probe of **Higgs couplings to the bottom quark** ($\mathbf{y_b}$) in production
- **Bottom Yukawa coupling**: Important due to its **enhancement in New Physics models** like minimal supersymmetric extensions of the SM
- $b\bar{b}H$ enters as a **background** in other **Higgs searches** (notably HH)

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

$b\bar{b}H$ is also interesting on **how bottom quark is treated**

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4 flavor scheme (4FS)

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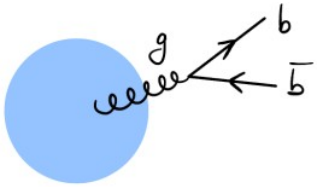

[Image courtesy : C. Biello]

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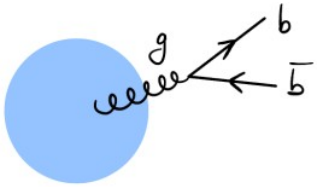

- **Active parton** inside the proton.
- **Included** in the parton distribution functions (**PDFs**) of the proton.
- It is taken to be **massless except** in the **Yukawa** coupling

[Image courtesy : C. Biello]

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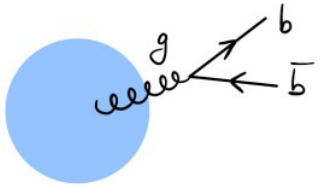

- Considered as a **heavy quark**
- The bottom quark's contribution is **neglected** in the **PDFs**.
- A **massive** bottom quark is produced from **gluon splitting**

[Image courtesy : C. Biello]

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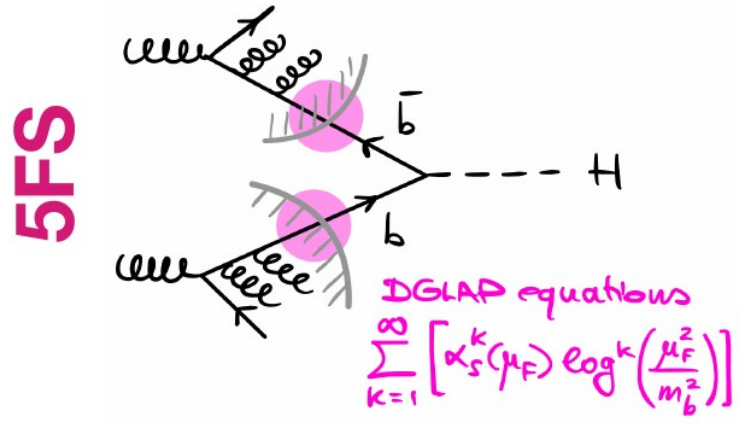

- Computing **higher orders** is **easier**
- The **DGLAP** evolution **resums** initial state collinear **logs** into the bottom PDFs
- Neglects power-suppressed terms of the $O(m_b/m_H)$

[Image courtesy : C. Biello]

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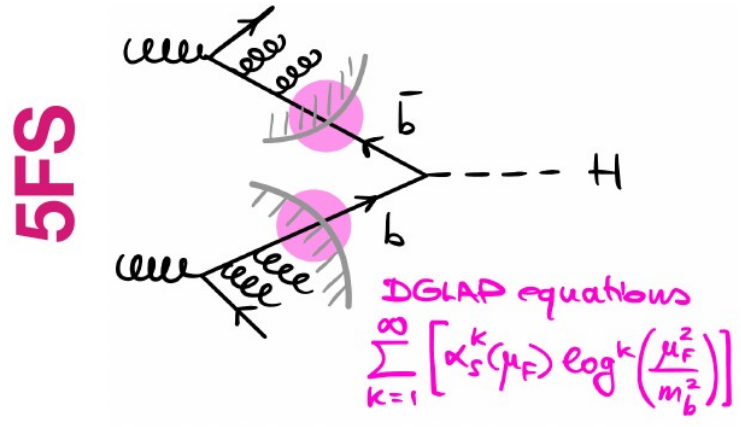

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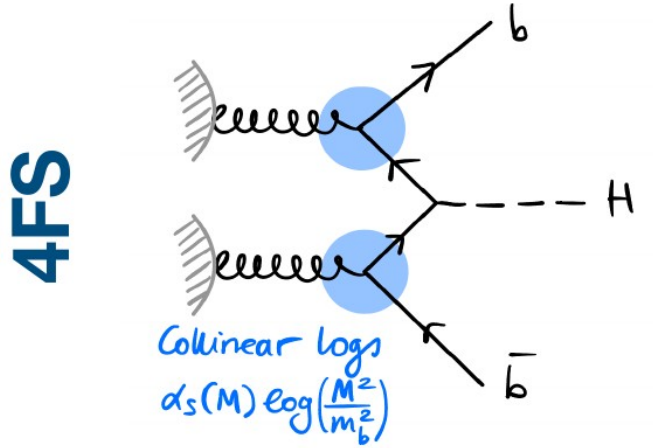

- Computing **higher orders** is more **difficult** due to higher multiplicity & also due to the massive bottom
- It **does not resum** possibly large **collinear logs**
- ✔ **Full kinematics** of the **massive bottom** quark is taken into account

[Image courtesy : C. Biello]

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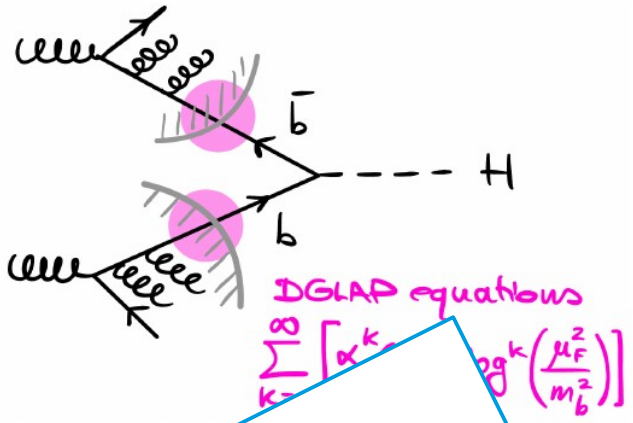
5FS



This talk

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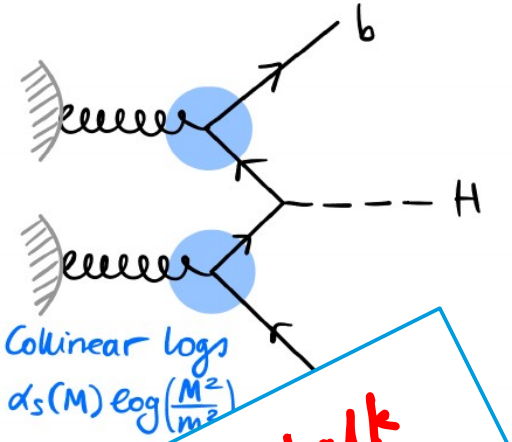
4FS



Christian's talk

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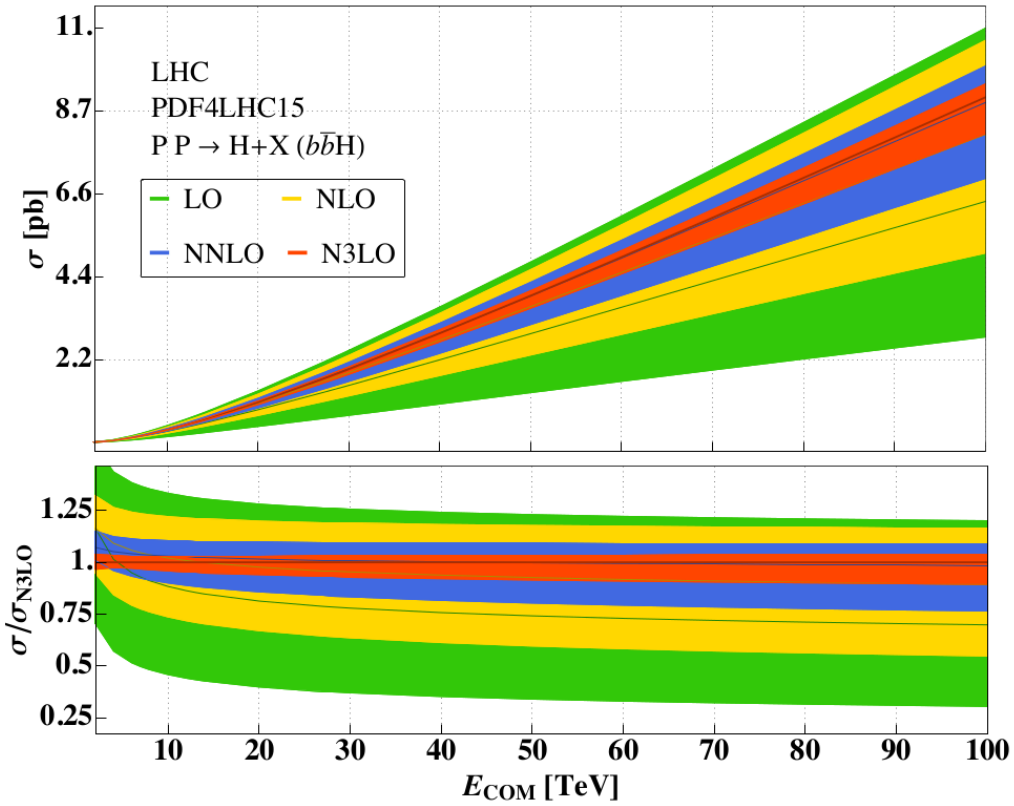
STATE OF THE ART
N3LO QCD in 5FS

[Duhr, Dulat, Mistlberger (1904.09990)]



Substantial reduction of the residual scale uncertainty
&
good convergence of the perturbative

S [TeV]	σ_{bbH} [pb]	scale	PDF+α_s	m_b	N^{3}LO PDFs
13	0.542	$^{+3.0\%}_{-4.8\%}$	$\pm 8.5\%$	$^{+2.3\%}_{-1.7\%}$	$\pm 2.5\%$

$b\bar{b}H$ simulation

Precise and realistic LHC phenomenology requires full-fledged event simulations.

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Hadronization

$\mu \approx \Lambda_{QCD}$

Non-perturbative model

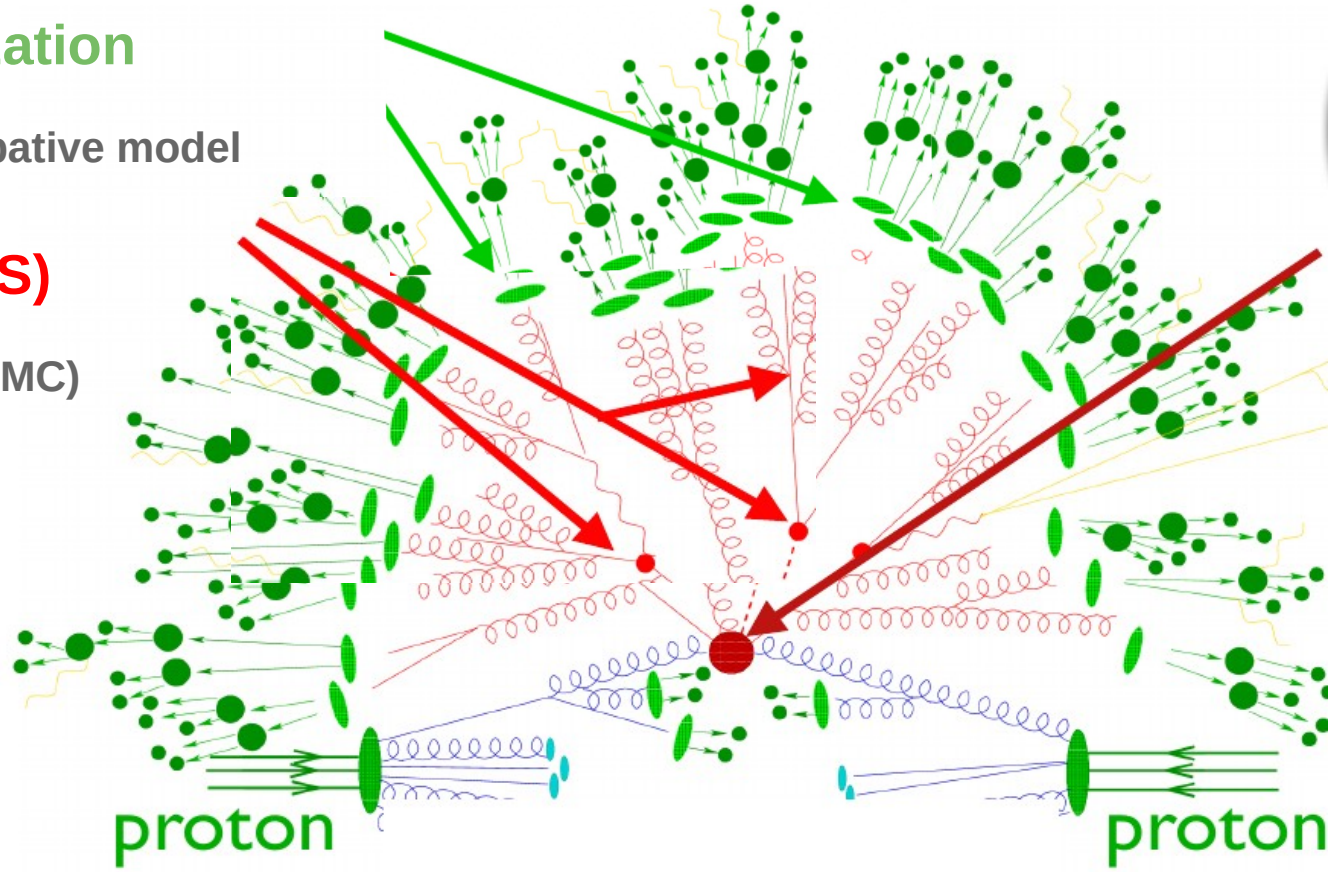
Parton shower (PS)

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

Shower Monte Carlo (SMC)

Resummation of soft/collinear radiation

Less accurate



Hard scattering

($\Lambda_{QCD} << \mu \approx Q$)

Perturbation theory

NNLO is the frontier!

[Sherpa's artistic view]

$b\bar{b}H$ simulation

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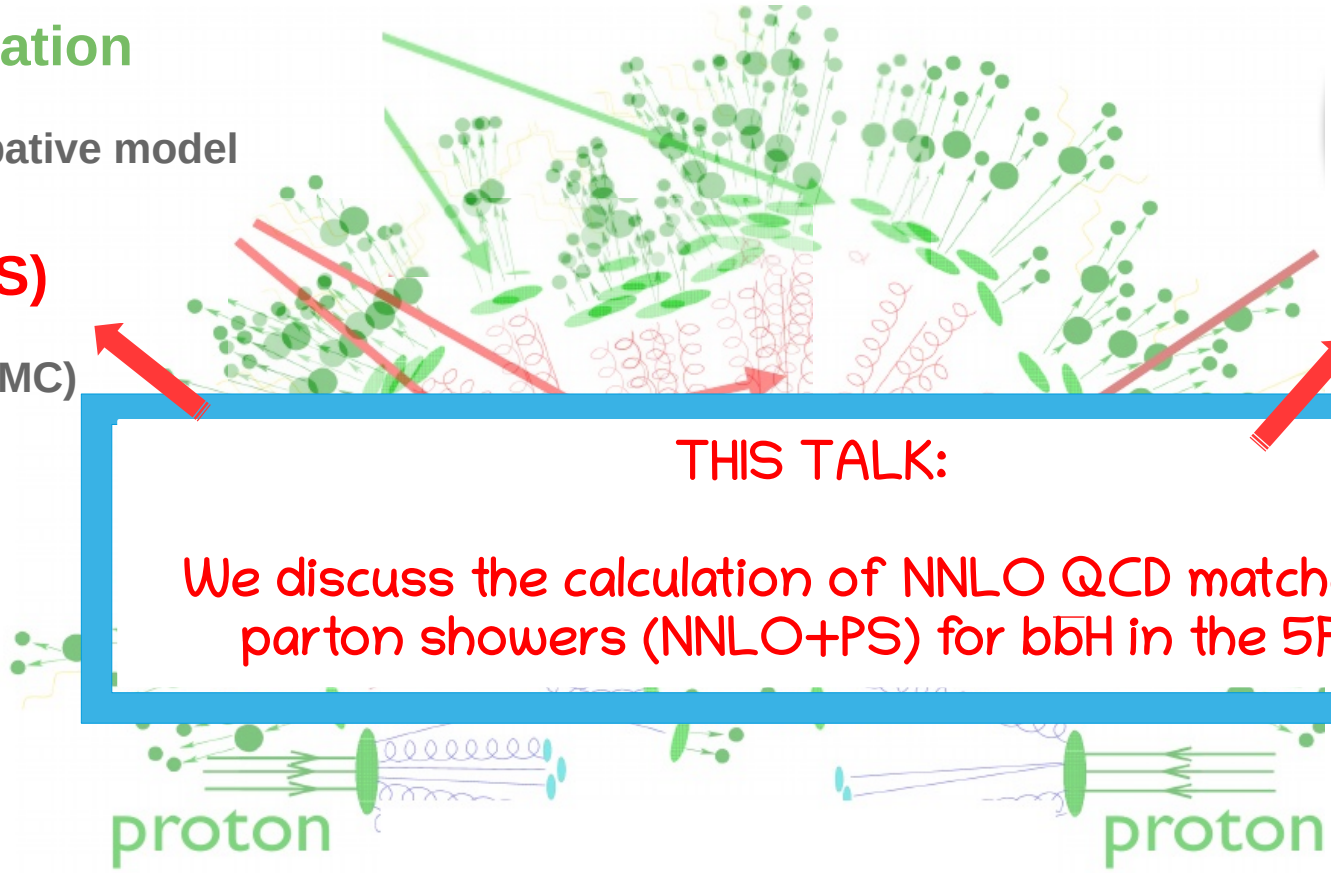

Hard scattering
$(\Lambda_{QCD} << \mu \approx Q)$
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THIS TALK:

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

[Sherpa's artistic view]

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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MINNLO$_{PS}$

2->1 : [Monni, Nason, Re, Wisemann, Zanderighi (1908.06987)]
[Monni, Re, Wiesemann (2006.04133)]

2->2 : [Lombardi, Wiesemann, Zanderighi (2010.10478)]

tt **:** [Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi (2012.14267)]

bbZ **:** [Mazzitelli, Sotnikov, Wiesemann (2404.08598)]

Javier's talk

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Javier's talk

- ✔ 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 first** with **NLO** accuracy, then attaching a **parton shower** with **softer** emissions.

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MiNNLO$_{PS}$ in **POWHEG** framework: starts 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} ~ 1 GeV

MiNNLO$_{PS}$ in a Nutshell

Central ingredient of MiNNLO$_{PS}$

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

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

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Sudakov form factor

suppresses $\bar{B}$ at low p_T

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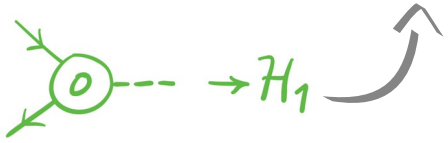

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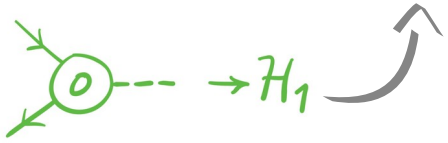
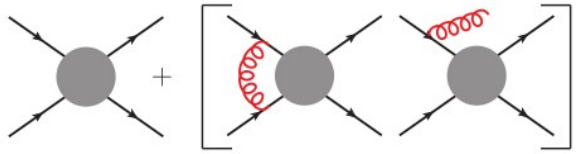


FO differential cross sections



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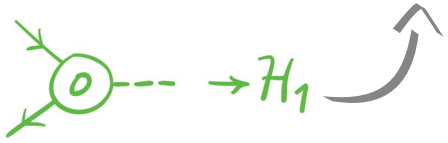

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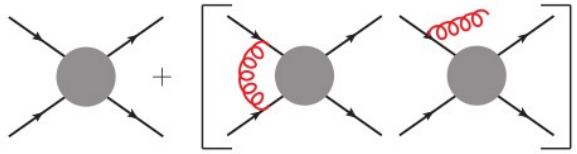
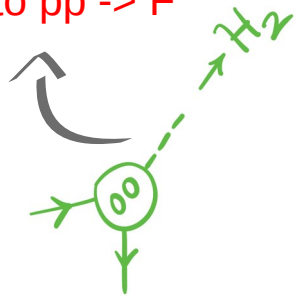


Luminosity

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

Additional terms to reach **NNLO** accuracy

contains double virtual correction to pp -> F



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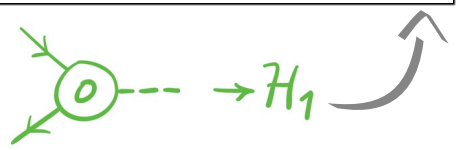

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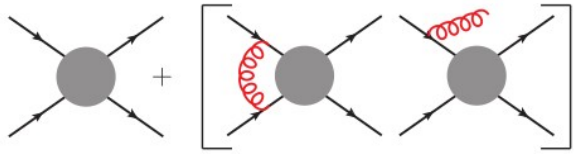

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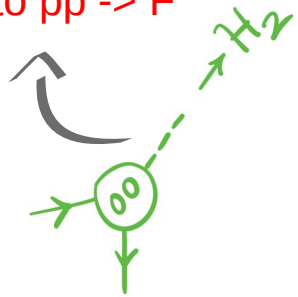

- In the singular part : $\mu_R \sim \mu_F \sim p_T$
- For the regular part, different scale choices can be performed:
  - **Transverse momentum p_T (original choice)**
  - **Hard scale Q (`FoatQ =1`)**

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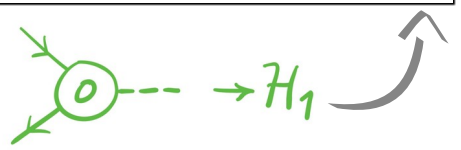
suppresses $\bar{B}$ at low p_T

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

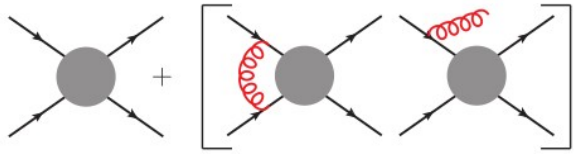
$$A(\alpha_S) = \left(\frac{\alpha_S}{2\pi}\right) A^{(1)} + \left(\frac{\alpha_S}{2\pi}\right)^2 A^{(2)} + \left(\frac{\alpha_S}{2\pi}\right)^3 A^{(3)}$$

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

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



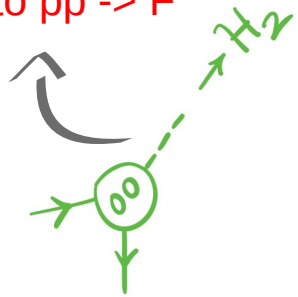
FO differential cross sections



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
contains double virtual correction to pp -> F



- In the singular part : $\mu_R \sim \mu_F \sim p_T$
- For the regular part, different scale choices can be performed:
  - **Transverse momentum p_T (original choice)**
  - **Hard scale Q (`FoatQ =1`)**

For $b\bar{b}H$: We revised the original **MiNNLO$_{PS}$** method to account for the **Yukawa** coupling in **$\overline{MS}$ scheme**

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

- **MiNNLO$_{PS}$ $b\bar{b}$ → H** generator implemented within the **Powheg-Box-Res** framework
- Tree-level amplitudes of the **HJ & HJJ** : **OpenLoops**
- **Virtual** correction : **analytic results**

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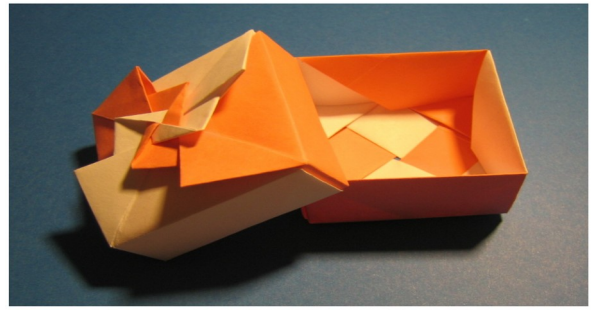
The POWHEG BOX



- **Inputs:**
  - Center-of-mass energy: **13 TeV** at LHC.
  - Higgs boson mass (m_H): **125 GeV**, Γ_H (decay width): 0 GeV.
  - Default PDF: **NNPDF40_nnlo_as_01180** with 5 active flavours.
  - Central μ_R and μ_F scales set via **MiNNLO$_{PS}$** method [$\mu_R \sim \mu_F \sim p_T$].
  - **Yukawa coupling** renormalized in **$\overline{MS}$ scheme** [$Y_b(m_b$=4.18 GeV) -> $Y_b(m_H)$ = 2.79].

- **Scale Settings and Uncertainties:**
  - Scale uncertainities 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 to fixed-order results

Total inclusive cross section from **MiNLO′** & **MiNNLO$_{PS}$** predictions checked against 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$_{PS}$	MiNNLO$_{PS}$ (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

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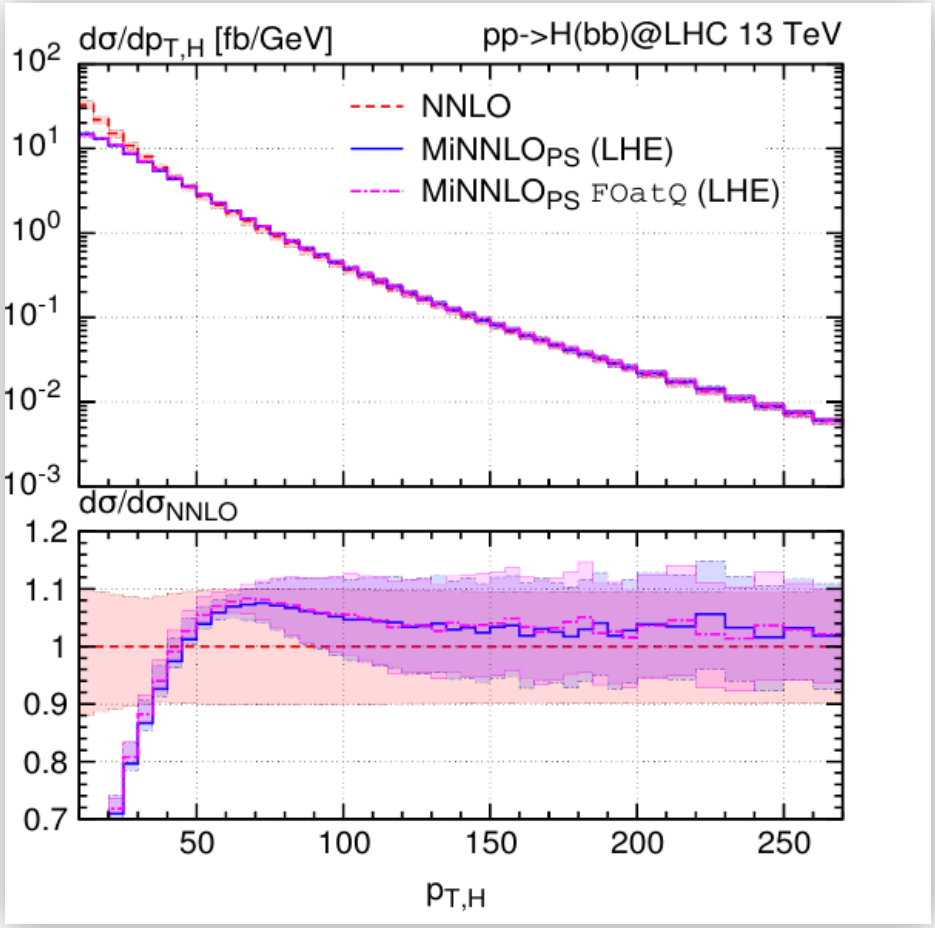
- NNLO QCD corrections **reduce cross section** by > 10%
- Scale **uncertainities** significantly **reduced** with NNLO QCD corrections
- Our **MiNNLO$_{PS}$** predictions are in **agreement with NNLO** QCD cross section within quoted uncertainties

Comparison to fixed-order results

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

Les Houches level (LHE)



NNLO [Harlander, Tripathi, Wiesemann (1403.7196)]

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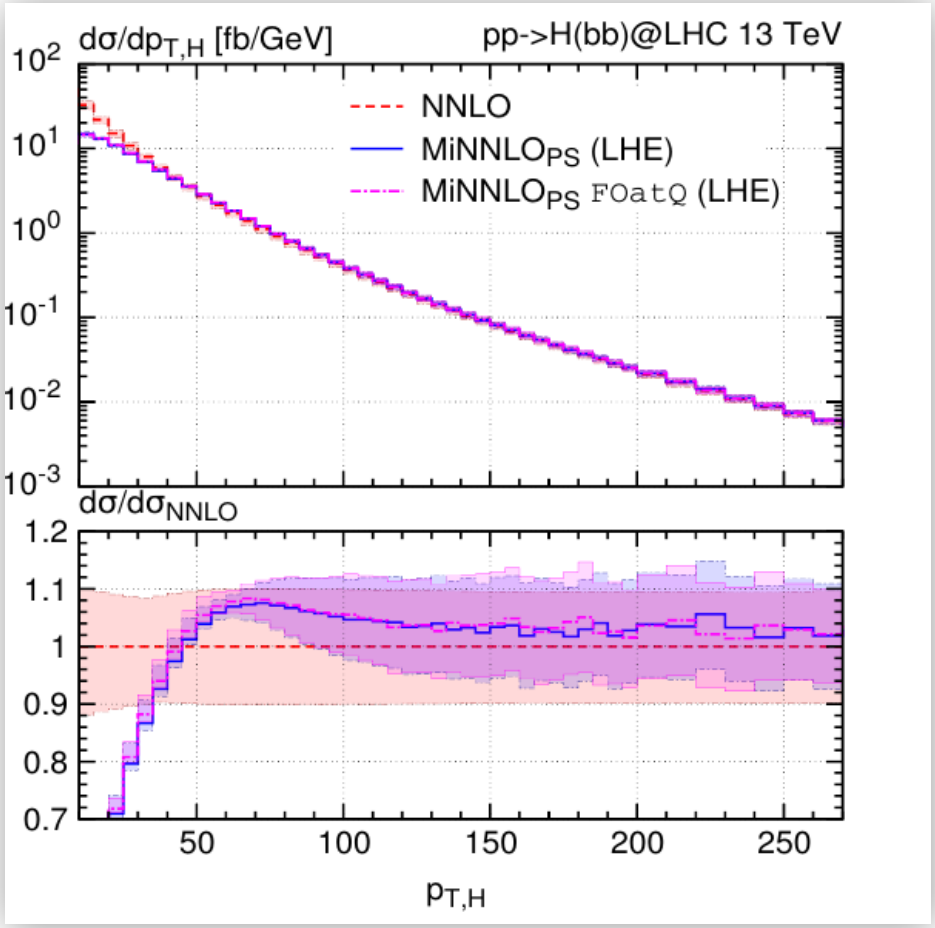


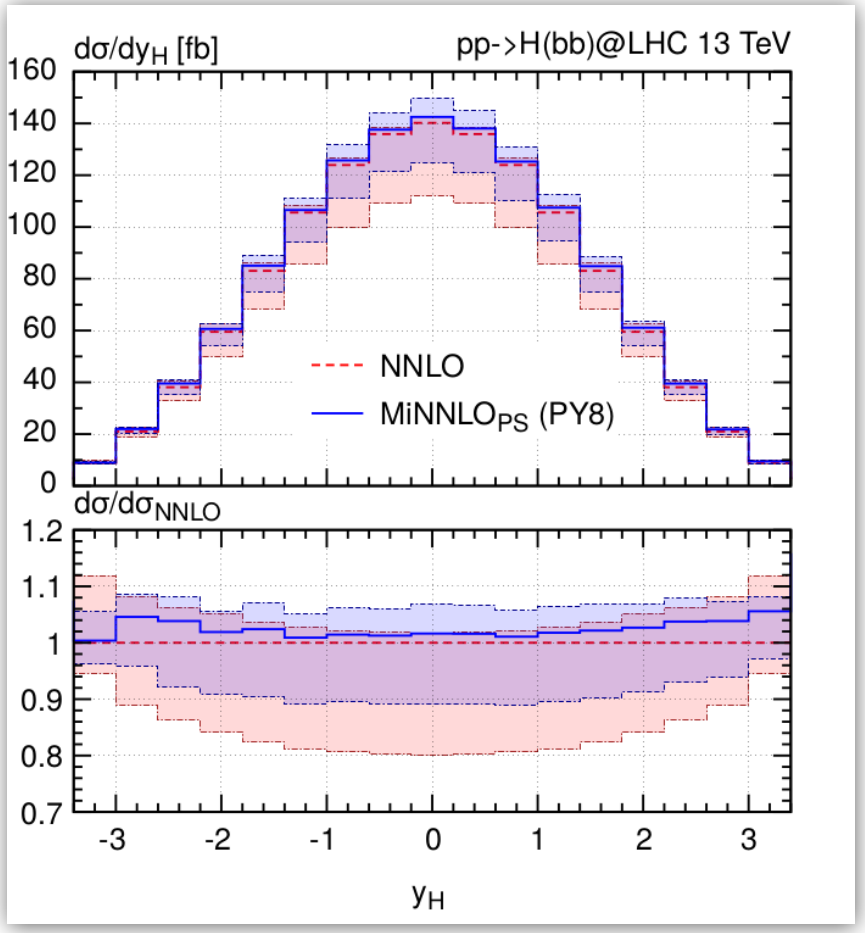
- **Full agreement** in **large $p_{T,H}$** regime with fixed-order predictions within quoted uncertainities
- **MiNNLO$_{PS}$** results with and without the **FOatQ** setting are very close
- Fixed-order calculations diverge for $p_{T,H} \to 0$ **MiNNLO$_{PS}$** prediction remains **finite**

NNLO [Harlander, Tripathi, Wiesemann (1403.7196)]

Comparison to fixed-order results

Rapidity distribution of the Higgs boson (y_H)

PY8 level



CT14nnlo_as_0118

NNLO [Mondini, Williams (2102.05487)]

Comparison to fixed-order results

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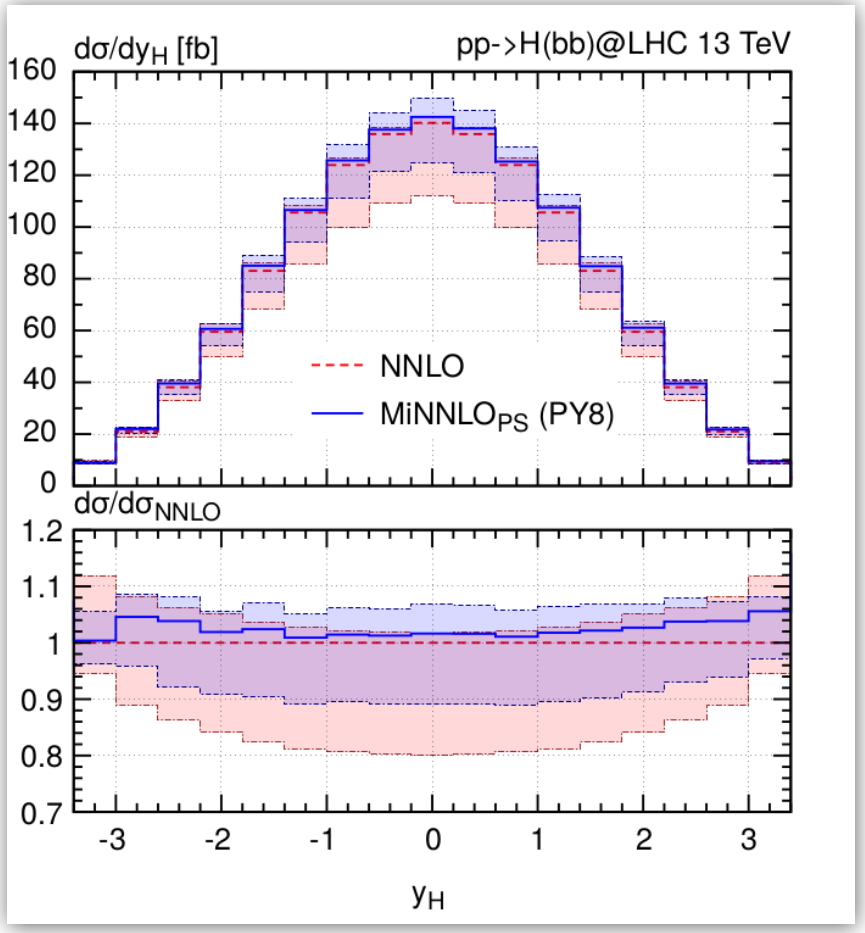


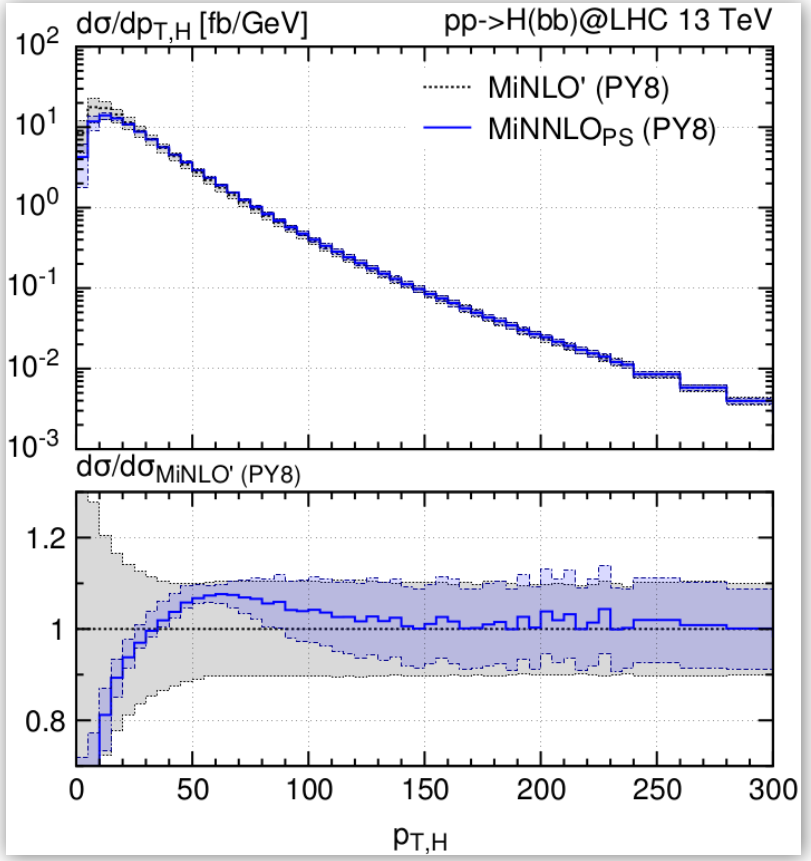
CT14nnlo_as_0118

- 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.

NNLO [Mondini, Williams (2102.05487)]

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

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



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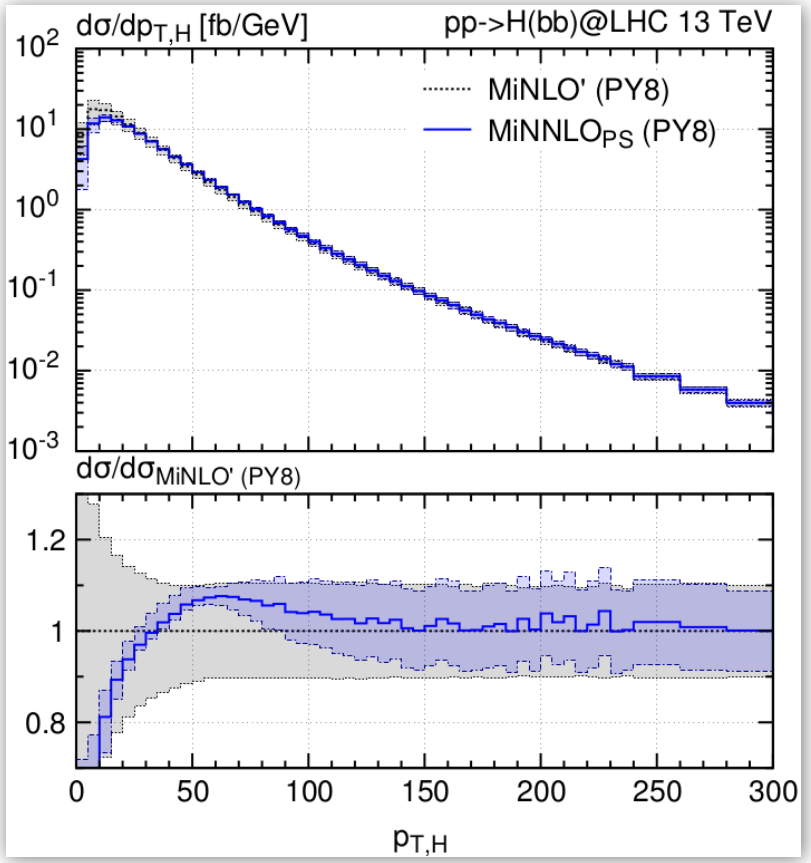

PY8 level

- At small p_T, **MiNNLO$_{PS}$ significantly dampens** distributions, **reduces scale uncertainties.**
- At large p_T, **MiNLO'** & **MiNNLO$_{PS}$** predictions **coincide**, both **NLO** accurate.

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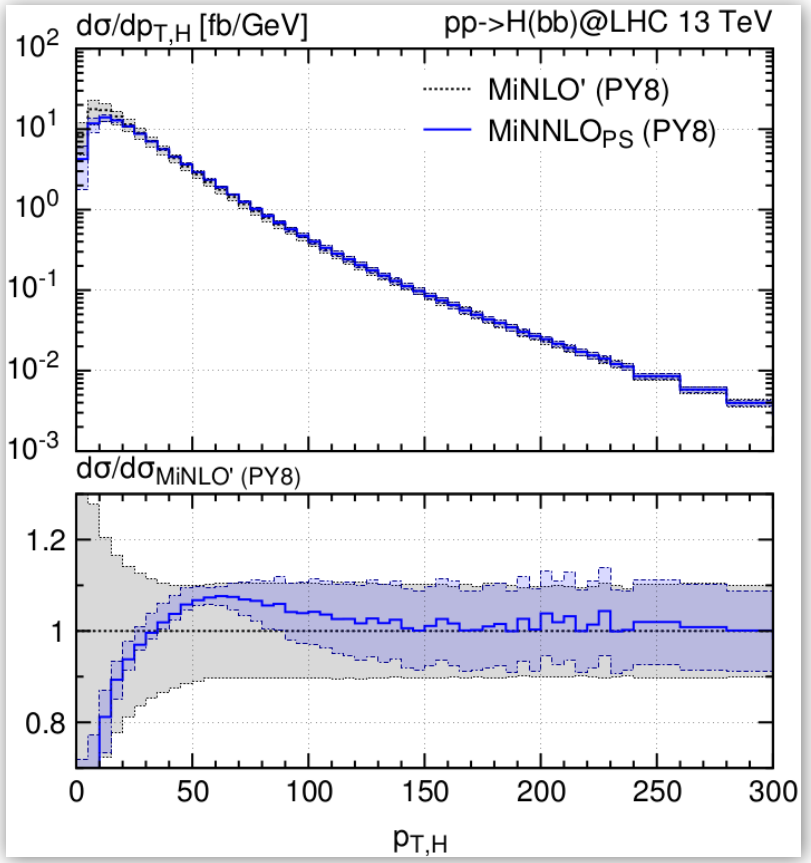
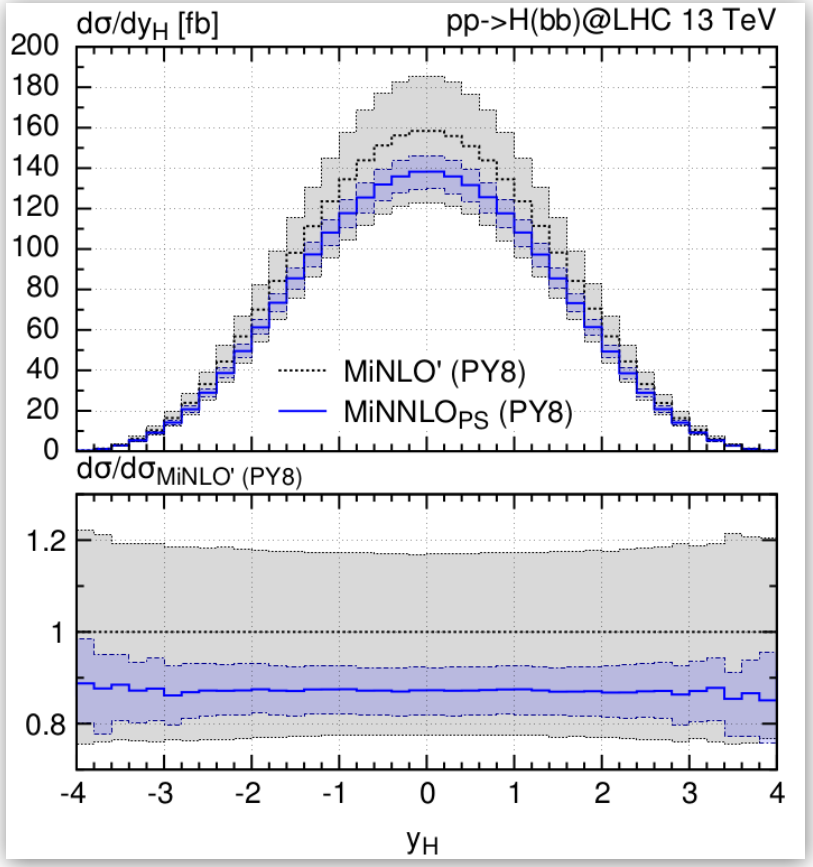
Transverse-momentum spectrum of the Higgs boson ($p_{T,H}$)



Rapidity distribution of the Higgs (y_H)



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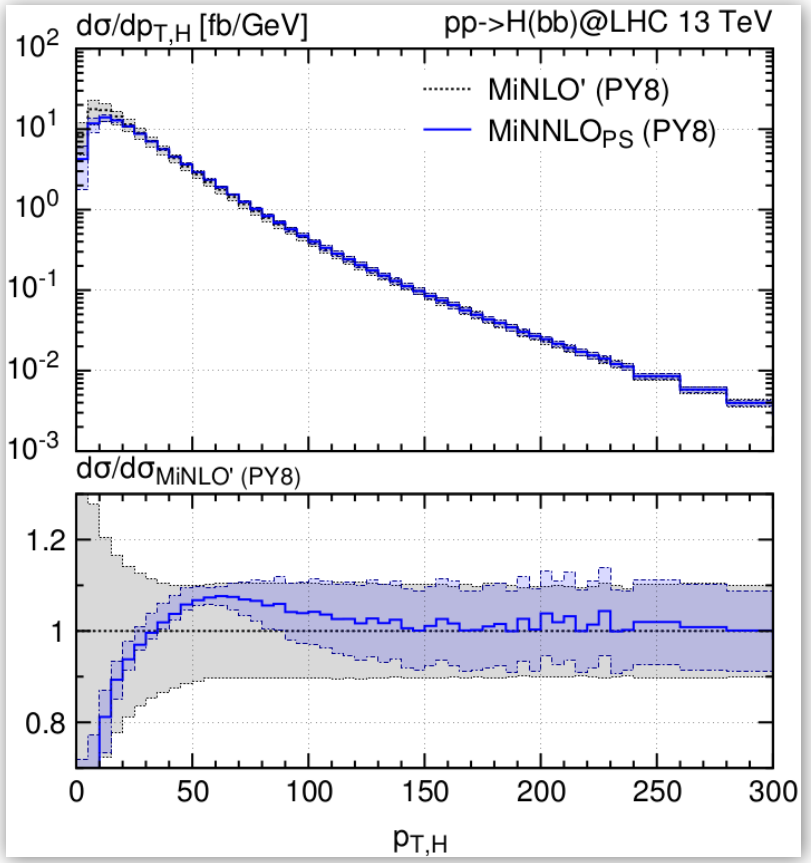

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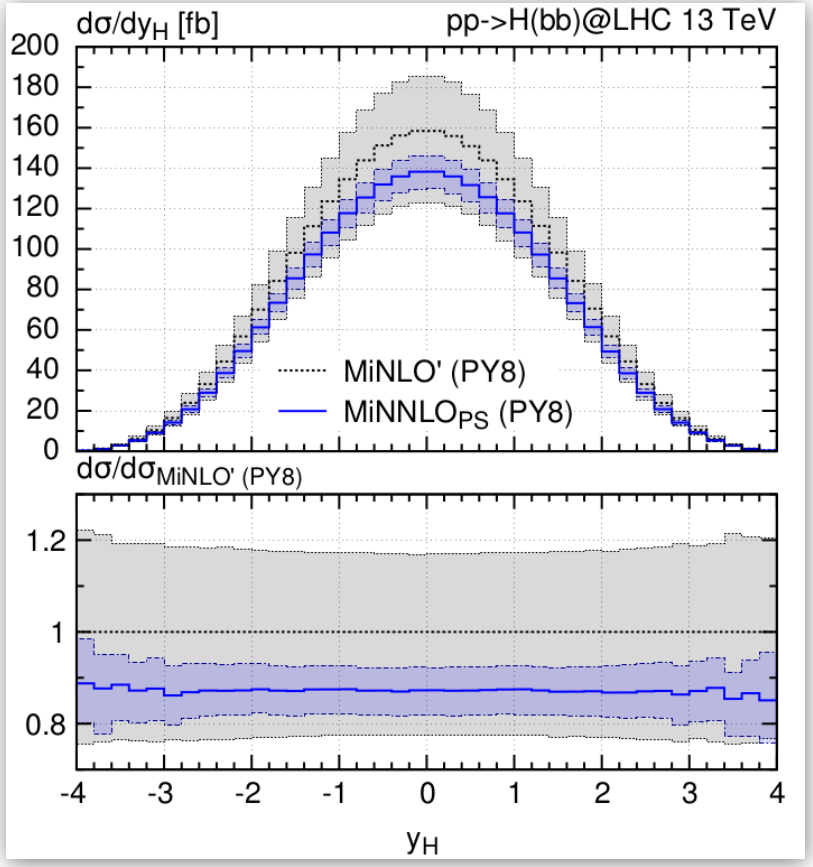

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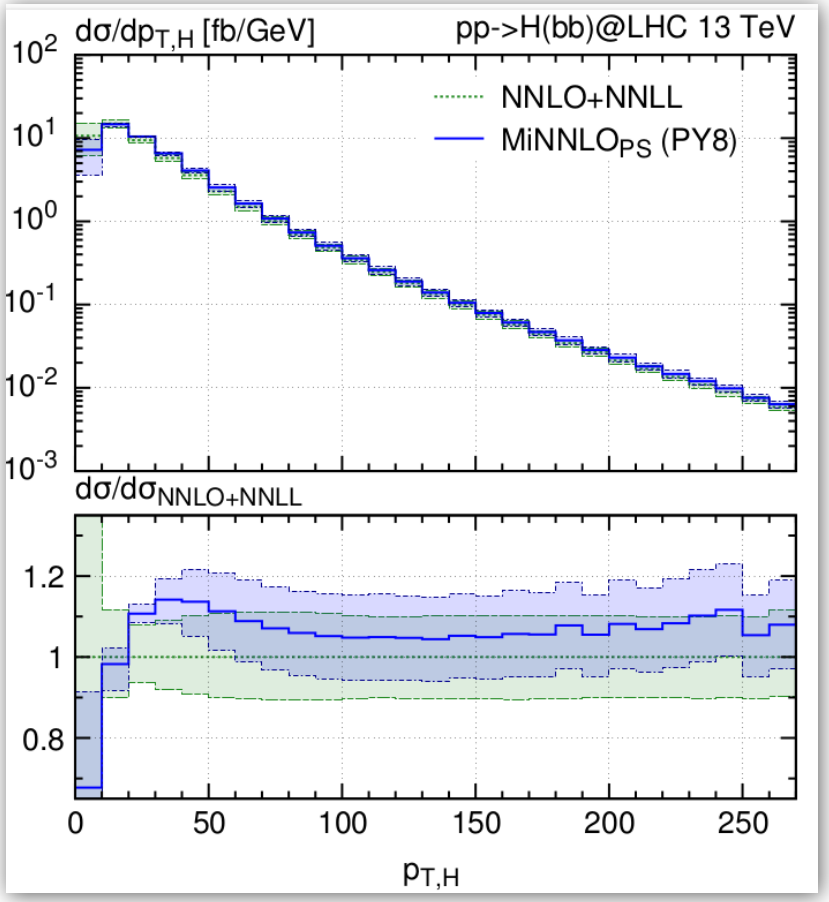
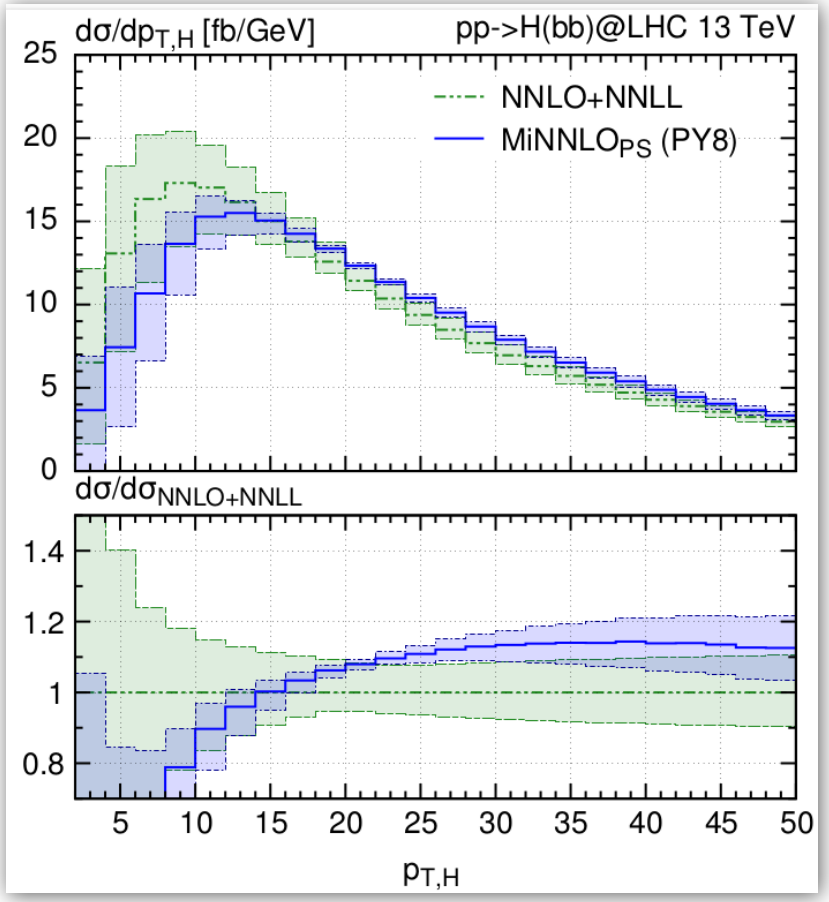
- At small p_T, **MiNNLO$_{PS}$ significantly dampens** distributions, **reduces scale uncertainties.**
- At large p_T, **MiNLO'** & **MiNNLO$_{PS}$** predictions **coincide**, both **NLO** accurate.
- **y_H distribution**: **MiNNLO$_{PS}$** introduces a flat 12% negative correction, **reduces scale uncertainties.**

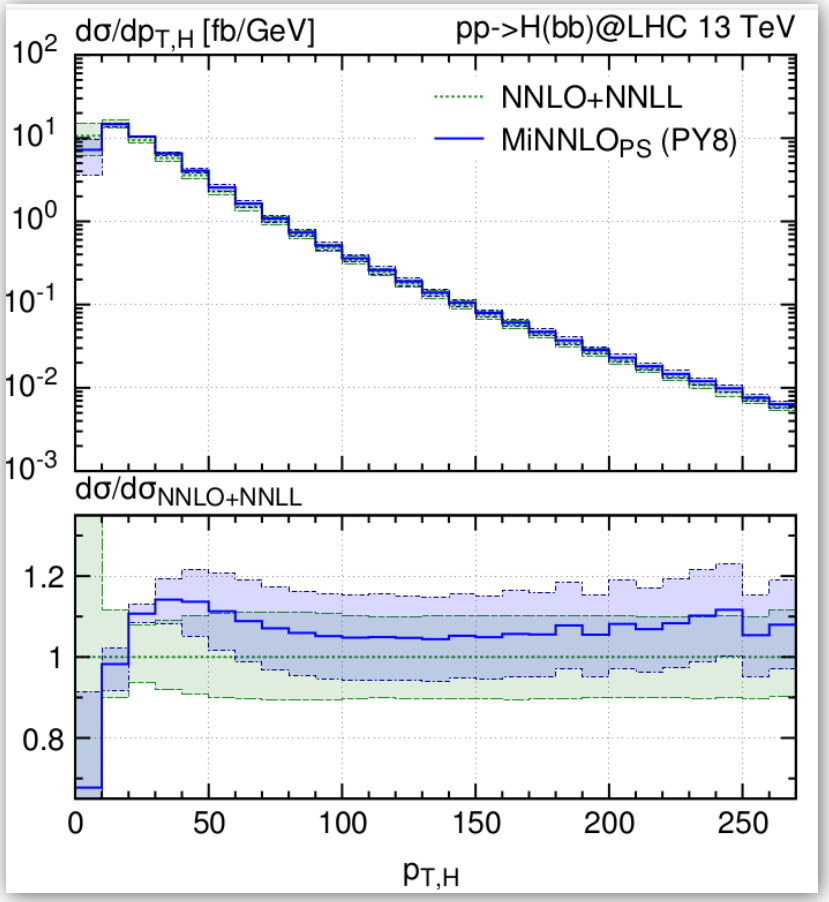
Comparison to NNLO+NNLL

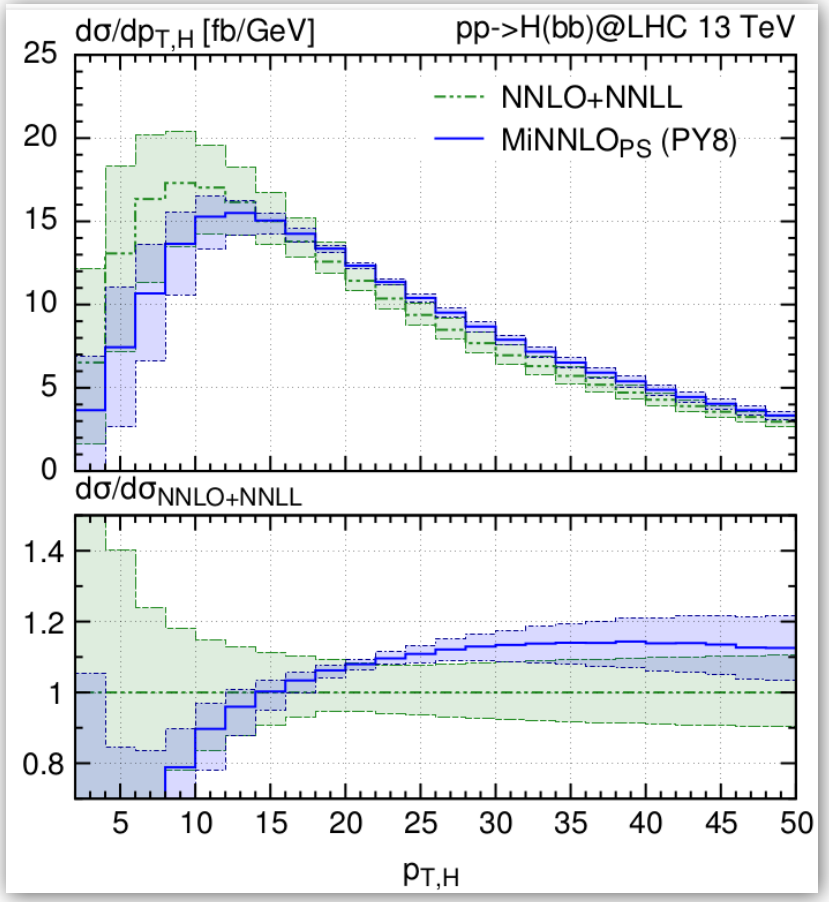




NNLO+NNLL [Harlander, Tripathi, Wiesemann (1403.7196)]

Comparison to NNLO+NNLL





- **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.**

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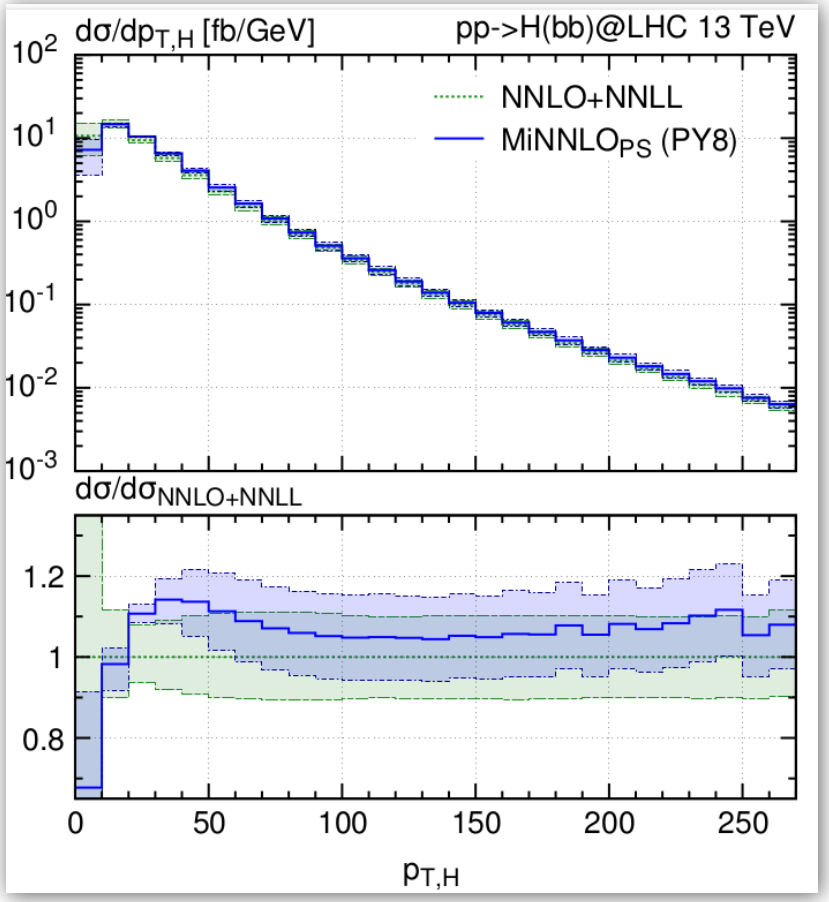

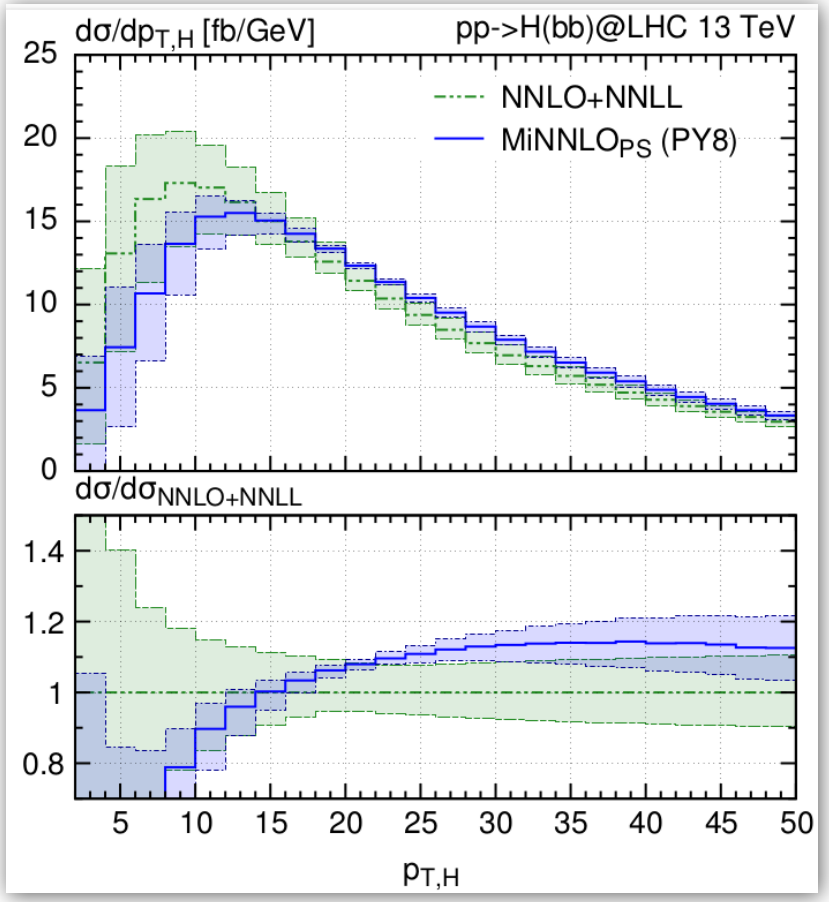

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  MiNNLO$_{PS}$ shifted 10% up, well within the given scale-uncertainty bands.
- **At small $p_{T,H}$**:
  slightly worsen the agreement. **MiNNLO$_{PS}$** uncertainities are **underestimated.**
- **Massless** approximation **misses** potentially **relevant mass effects at small p_T** , need to **combine** with **massive 4FS** calculation.

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

Summary & Outlook

- **First presentation** of **NNLO+PS** computation for **$b\bar{b}$ → 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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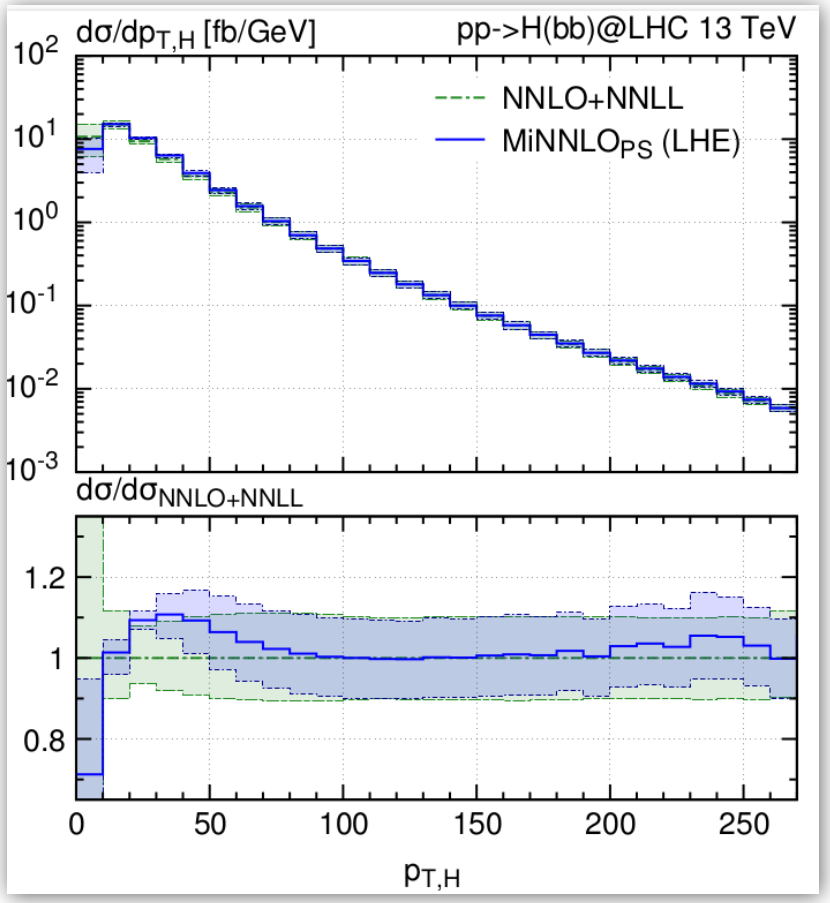
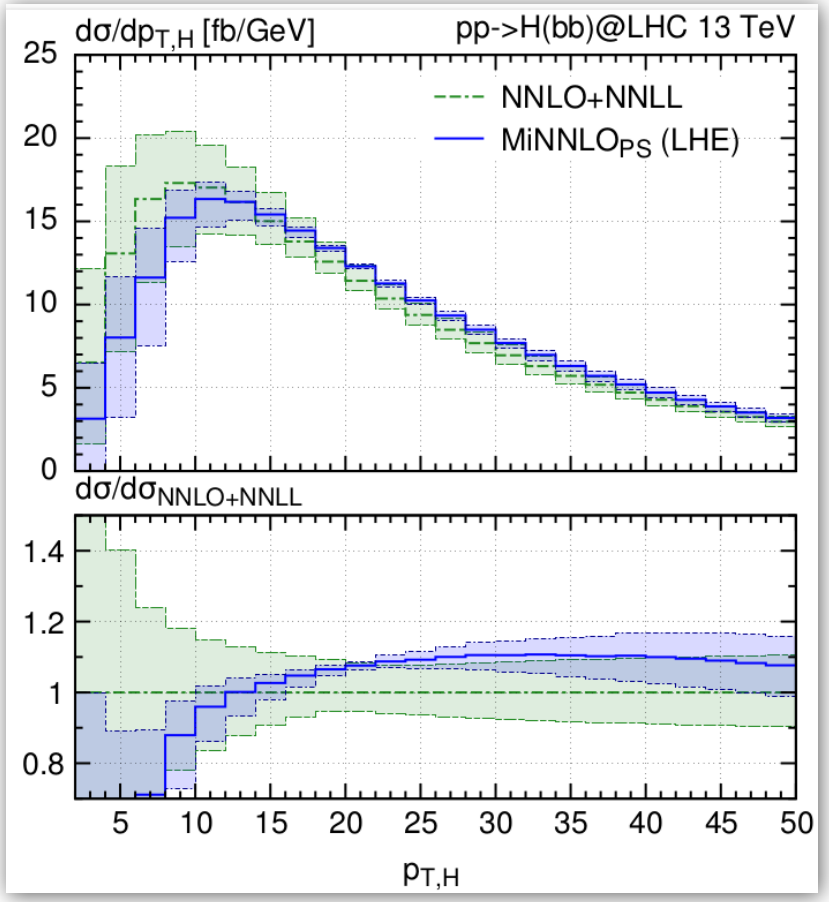
THANK YOU !

Backup slides

Comparison to NNLO+NNLL





Les Houches level (LHE)

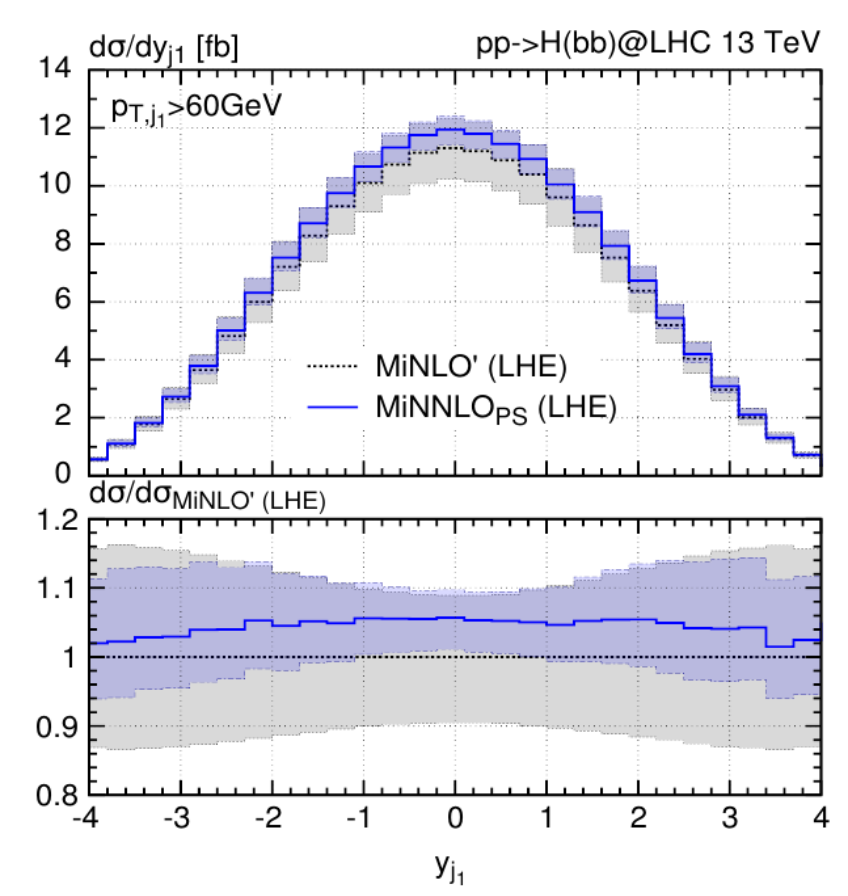
At high $p_{T,H}$:
they coincide again

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

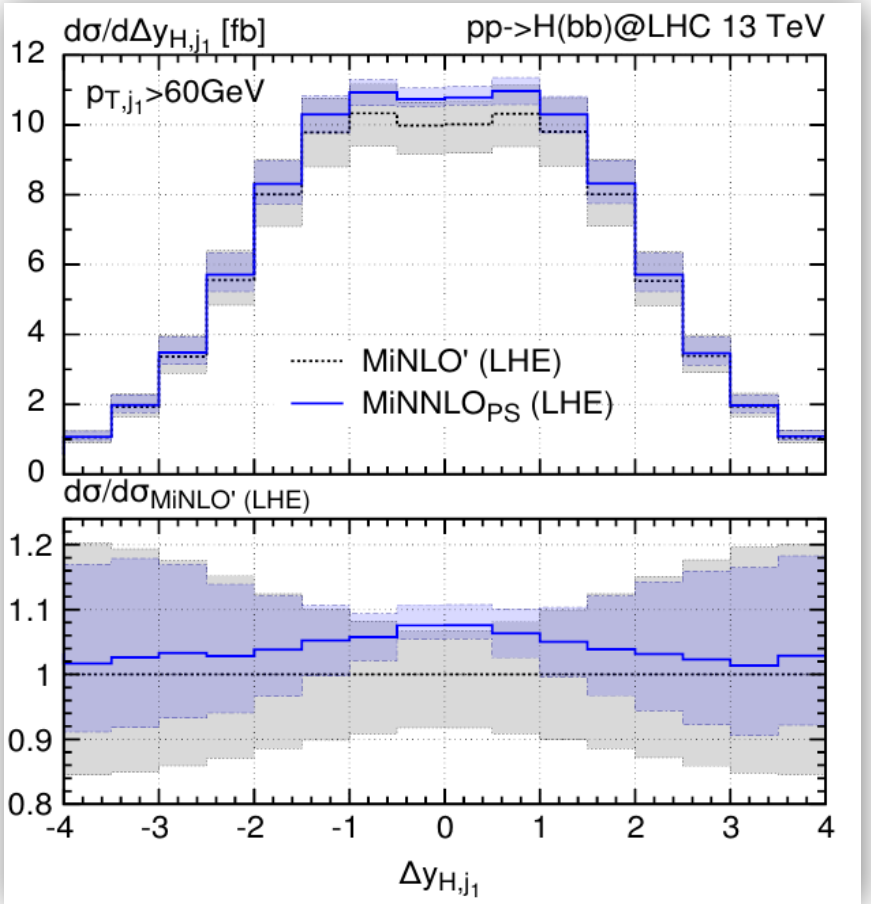
NNLO+NNLL [Harlander, Tripathi, Wiesemann (1403.7196)]

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

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

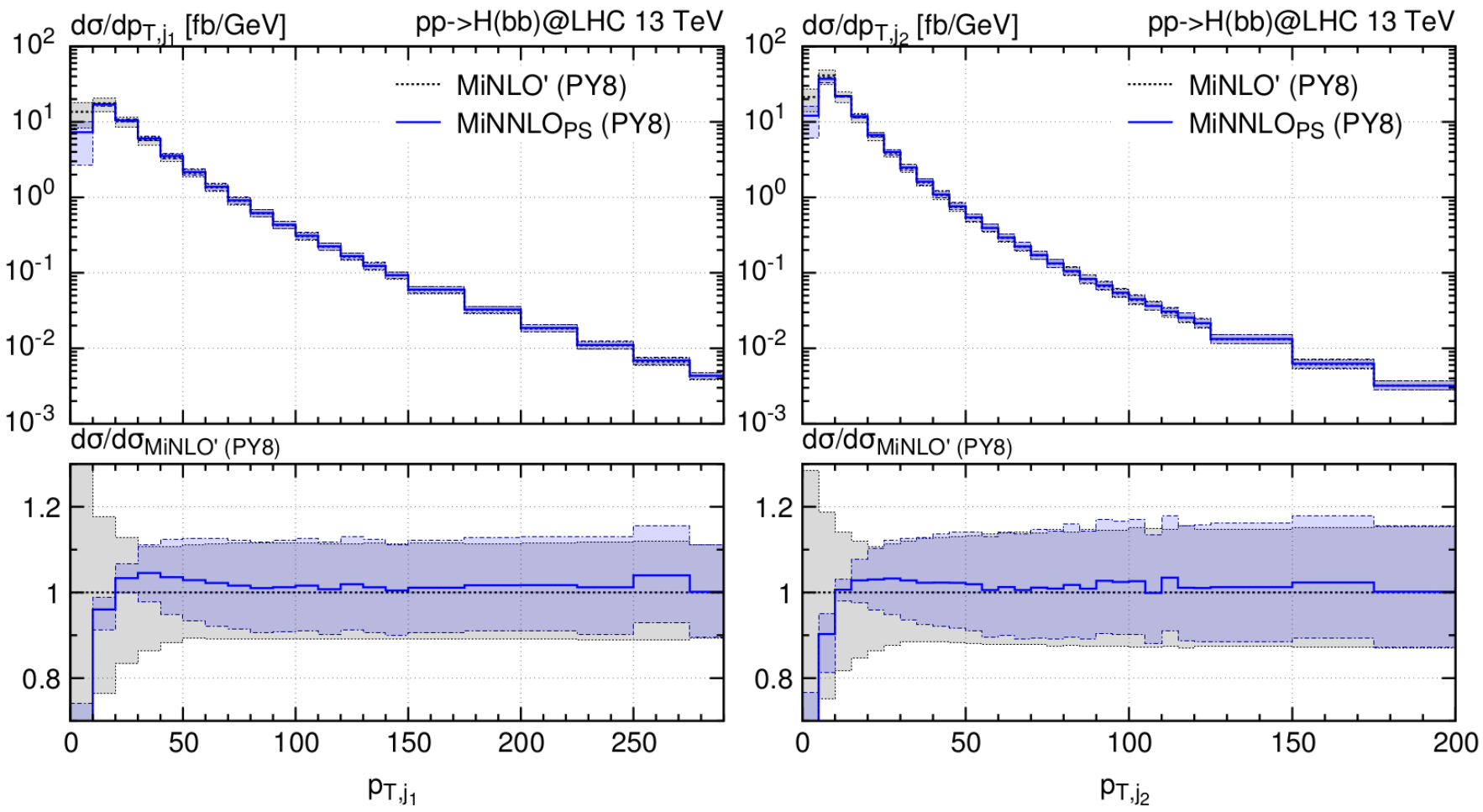


Rapidity difference between the Higgs boson & the leading jet ($\Delta y_{H,j1}$)



- 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

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

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

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