NNLO+PS predictions for Higgs production in bottom quark fusion with $\text{MiNNLO}_{\text{PS}}$

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In collaboration with
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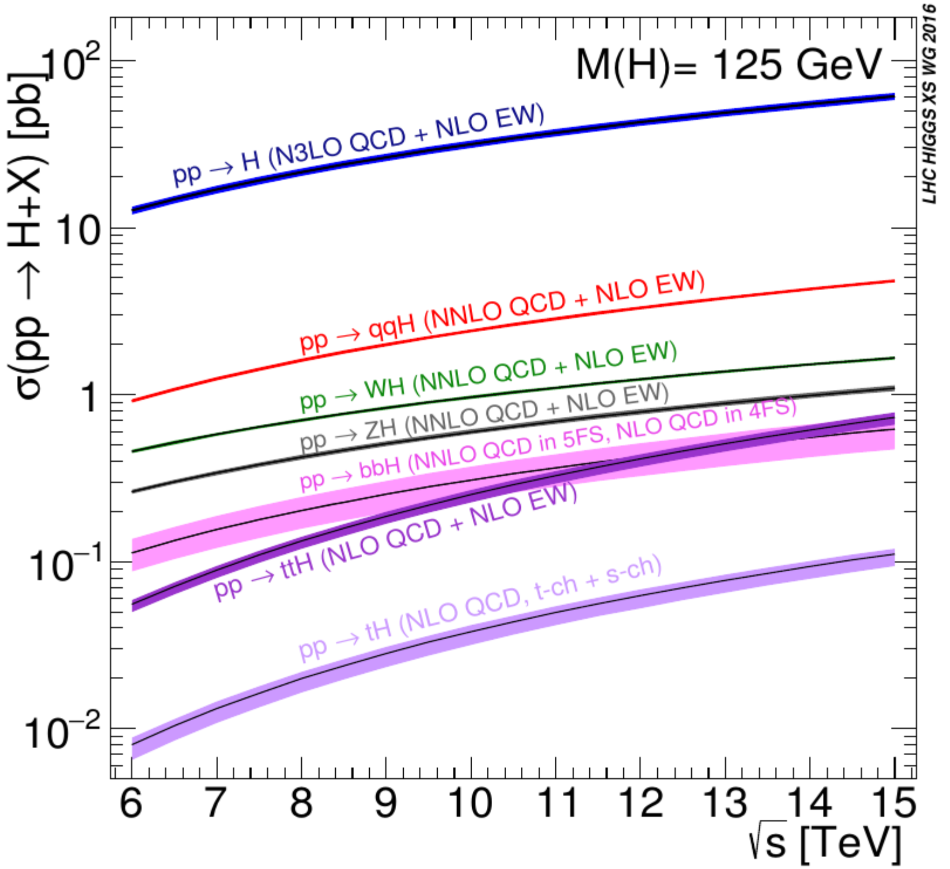
Dallas Texas USA, 20 May 2024

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



[LHC HIGGS XS WG 2016]

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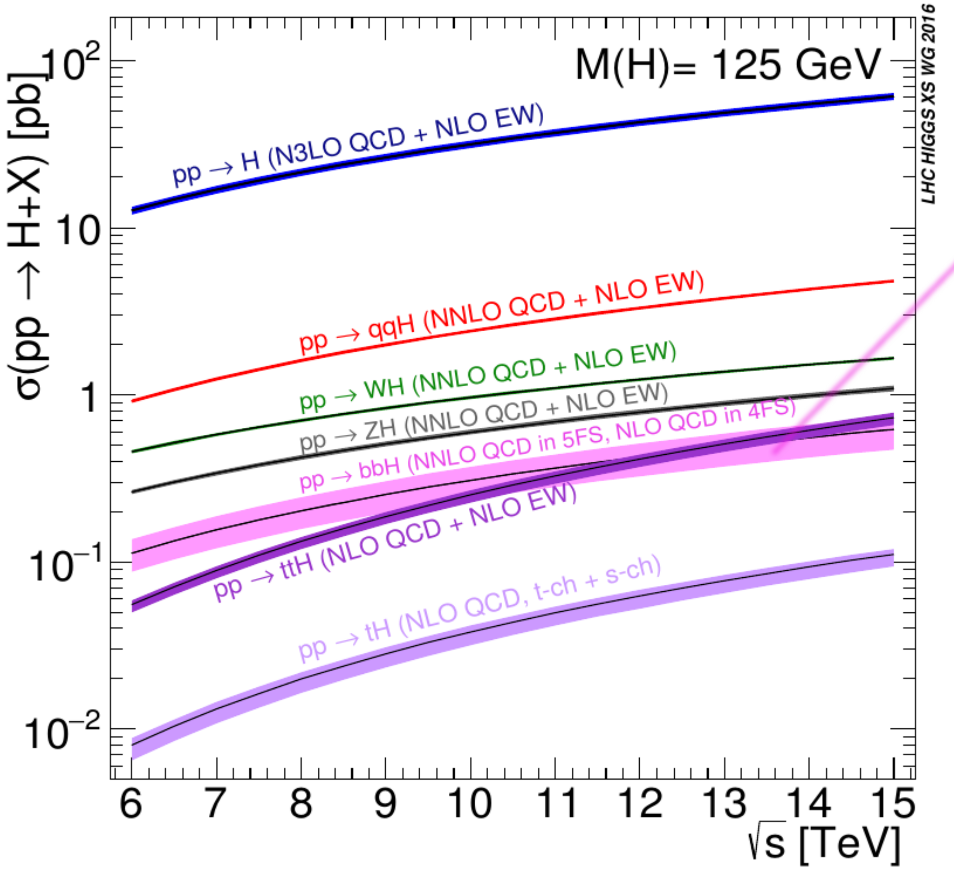

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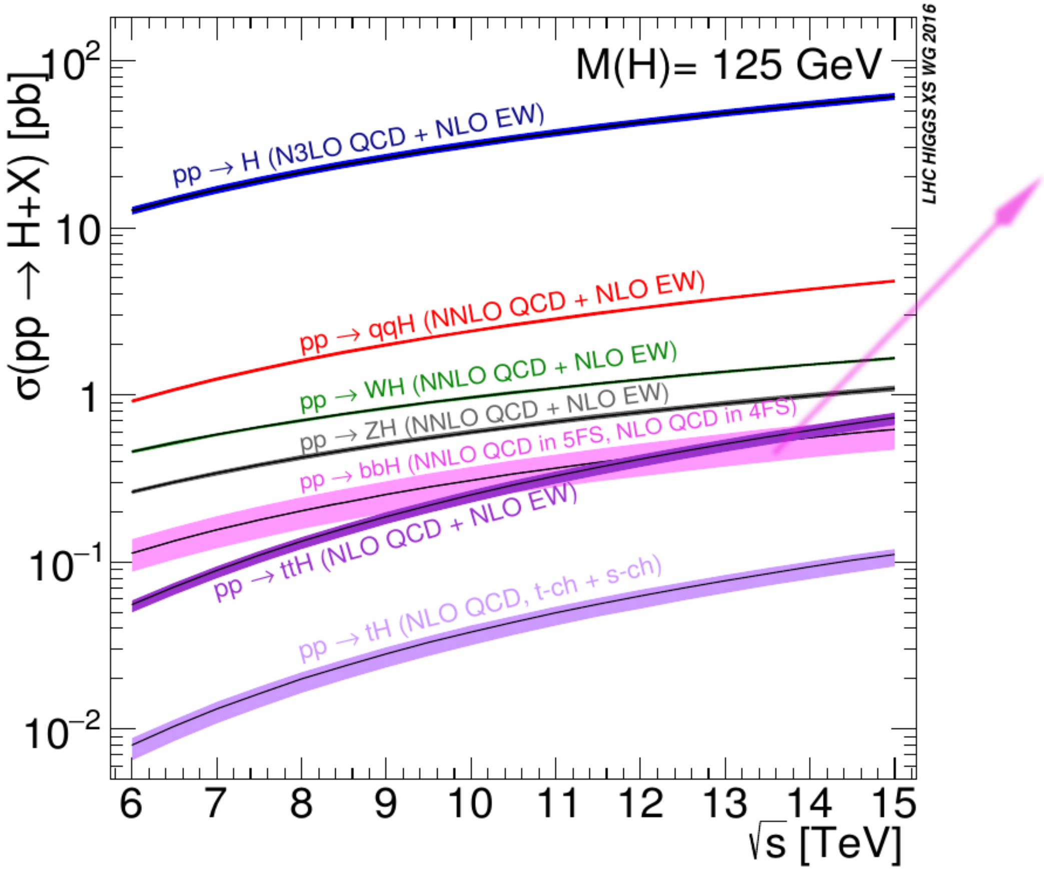

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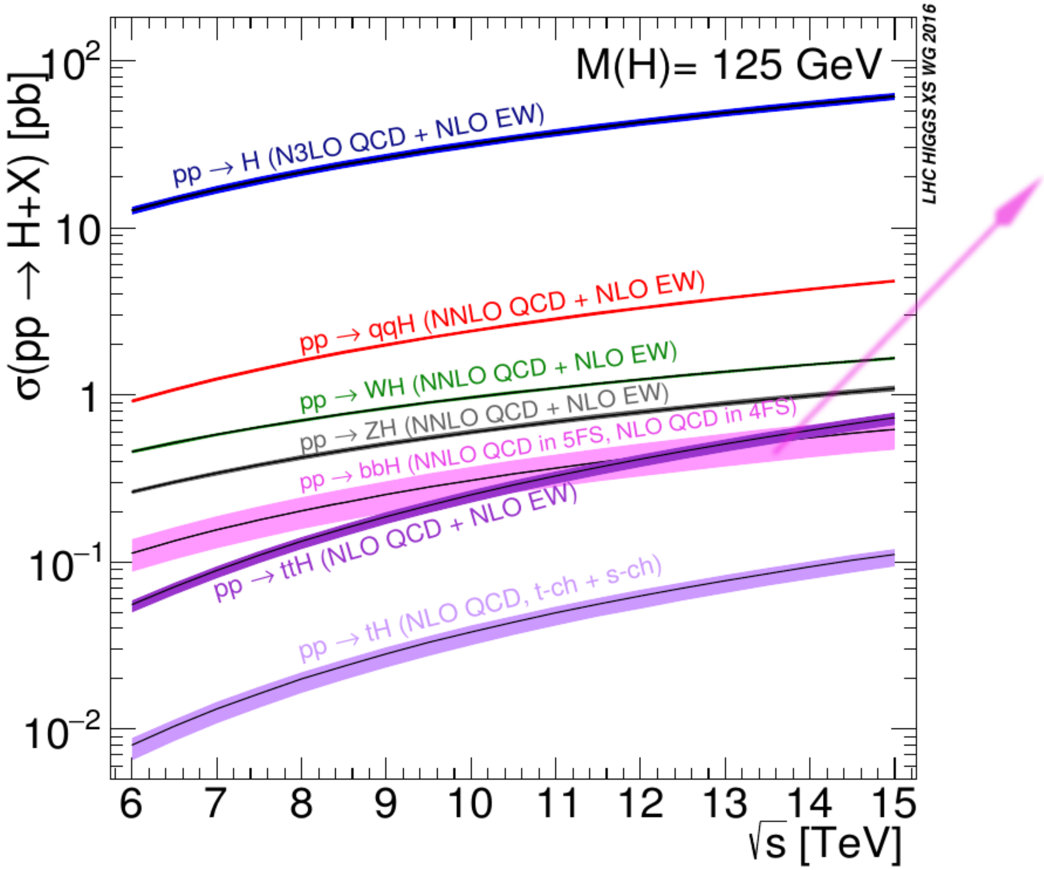

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- Direct probe of **Higgs couplings to the bottom quark** (**y_b**) in production
- **Bottom Yukawa coupling**: Important due to its **enhancement in New Physics models** like minimal supersymmetric extensions of the SM
- $b\bar{b}H$ enters as a **background**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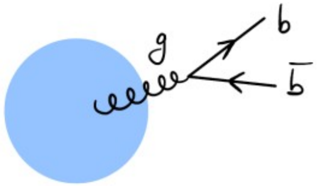

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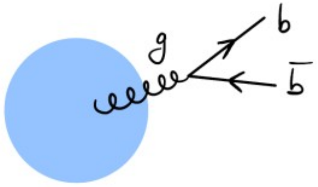

- **Active parton** inside the proton.
- **Included** in the parton distribution functions (**PDFs**) of the proton.
- It is taken to be **massless except** in the **Yukawa** coupling

[Image courtesy : C. Biello]

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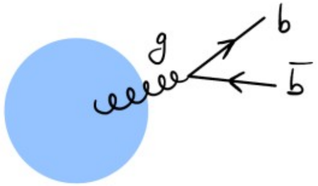
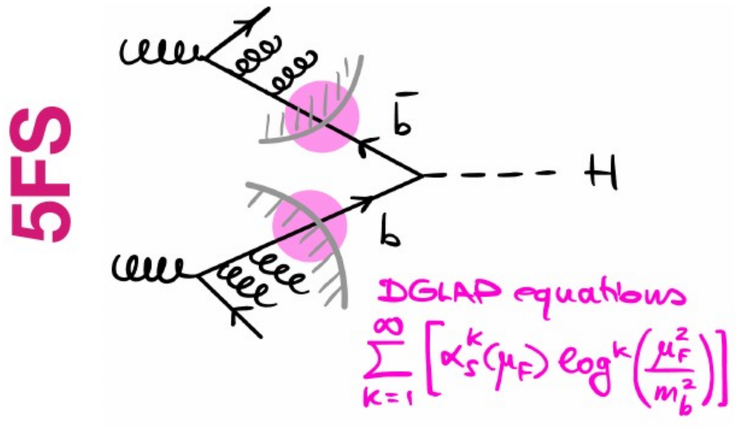


- Considered as a **heavy quark**
- The bottom quark's contribution is **neglected** in the **PDFs**.
- A **massive** bottom quark is produced from **gluon splitting**

[Image courtesy : C. Biello]

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



- 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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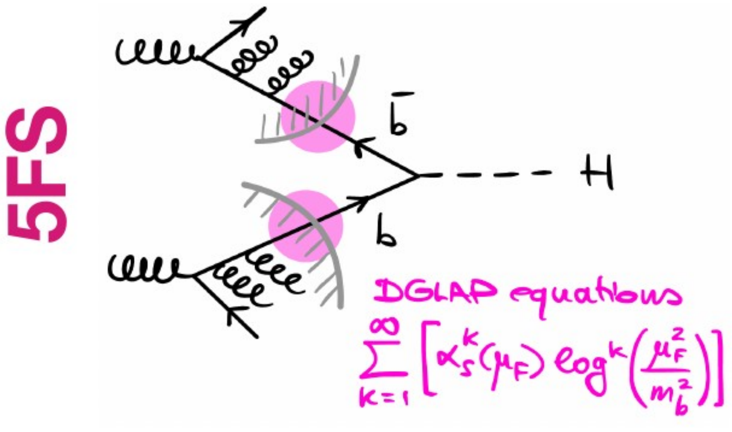
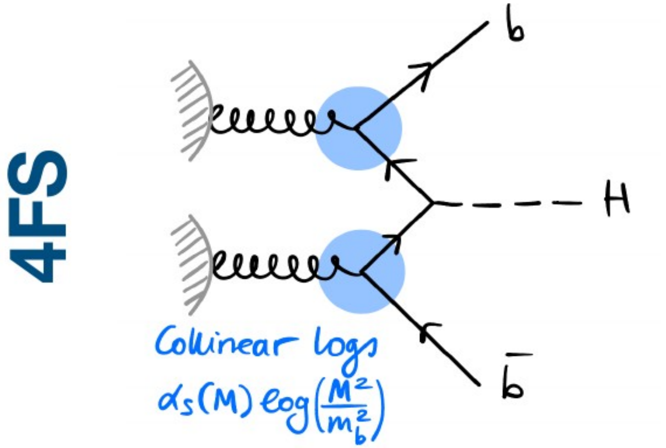




- ✓ Computing **higher orders** is **easier**
- ✓ The **DGLAP** evolution **resums** initial state collinear **logs** into the bottom PDFs
- • Neglects power-suppressed terms of the $O(m_b/m_H)$

- • 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 already at LO

[Image courtesy : C. Biello]

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

STATE OF THE ART:

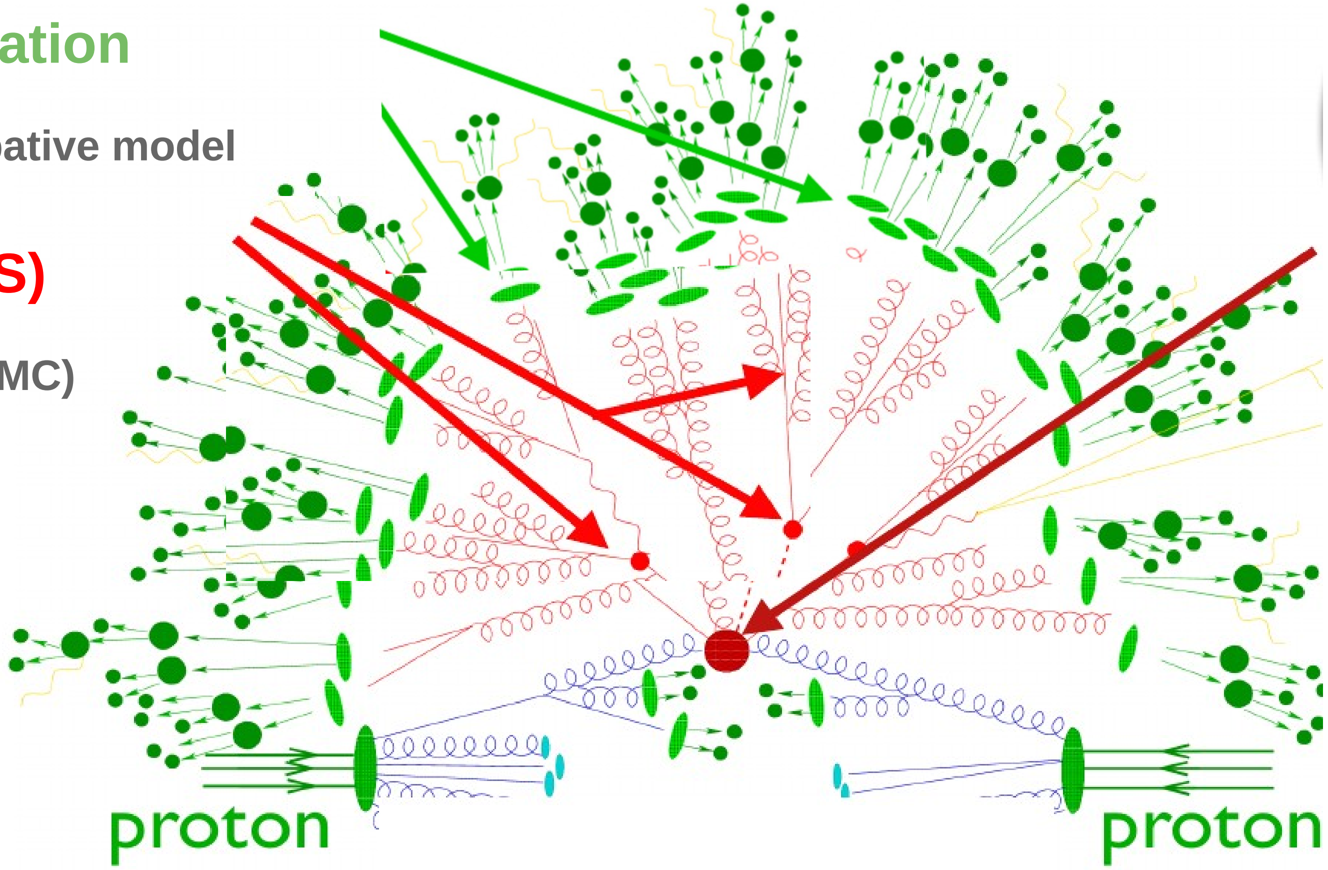
- **N3LO** for the total cross section in the **5FS** [Duhr, Dulat, Mistlberger (1904.09990)]
- **N3LO matched** to **NLO** in the **4FS** by a prescription, namely, **FONLL** [Duhr, Dulat, Hirschi, Mistlberger (2004.04752)] [Forte, Napoletano, Ubiali [1508.01529, (1607.00389)]
- **NLO+PS** in the **4FS** (MadGraph5_aMC@NLO framework) [Wiesemann, Frederix, Frixione, Hirschi, Maltoni, Torrielli (1409.5301)]
- **NLO+PS** in the **4FS** using **POWHEG+PYTHIA6** [Jäger, Reina, Wackeroth (1509.05843)]
- **NLO-QCD+PS** combined with **NLO-EW** in the **4FS** [Pagani, Shao, Zaro (2005.10277)]
- **Full NLO-QCD** (y_b^2 , y_t^2 & $y_b y_t$) +**PS** in the **4FS** [Manzoni, Mazzeo, Mazzitelli ,Wiesemann, Zaro (2307.09992)]

$b\bar{b}H$ simulation

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

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]

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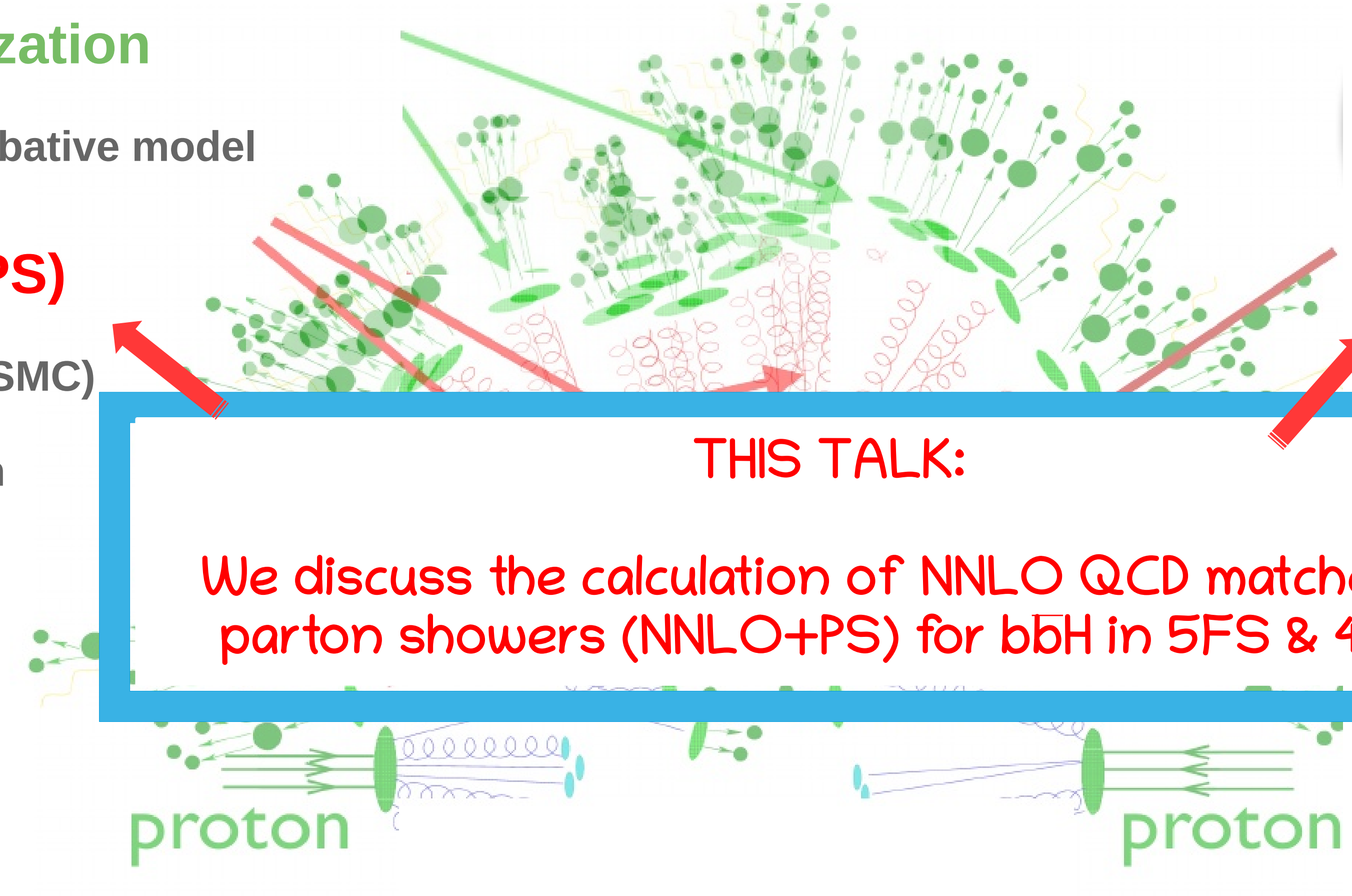

THIS TALK:

We discuss the calculation of NNLO QCD matched to parton showers (NNLO+PS) for $b\bar{b}H$ in 5FS & 4FS.

[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)]

$t\bar{t}$: [Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi (2012.14267)]

$b\bar{b}Z$: [Mazzitelli, Sotnikov, Wiesemann (2404.08598)]

Talk by M. Wiesemann

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

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

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

NNLO+PS accuracy

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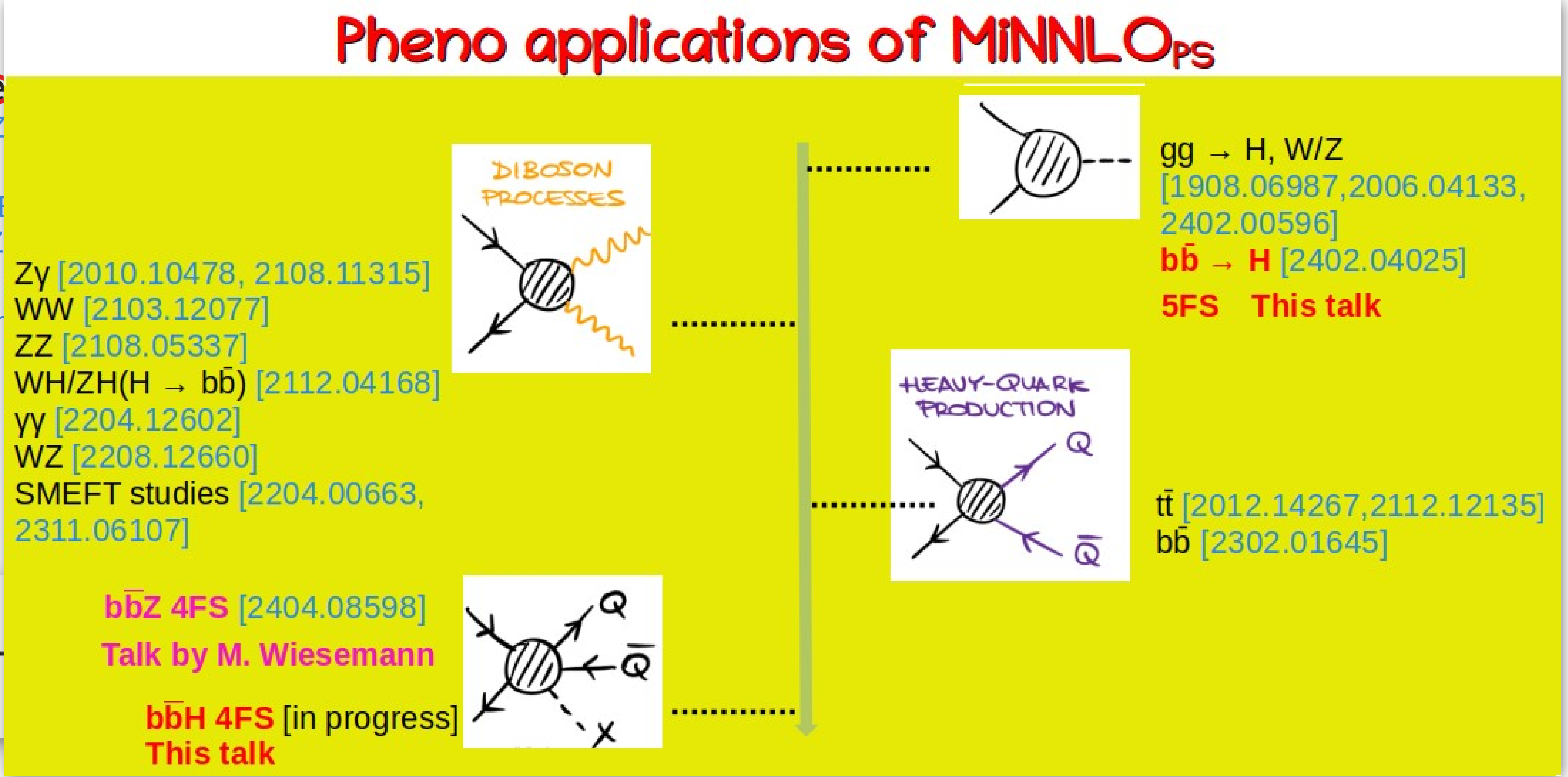
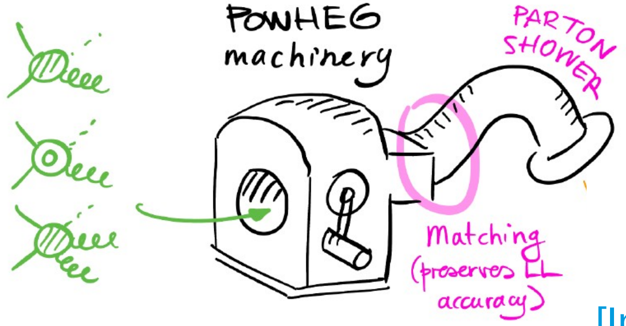


MiNNLO$_{PS}$ in a nutshell

- 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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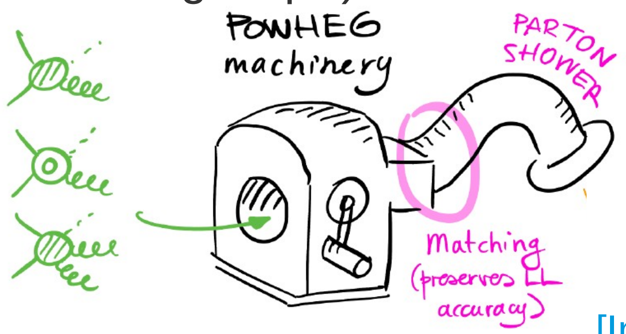

[Image courtesy : C. Biello]

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

POWHEG Sudakov form factor

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

Describes the generation of the 1st radiation

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

$\texttt{MiNNLO}_{\texttt{PS}}$ in a nutshell

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

Very simplified notation!

$\mu_R = \mu_F = p_T$

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

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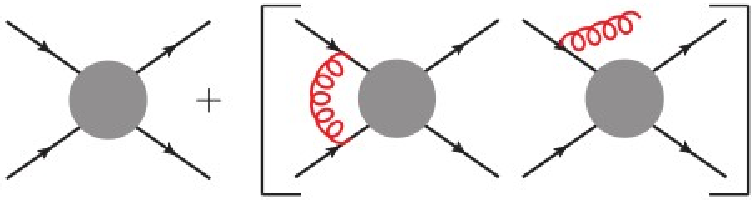

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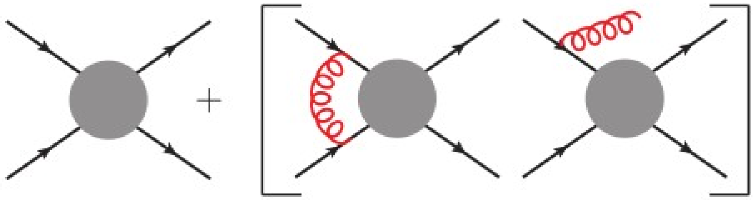
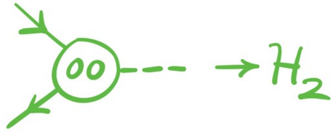


Luminosity

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

Additional terms to reach **NNLO** accuracy
contains double virtual correction to pp -> F



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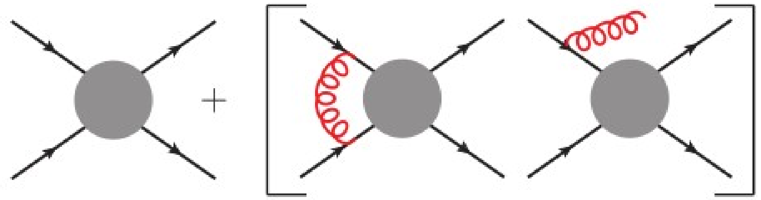

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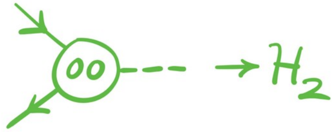
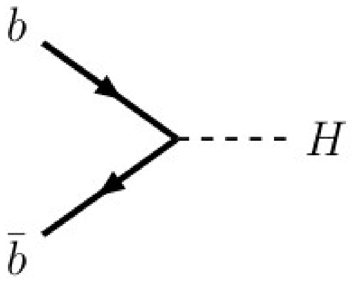


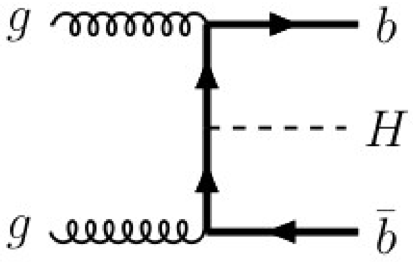
For $b\bar{b}H$: We revised the original **MiNNLO$_{PS}$** method to account for the **Yukawa** coupling in $\overline{\mathrm{MS}}$ **scheme**

The computation

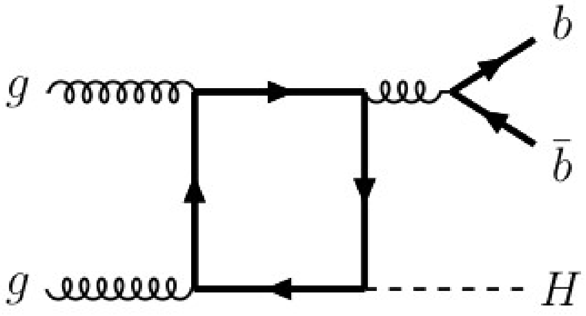
Sample Feynman diagrams for Higgs production in association with bottom quarks



LO Y_b in 5FS



LO Y_b in 4FS



LO Y_t

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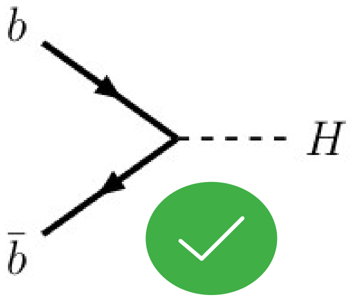

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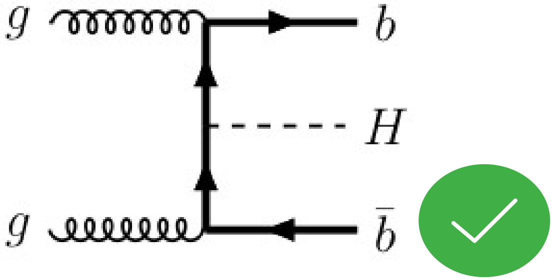
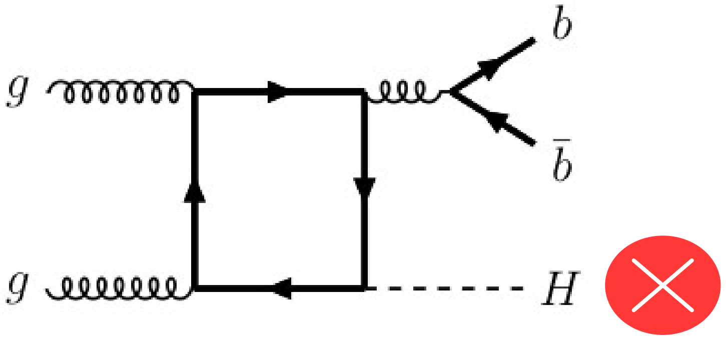


LO Y_b in 4FS



LO Y_t

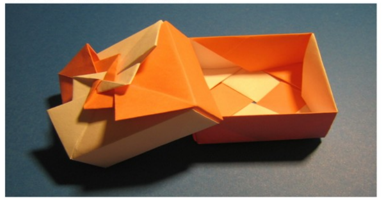
We focus on the 5FS & 4FS calculation of the $b\bar{b}H$ process proportional to Y_b^2 at NNLO+PS

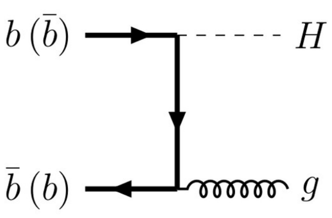
The computation (5FS)

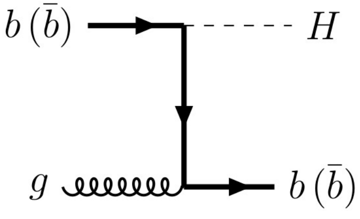
- **MiNNLO$_{PS}$ b$\bar{b}$ → H** generator implemented in the **Powheg–Box–Res** [T. Ježo and P. Nason (1509.09071)]

- First, we implemented a **NLO+PS** generator for **HJ** production in bottom fusion using the **Powheg** method [P. Nason (0409146), S. Alioli et al (1002.2581), S. Frixione et al (0709.2092)]

The POWHEG BOX







- Tree-level amplitudes of the **HJ & HJJ** : **OPENLOOPS** [F. Buccioni, S. Pozzorini and M. Zoller (1710.11452), F. Buccioni et al (1907.13071)]

- **Virtual** corrections : **Analytic results** [R.V. Harlander et al (1007.5411)]

  substantially improve the numerical performance of the code

- In a second step, we extended the **HJ NLO+PS** implementation to **NNLO accuracy** through the **MiNNLO$_{PS}$** method

[Monni, Nason, Re, Wisemann, Zanderighi (1908.06987)]
[Monni, Re, Wiesemann (2006.04133)]

Phenomenological Results for $b\bar{b}H$ (5FS)

The Setup

- **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 **$\overline{\text{MS}}$ 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

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

[Biello, **AS**, Wiesemann, Zanderighi (2402.04025)]

Comparison to fixed-order results

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$_{PS}$
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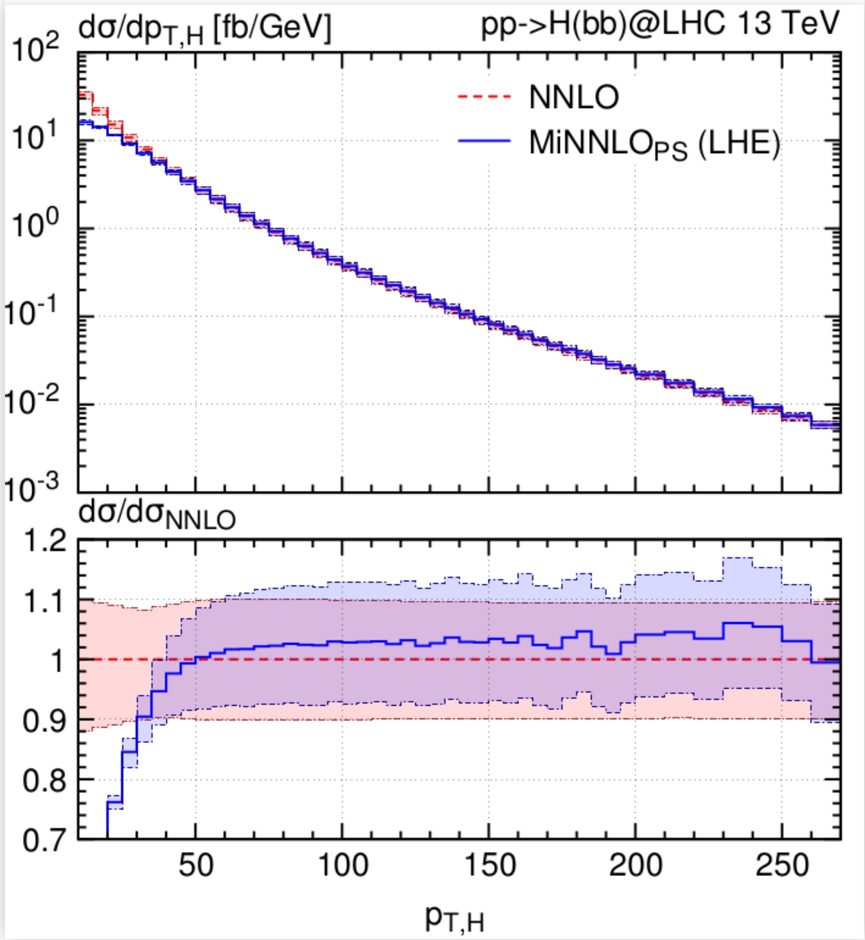
[Biello, **AS**, Wiesemann, Zanderighi (2402.04025)]

- 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)]
$\text{MiNNLO}_{\text{PS}}$ [Biello, **AS**, Wiesemann, Zanderighi (2402.04025)]

Comparison to fixed-order results

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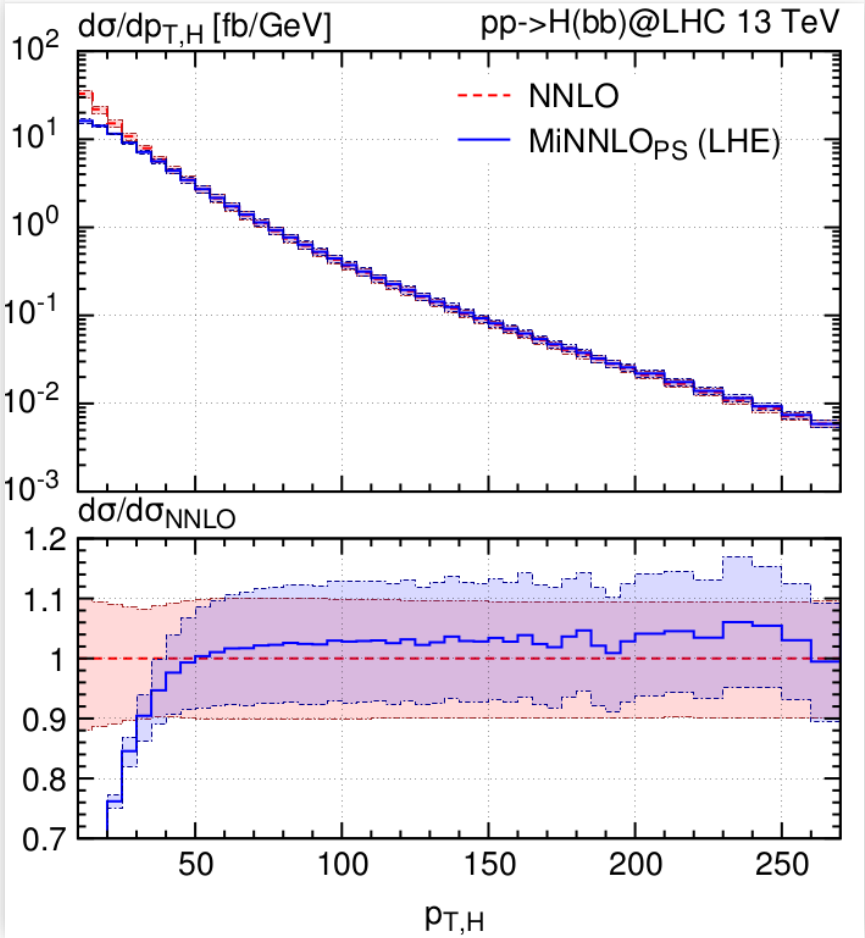


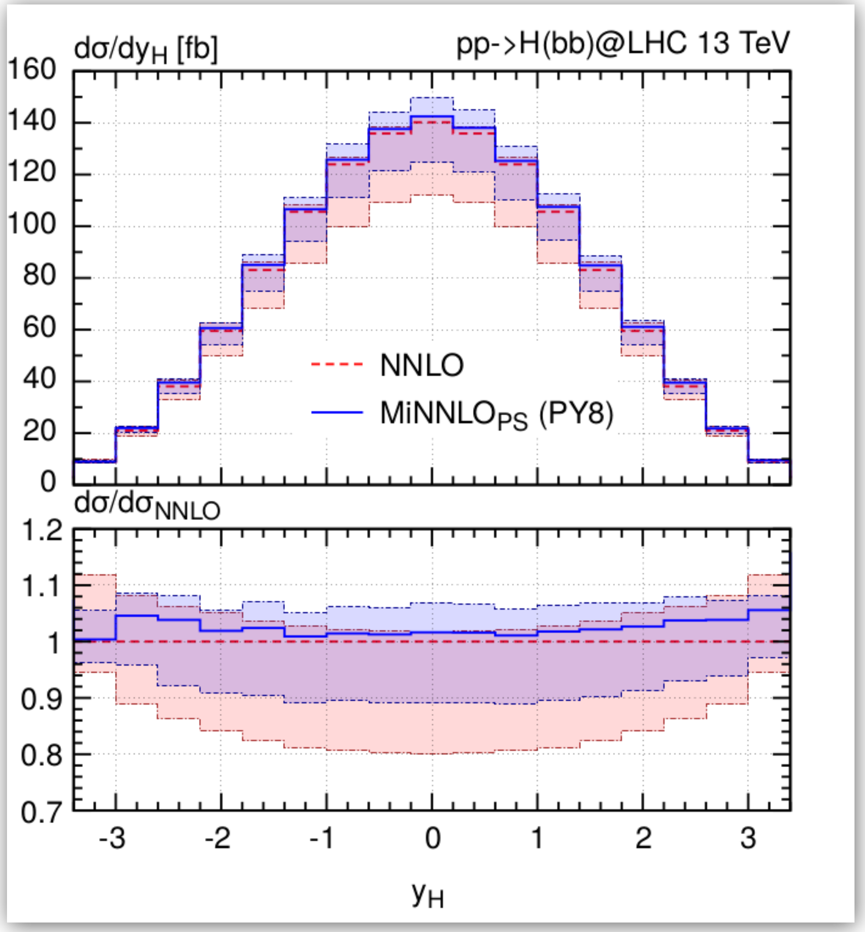
- **Full agreement** in **large $p_{T,H}$** regime with fixed-order predictions within quoted uncertainities
- Fixed-order calculations diverge for $p_{T,H} \to 0$ **MiNNLO$_{PS}$** prediction remains **finite**

NNLO [Harlander, Tripathi, Wiesemann (1403.7196)]
MiNNLO$_{PS}$ [Biello, **AS**, Wiesemann, Zanderighi (2402.04025)]

Comparison to fixed-order results

Rapidity distribution of the Higgs boson (y_H)

PY8 level



NNLO [Mondini, Williams (2102.05487)]
MiNNLO$_{PS}$ [Biello, **AS**, Wiesemann, Zanderighi (2402.04025)]

Comparison to fixed-order results

Rapidity distribution of the Higgs boson (y_H)

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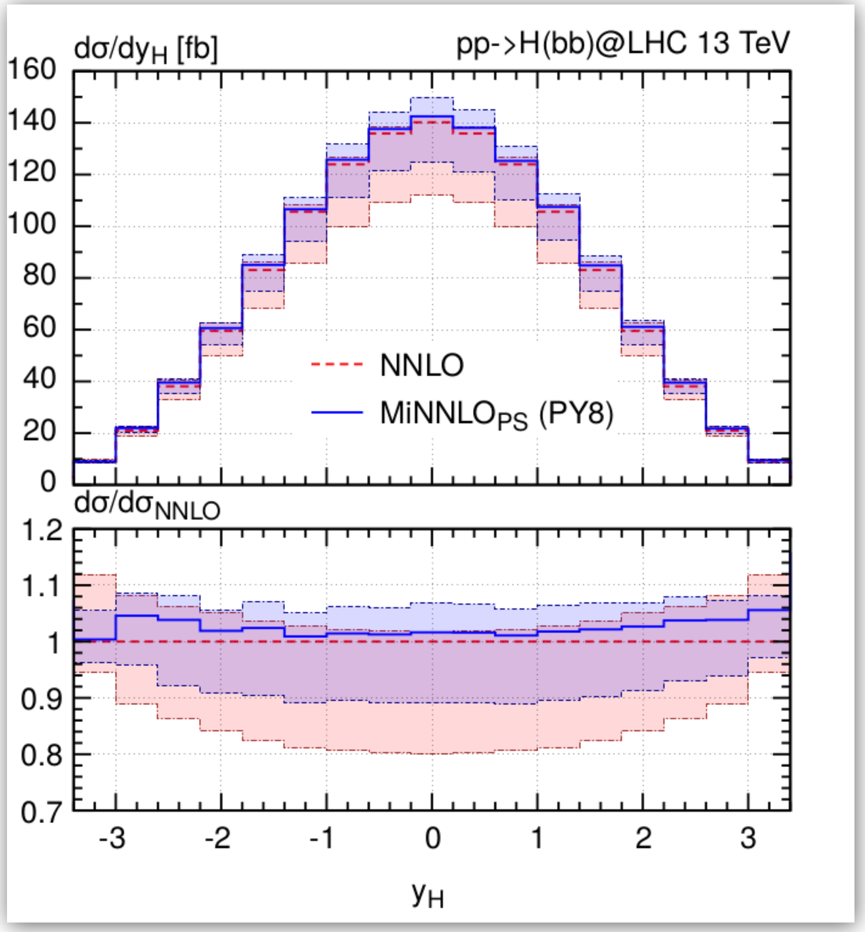


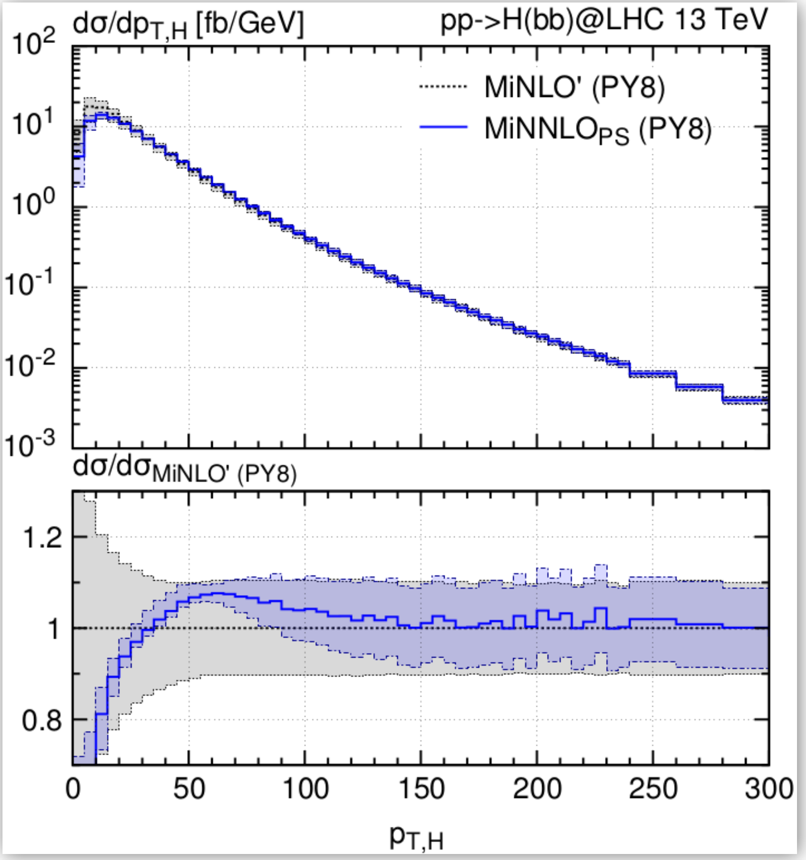
- A **good agreement**, both in terms of normalization and in terms of shape, between the two central predictions.
- The **bands** of **MiNNLO$_{PS}$** result are **more symmetric** & slightly **smaller** than the **NNLO** ones.

NNLO [Mondini, Williams (2102.05487)]
MiNNLO$_{PS}$ [Biello, **AS**, Wiesemann, Zanderighi (2402.04025)]

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

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

PY8 level



[Biello, **AS**, Wiesemann, Zanderighi (2402.04025)]

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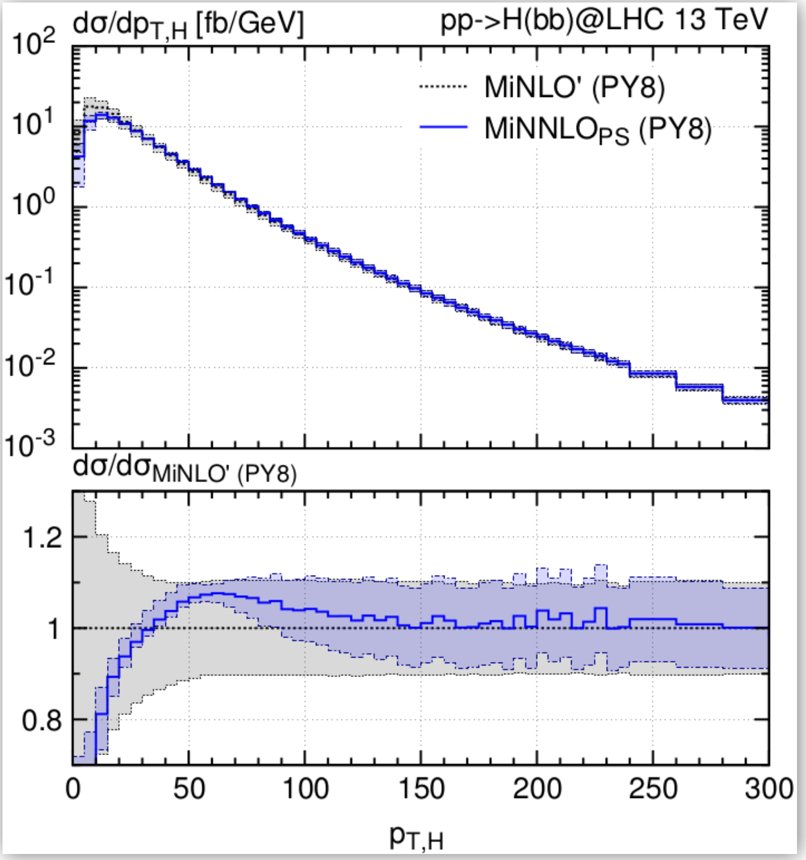
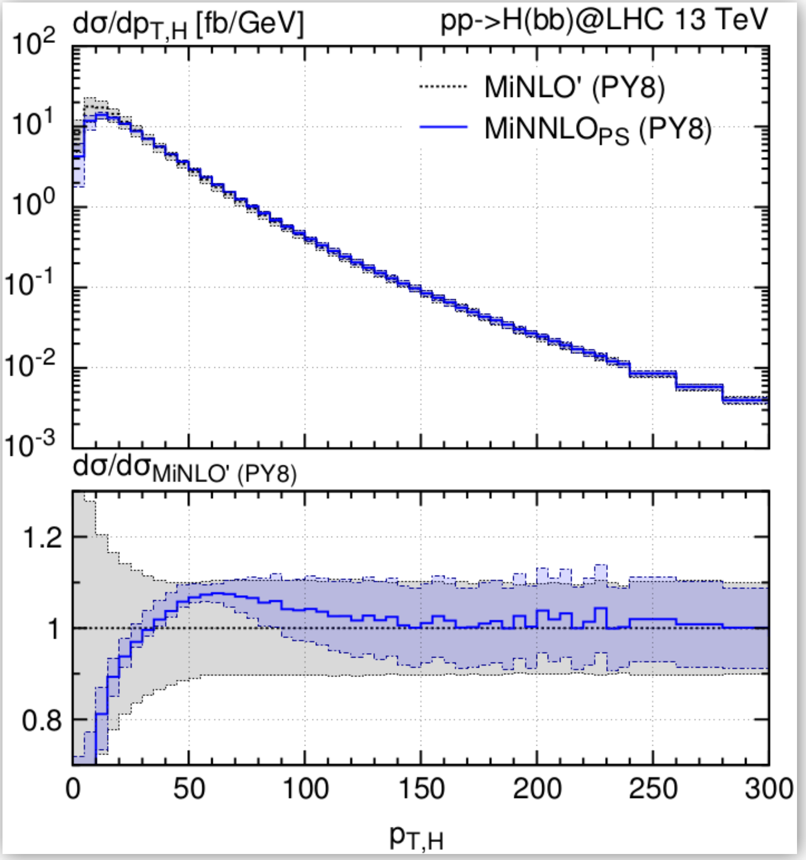


[Biello, **AS**, Wiesemann, Zanderighi (2402.04025)]

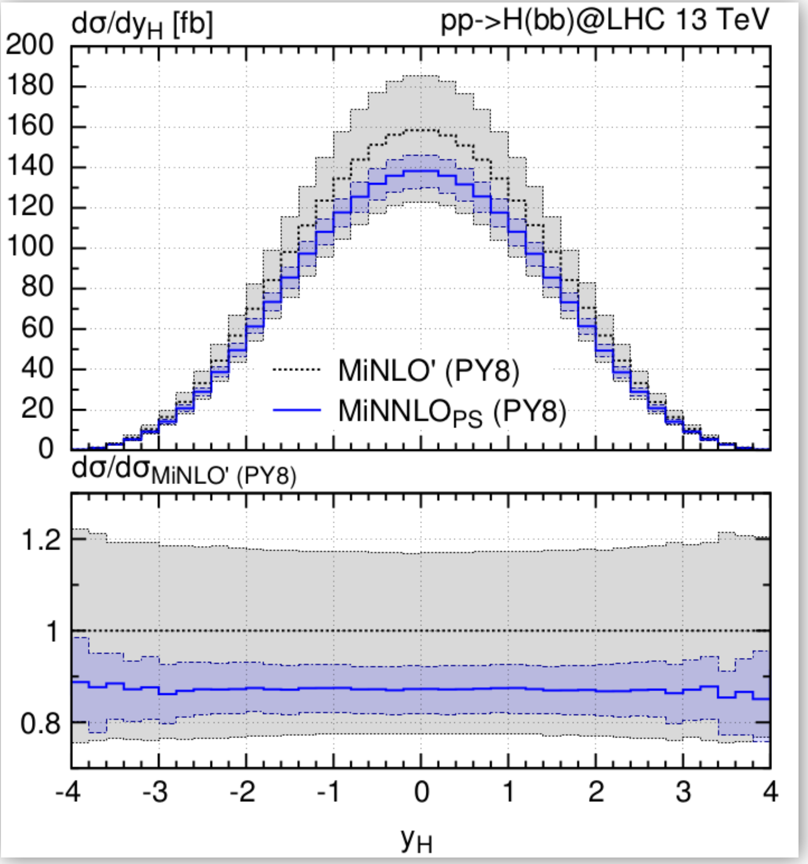
- At small p_T, **MiNNLO$_{PS}$** **significantly dampens** distributions, **reduces scale uncertainties.**
- At large p_T, **MiNLO'** & **MiNNLO$_{PS}$** predictions **coincide**, both **NLO** accurate.

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

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



Rapidity distribution of the Higgs (y_H)

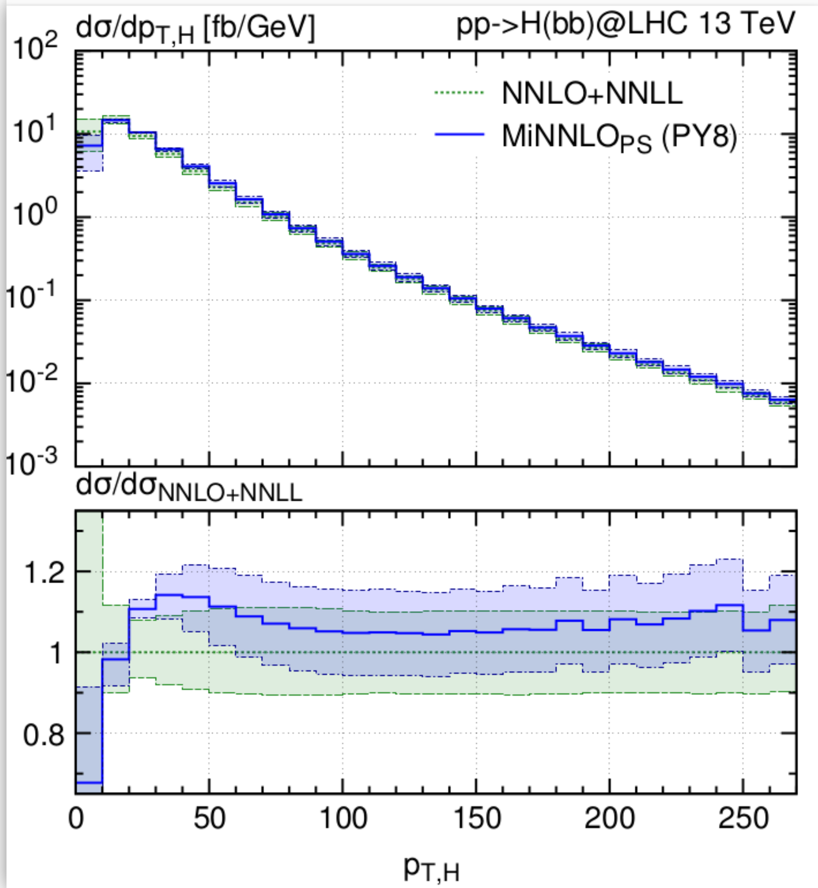


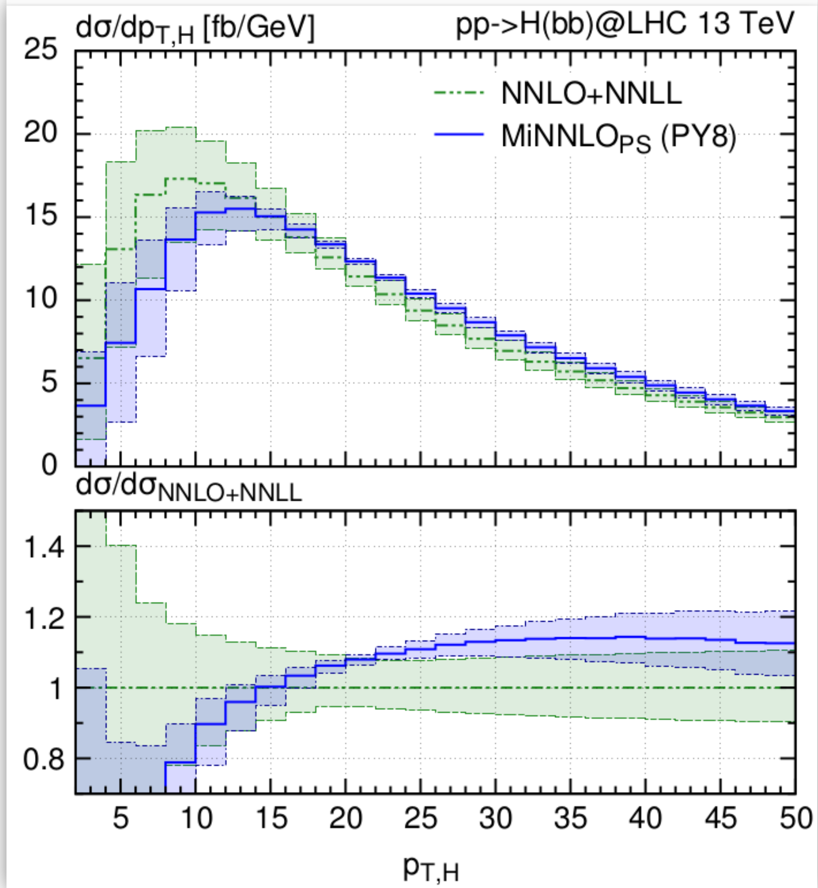
PY8 level

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

[Biello, **AS**, Wiesemann, Zanderighi (2402.04025)]

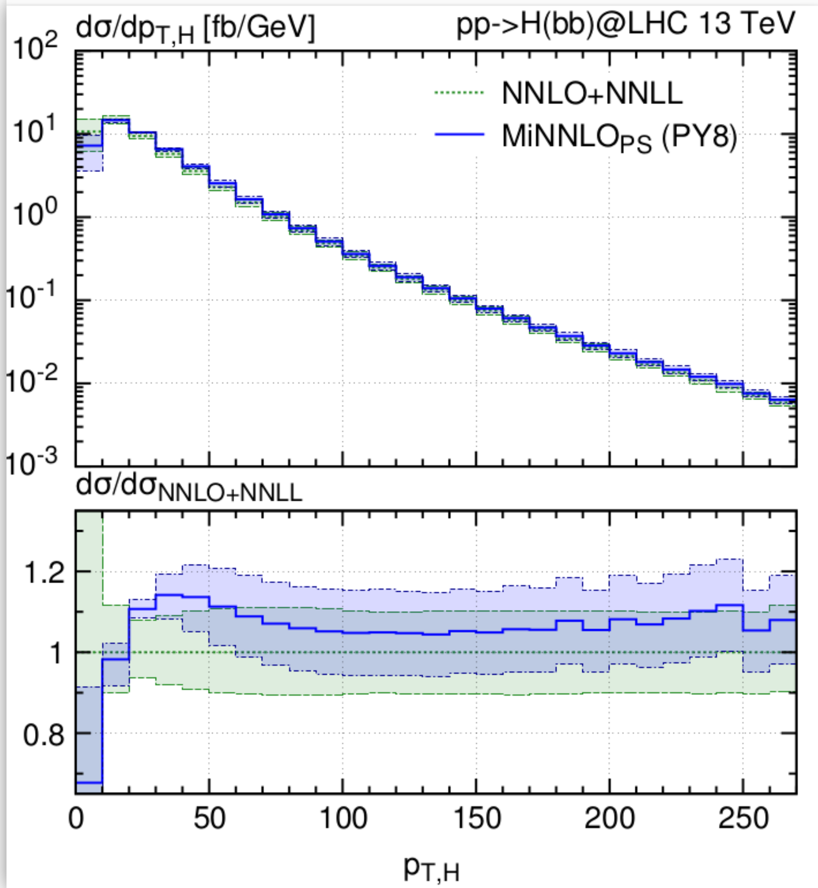
Comparison to NNLO+NNLL

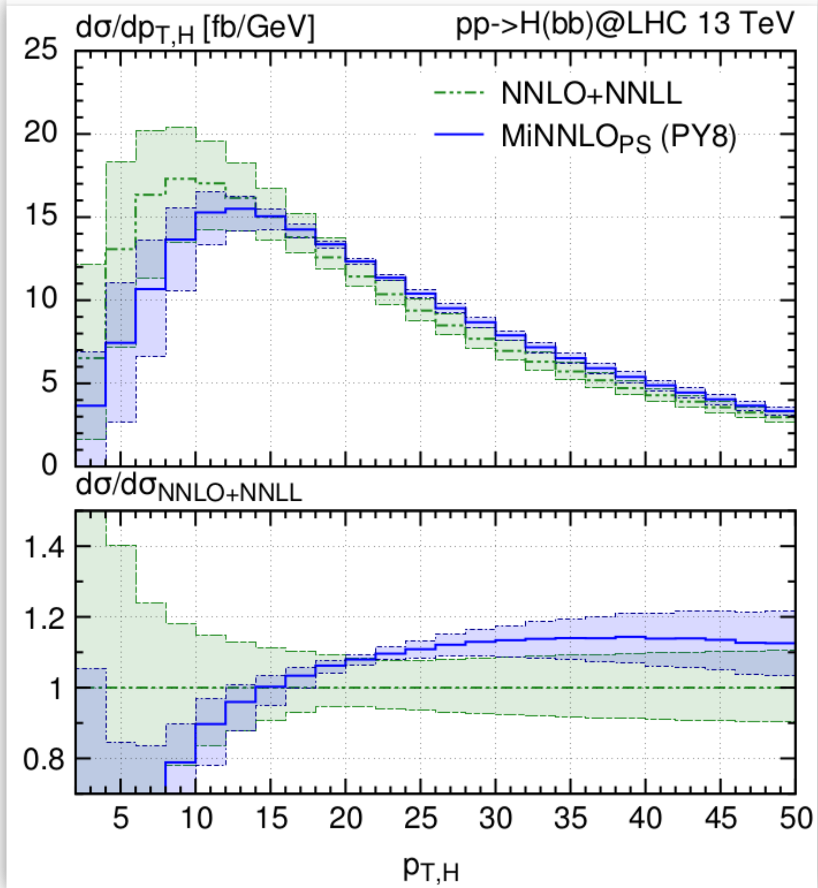




NNLO+NNLL [Harlander, Tripathi, Wiesemann (1403.7196)]
$\text{MiNNLO}_{\text{PS}}$ [Biello, **AS**, Wiesemann, Zanderighi (2402.04025)]

Comparison to NNLO+NNLL

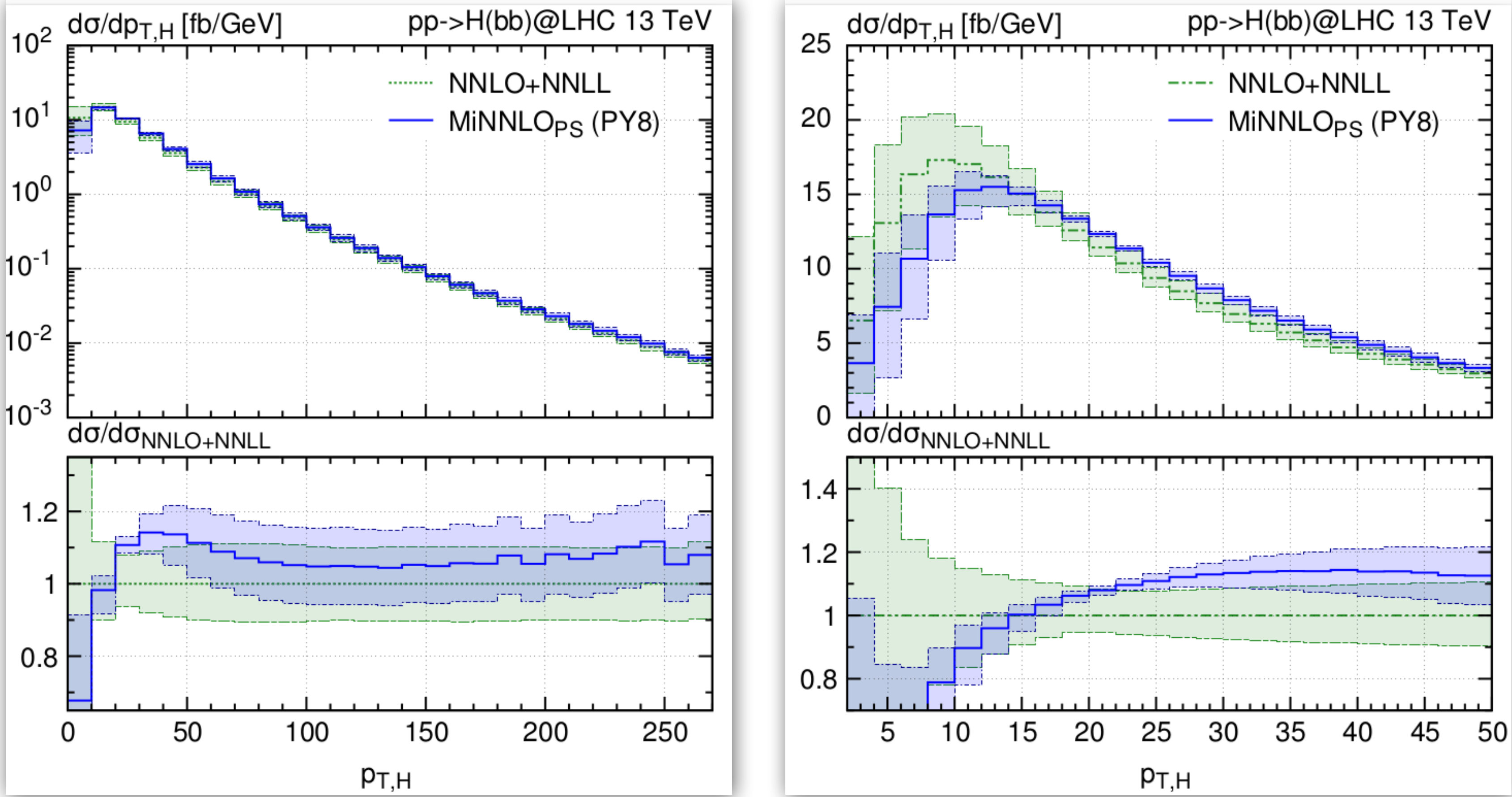




- **At large $p_{T,H}$:** MiNNLO$_{PS}$ shifted 10% up, well within the given scale-uncertainty bands.
- **At small $p_{T,H}$:** slightly worsen the agreement. MiNNLO$_{PS}$ uncertainities are **underestimated.**

NNLO+NNLL [Harlander, Tripathi, Wiesemann (1403.7196)]
MiNNLO$_{PS}$ [Biello, **AS**, Wiesemann, Zanderighi (2402.04025)]

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.**
- **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)]
MiNNLO$_{PS}$ [Biello, **AS**, Wiesemann, Zanderighi (2402.04025)]

$b\bar{b}H$ in the 4FS

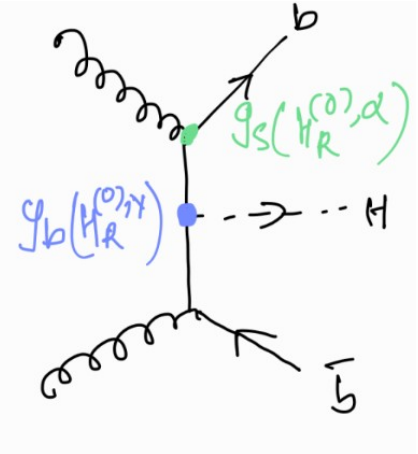
$b\bar{b}H$ in the 4FS

We implemented **NLO+PS** for **$Hb\bar{b}$** in **POWHEG** and compared it against **MiNLO'** obtained from a **$Hb\bar{b}j$** generator

$(\mu_R^{(0),\alpha}, \mu_R^{(0),y})$	NLO$_{PS}$	MiNLO'
$(\frac{H_T}{4}, m_H)$	$0.381(2)^{+20.2\%}_{-15.9\%}$ pb	$0.277(5)^{+34.5\%}_{-27.0\%}$ pb
$(\frac{H_T}{4}, \frac{H_T}{4})$	$0.406(4)^{+16.6\%}_{-14.3\%}$ pb	$0.315(3)^{+30.6\%}_{-27.5\%}$ pb

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

MiNLO' more than 20% less than NLO



[Biello, Mazzitelli, **AS**, Wiesemann, Zanderighi (in progress)]

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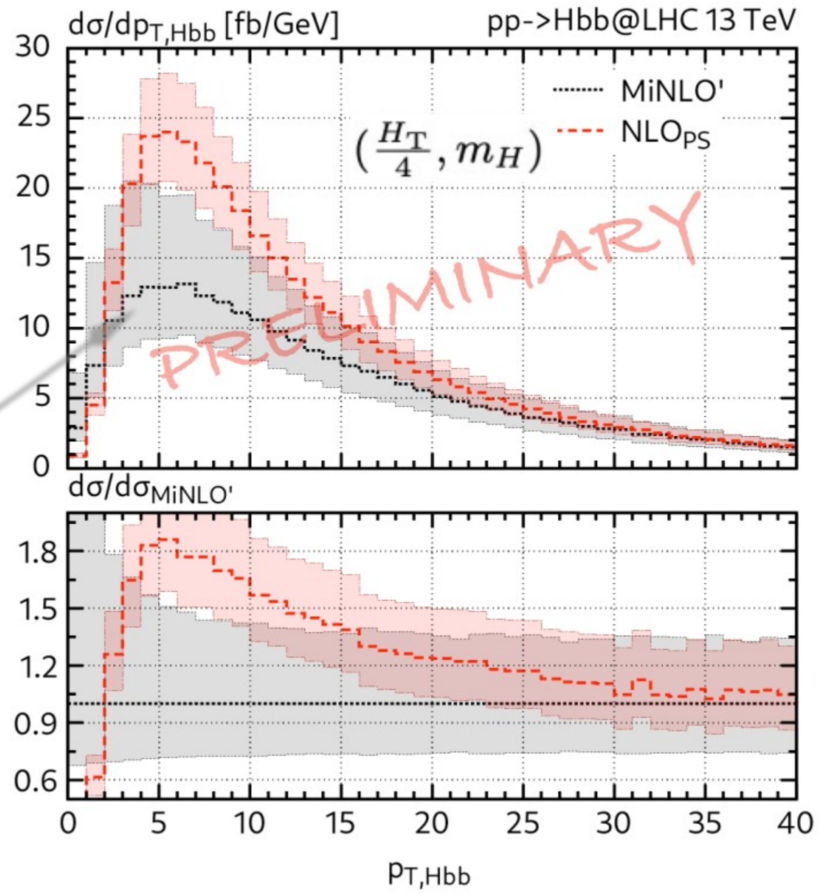
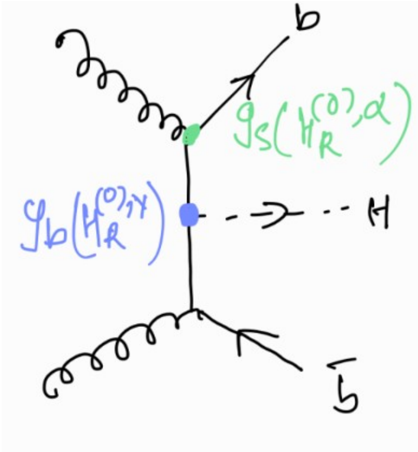




- In **`MiNLO'`**, the **large log(m_b)** terms in RV & RR contributions are **not balanced**.
- We need the **double virtual** (VV) to **cancel** this quasi-collinear **divergence**.

[Biello, Mazzitelli, **AS**, Wiesemann, Zanderighi (in progress)]

$b\bar{b}H$ in the 4FS

Double virtual Amplitude

The **VV correction** for a **massive bottom** pair and Higgs production is not known:
Approximation using the **massification procedure: leading mass corrections** are restored

Collinear poles in 5FS ⟷ **Logs of m_b in 4FS**

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

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

Massification coefficients

Massless double virtual amplitude

Double virtual Amplitude

The **VV correction** for a **massive bottom** pair and Higgs production is not known:
Approximation using the **massification procedure: leading mass corrections** are restored

Collinear poles in 5FS ⟷ **Logs of m_b in 4FS**

Predictions using **MiNNLO$_{PS}$**

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

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

Massification coefficients

Massless double virtual amplitude

$(\mu_R^{(0),\alpha}, \mu_R^{(0),y})$	NLO$_{PS}$	MiNLO'	MiNNLO$_{PS}$ ($\mathcal{F}^{(0)}=0$)
$(\frac{H_T}{4}, m_H)$	$0.381(2)^{+20.2\%}_{-15.9\%}$ pb	$0.277(5)^{+34.5\%}_{-27.0\%}$ pb	$0.434(1)^{+6.4\%}_{-9.9\%}$ pb
$(\frac{H_T}{4}, \frac{H_T}{4})$	$0.406(4)^{+16.6\%}_{-14.3\%}$ pb	$0.315(3)^{+30.6\%}_{-27.5\%}$ pb	$0.443(9)^{+4.0\%}_{-8.7\%}$ pb

[Biello, Mazzitelli, **AS**, Wiesemann, Zanderighi (in progress)]

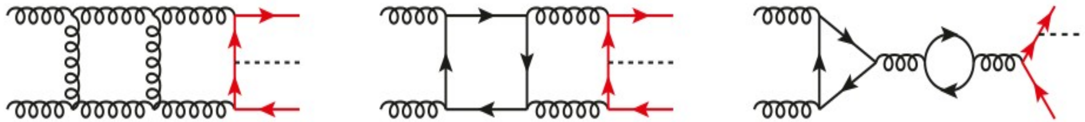
MiNNLO$_{PS}$ with **only logarithmic** contributions in the 2-loop predicts a total cross-section **bigger** than the **NLO+PS** one.

Double virtual Amplitude

- We used analytic VV amplitudes for massless bottoms computed in the leading color approximation

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

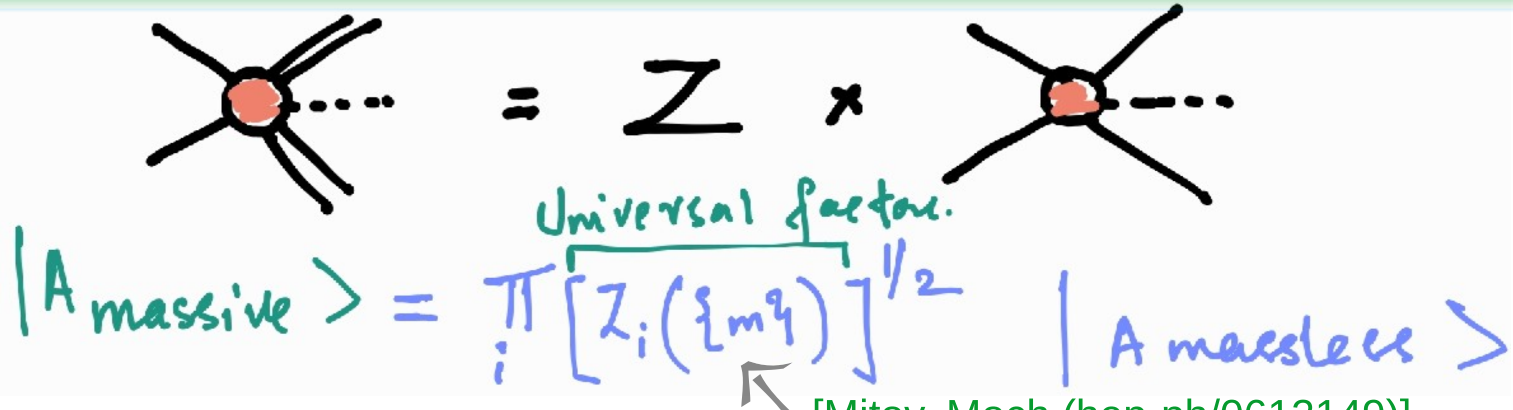
[Badger, Hartanto, Kryś, Zoia (2107.14733)]



- Evaluation of special functions through **PentagonFunctions++** [Chicherin, Sotnikov, Zoia (2110.10111)]
- C++ code interfaced with POWHEG
- We cross-checked against the Zurich implementation (Chiara Savoini)

Massification procedure

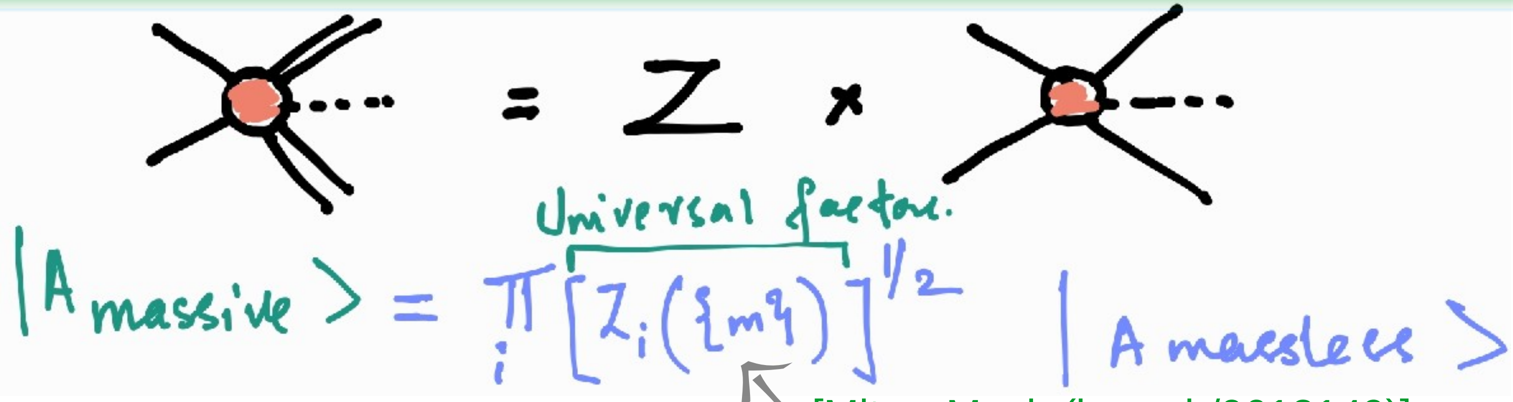
Original massification (OM)



[Mitov, Moch (hep-ph/0612149)]

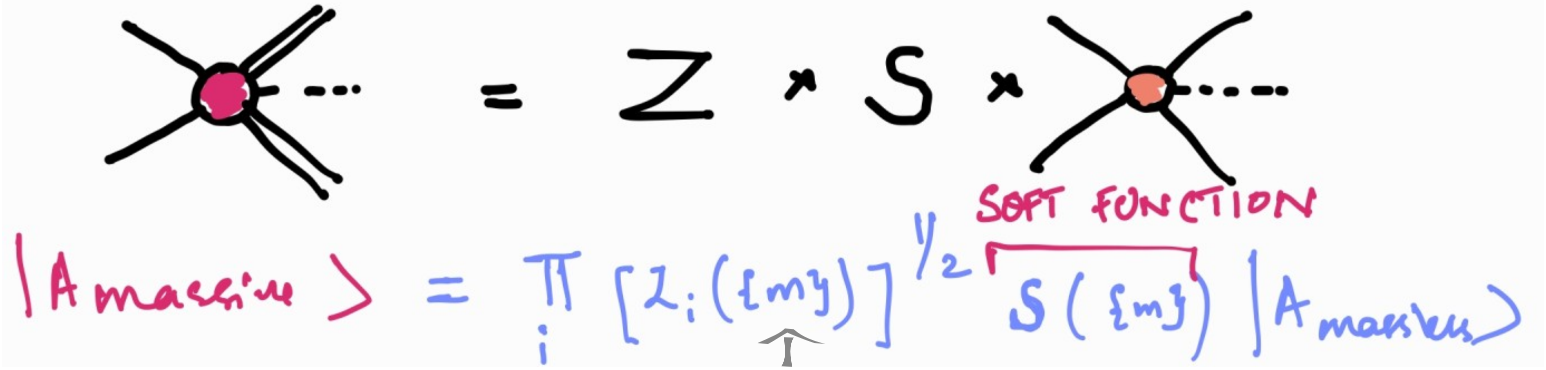
Massification procedure

Original massification (OM)



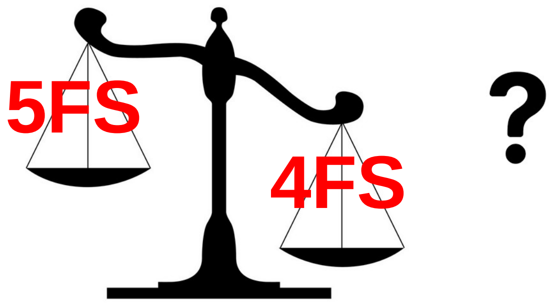
[Mitov, Moch (hep-ph/0612149)]

Generalised massification (GM)

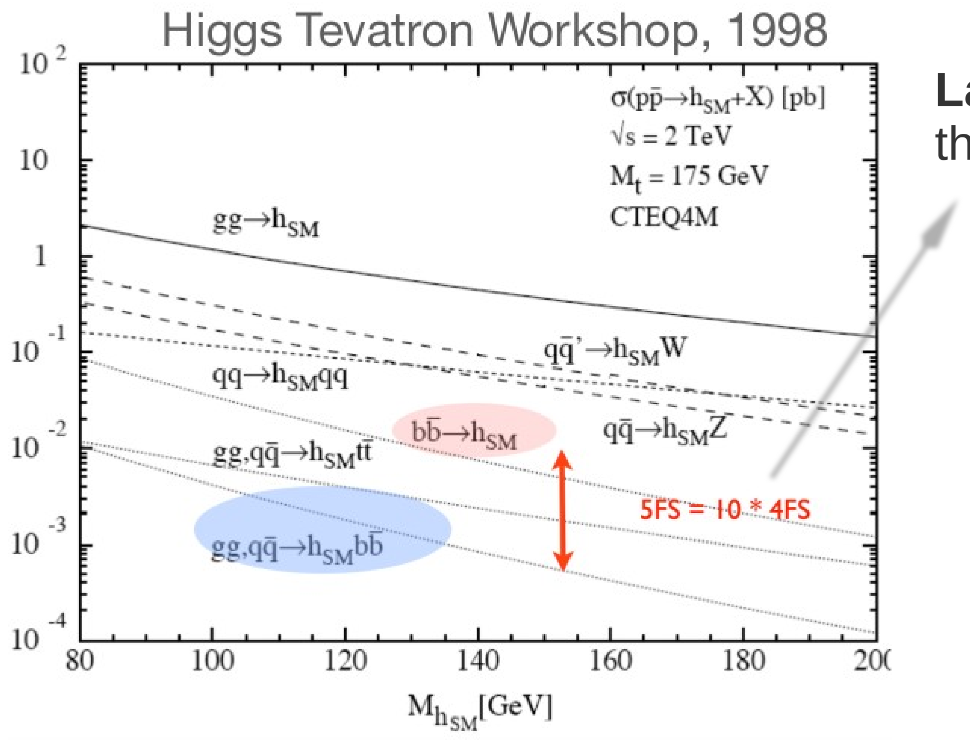


Additional contribution to account for closed b loops
[Wang, Xia, Yang, Ye (2312.12242)]

Flavour scheme comparisons

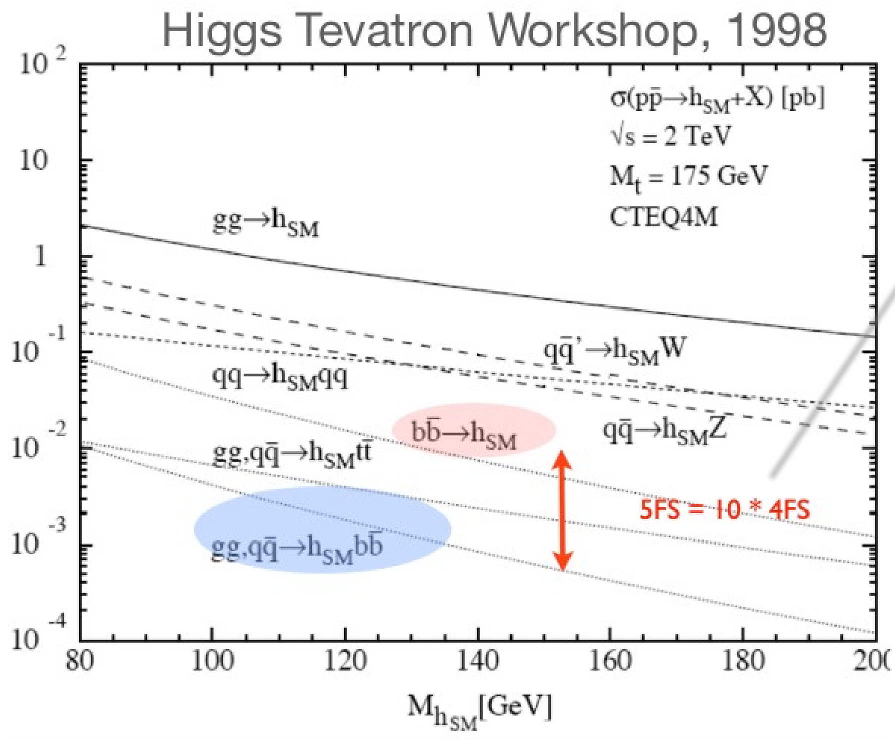


Total cross-section



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

Total cross-section

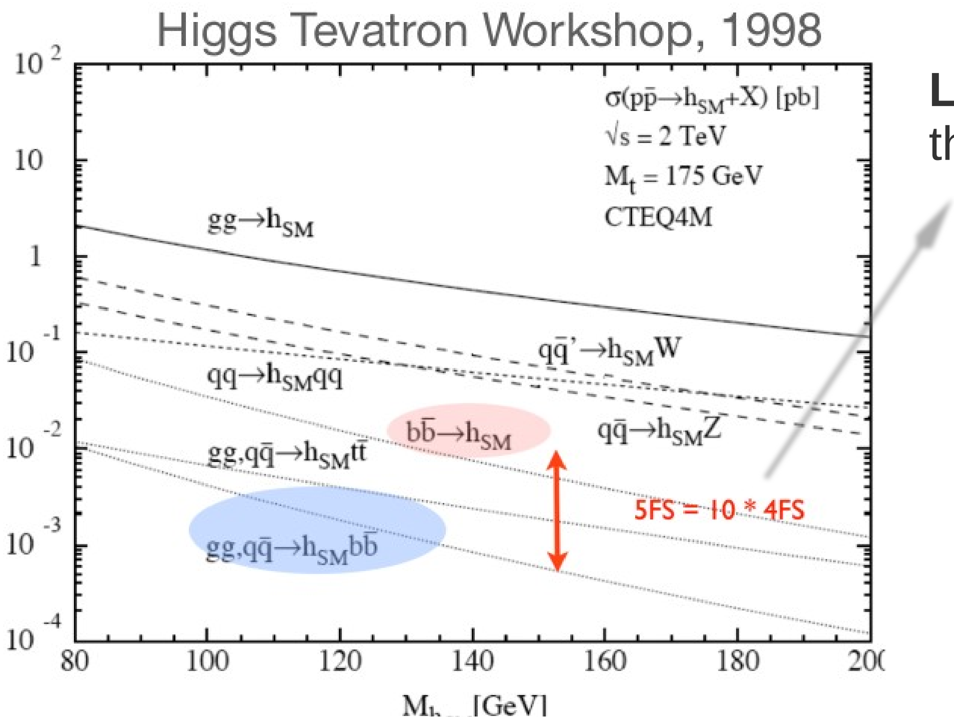


Large differences in the predictions were first observed at the **LO**: the effect of collinear resummation is extremely large.

NLO : 5FS = 1.78 * 4 FS

NLO+PS (5FS)	NLO+PS (4FS)
$0.677(2)^{+11\%}_{-11\%}$ pb	$0.381(0)^{+20\%}_{-16\%}$ pb

Total cross-section



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

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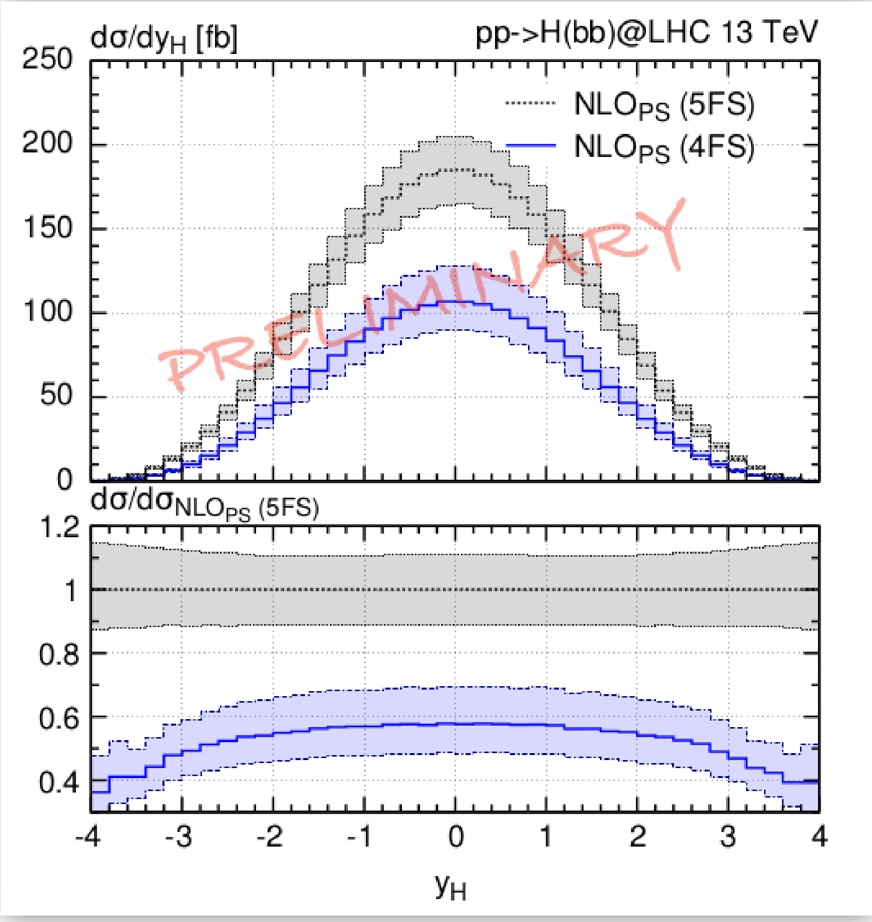
NLO+PS (5FS)	NLO+PS (4FS)
$0.677(2)^{+11\%}_{-11\%}$ pb	$0.381(0)^{+20\%}_{-16\%}$ pb

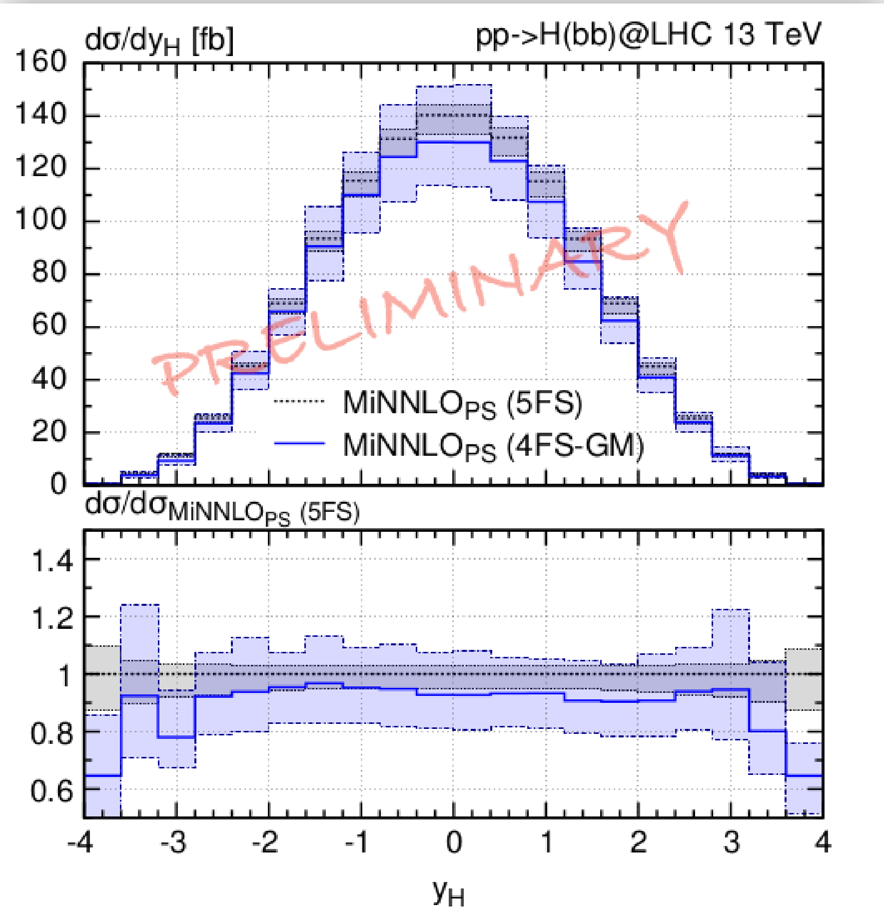
NNLO : 5FS = 1.09 * 4 FS : The best prediction till today..

MiNNLO$_{PS}$ (5FS)	MiNNLO$_{PS}$ (4FS- $\mathscr{F}^0$ =0, OM)	MiNNLO$_{PS}$ (4FS-$\mathscr{F}^0$=1, OM)	MiNNLO$_{PS}$ (4FS-$\mathscr{F}^0$=1, GM)
$0.509(8)^{+3.0\%}_{-5.0\%}$ pb	$0.434(1)^{+6.4\%}_{-9.9\%}$ pb	$0.460(7)^{+13.0\%}_{-13.0\%}$ pb	$0.464(9)^{+14\%}_{-13\%}$ pb

[Biello, Mazzitelli, **AS**, Wiesemann, Zanderighi (in progress)]

Higgs rapidity



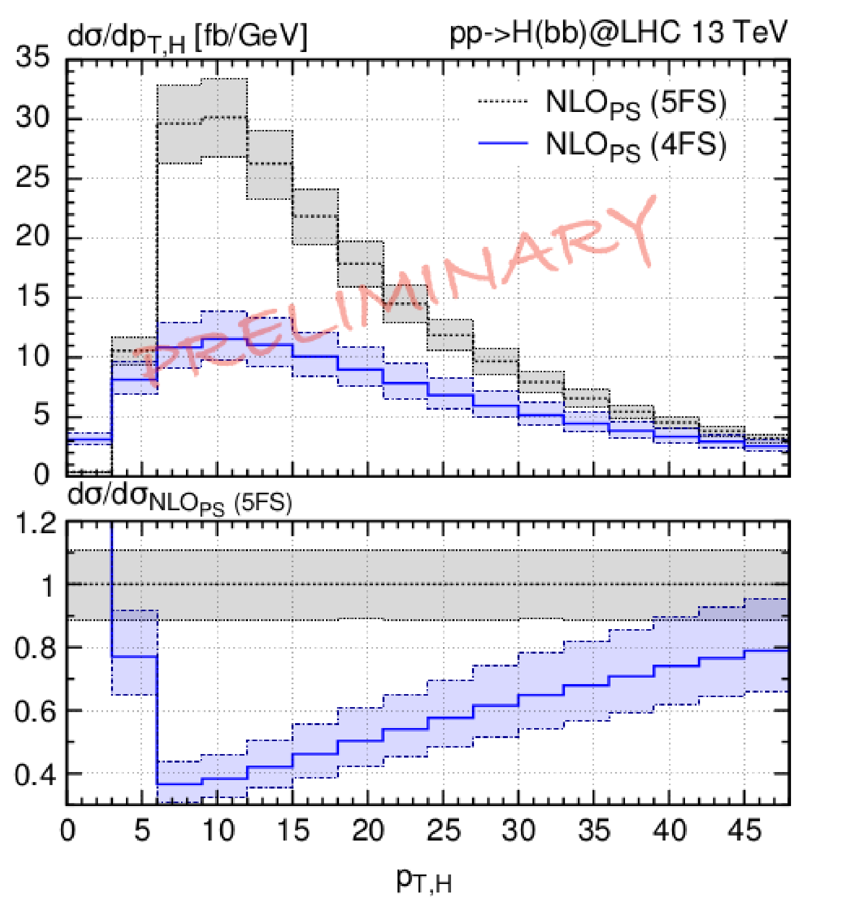


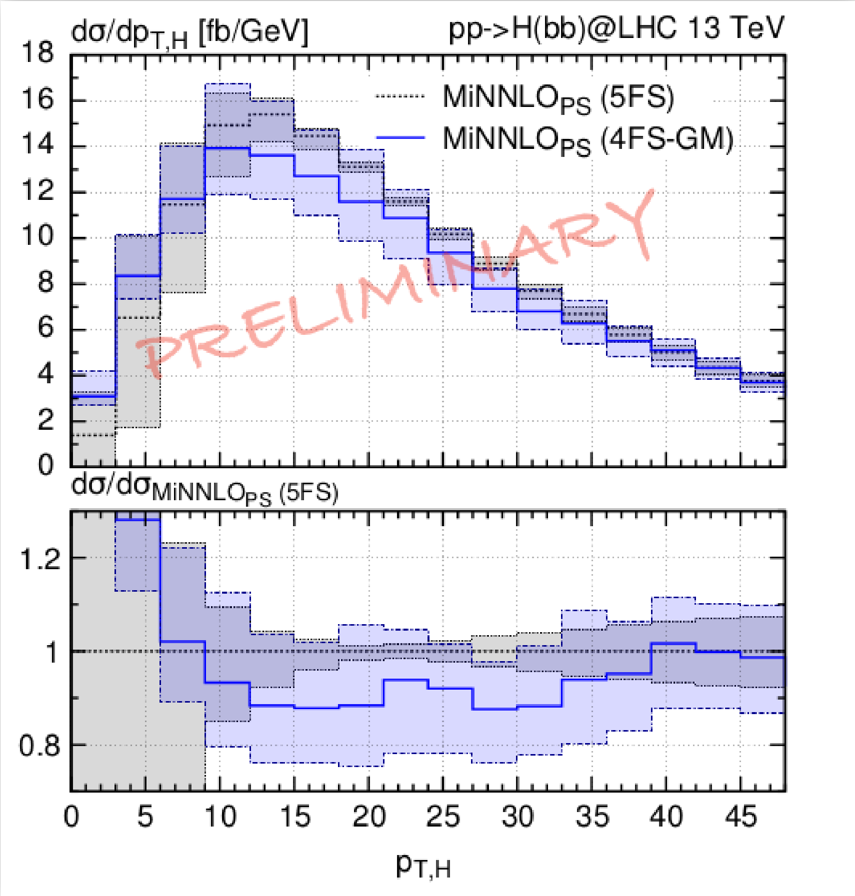
4FS

$\left(\frac{H_T}{4}, m_H\right)$

[Biello, Mazzitelli, **AS**, Wiesemann, Zanderighi (in progress)]

Higgs p_T spectrum





4FS

$$\left(\frac{H_T}{4}, m_H\right)$$

[Biello, Mazzitelli, **AS**, Wiesemann, Zanderighi (in progress)]

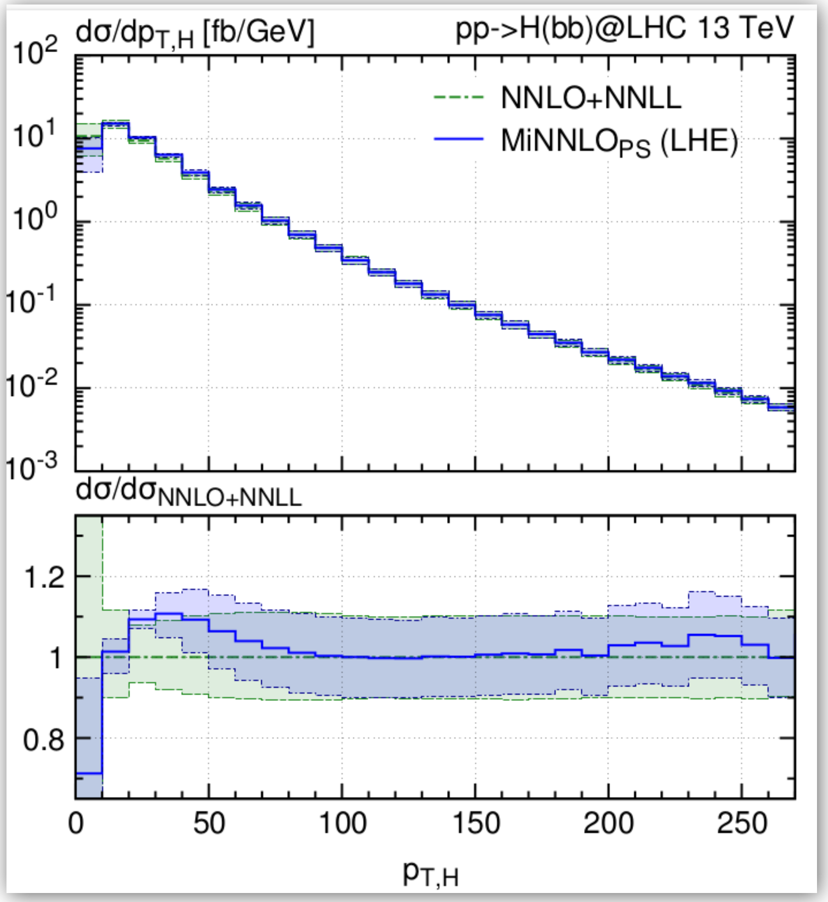
Summary & Outlook

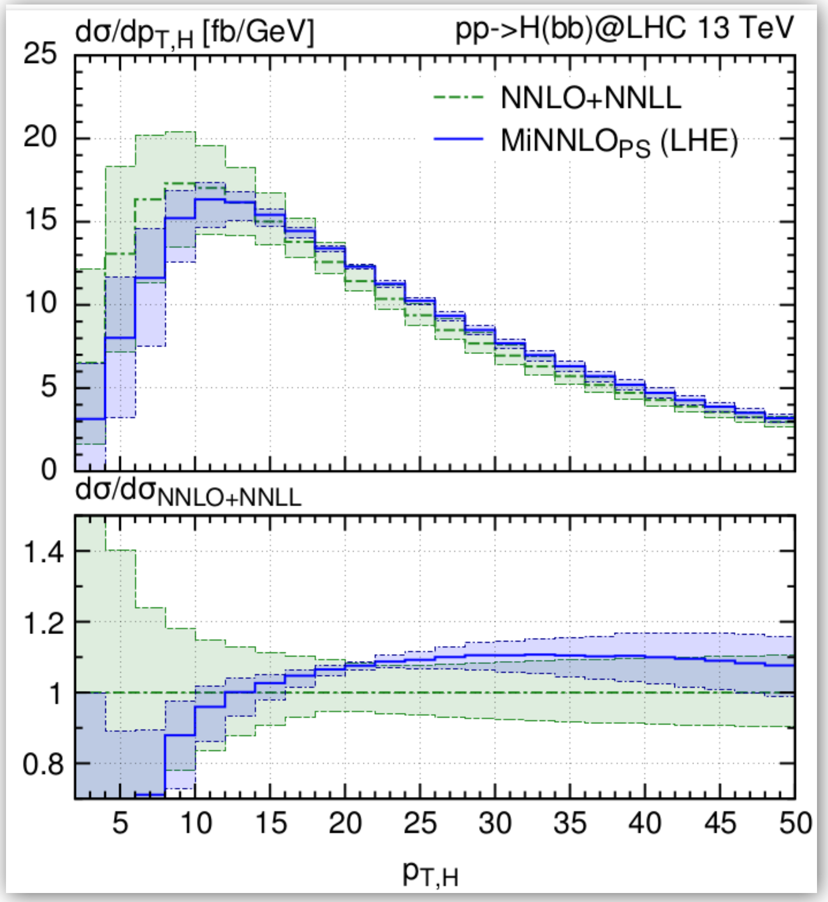
- Presented the **first NNLO+PS** computation for $\mathbf{b\bar{b}H}$ in both **5FS & 4FS** at the LHC by using $\texttt{MiNNLO}_{\texttt{PS}}$ method.
- Extensive **validation of 5FS** predictions against **fixed-order results** from literature, showcasing **consistency** in relevant kinematical regions.
- **For the 4FS, approximation** of the **double virtual** using the **massification** procedure
- Theoretical **tension** between the **4FS** & **5FS** predictions seem to stabilise **at NNLO**.
- **Future** directions include **combination** of full **4FS–5FS at NNLO+PS** and also **b-tagging** of the $\texttt{MiNNLO}_{\texttt{PS}}$ events.

THANK YOU !

Backup slides.....

Comparison to NNLO+NNLL

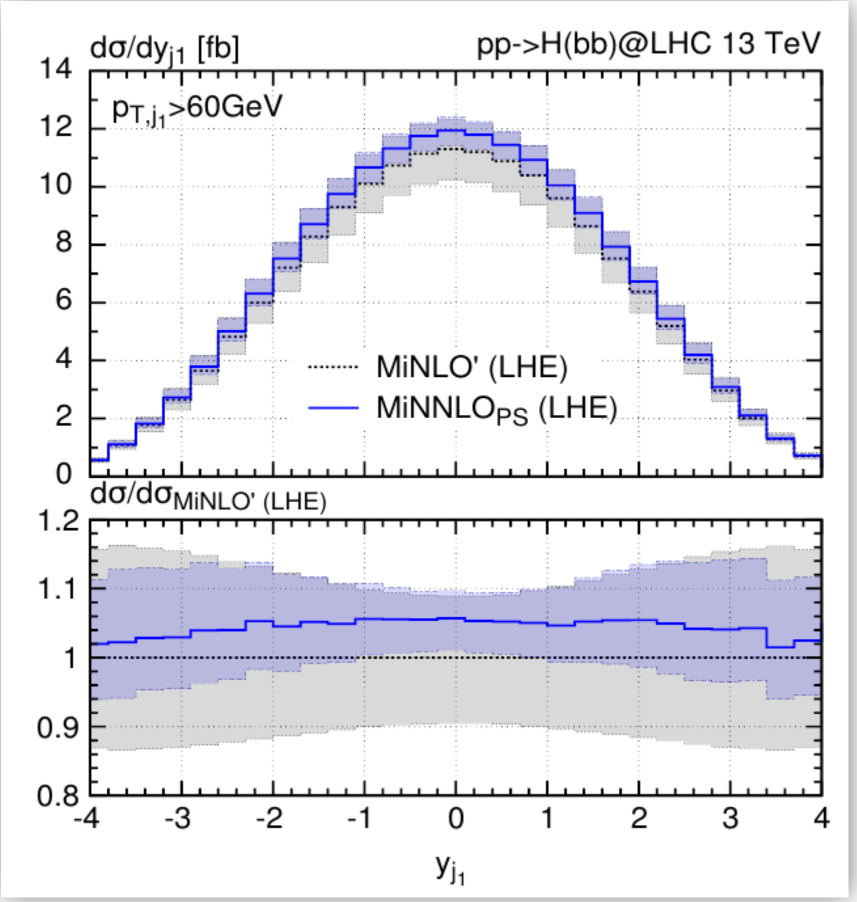


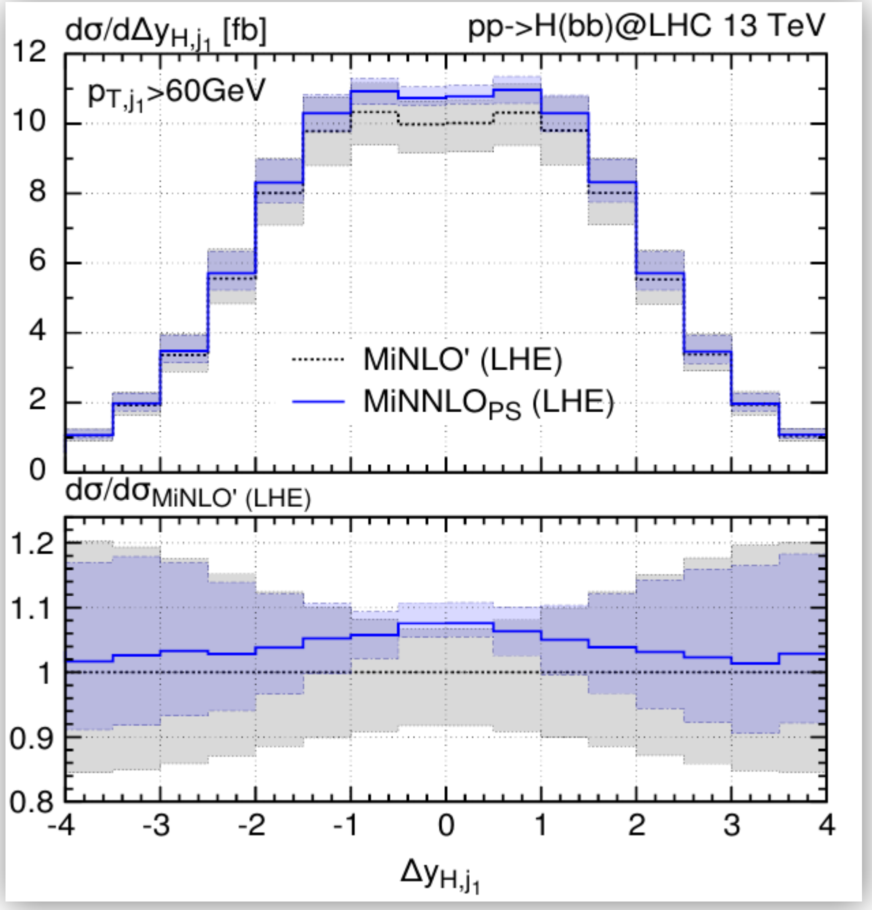


At high $p_{T,H}$:
they coincide again

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

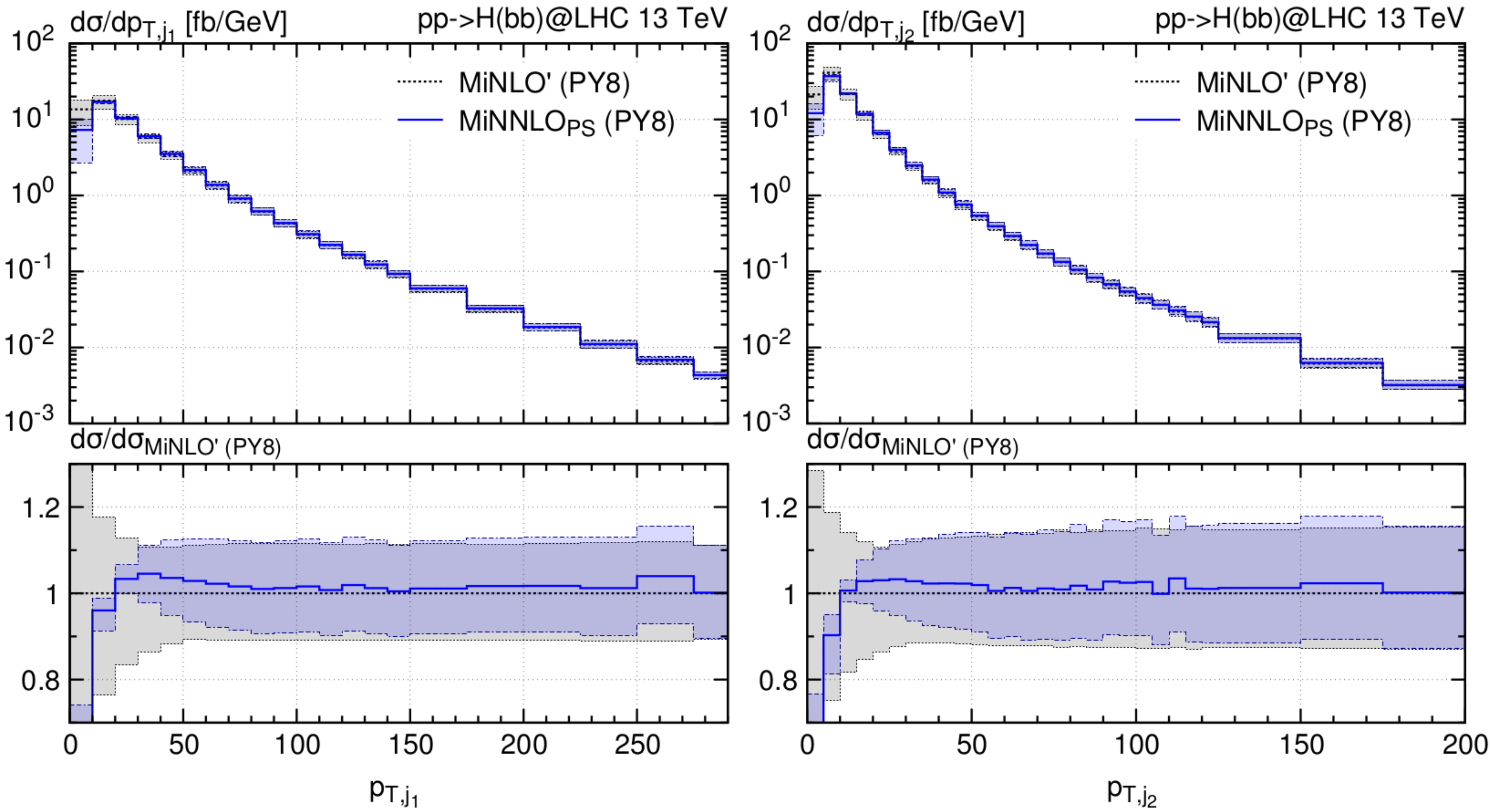
Comparison of MiNLO' & MiNNLO$_{PS}$





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

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



Momentum mappings | 4FS

- In 4FS, the phase-space integration is performed with $m_b \neq 0$.
- The massless amplitudes must be evaluated on on-shell phase-space points P_0 with $m_b = 0$.

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

- We need an explicit mapping of massive phase-space points P , $\eta : P \to P_0$, such that $\eta(P) = P_0 + O(m_b/m_H)$.
- We have to ensure that η does not cause amplitudes to be evaluated near their singularities.
- Since the quark- and gluon-initiated channels have distinct leading order momentum flows, we use dedicated mappings $\eta_{q\bar{q}}$, η_{gg} for each of the channels.

[Mazzitelli, Sotnikov, Wiesemann (2404.08598)]

Momentum mappings | 4FS

For $\eta_{q\bar{q}}$, we perform the simultaneous light-cone decomposition of the massive bottom and anti-bottom momenta p_b and $p_{\bar{b}}$, respectively, and determine the massless momenta $\hat{p}_b$ and $\hat{p}_{\bar{b}}$ as

$$\hat{p}_b = \alpha^+ p_b - \alpha^- p_{\bar{b}}, \qquad \alpha^\pm = \frac{1}{2}\left(1 \pm \left(1 - 4\frac{m_b^2}{m_{b\bar{b}}}\right)^{-\frac{1}{2}}\right)$$

$$\hat{p}_{\bar{b}} = \alpha^+ p_{\bar{b}} - \alpha^- p_b,$$

which preserves the total momentum $\hat{p}_{b\bar{b}} \equiv p_{b\bar{b}}$ of the $b\bar{b}$ system and prevents a collinear $g \to b\bar{b}$ splitting in the quark channel.

The mapping $\eta_{q\bar{q}}$ is minimal in the sense that only the bottom-quark momenta are modified.

[Mazzitelli, Sotnikov, Wiesemann (2404.08598)]

Momentum mappings | 4FS

An side effect of the mapping $\eta_{q\bar{q}}$ (when applied in the gluon channel) is that p_b or $p_{\hat{\bar{b}}}$ can become collinear to the initial state momenta p_1 or p_2 when the $b\bar{b}$ pair is produced at the threshold.

In the gluon channel this introduces a collinear singularity, and we therefore construct η_{gg} such that it avoids these configurations.

First, we set the massless momenta to

$$\hat{p}_x = p_x + \left(\sqrt{1 - \frac{m_b^2 n_x^2}{(p_x \cdot n_x)^2}} - 1\right) \frac{(p_x \cdot n_x)}{n_x^2}\, n_x \quad \text{with } x \in \{b, \bar{b}\}$$

$$n_x = p_x - p_1 \frac{(p_2 \cdot p_x)}{(p_1 \cdot p_2)} - p_2 \frac{(p_1 \cdot p_x)}{(p_1 \cdot p_2)},$$

where n_x are transverse to both p1 and p2 .

[Mazzitelli, Sotnikov, Wiesemann (2404.08598)]

Momentum mappings | 4FS

Then to restore momentum conservation we consider two options:

1. We redistribute $\Delta p_{b\bar{b}} = p_b + p_{\bar{b}} - \hat{p}_b - \hat{p}_{\bar{b}}$ into $\hat{p}_1$ and $\hat{p}_2$, such that $\hat{p}_{12} = \hat{p}_1 + \hat{p}2 = p1 + p2 - \Delta p_{b\bar{b}}$, by performing a Lorentz boost on p_1 and p_2 in the direction $-\hat{p}_{12}$ followed by rescaling with $\sqrt{\hat{p}_{12}^2/p_{12}^2}$

OR

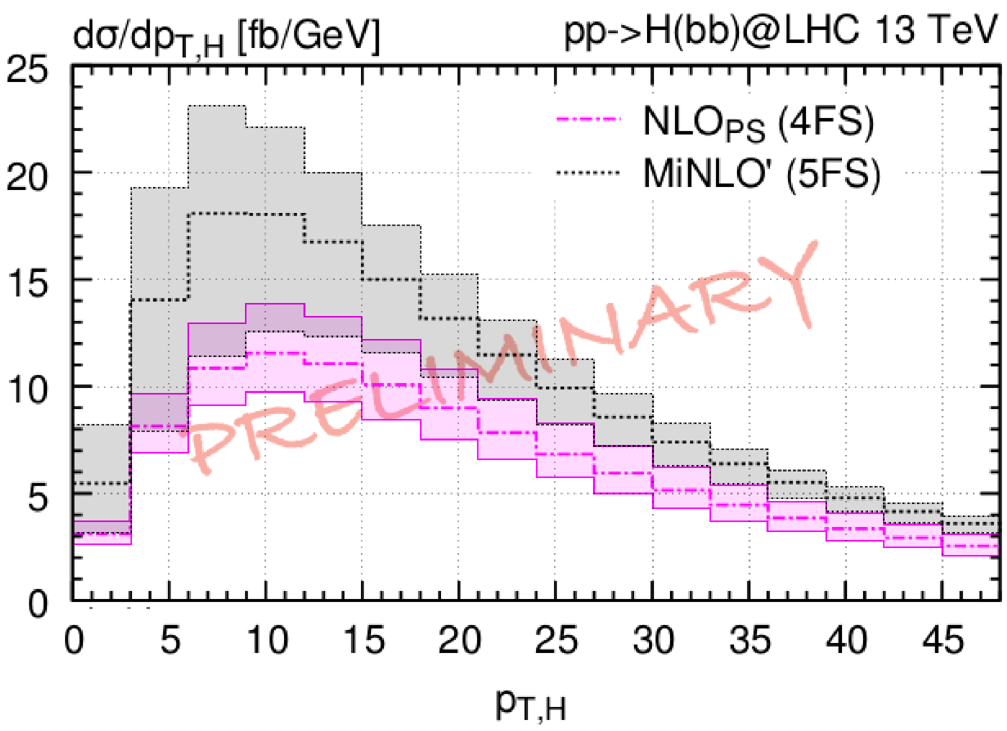
2. we redistribute $\Delta p_{b\bar{b}}$ into the Higgs momemtum instead.

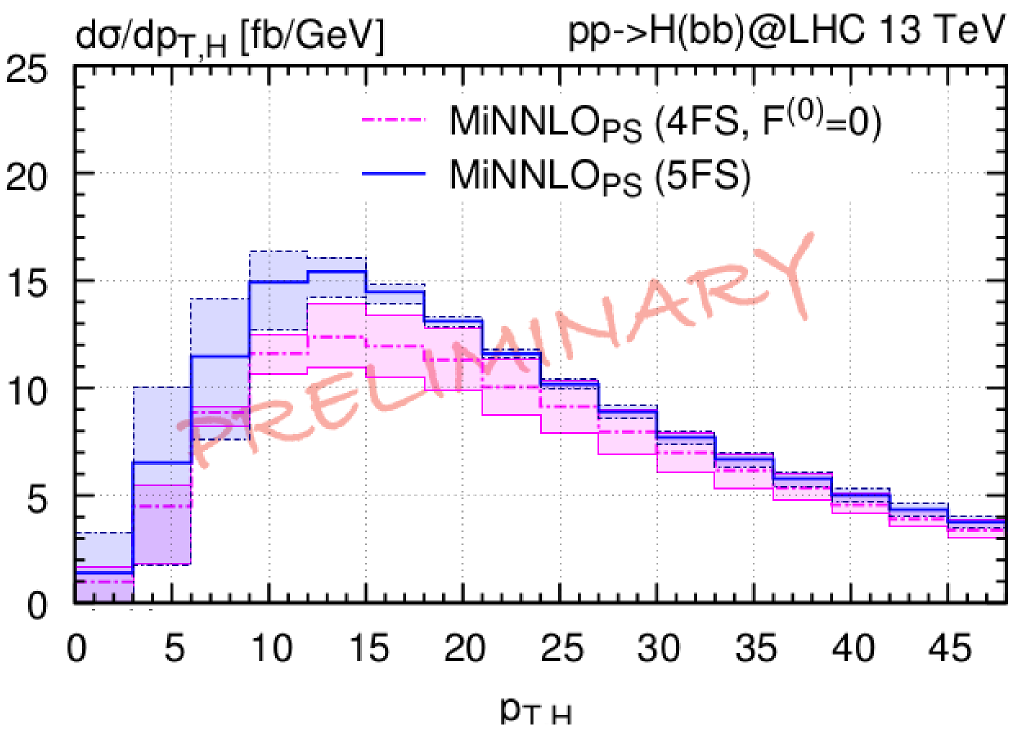
[Mazzitelli, Sotnikov, Wiesemann (2404.08598)]

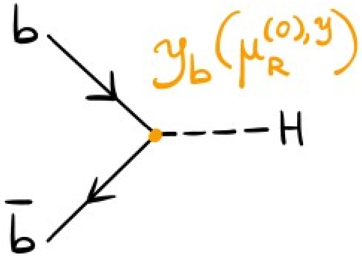
Cross-section details (4FS)

K_R	K_F	MiNLO$'$	MiNNLO$_{PS}$ (Orig. Mass.)	MiNNLO$_{PS}$ (Gen. Mass.)
1	1	0.277(0)	0.460(7)	0.464(9)
1	2	0.268(8)	0.465(2)	0.470(7)
2	1	0.192(5)	0.403(0)	0.408(1)
2	2	0.195(5)	0.407(0)	0.412(1)
1	$\frac{1}{2}$	0.258(9)	0.457(8)	0.466(0)
$\frac{1}{2}$	1	0.382(7)	0.520(7)	0.527(4)
$\frac{1}{2}$	$\frac{1}{2}$	0.375(3)	0.519(3)	0.525(1)
		$0.277(0)^{+34\%}_{-27\%}$ pb	$0.460(7)^{+13\%}_{-13\%}$ pb	$0.464(9)^{+14\%}_{-13\%}$ pb

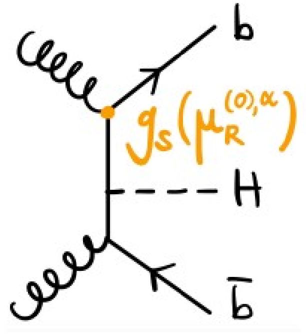
Before the two-loop | 4FS







$(\mu_R^{(0),\alpha}, \mu_R^{(0),y})$	NLO$_{PS}$ (5FS)	NLO$_{PS}$ (4FS)	MiNNLO$_{PS}$ (5FS)	MiNNLO$_{PS}$ (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



FONLL matching

- 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

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