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

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In collaboration with
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Frontiers in precision phenomenology: RAS 2024 Workshop

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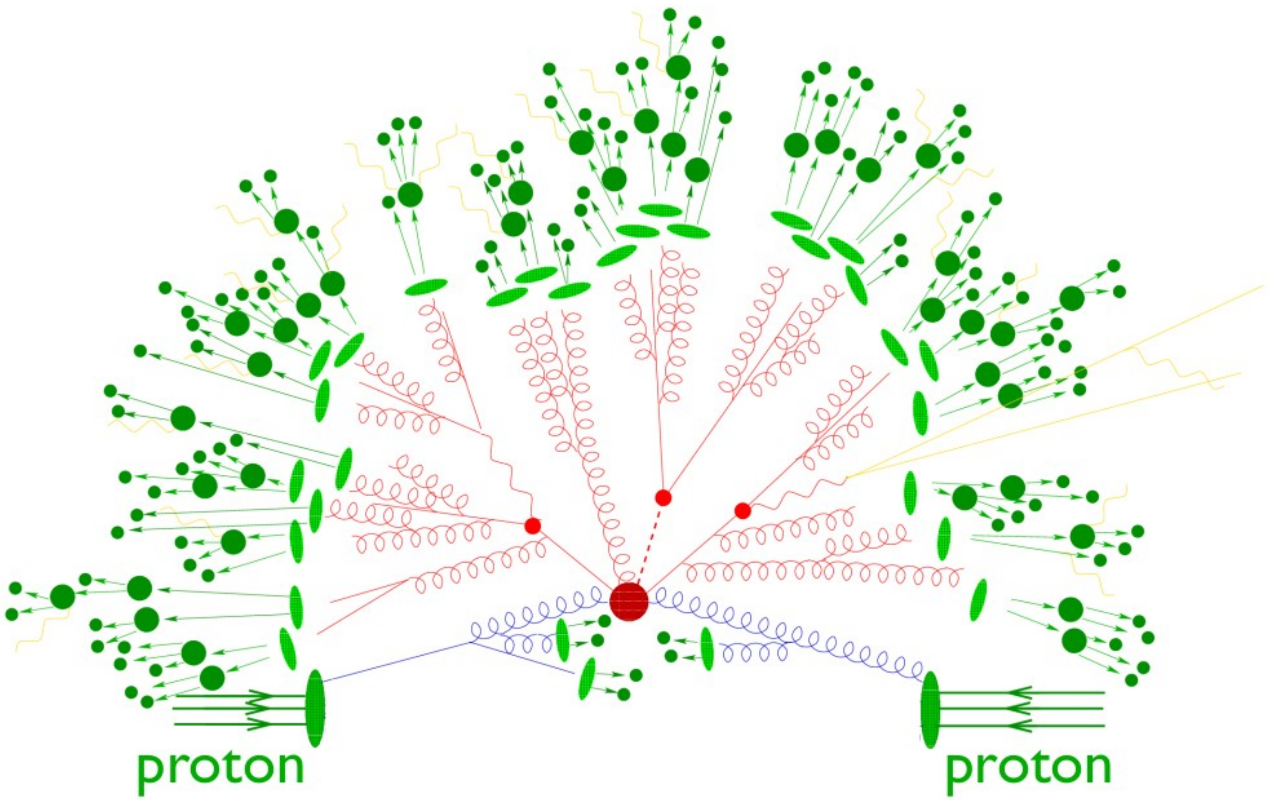
Events at the LHC

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



[Sherpa's artistic view]

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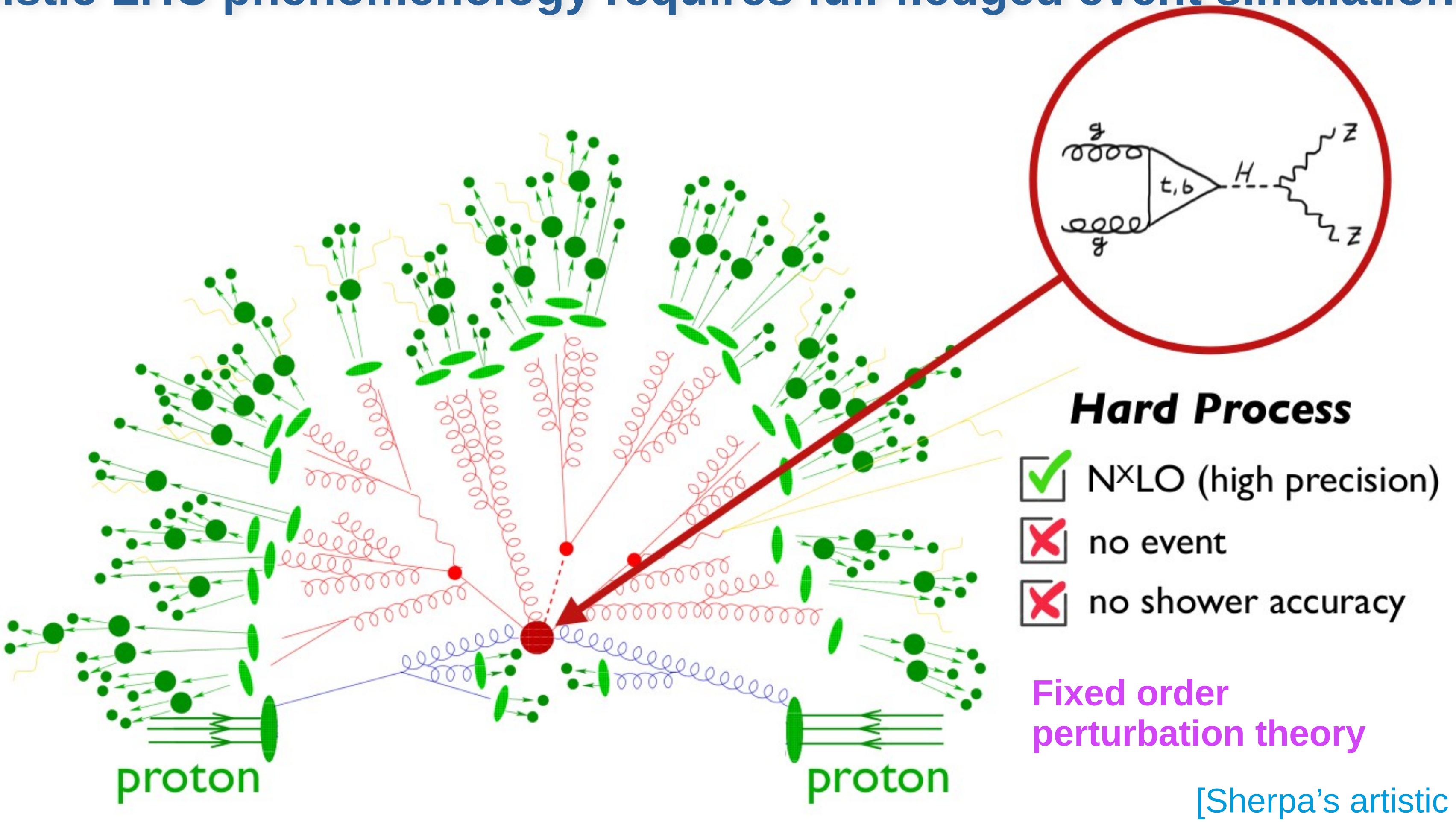

Fixed order perturbation theory

[Sherpa's artistic view]

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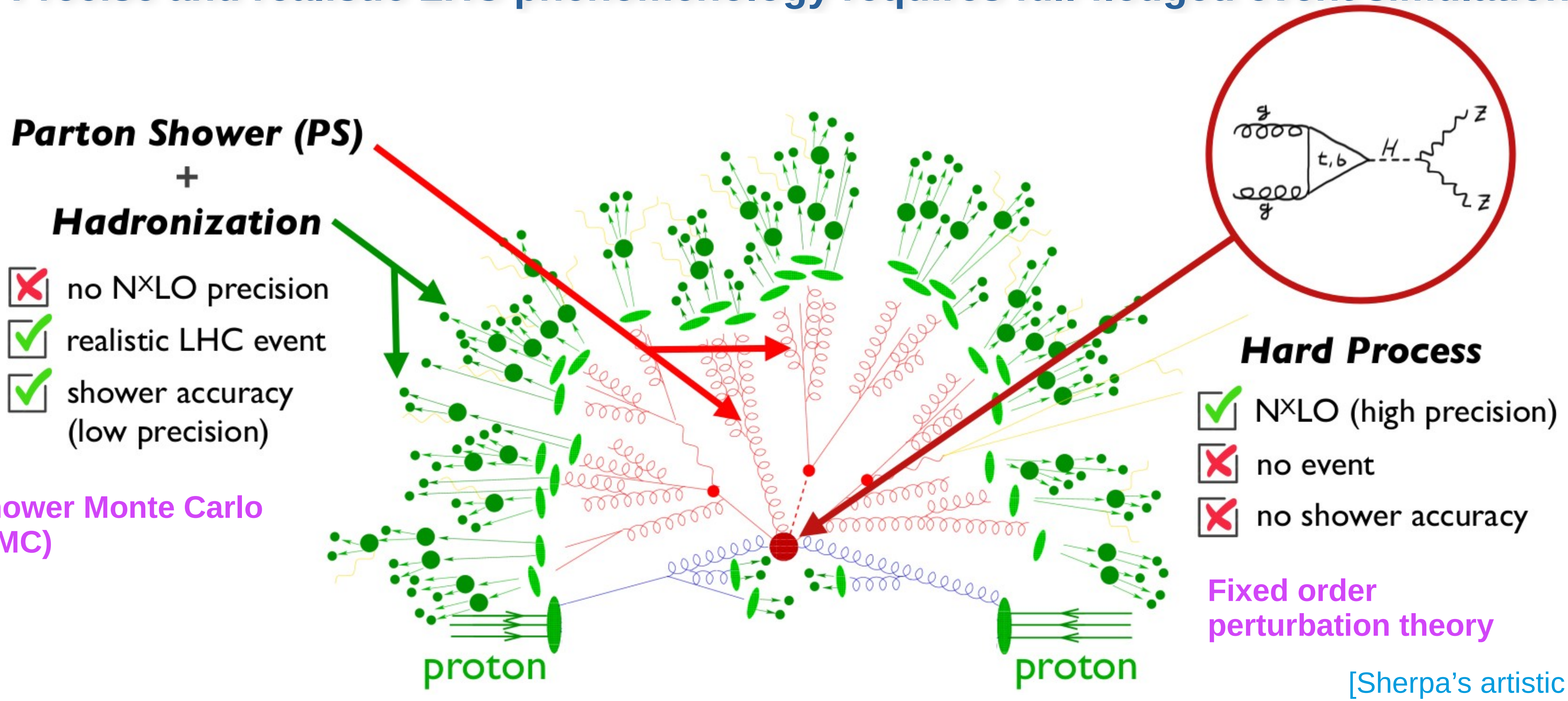


Shower Monte Carlo (SMC)

Fixed order perturbation theory

[Sherpa's artistic view]

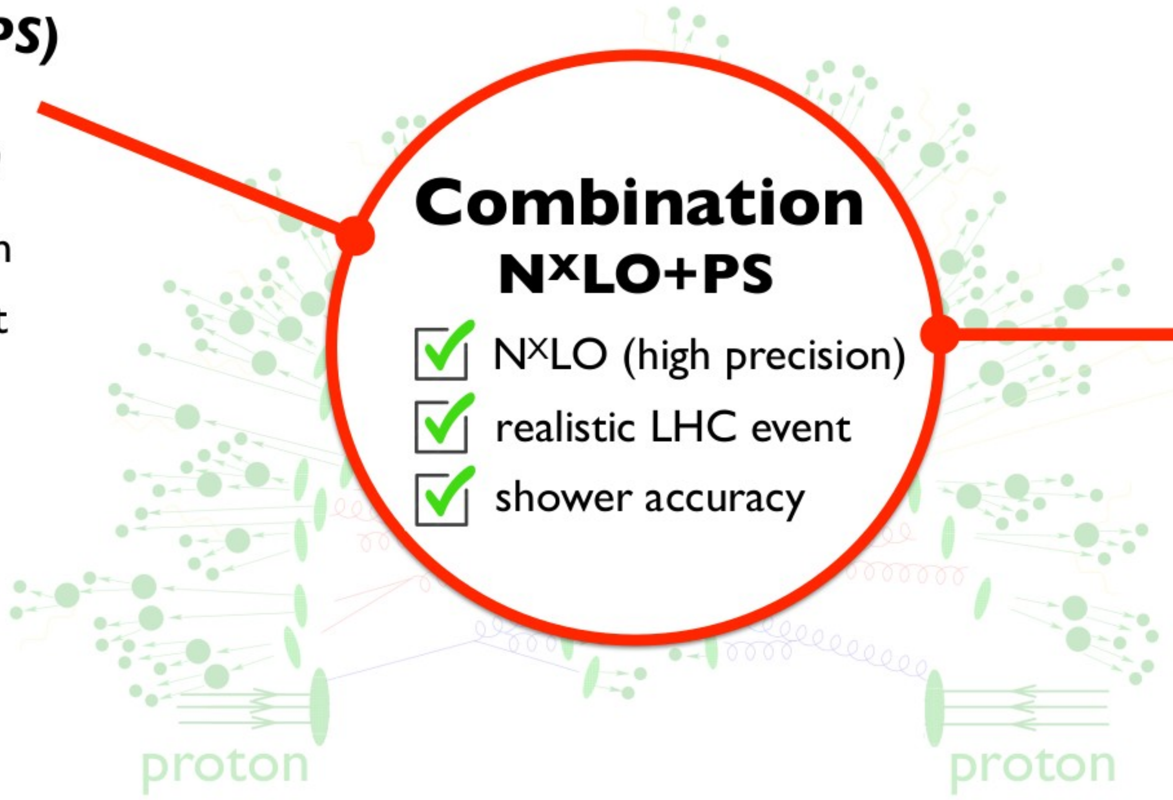
Events at the LHC

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

Parton Shower (PS)* + *Hadronization

- ✗ no N^xLO precision
- ✓ realistic LHC event
- ✓ shower accuracy (low precision)

Shower Monte Carlo (SMC)



Hard Process

- ✓ N^xLO (high precision)
- ✗ no event
- ✗ no shower accuracy

Fixed order perturbation theory

[Sherpa’s artistic view]

Events at the LHC

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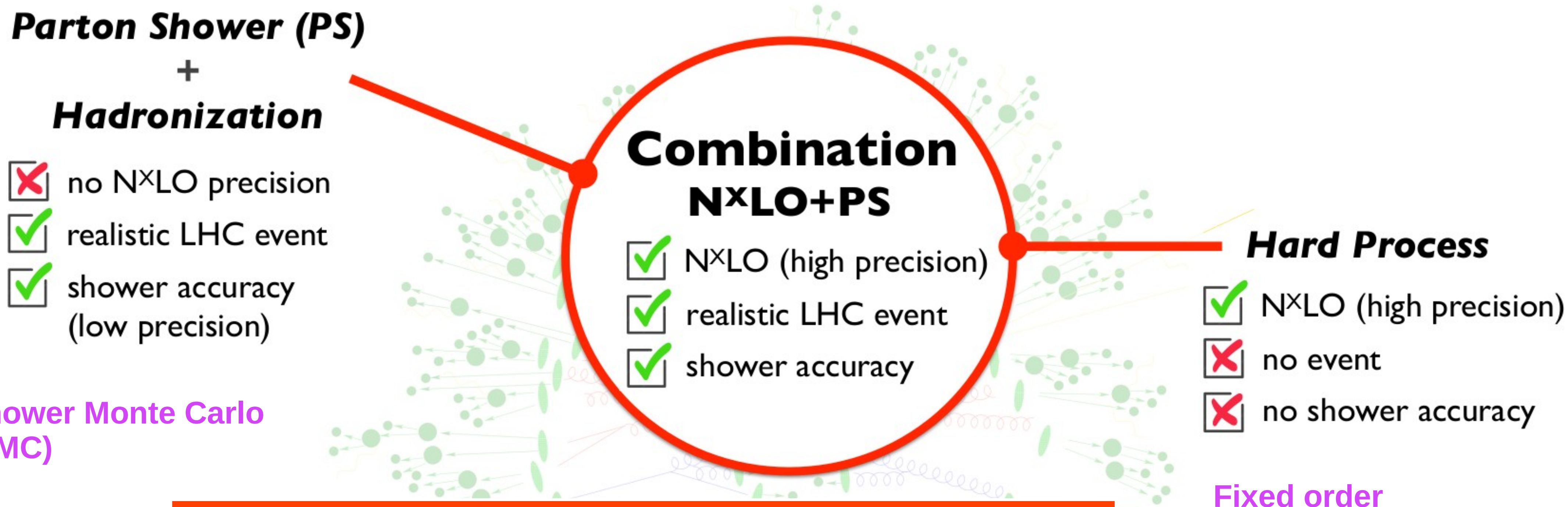

Shower Monte Carlo (SMC)

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Current frontier : NNLO+PS accuracy

[Sherpa's artistic view]

NNLO+PS: what do we want to achieve?

- Consider $F + X$ production (F=massive color singlet)
- NNLO accuracy for observables inclusive on radiation. $[d\sigma/dy_F]$
- NLO(LO) accuracy for $F + 1(2)$ jet observables (in the hard region). $[d\sigma/dp_{T,j1}]$
  - appropriate scale choice for each kinematics regime
- Sudakov resummation from the Parton Shower (PS)
- preserve the PS accuracy (leading log - LL)

NNLO+PS: methods

- **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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[Monni, Re, Wiesemann (2006.04133)]

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

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

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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

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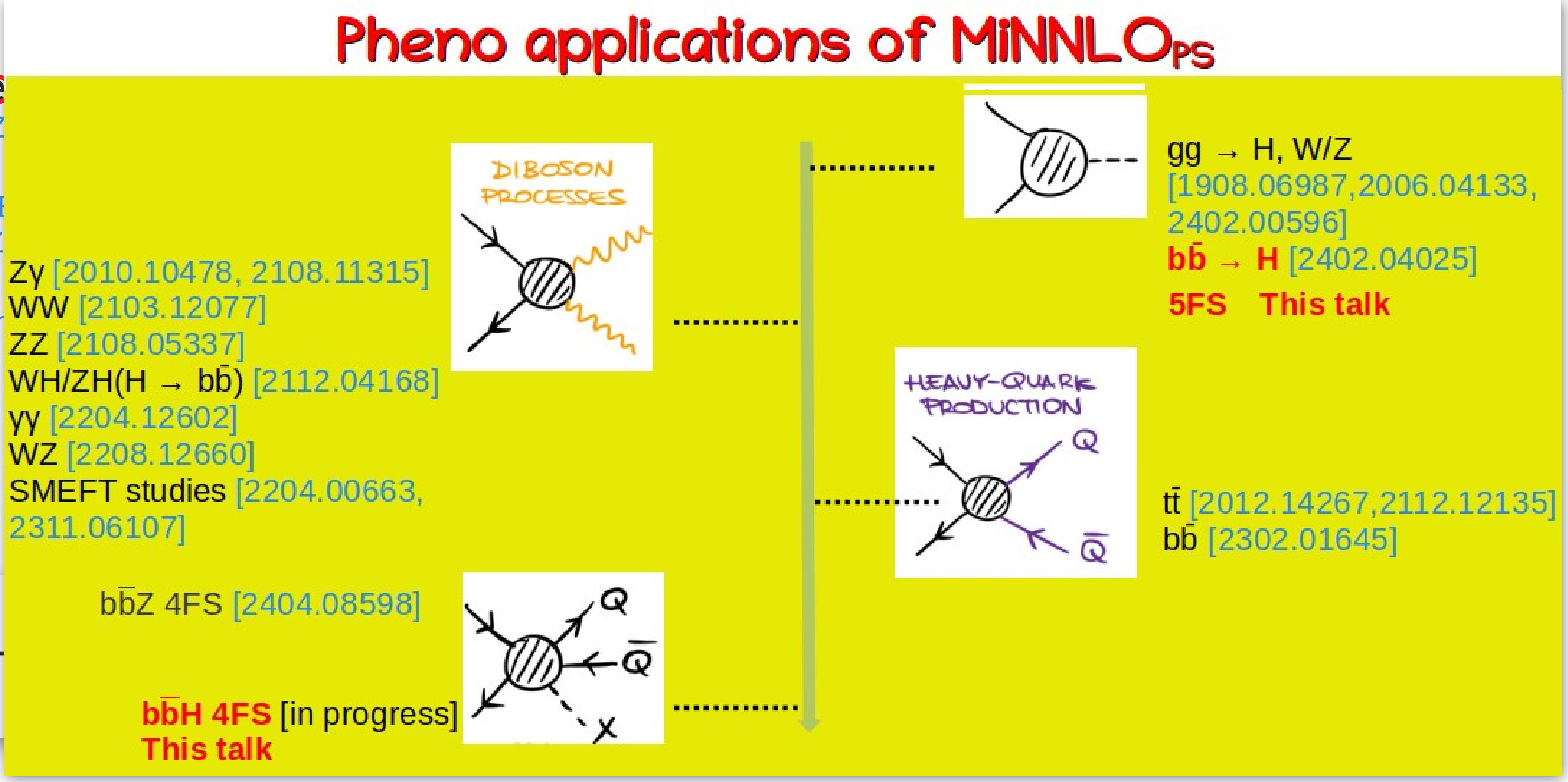

POWHEG

- The matching to the parton shower is performed according to the **POWHEG** method [P. Nason (0409146)]

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$$d\sigma^{POW} = \bar{B}(\Phi_n)d\Phi_n\left\{\Delta(\Phi_n,\Lambda) + \Delta(\Phi_n,p_T)\frac{R(\Phi_n,\Phi_r)}{B(\Phi_n)}d\Phi_r\right\}$$

FO calculation at NLO

$$\bar{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int d\Phi_r\left[R(\Phi_{n+1}) - C(\Phi_{n+1})\right]$$

POWHEG Sudakov for the emission of the first (hardest) radiation

$$\Delta(\Phi_n,p_T) = exp\left\{-\int d\Phi_r'\frac{R(\Phi_n,\Phi_r')}{B(\Phi_n)}\Theta(p_T'-p_T)\right\}$$

	F	F+J	F+JJ
F@POWHEG	NLO	LO	LL

pt-veto on subsequent emissions generated by the shower

MiNLO'

$$\bar{B}(\Phi_n) = e^{-\tilde{S}(p_T)}\left(B(\Phi_n)(1+\alpha_s(p_T)[\tilde{S}]^{(1)}) + V(\Phi_n) + \int d\Phi_r\big[R(\Phi_{n+1}) - C(\Phi_{n+1})\big]\right)$$

Sudakov form factor

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

$$A = \sum_{k=1}^{2}\left(\frac{\alpha_s}{2\pi}\right)^k A^{(k)}, \qquad B = \sum_{k=1}^{2}\left(\frac{\alpha_s}{2\pi}\right)^k B^{(k)}$$

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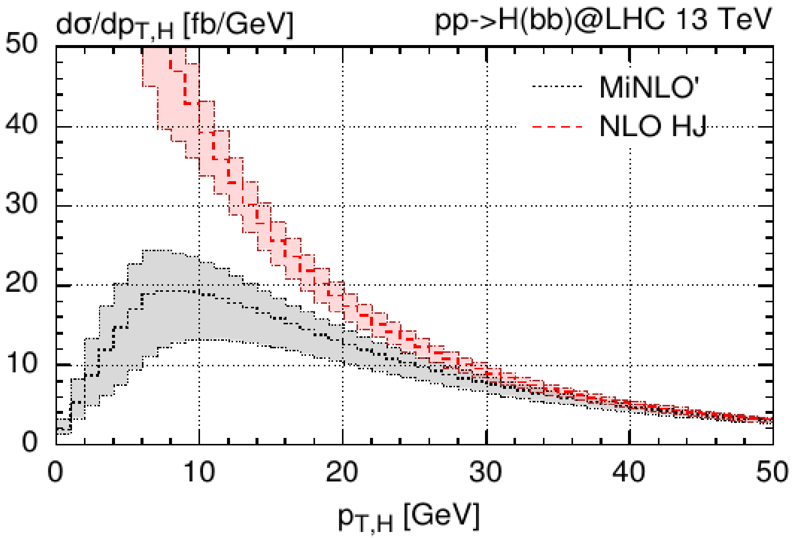
- **Finite result** for F+J production when the **jet is unresolved**
- Prescription in the **choice of the scales** μ_R and μ_F ($\mu_R = \mu_F \sim p_T$)
- **NLO** accuracy for observables inclusive in F and F+J

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



MiNNLO$_{\text{PS}}$

Hard function

✦ starting equation:

$$\frac{\mathrm{d}\sigma_F^{\mathrm{res}}}{\mathrm{d}p_T\,\mathrm{d}\Phi_{\mathrm{B}}} = \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{e^{-S}\mathscr{L}\right\} = e^{-S}\underbrace{\left\{S'\mathscr{L} + \mathscr{L}'\right\}}_{\equiv D}$$

$$\mathscr{L} \sim H\,(C \otimes f)\,(C \otimes f)$$

Luminosity (symbolically)

MiNNLO$_{\rm PS}$

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✦ combine with F + jet fixed order $d\sigma_{FJ}$:

$$d\sigma^F = d\sigma_F^{\rm res} + [d\sigma_{FJ}]_{\rm f.o.} - [d\sigma_F^{\rm res}]_{\rm f.o.} = e^{-S}\left\{D + \frac{[d\sigma_{FJ}]_{\rm f.o.}}{\underbrace{[e^{-S}]_{\rm f.o.}}_{1-S^{(1)}\ldots}} \underbrace{- \frac{[d\sigma_F^{\rm res}]_{\rm f.o.}}{[e^{-S}]_{\rm f.o.}}}_{-D^{(1)}-D^{(2)}\ldots}\right\}$$

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✦ expanded up to $\alpha_s^3(p_T)$ we have: (resummation scheme: $\mu_R = \mu_F \sim p_T$)

$$d\sigma_F^{\text{MiNNLO}} \sim e^{-S}\left\{ \underbrace{d\sigma_{FJ}^{(1)}}_{\sim\alpha_s(p_T)}\underbrace{\left(1 + S^{(1)}\right) + d\sigma_{FJ}^{(2)}}_{\sim\alpha_s^2(p_T)} + \underbrace{\left(D - D^{(1)} - D^{(2)}\right)}_{\sim\alpha_s^3(p_T)} + \text{regular} \right\}$$

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MiNLO'

NNLO corrections

Beyond accuracy

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

- Apply the idea to POWHEG FJ calculation

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

$$\tilde{\bar{B}}^{FJ} \sim \left\{ \mathrm{d}\sigma_{FJ}^{(1)} + \mathrm{d}\sigma_{FJ}^{(2)} \right\}$$

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$$\bar{\tilde{B}}^{FJ} \sim \left\{ \mathrm{d}\sigma^{(1)}_{FJ} + \mathrm{d}\sigma^{(2)}_{FJ} \right\}$$

- NNLO+PS by turning POWHEG weight (B̃ function) NNLO accurate

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

$$\bar{B}^{\rm MiNNLO_{PS}} \sim e^{-S}\left\{ \mathrm{d}\sigma^{(1)}_{FJ}\left(1 + S^{(1)}\right) + \mathrm{d}\sigma^{(2)}_{FJ} + \left(D - D^{(1)} - D^{(2)}\right) \times F^{\rm corr} \right\}$$

→ *spreads NNLO corrections in the $F+\mathrm{jet}$ phase space*

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

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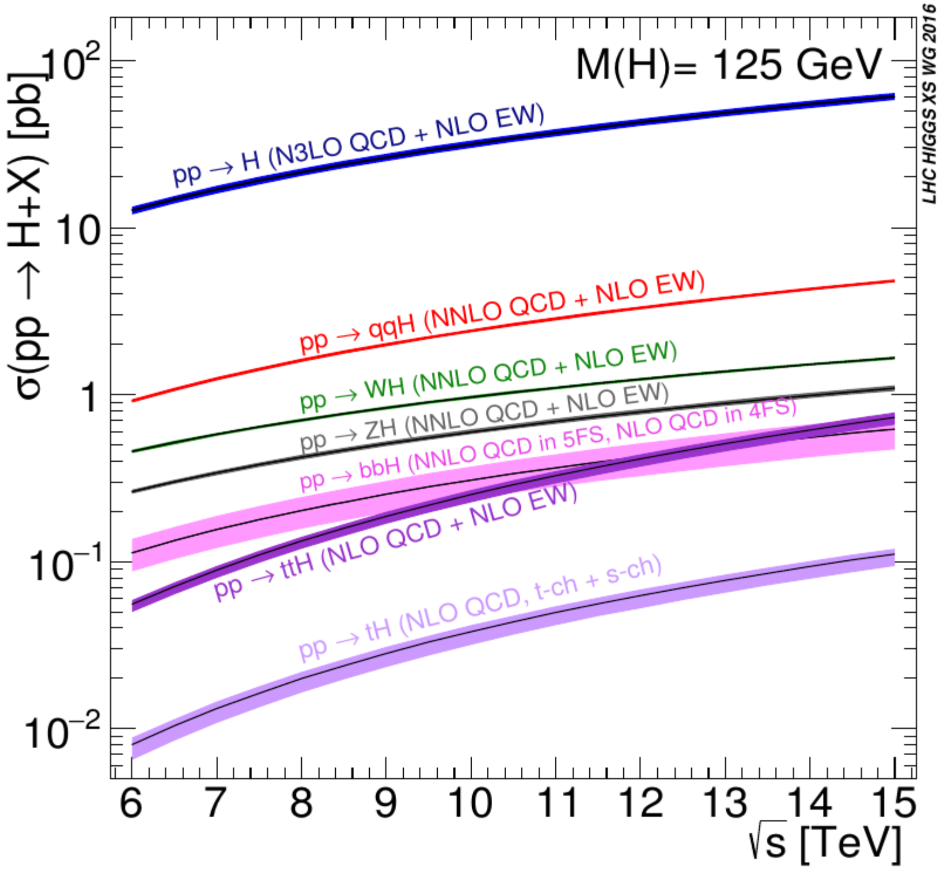

[LHC HIGGS XS WG 2016]

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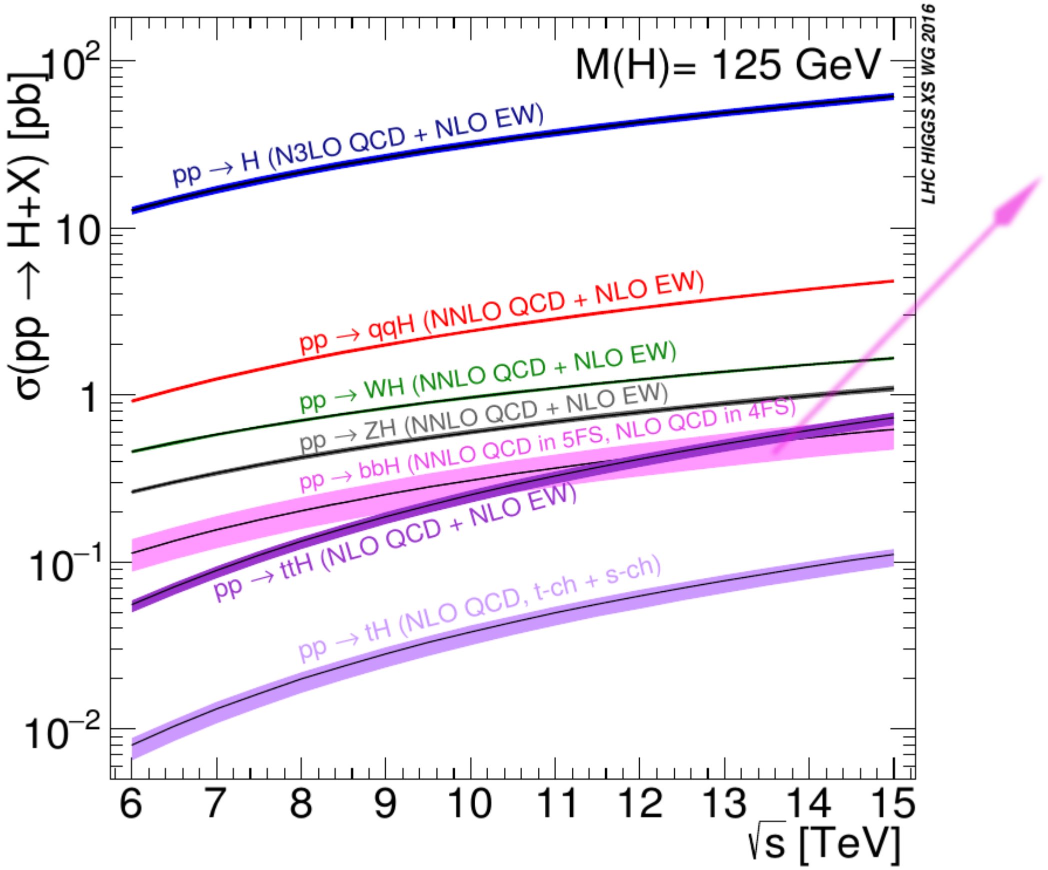

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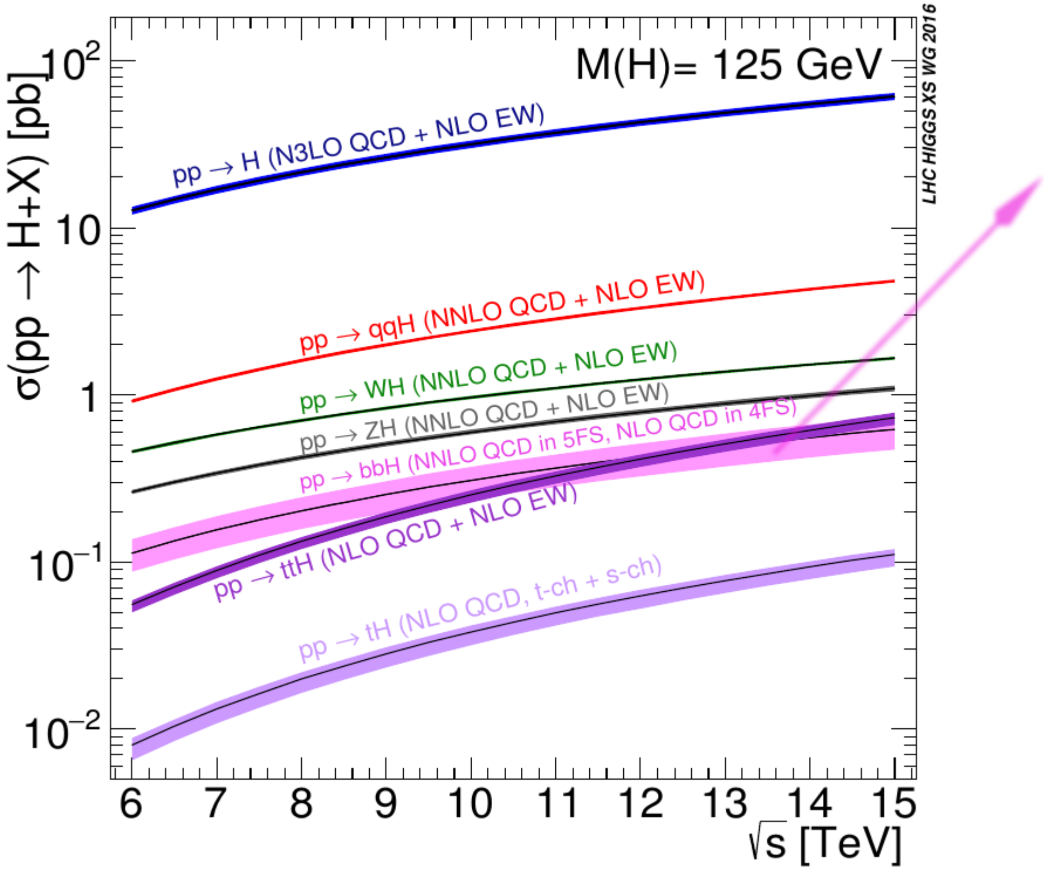

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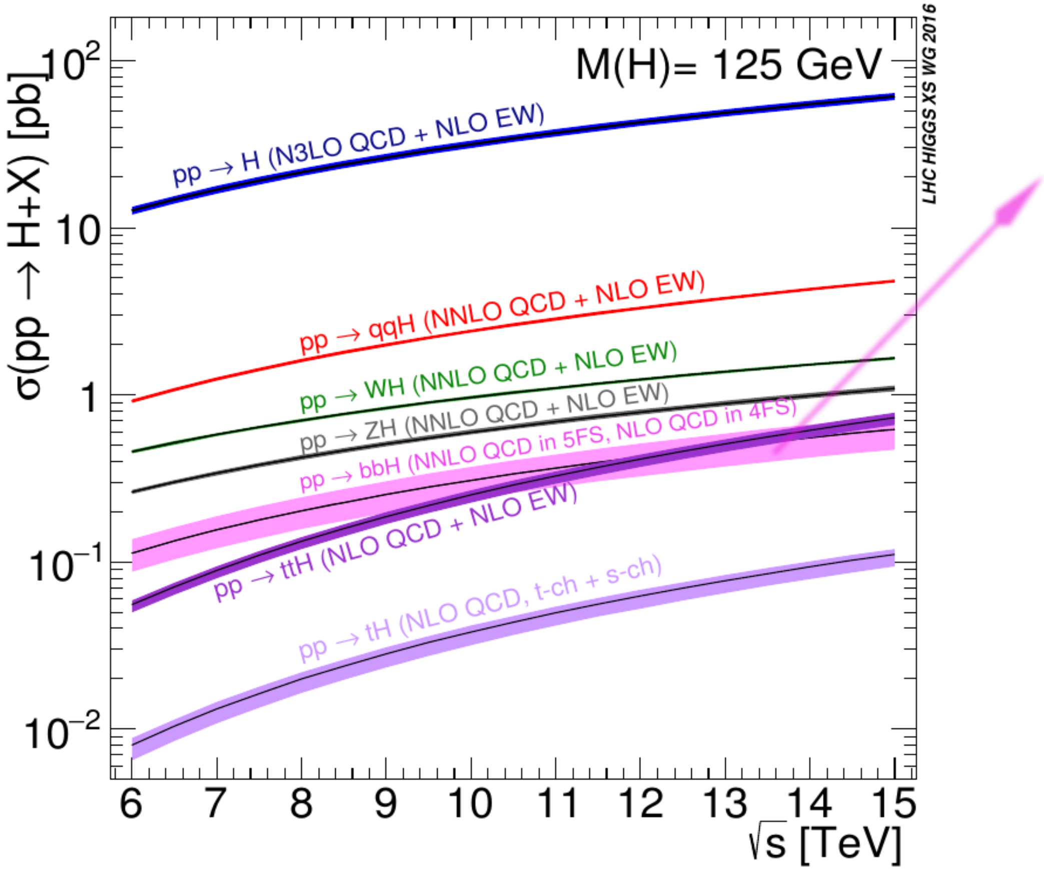

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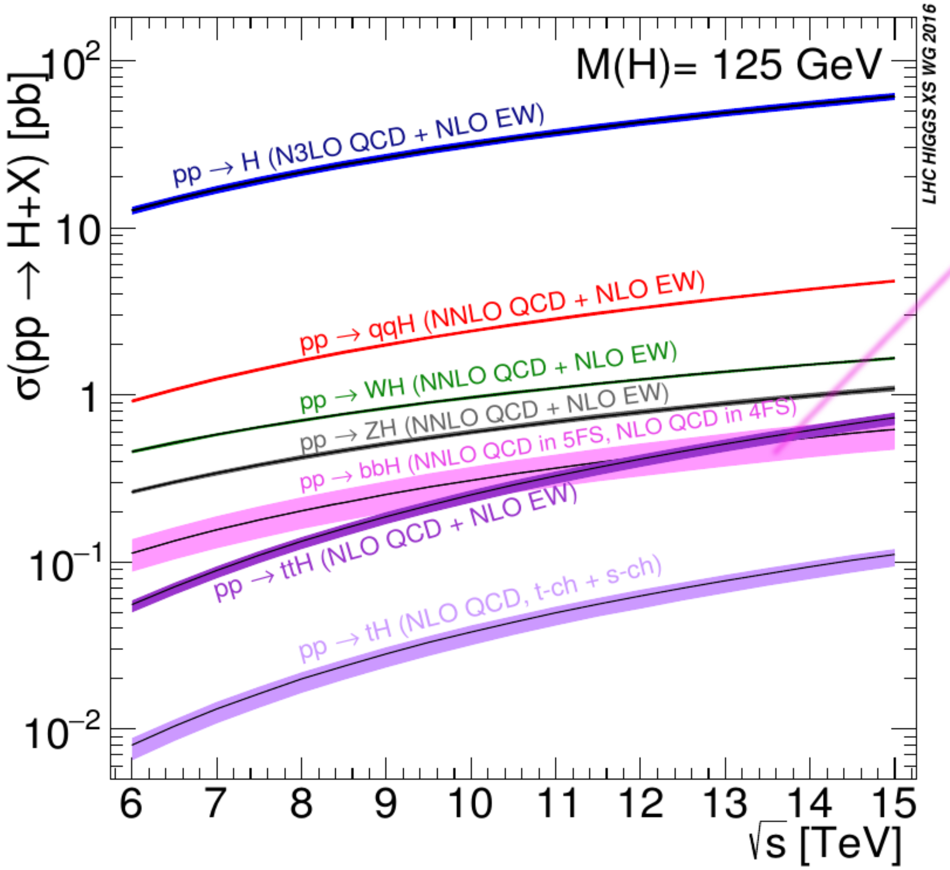

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- Direct probe of **Higgs couplings to the bottom quark** (**y_b**) in production
- **Bottom Yukawa coupling**: Important due to its **enhancement in New Physics models** like minimal supersymmetric extensions of the SM
- $b\bar{b}H$ enters as a **background**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

[Image courtesy : C. Biello]

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5 flavor scheme (5FS)

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

4 flavor scheme (4FS)

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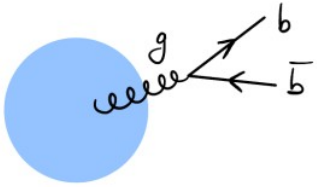

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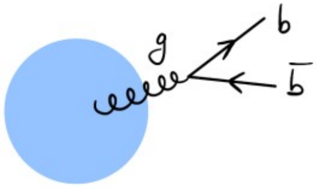

- **Active parton** inside the proton.
- **Included** in the parton distribution functions (**PDFs**) of the proton.
- It is taken to be **massless except** in the the **Yukawa** coupling

[Image courtesy : C. Biello]

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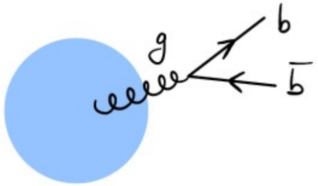
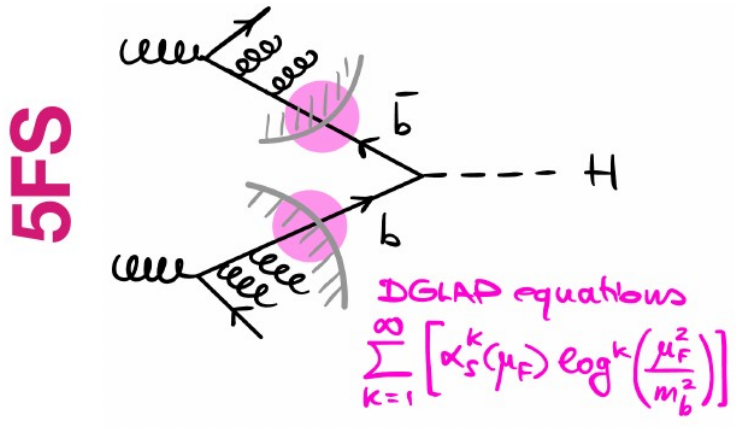


- Considered as a **heavy quark**
- The bottom quark's contribution is **neglected** in the **PDFs**.
- A **massive** bottom quark is produced from **gluon splitting**

[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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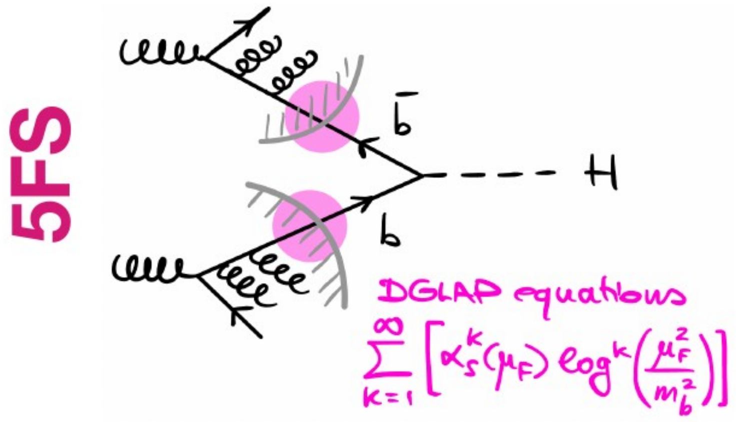

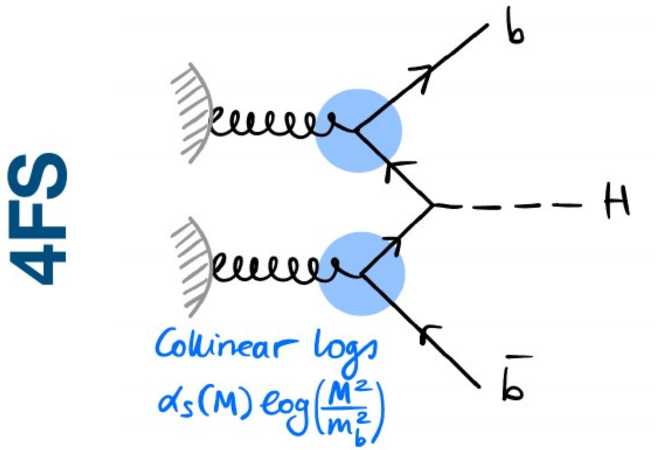

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- Computing **higher orders** is more **difficult** due to higher multiplicity & also due to the massive bottom
- It **does not resum** possibly large **collinear logs**
- ✔ **Full kinematics** of the **massive bottom** quark is taken into account 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)]
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- **NLO-QCD+PS** combined with **NLO-EW** in the **4FS** [Pagani, Shao, Zaro (2005.10277)]

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

STATE OF THE ART:

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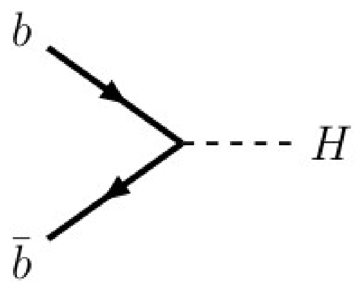
THIS TALK:

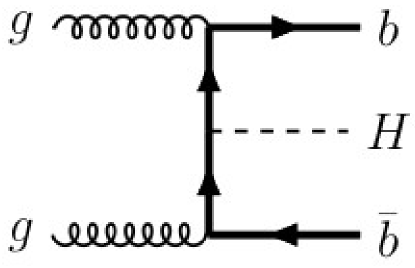
We discuss the calculation of NNLO QCD matched to parton showers (NNLO+PS) for $b\bar{b}H$ in 5FS & 4FS.

The computation

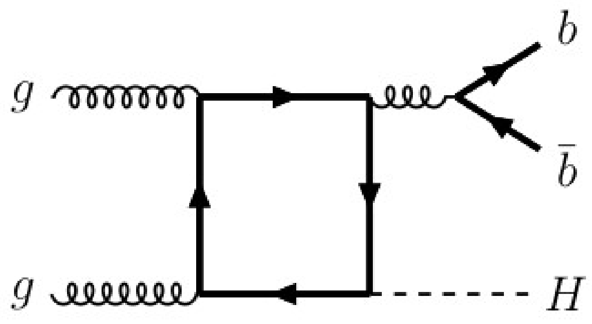
Sample Feynman diagrams for Higgs production in association with bottom quarks



LO Y_b in 5FS



LO Y_b in 4FS



LO Y_t

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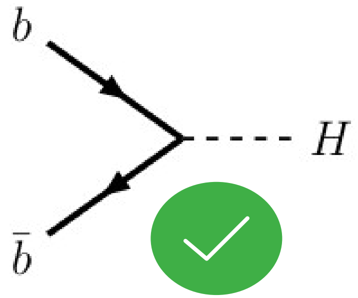

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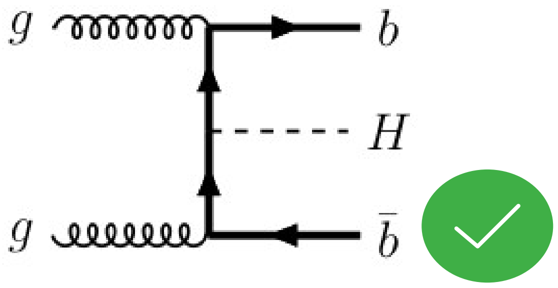

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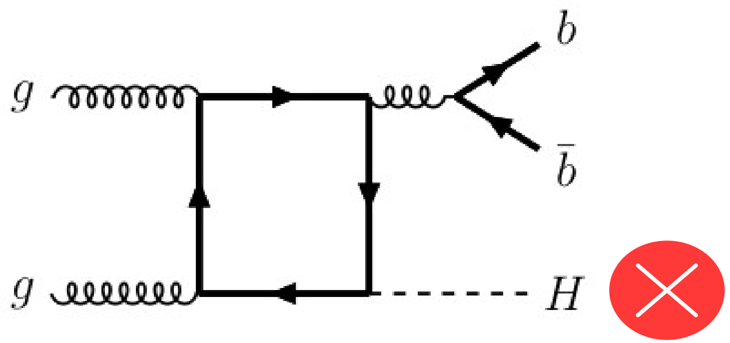


LO Y_t

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)

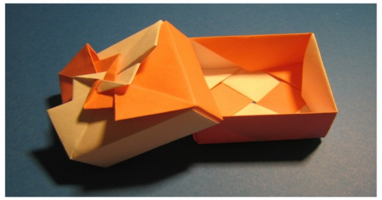
- **MiNNLO$_{PS}$ $b\bar{b}$ → H** generator implemented in the **Powheg−Box−Res**

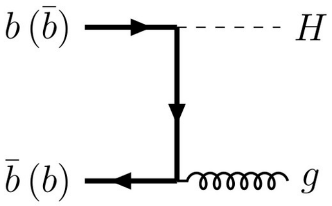
[T. Ježo and P. Nason (1509.09071)]

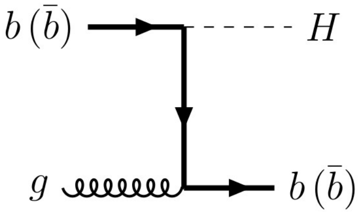
- First, we implemented a **NLO+PS** generator for **HJ** production in bottom fusion using the **Powheg** method

[P. Nason (0409146), S. Alioli et al (1002.2581), S. Frixione et al (0709.2092)]

The POWHEG BOX







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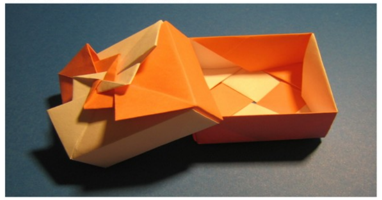

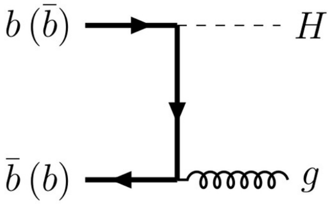

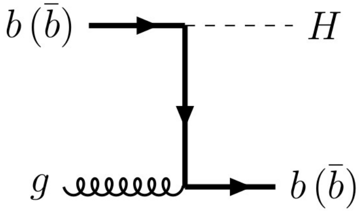

- Tree-level amplitudes of the **HJ & HJJ** : **OPENLOOPS** [F. Buccioni, S. Pozzorini and M. Zoller (1710.11452), F. Buccioni et al (1907.13071)]

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

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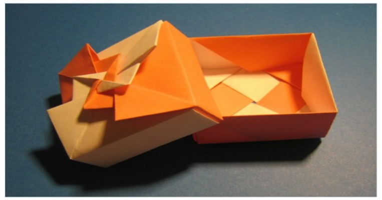

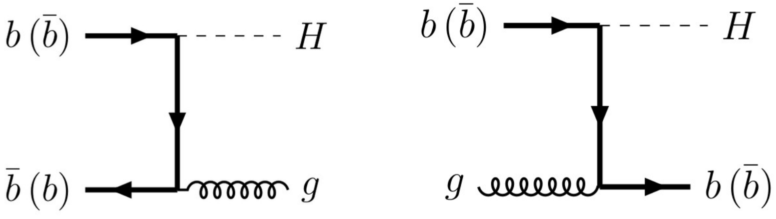

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  substantially improve the numerical performance of the code

- In a second step, we extended the **HJ NLO+PS** implementation to **NNLO+PS accuracy** through the **MiNNLO$_{PS}$** method for the 2->1 case. [Monni, Nason, Re, Wiesemann, 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.

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)]

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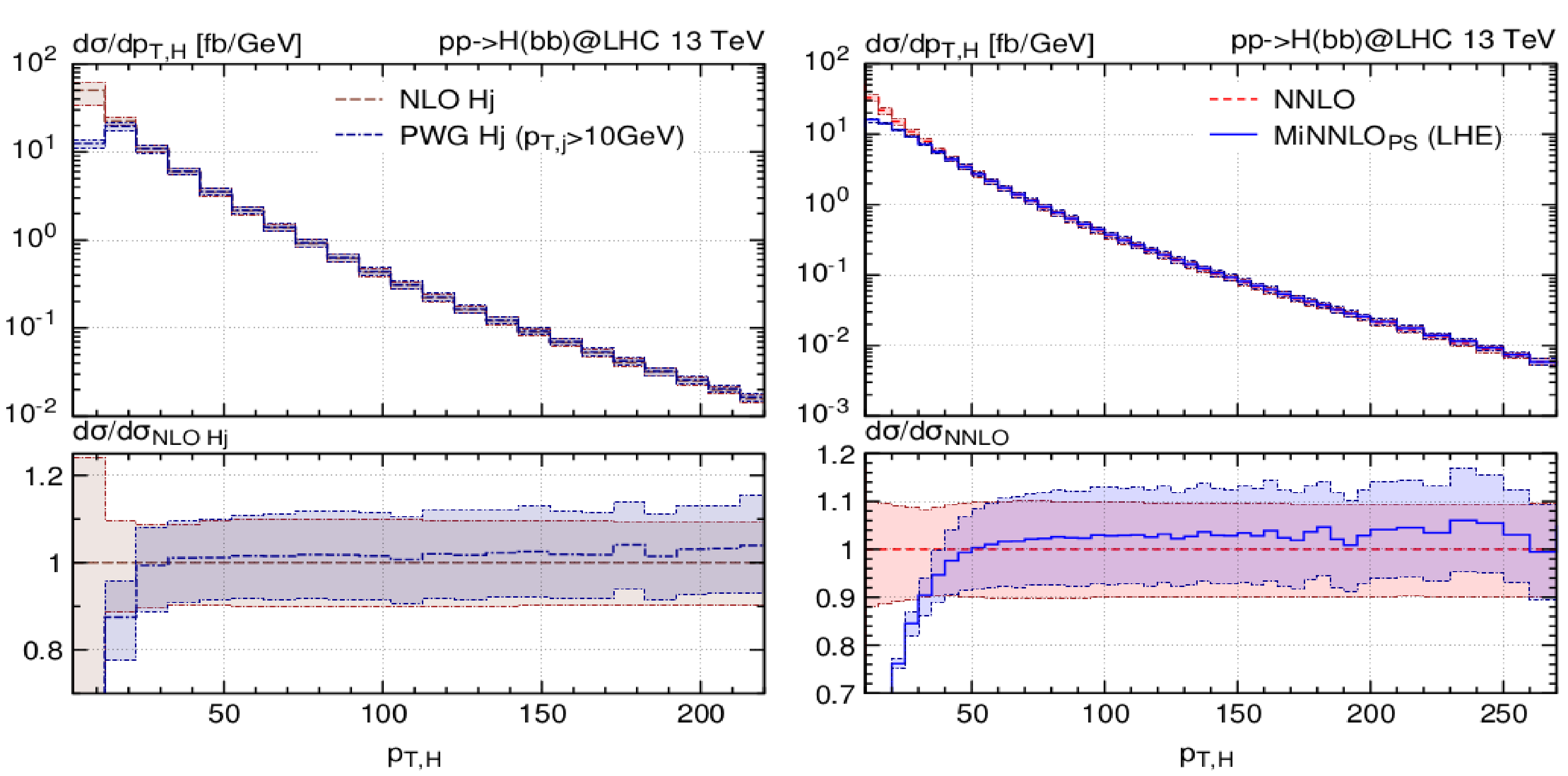
[Biello, **AS**, Wiesemann, Zanderighi (2402.04025)]

- 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)



NLO HJ [Harlander, Ozeren, Wiesemann (1007.5411)]
NNLO [Harlander, Tripathi, Wiesemann (1403.7196)]
$\text{MiNNLO}_{\text{PS}}$ [Biello, **AS**, Wiesemann, Zanderighi (2402.04025)]

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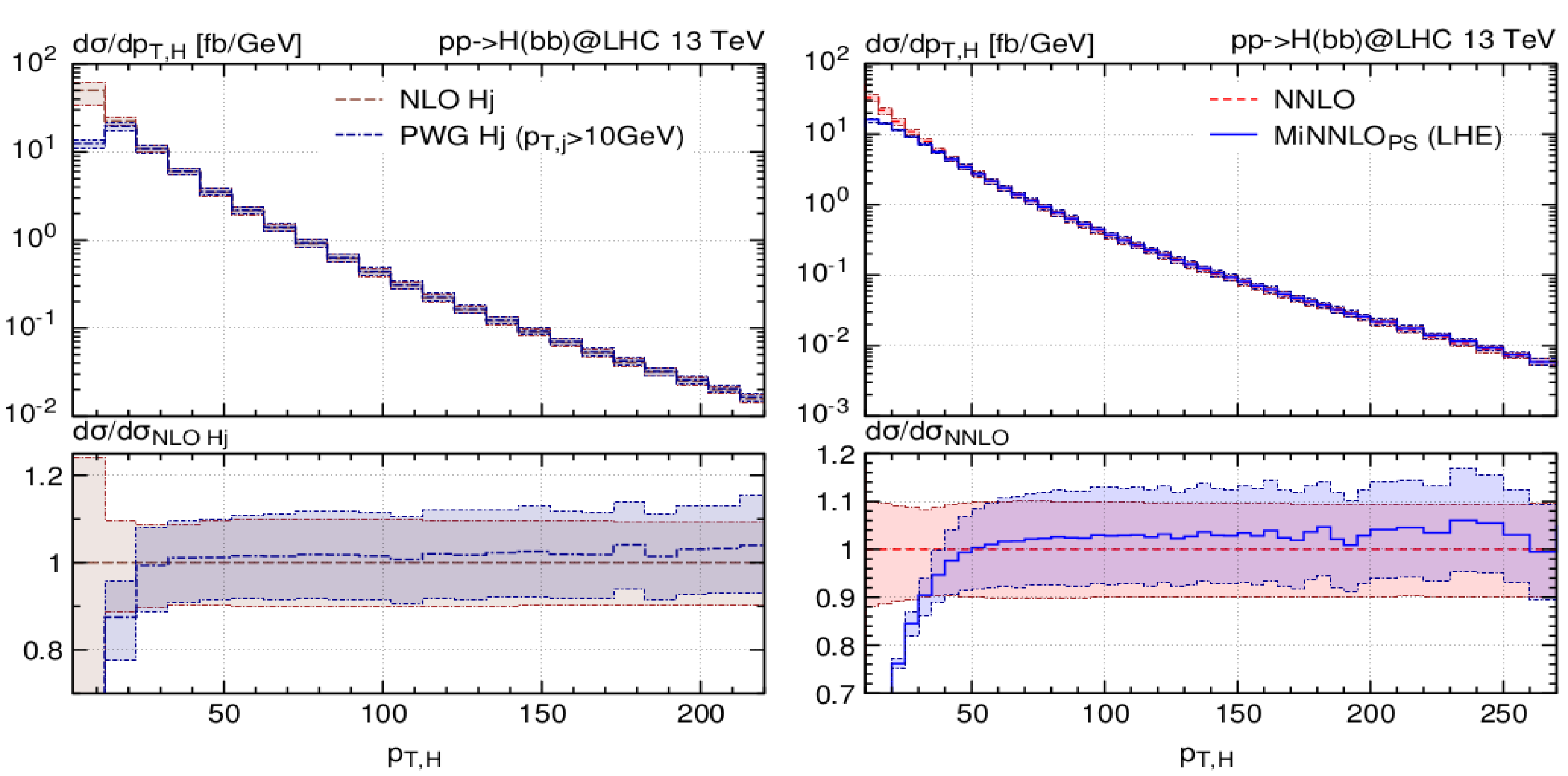


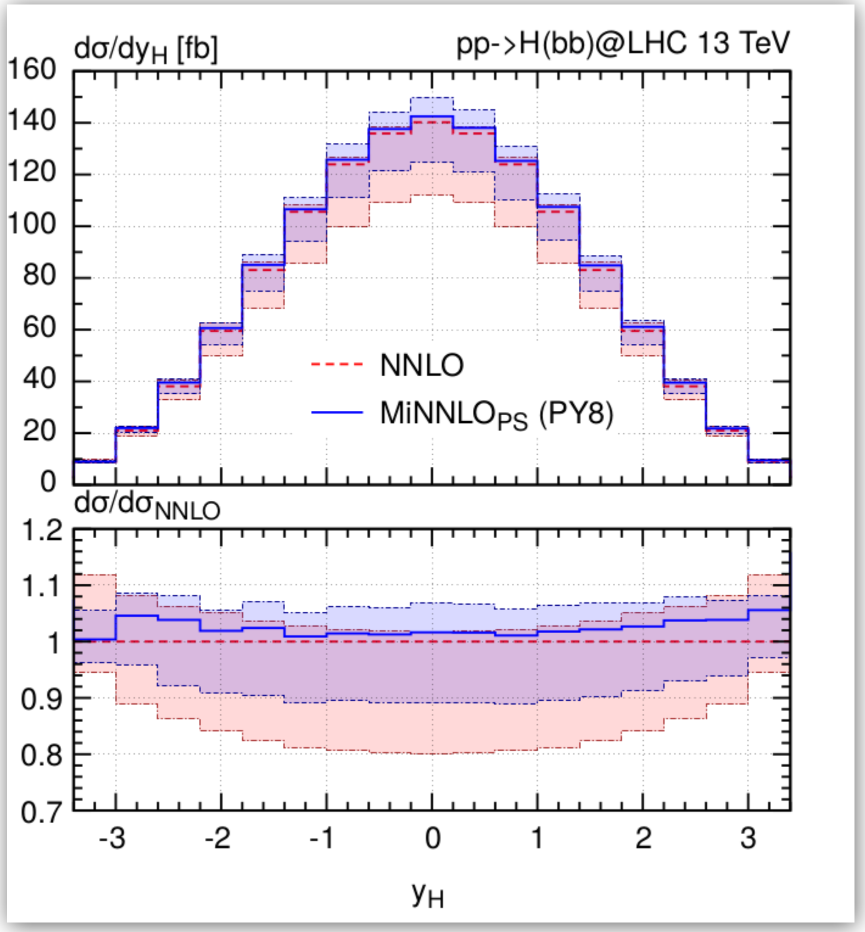
- **Full agreement** in **large $p_{T,H}$** regime with fixed-order predictions within quoted uncertainities
- Fixed-order calculations diverge for $p_{T,H} \to 0$, **MiNNLO$_{PS}$** prediction remains **finite**

NLO HJ [Harlander, Ozeren, Wiesemann (1007.5411)]
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)]
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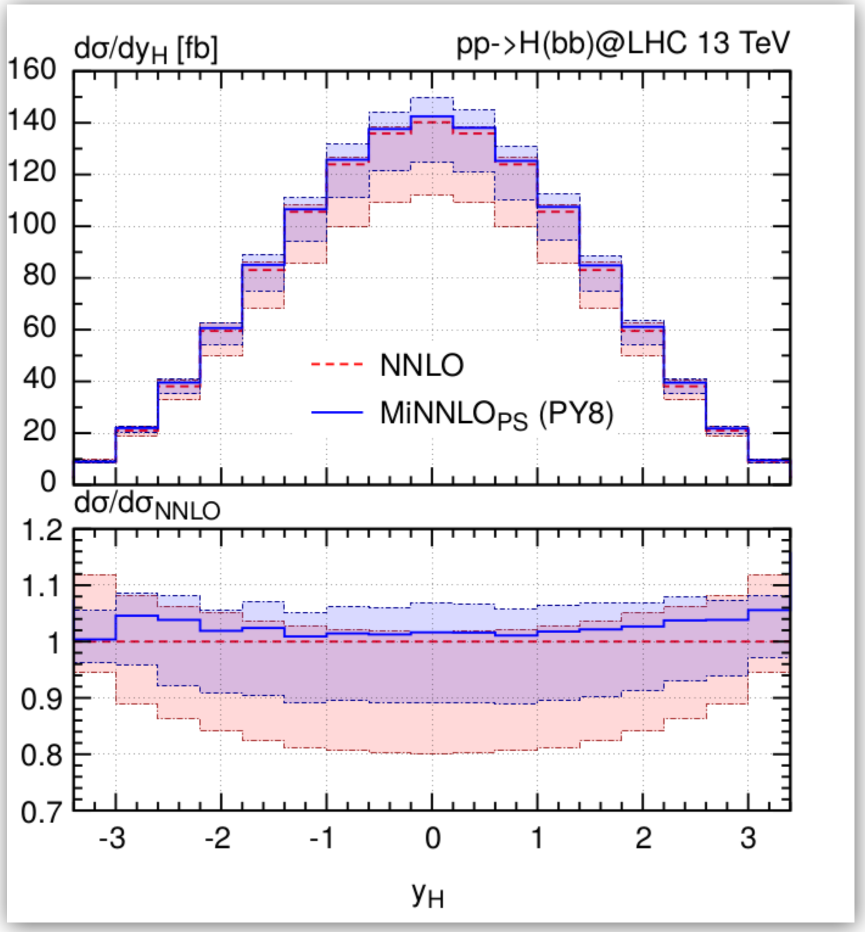

- A **good agreement**, both in terms of normalization and in terms of shape, between the two central predictions.
- The **bands** of **MiNNLO$_{PS}$** result are **more symmetric** & slightly **smaller** than the **NNLO** ones.

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 ($p_{T,H}$)

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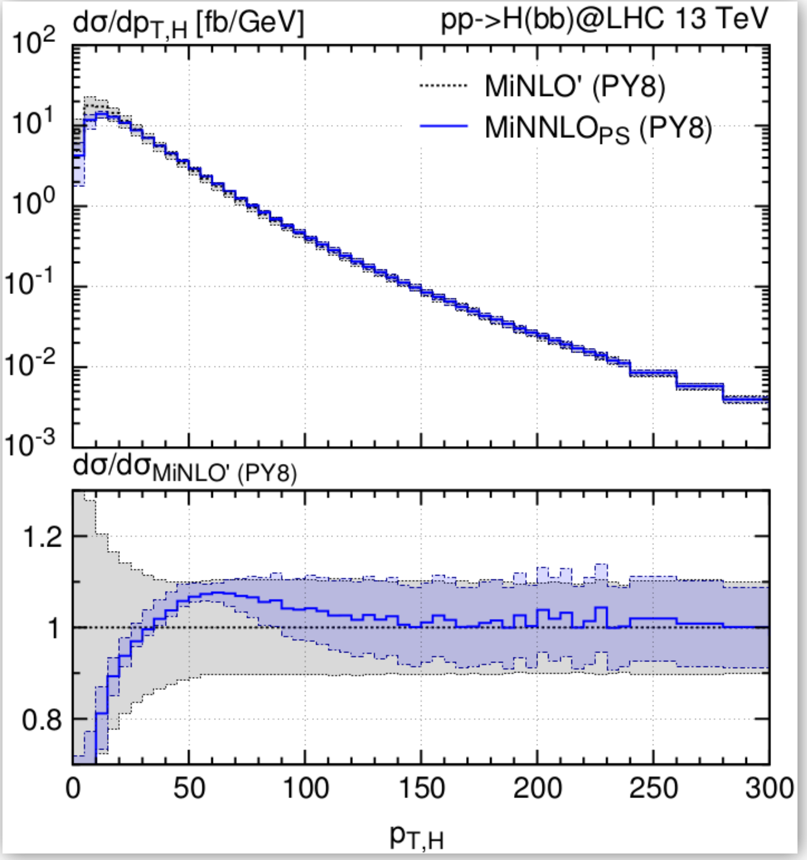

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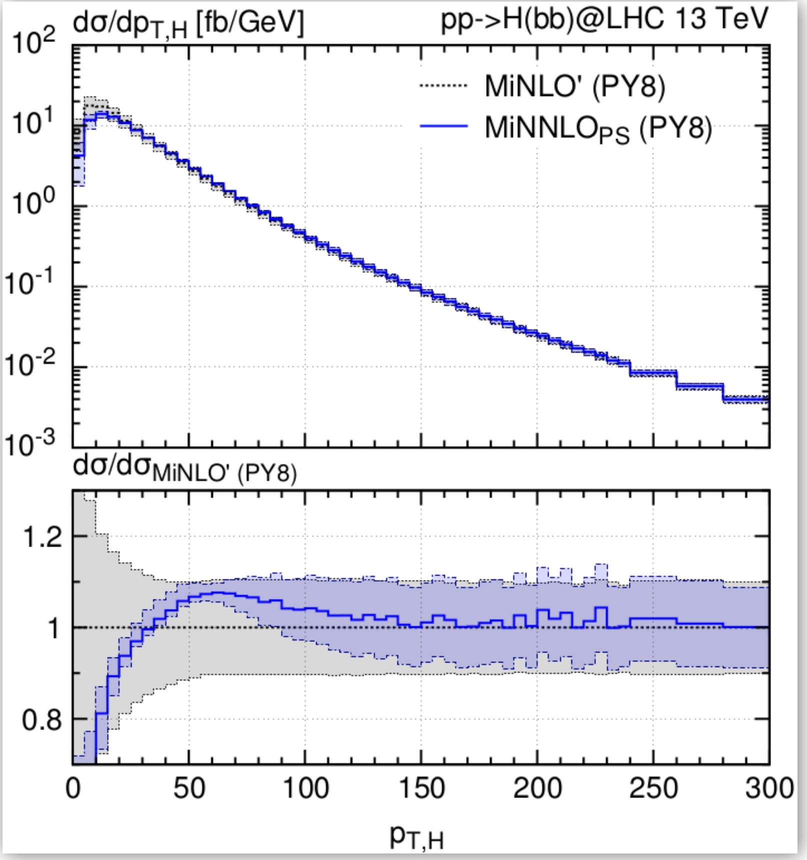

[Biello, **AS**, Wiesemann, Zanderighi (2402.04025)]

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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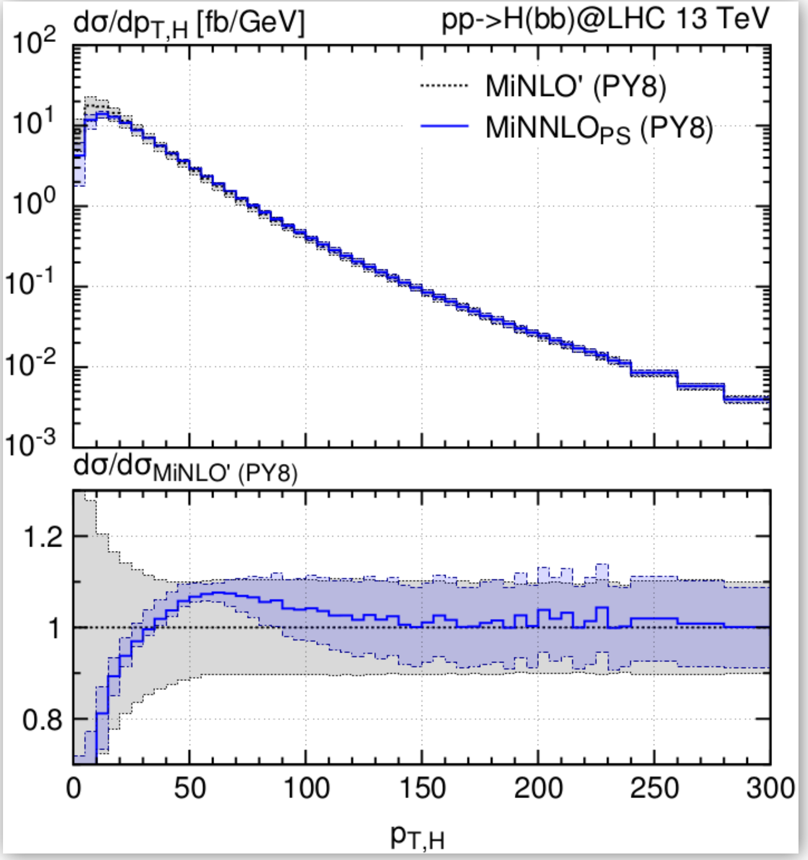
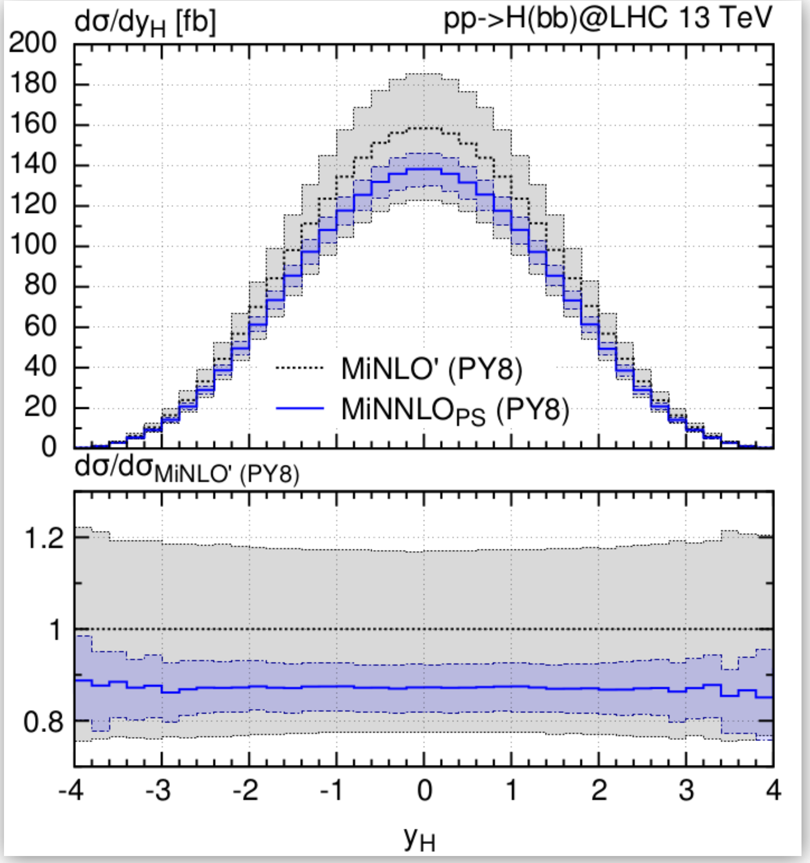


Rapidity distribution of the Higgs (y_H)



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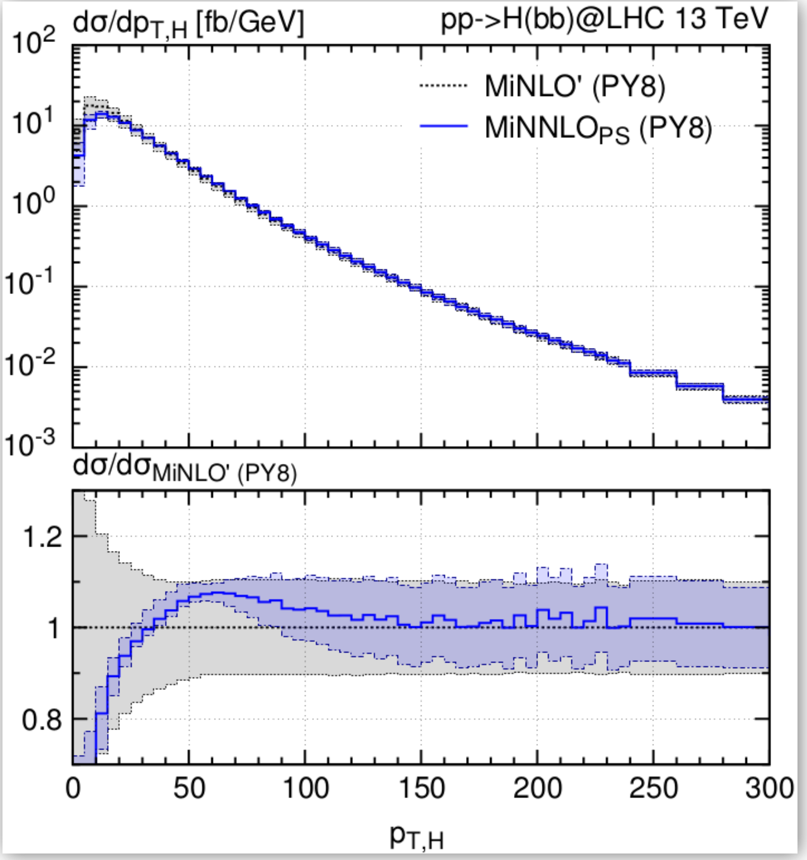

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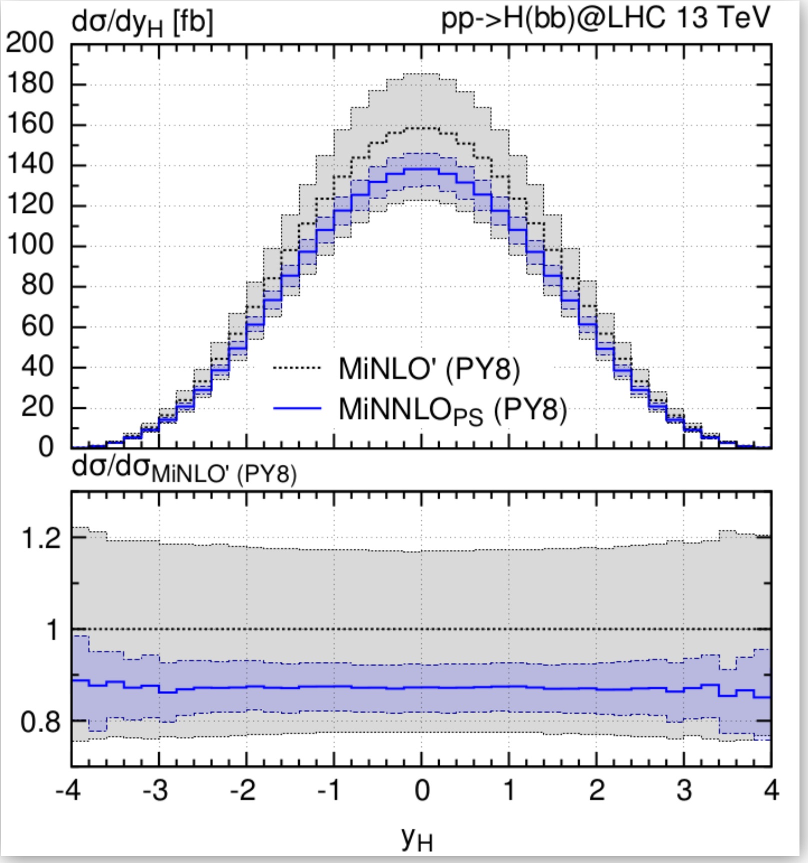
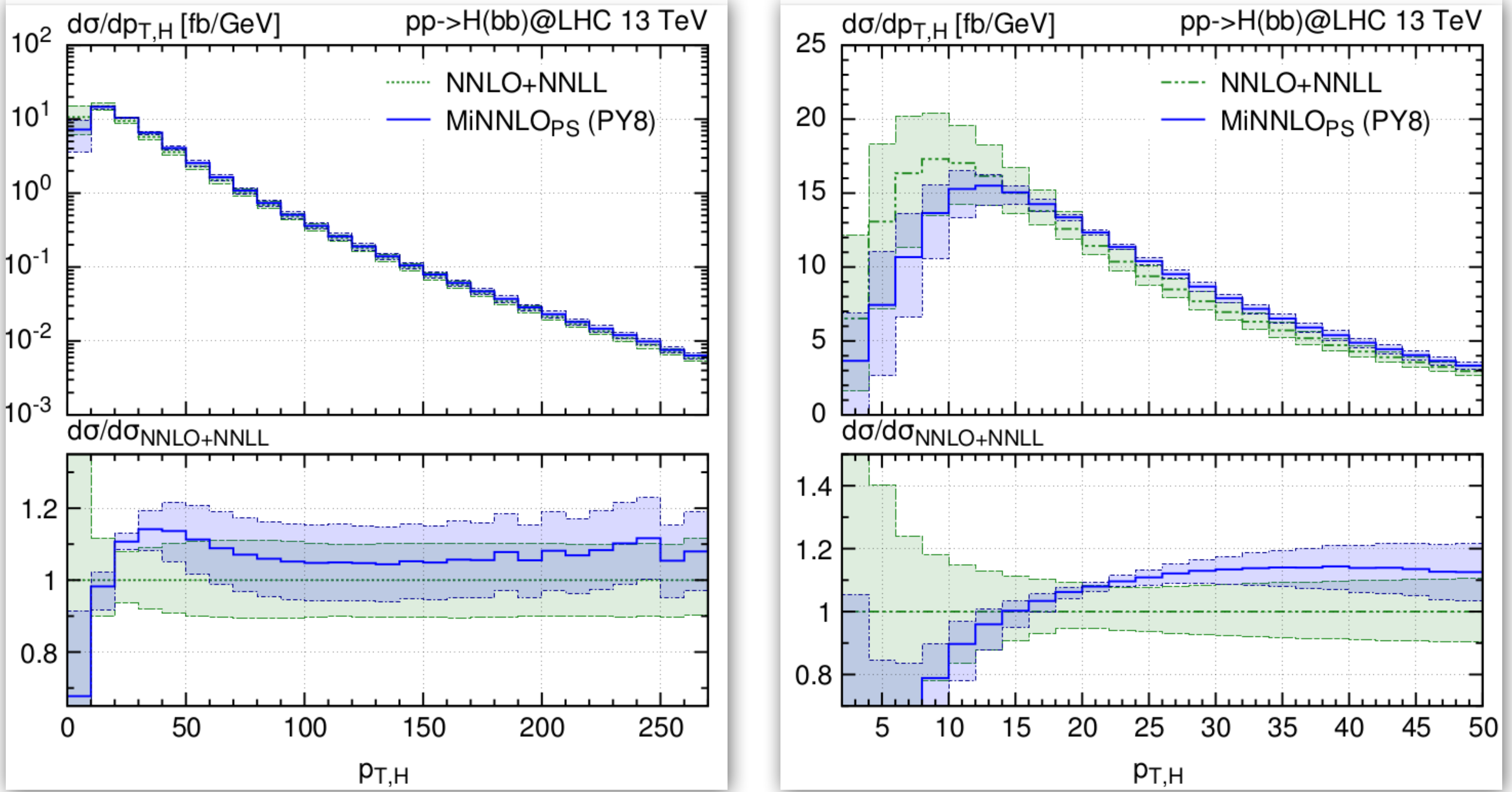


[Biello, **AS**, Wiesemann, Zanderighi (2402.04025)]

PY8 level

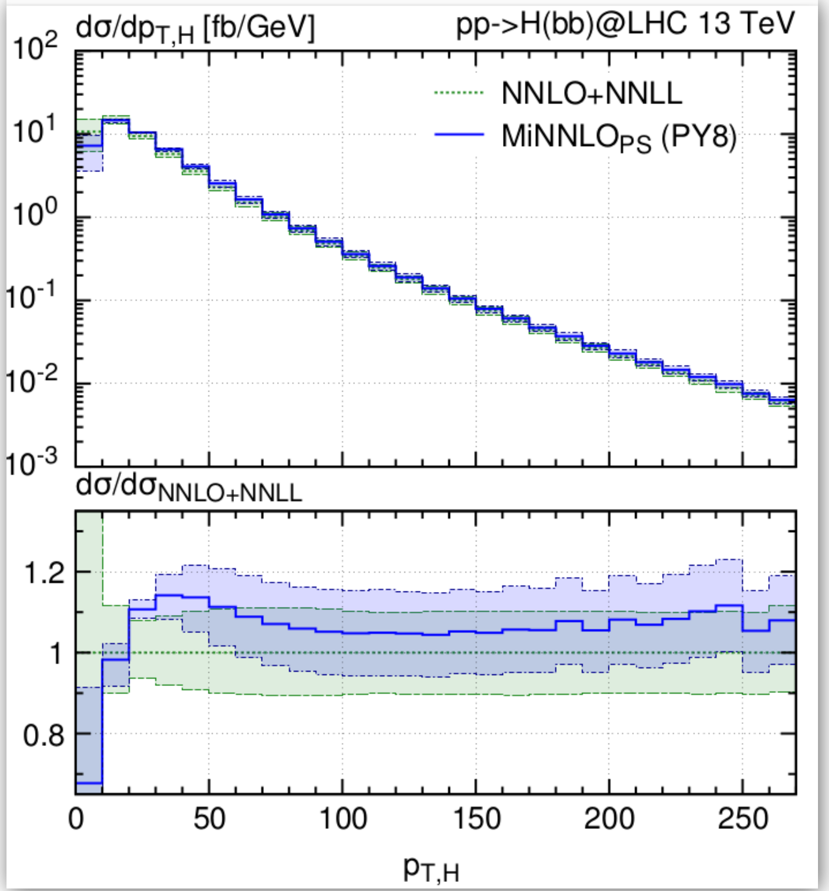
- At small p_T, MiNNLO$_{PS}$ **significantly dampens** distributions, **reduces scale uncertainties.**
- At large p_T, MiNLO' & MiNNLO$_{PS}$ predictions **coincide**, both **NLO** accurate.
- **y_H distribution**: MiNNLO$_{PS}$ introduces a flat 14% negative correction, **reduces scaleuncertainties.**

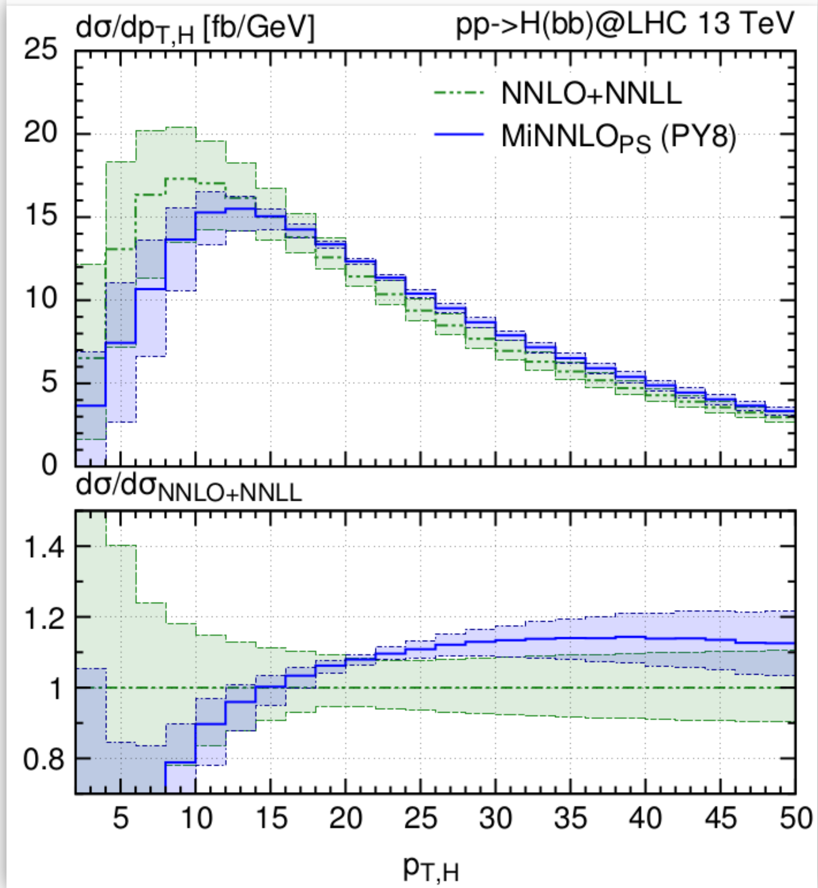
Comparison to NNLO+NNLL



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.**

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

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

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We implemented **NLO+PS** for **$Hb\bar{b}$** in **`POWHEG`** (checked our code against Jäger, Reina, Wackeroth [1509.05843]) and compared it against **`MiNLO'`** obtained from a **$Hb\bar{b}j$** generator

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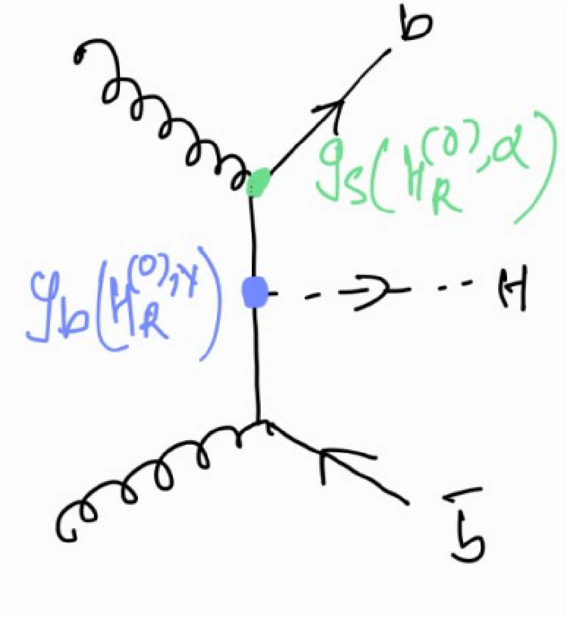

The scales (Yb and alphas) at Born can be disentangled

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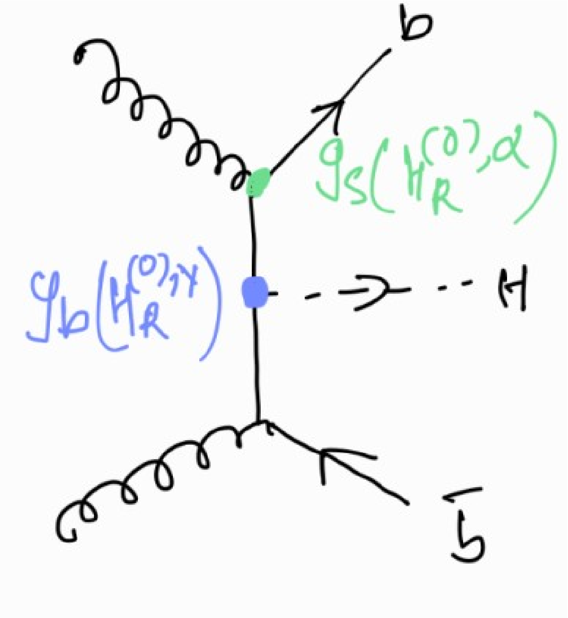

The scales (Yb and alphas) at Born can be disentangled

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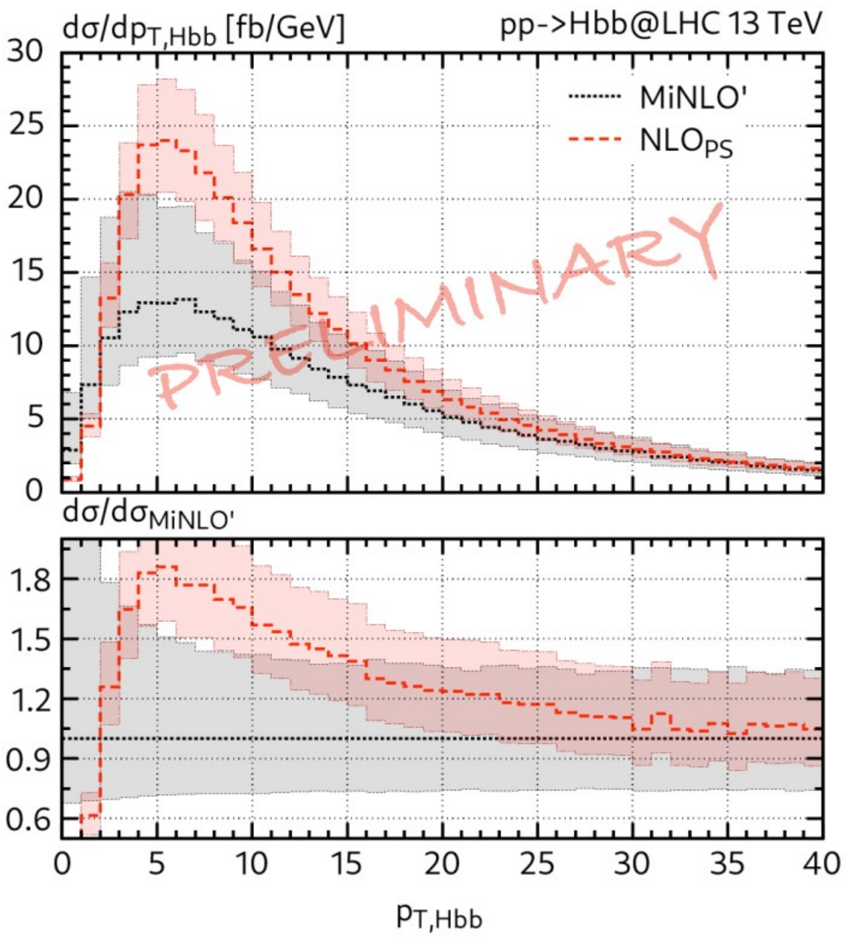
$(\mu_R^{(0),\alpha}, \mu_R^{(0),y})$	NLO$_{\text{PS}}$	MiNLO'
$(\frac{H_T}{4}, m_H)$	$0.381(2)^{+20.2\%}_{-15.9\%}$ pb	$0.277(5)^{+34.5\%}_{-27.0\%}$ pb
$(\frac{H_T}{4}, \frac{H_T}{4})$	$0.406(4)^{+16.6\%}_{-14.3\%}$ pb	$0.315(3)^{+30.6\%}_{-27.5\%}$ pb

MiNLO' more than 20% less than NLO

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

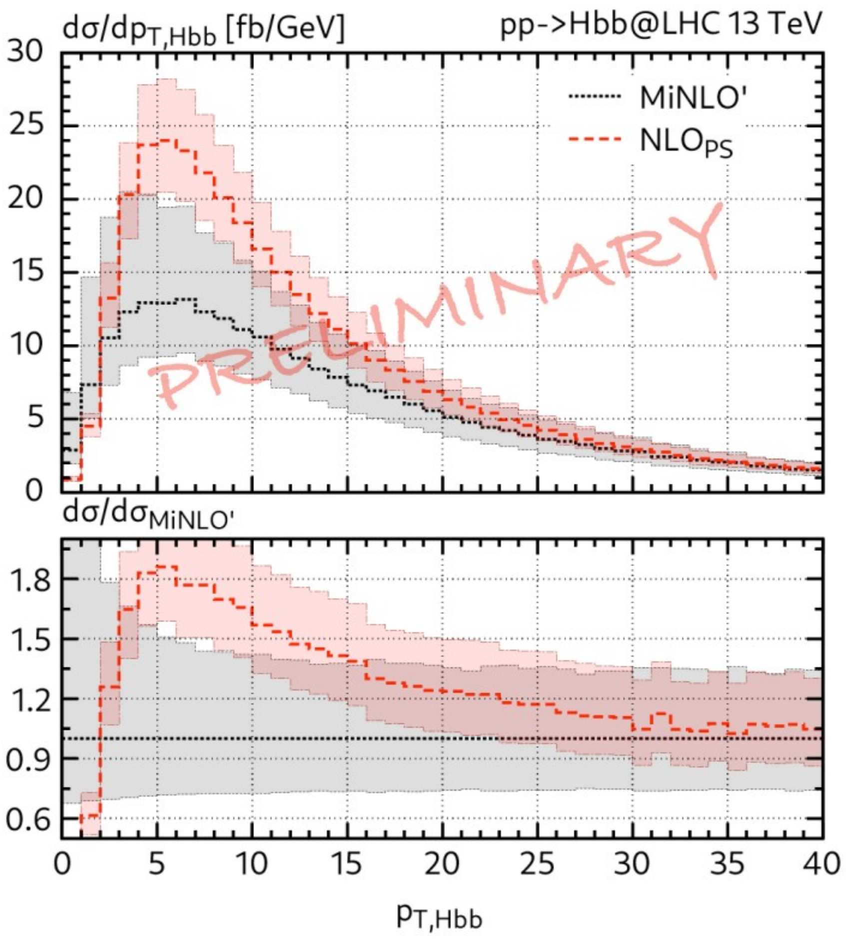
[Biello, Mazzitelli, **AS**, Wiesemann, Zanderighi (in progress)]

The issue of MiNLO'



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

The issue of `MiNLO'`



$$\bar{B}(\Phi_{XJ}) = e^{-\tilde{S}(p_T)} \left\{ B\left(1 - \alpha_s(p_T)\,\tilde{S}^{(1)}\right) + V + \int \mathrm{d}\phi_{rad}\, R + \cancel{\left[D^{(3)}(p_T)\right] \times F^{corr}} \right\}$$

included in the Luminosity for MiNNLO$_{PS}$

- In **`MiNLO'`**, the **large log(m_b)** terms in RV & RR contributions are **not balanced**.

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

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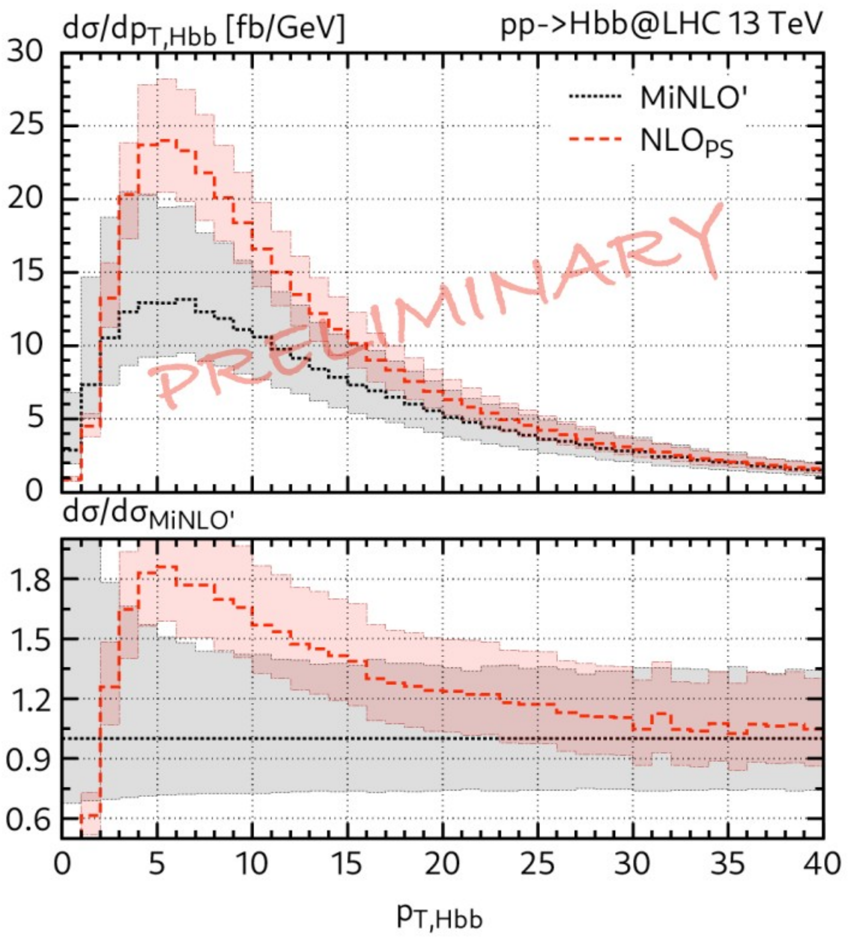

[Biello, Mazzitelli, **AS**, Wiesemann, Zanderighi (in progress)]

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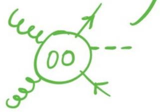


included in the Luminosity for MiNNLO$_{PS}$

- 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**.
- Same behaviour was observed in bbZ

[Mazzitelli, Sotnikov, Wiesemann (2404.08598)]

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**

$$\mathscr{A}^{(2)} = \underbrace{\log(m_b)\text{-terms} + \text{const.}}_{\mathscr{F}^{(2)}\,\mathscr{A}^{(0)}_{m_b=0} + \mathscr{F}^{(1)}\,\mathscr{A}^{(1)}_{m_b=0} + \mathscr{F}^{(0)}\,\boxed{\mathscr{A}^{(2)}_{m_b=0}}} + \mathscr{O}\left(\frac{m_b}{Q}\right)$$

Massification coefficients

Massless double virtual amplitude

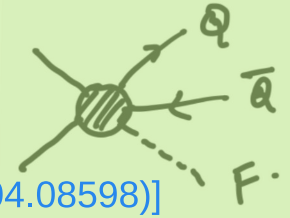
Double virtual amplitude

$(\mu_R^{(0),\alpha}, \mu_R^{(0),y})$	NLO$_{\text{PS}}$	MiNLO'	MiNNLO$_{\text{PS}}$ $(\mathcal{F}^{(0)}=0)$
$(\frac{H_T}{4}, m_H)$	$0.381(2)^{+20.2\%}_{-15.9\%}$ 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)]

Predictions using recent extension of **MiNNLO$_{\text{PS}}$ for $Q\bar{Q}F$**

[Mazzitelli, Sotnikov, Wiesemann (2404.08598)]



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

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

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

Double virtual amplitude

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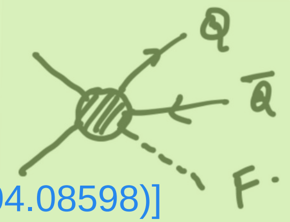

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$$\mathcal{F}^{(2)}\mathcal{A}^{(0)}_{m_b=0} + \mathcal{F}^{(1)}\mathcal{A}^{(1)}_{m_b=0} + \mathcal{F}^{(0)}\boxed{\mathcal{A}^{(2)}_{m_b=0}}$$

What about the 2-loop?

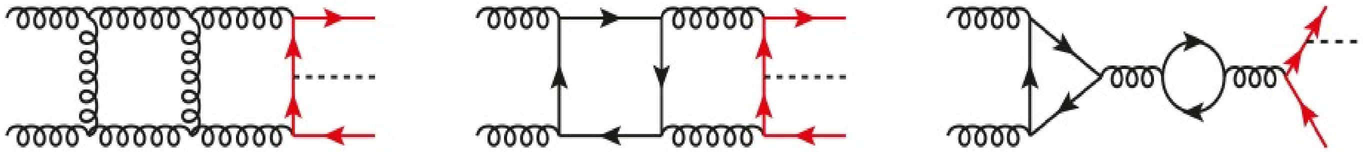
MiNNLO$_{PS}$ with **only logarithmic** contributions in the 2-loop predicts a total cross-section **bigger** than the **NLO+PS** one.

Double virtual amplitude

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

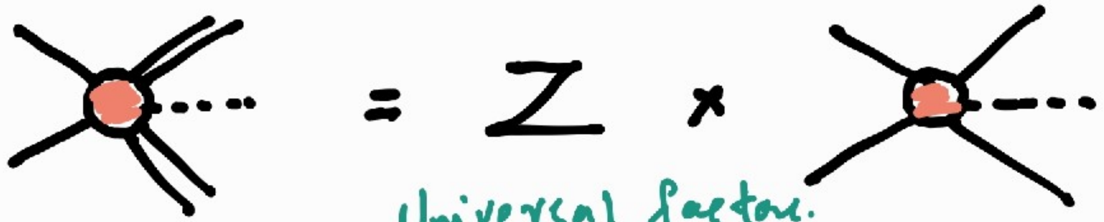
$$\mathscr{F}^{(2)}\,\mathscr{A}^{(0)}_{m_b=0} + \mathscr{F}^{(1)}\,\mathscr{A}^{(1)}_{m_b=0} + \mathscr{F}^{(0)}\,\mathscr{A}^{(2)}_{m_b=0}$$

[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 by Chiara Savoini

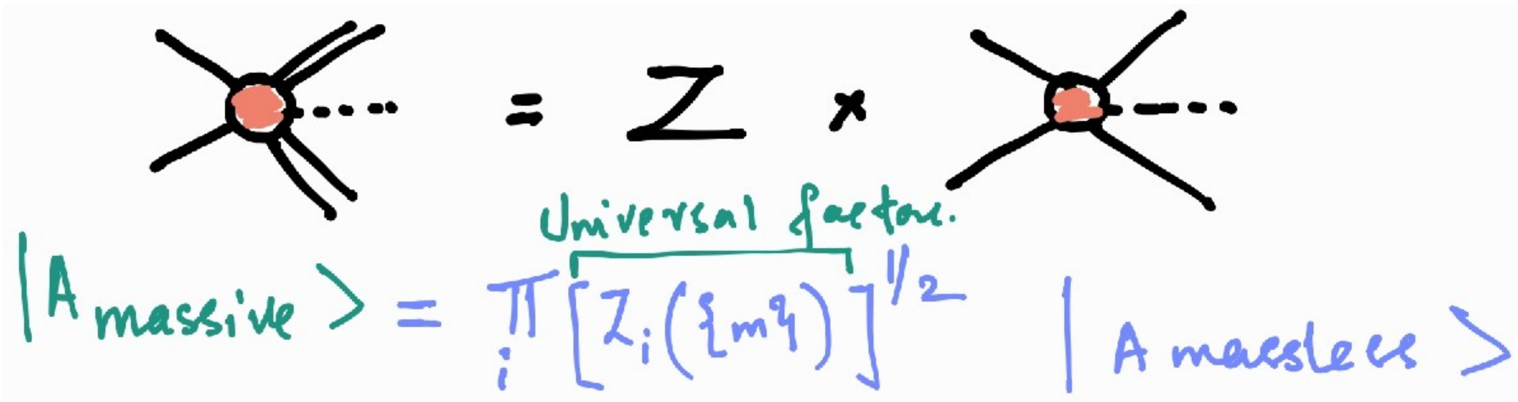
Original massification (OM)



$$|A_{\text{massive}}\rangle = \prod_i \Big[\overbrace{Z_i(\{m_q\})}^{\text{Universal factor}}\Big]^{1/2} \, |A_{\text{massless}}\rangle$$

Massification procedure

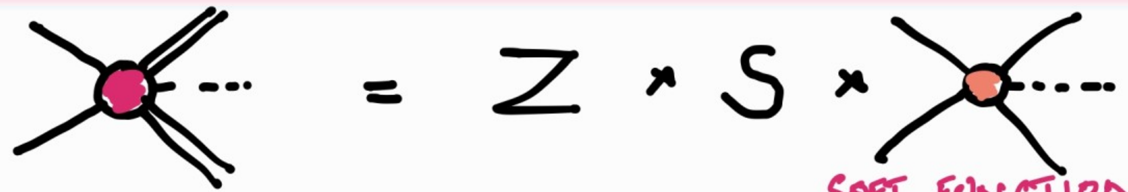
Original massification (OM)



- 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 check in $q\bar{q} \to Q\bar{Q}$ [Czakon, Mitov, Moch (0705.1975)]

Massification procedure

Generalised massification (GM)

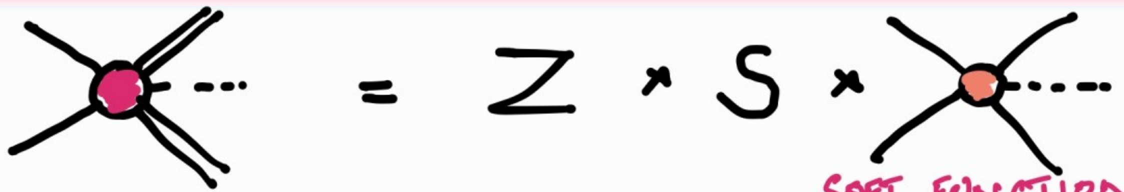


$$|A_{\text{massive}}\rangle = \prod_i \left[Z_i(\{m\})\right]^{1/2} \overbrace{S(\{m\})}^{\text{SOFT FUNCTION}} |A_{\text{massless}}\rangle$$

Additional contribution to account for closed fermion loops

Massification procedure

Generalised massification (GM)



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Additional contribution to account for closed fermion loops

- 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)]

Momentum mappings

- 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 $m_b = 0$.

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

- We need an explicit mapping of massive phase-space points P , $\eta : P \rightarrow P_0$, such that $\eta(P) = P_0 + O(m_b/m_H)$.

- 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.

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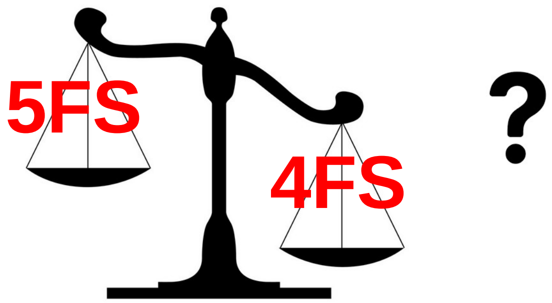
Mapping $\eta : \mathrm{PS}_{m_b} \mapsto \mathrm{PS}_{m=0}$

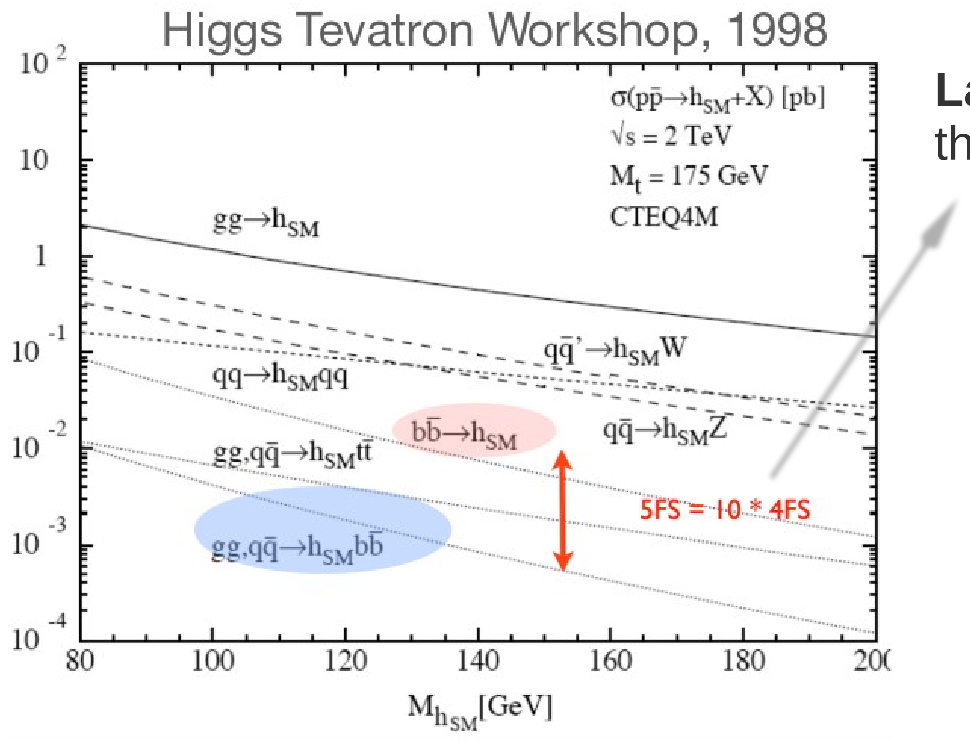
$\eta_{q\bar{q}}$ preserves the total momentum of $b\bar{b}$

η_{gg} avoids a collinear singularity

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.

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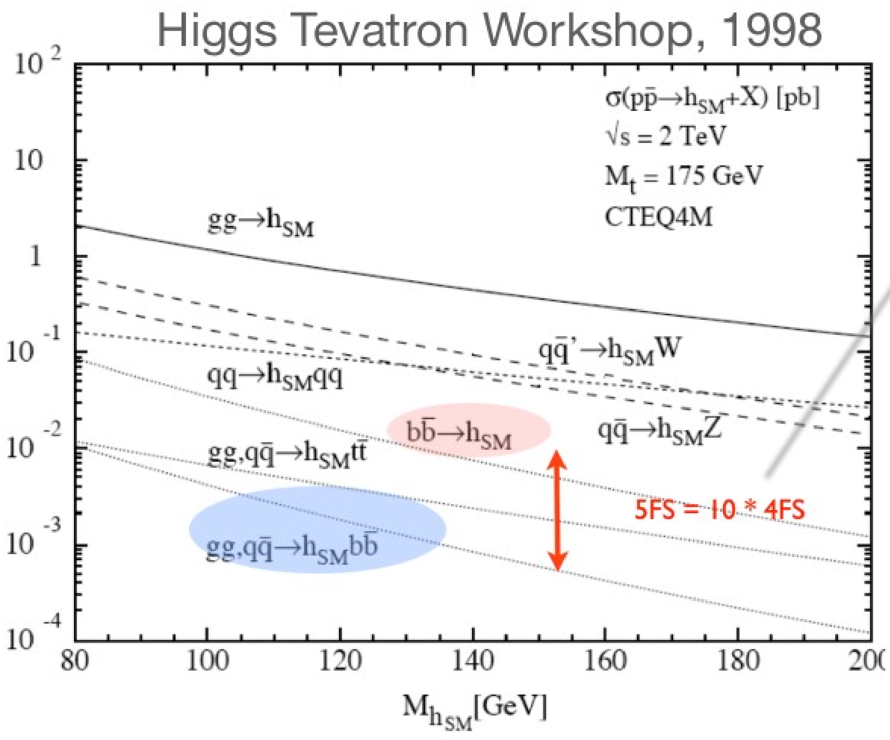

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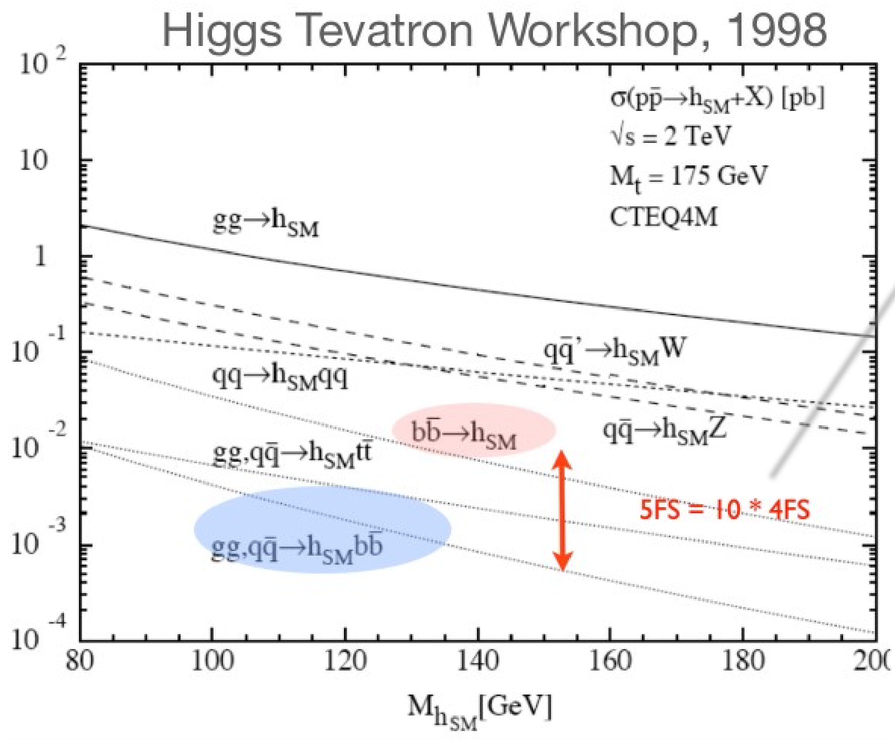
NLO : 5FS = 1.78 * 4 FS

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

Total cross-section



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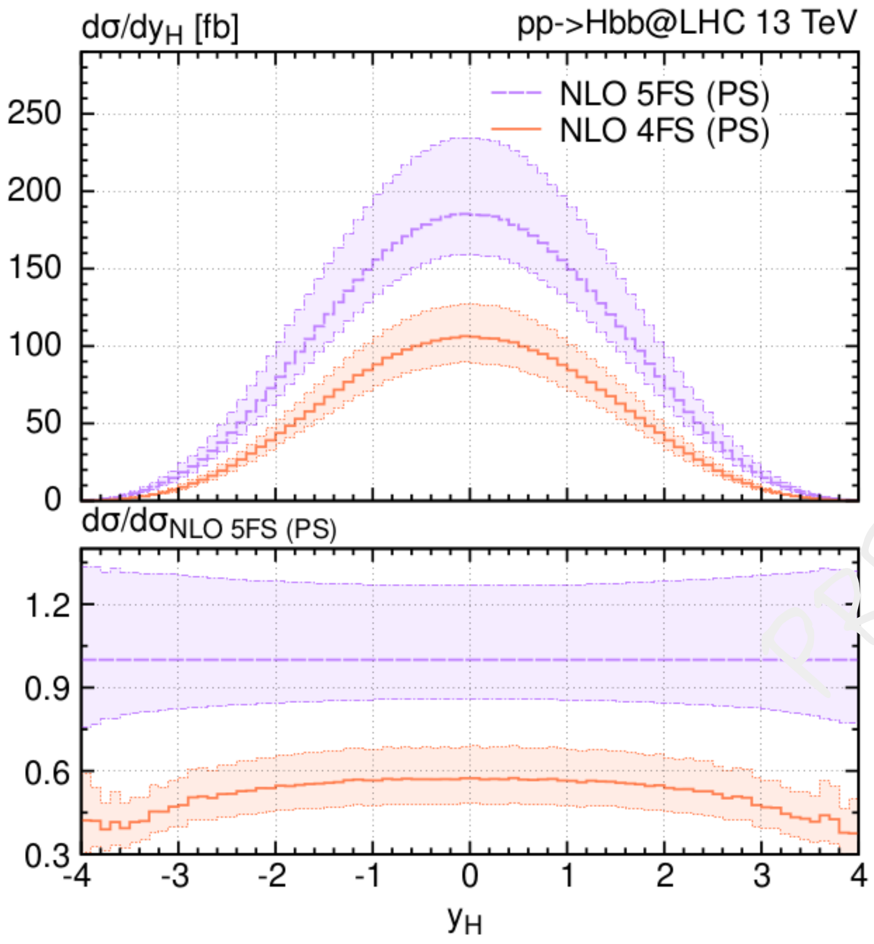
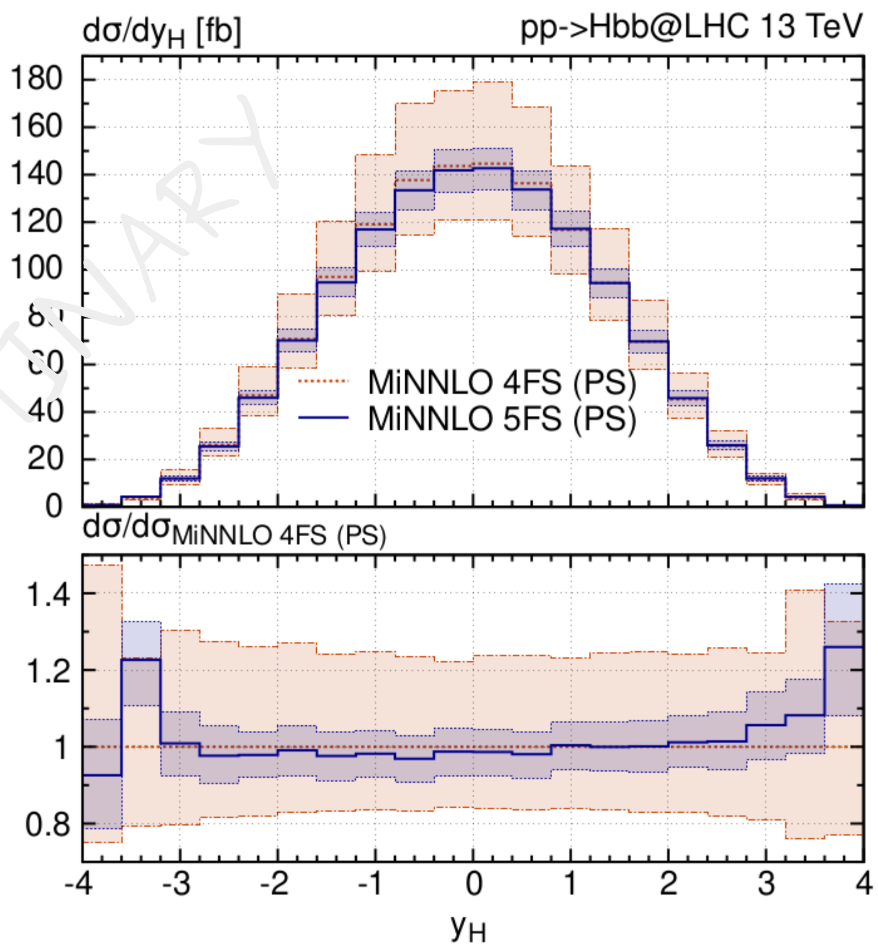
NNLO : 5FS = 0.97 * 4 FS !!

MiNNLO$_{PS}$(5FS)	MiNNLO$_{PS}$(4FS)
$0.509(8)^{+2.9\%}_{-5.3\%}$ pb	$0.506(7)^{+24.1\%}_{-16.5\%}$ pb

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

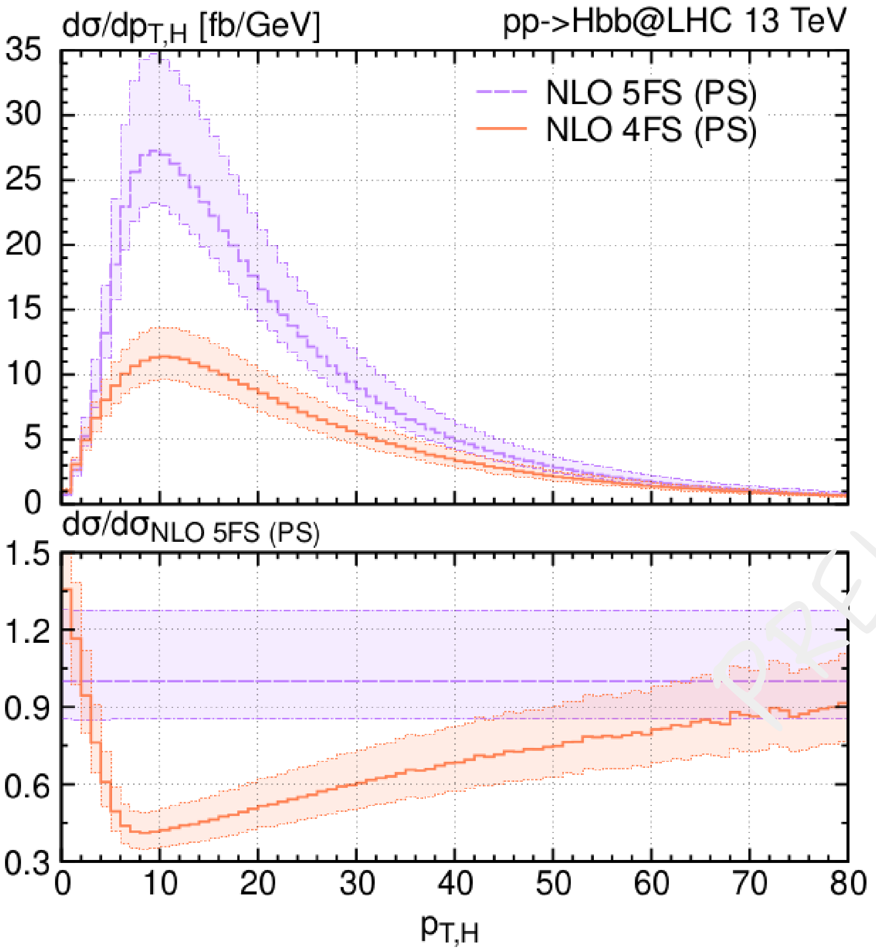
Higgs rapidity

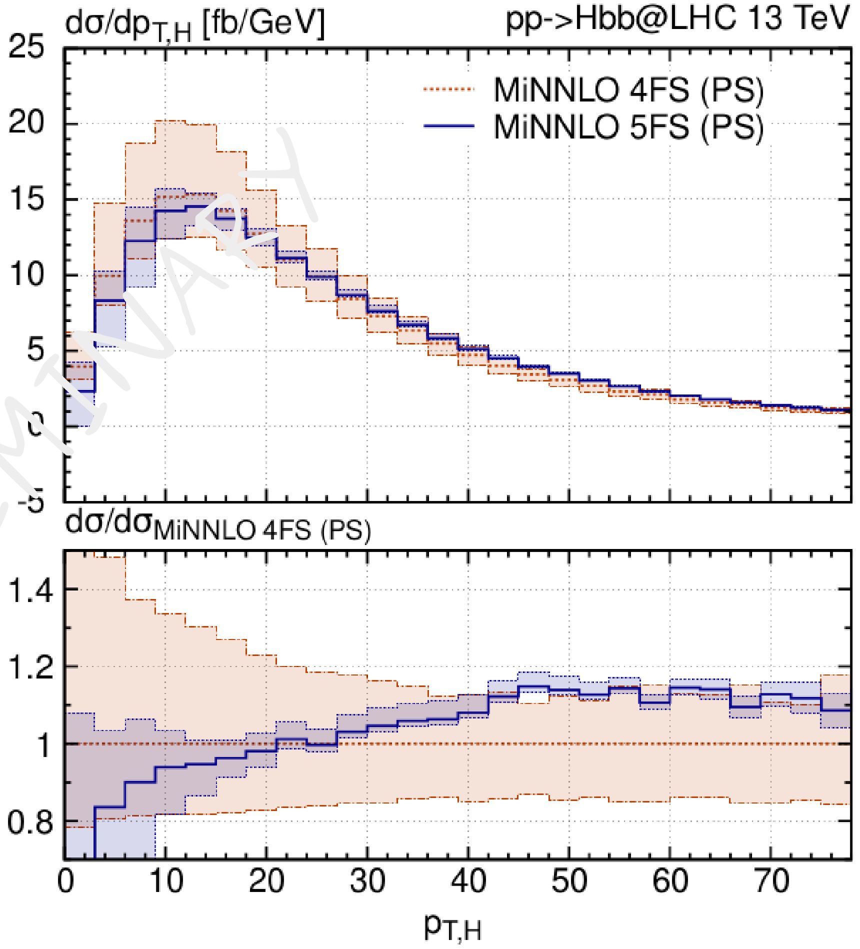




[Biello, Mazzitelli, **AS**, Wiesemann, Zanderighi (in progress)]

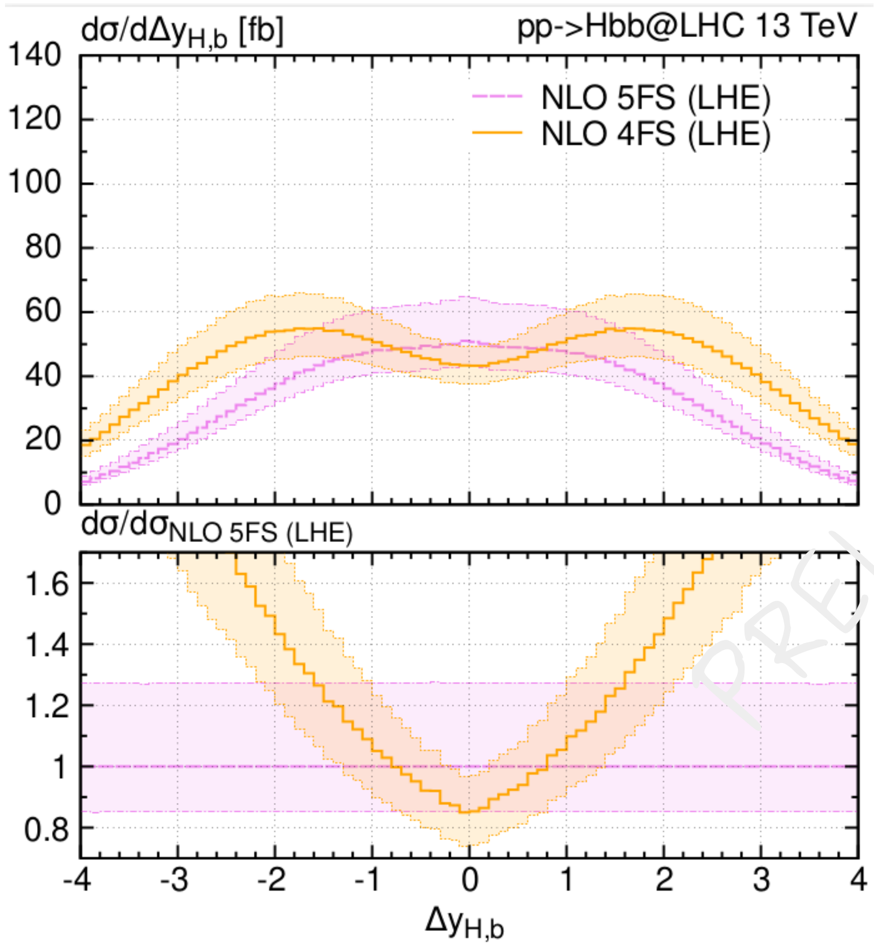
Higgs p_T spectrum

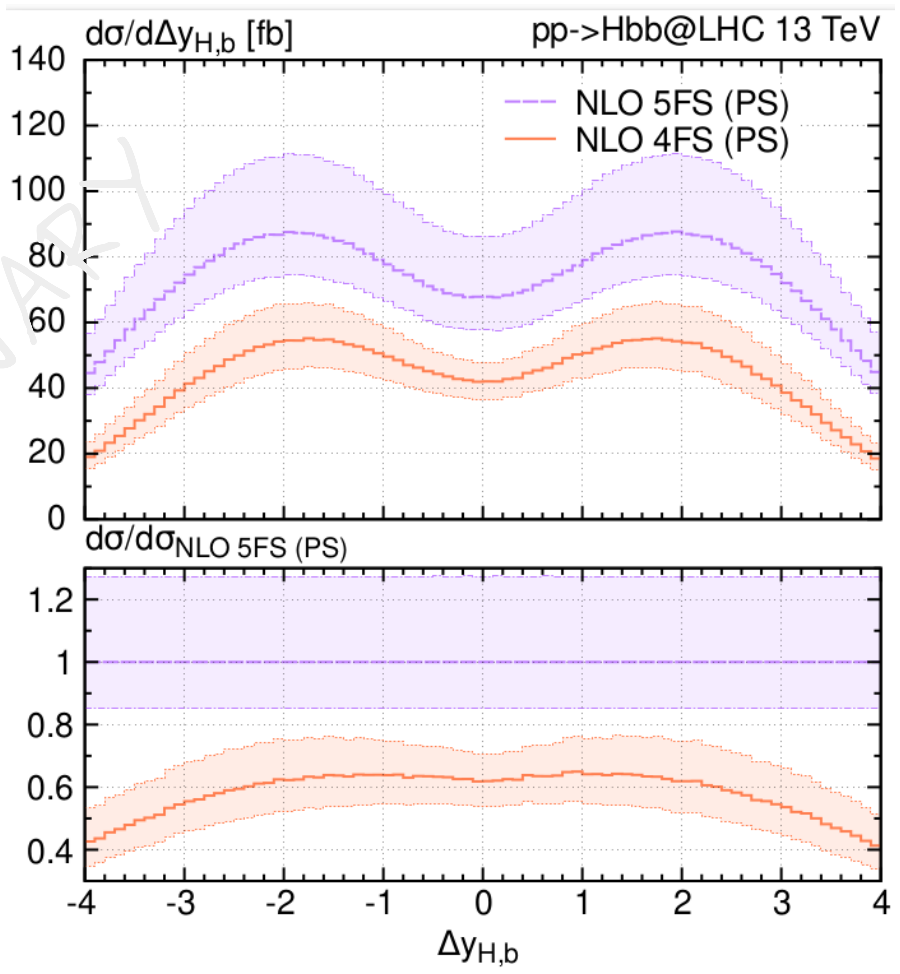




[Biello, Mazzitelli, **AS**, Wiesemann, Zanderighi (in progress)]

Rapidity difference (Higgs, bottom)





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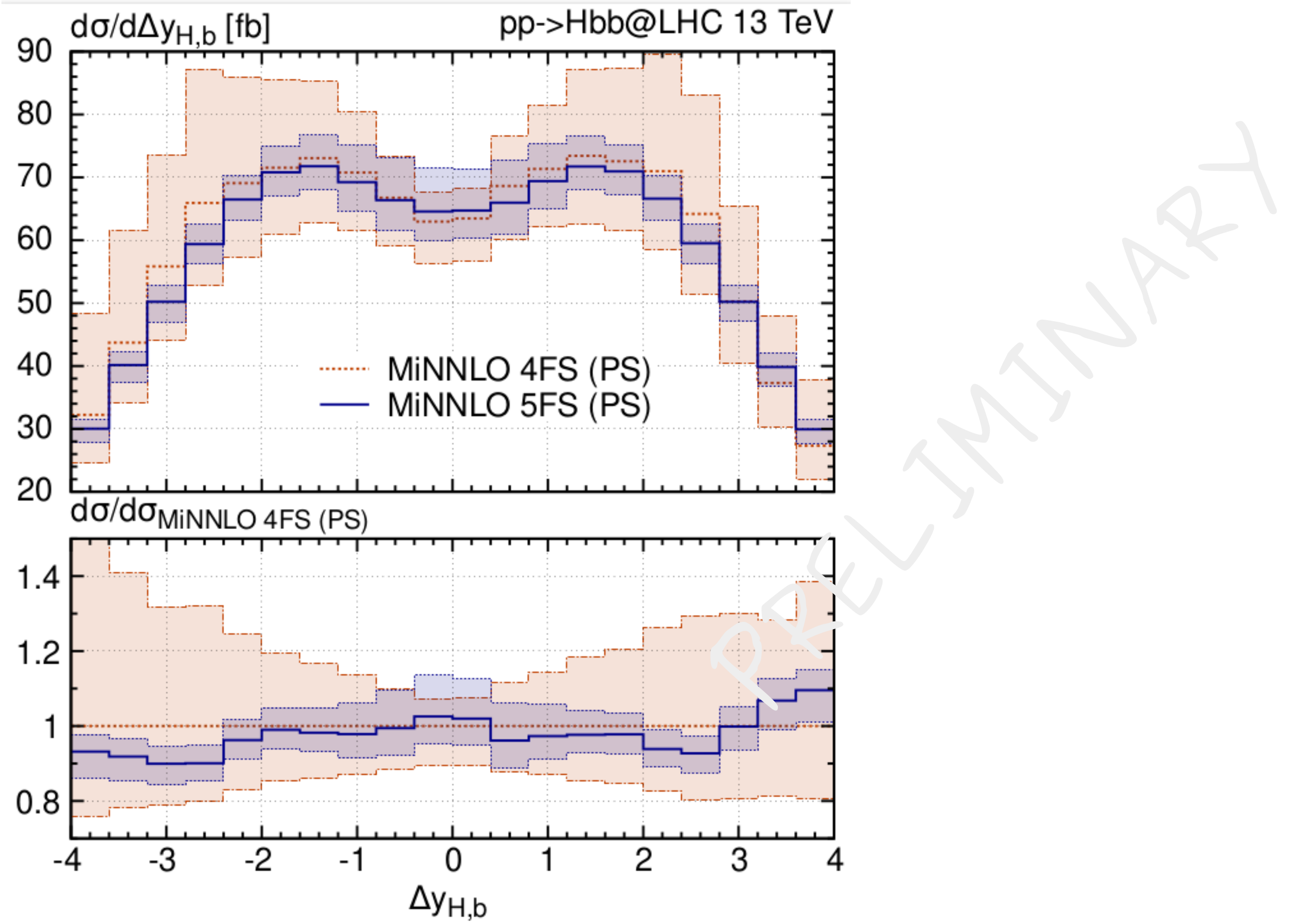

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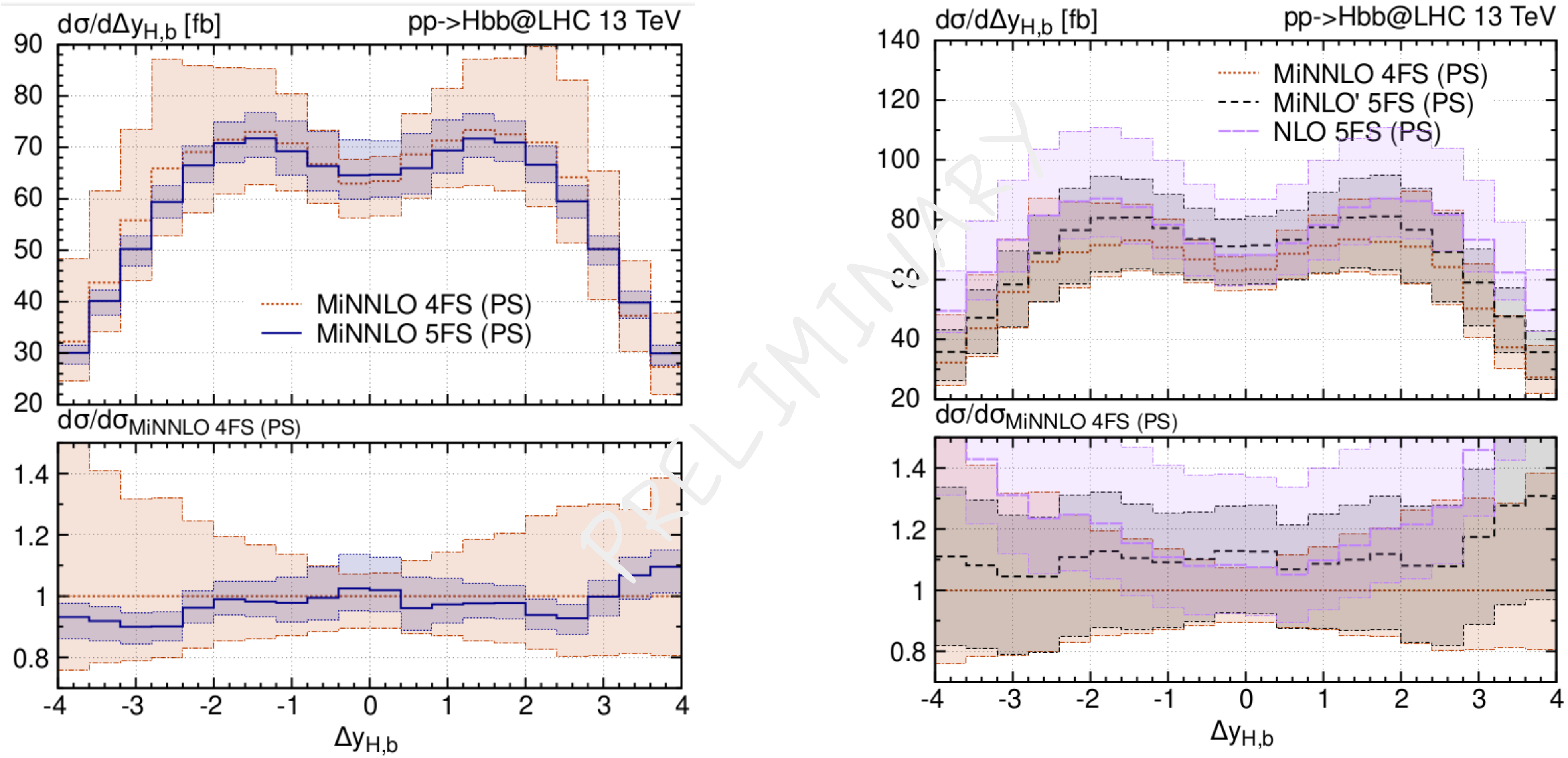
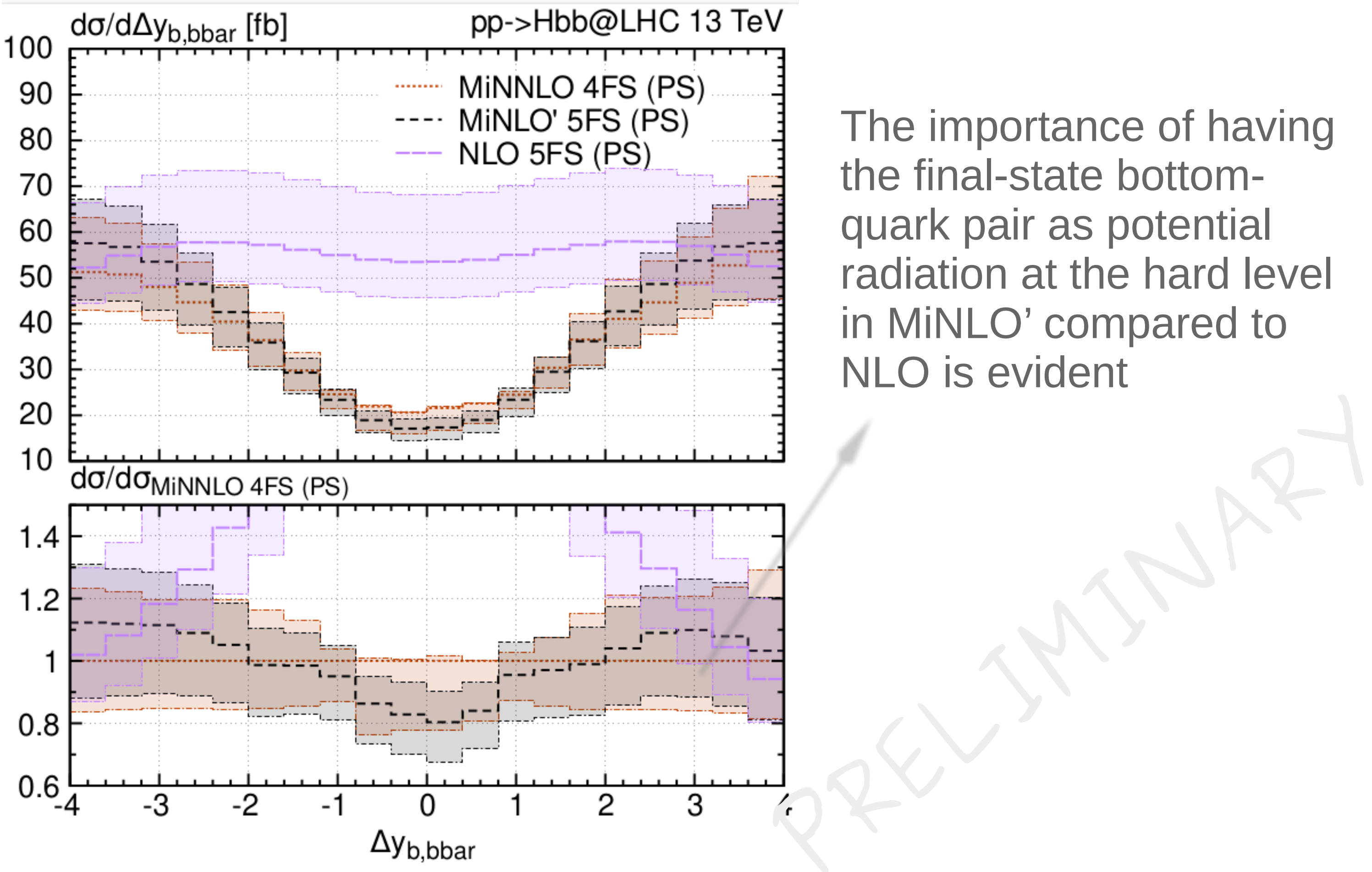


[Biello, Mazzitelli, **AS**, Wiesemann, Zanderighi (in progress)]

Rapidity difference (b, $\bar{b}$)



The importance of having the final-state bottom-quark pair as potential radiation at the hard level in MiNLO' compared to NLO is evident

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

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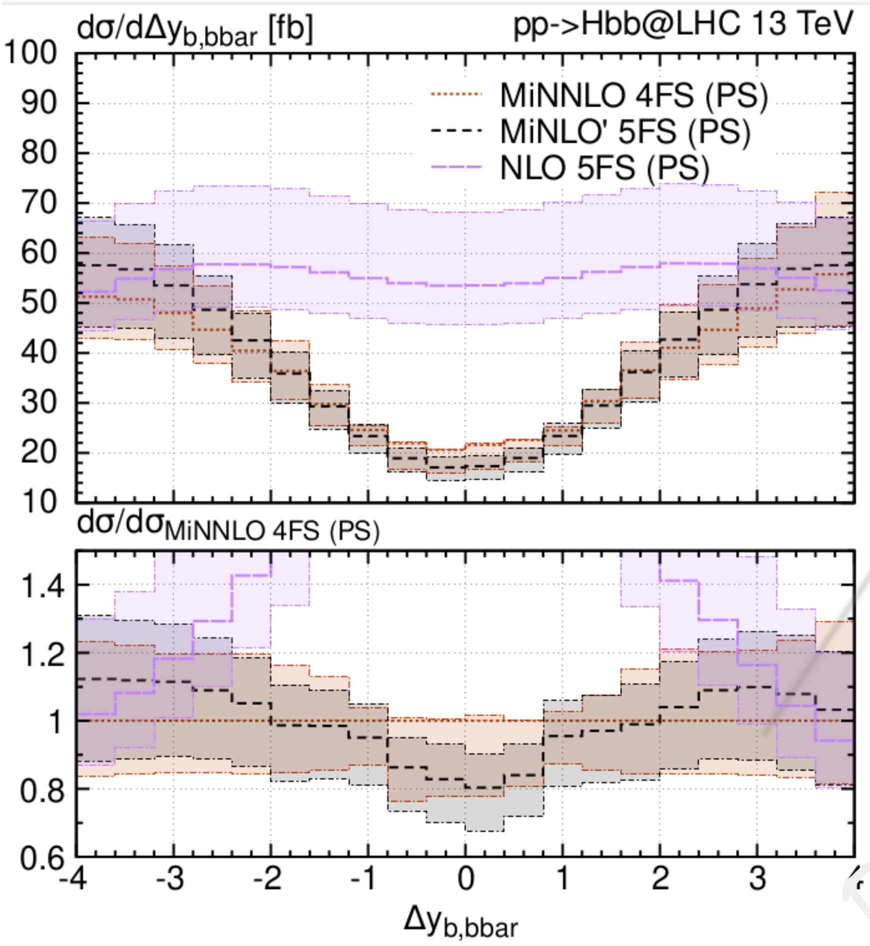

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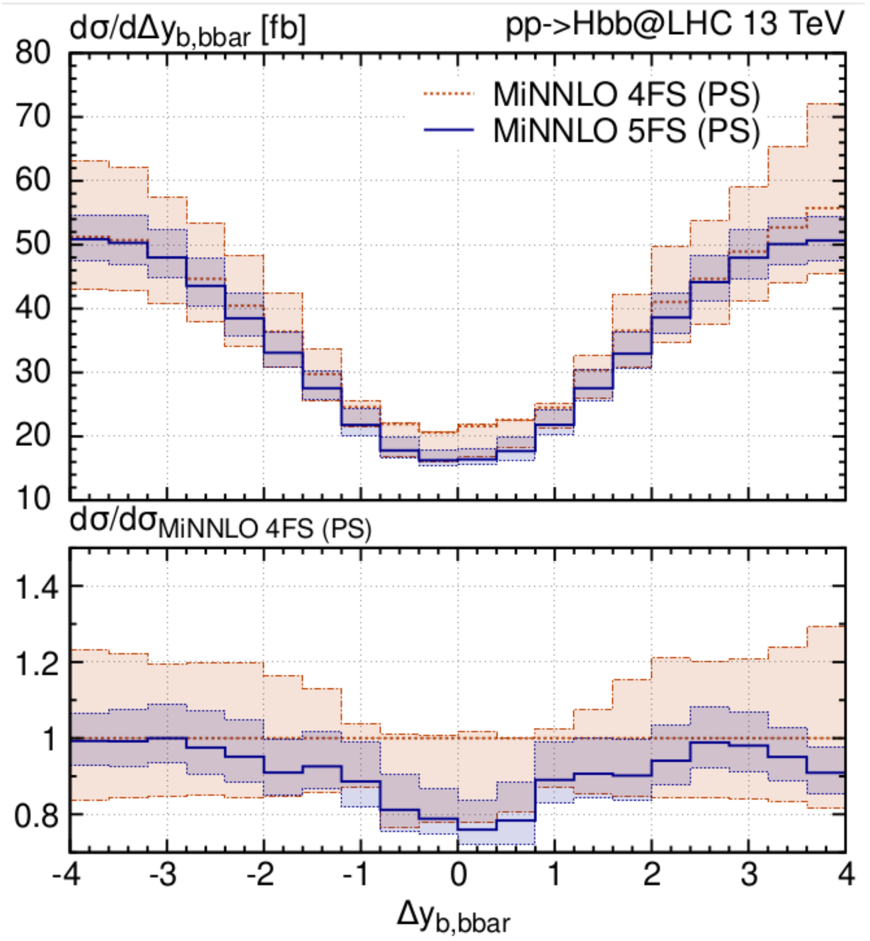

PRELIMINARY

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

Fiducial analysis with b-tagging

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Fiducial cuts for an experimental CMS-like analysis, as done for the Z + b jets [Mazzitelli, Sotnikov, Wiesemann (2404.08598)]

The final state: on-shell Higgs & at least one (or two) b-jets.

Jets are defined by clustering all light partons plus the bottom quark using the anti-kT, R = 0.4.

$p_{T,b\text{-jet}} > 30$ GeV & $|\eta_{b\text{-jet}}| < 2.4$

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	NLOPS (5FS)	NLOPS (4FS)	MiNNLO$_{PS}$ (5FS)	MiNNLO$_{PS}$ (4FS)
H+$\geq 1b$	$0.099(4)^{+27\%}_{-15\%}$ pb	$0.074(4)^{+20\%}_{-15\%}$ pb	$0.111(7)^{+2.7\%}_{-2.5\%}$ pb	$0.121(2)^{+16\%}_{-15\%}$ pb
H+$\geq 2b$	$0.0055^{+27\%}_{-15\%}$ pb	$0.0050^{+24\%}_{-18\%}$ pb	$0.0082^{+5.1\%}_{-4.2\%}$ pb	$0.0072^{+4.2\%}_{-10\%}$ pb

Agreement between the MiNNLOPS 5FS & 4FS is better for the 1-bjet case.

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

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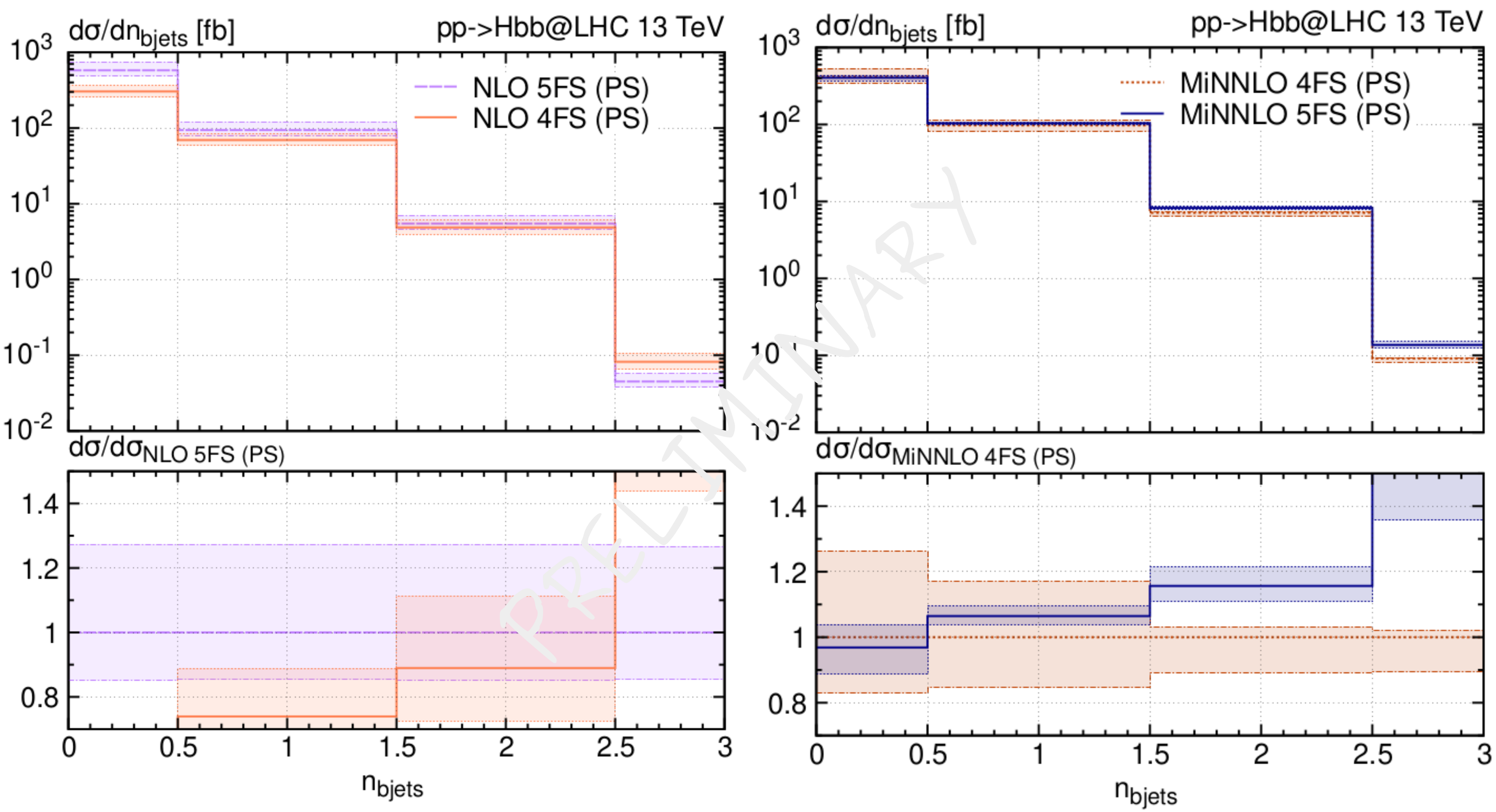

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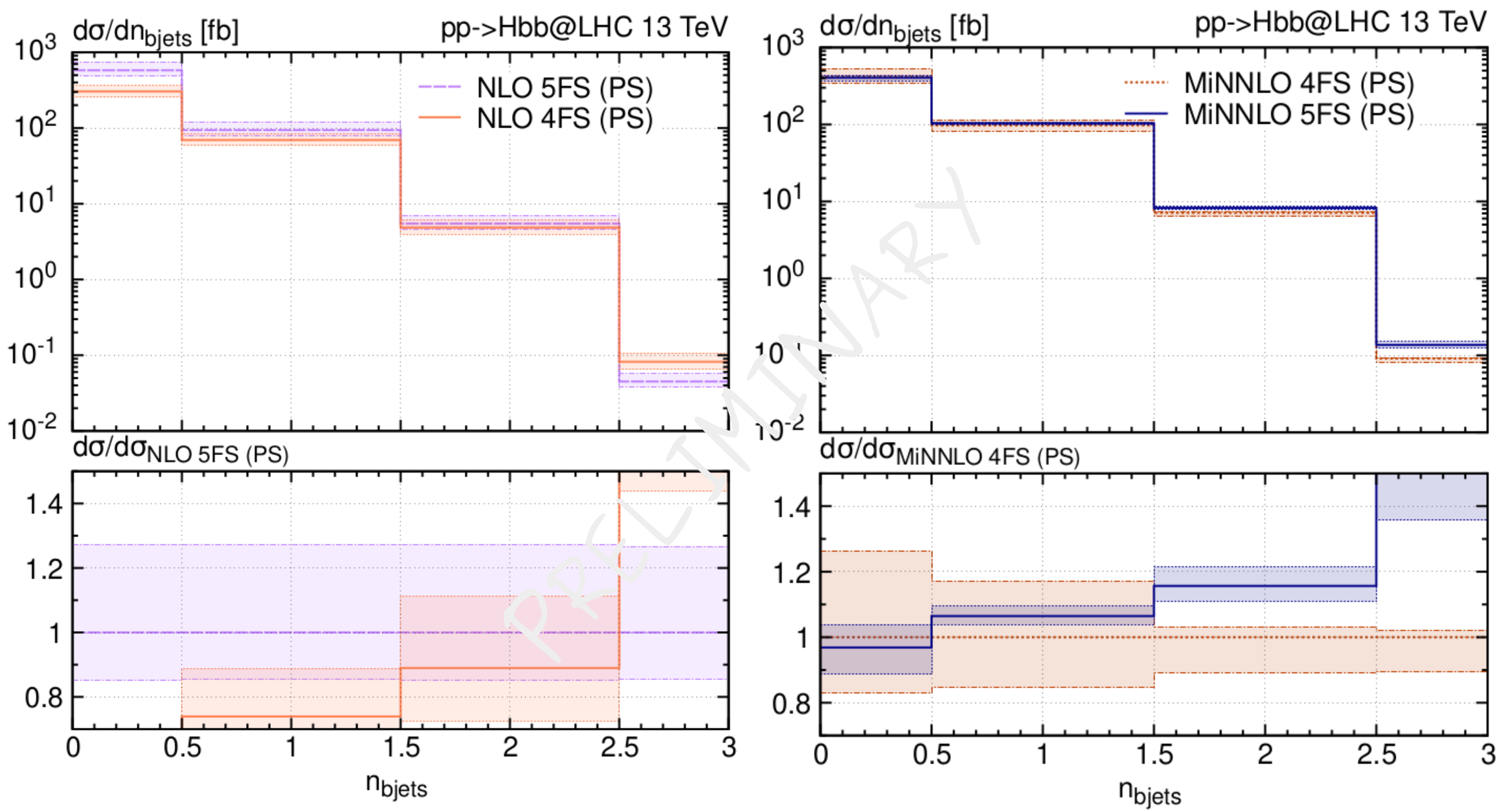
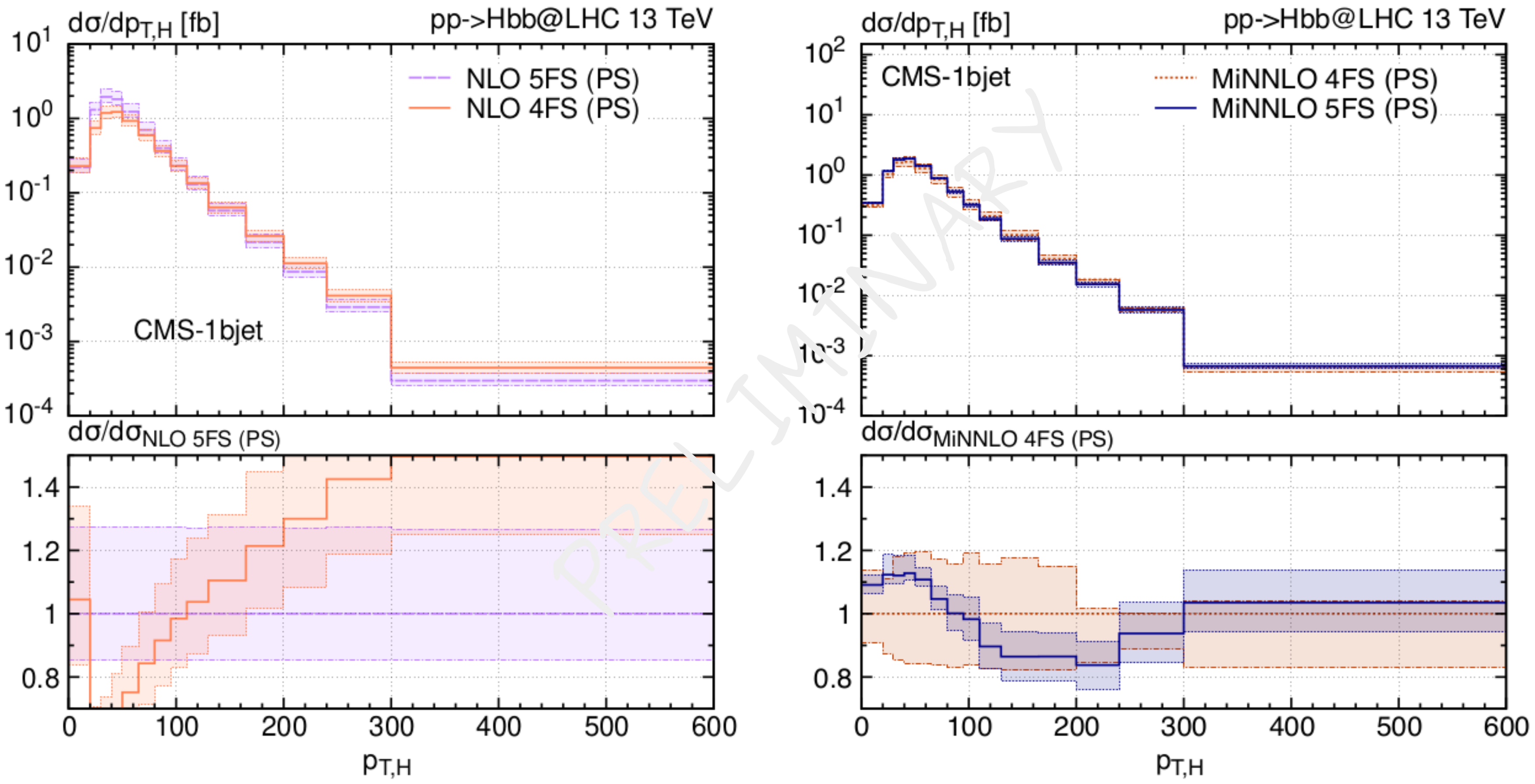


[Biello, Mazzitelli, **AS**, Wiesemann, Zanderighi (in progress)]

Agreement only for small numbers of b-jets, precisely we have a similar amount of events with one or without b-jets

The discrepancy for higher numbers of b-jets is due to the smaller number of hard-level bottoms in the 5FS.

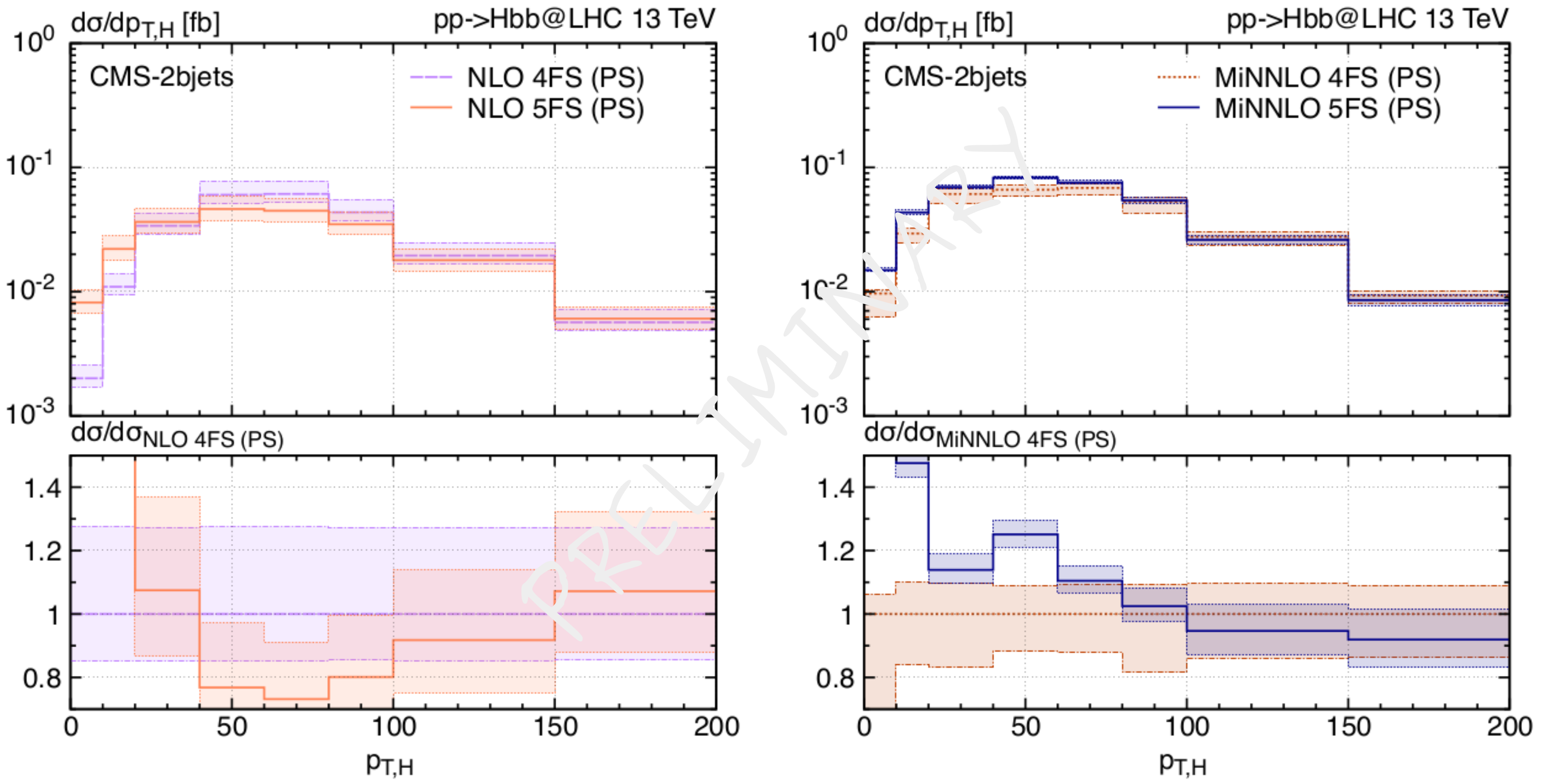
Fiducial analysis with b-tagging



Improvement of the 5FS at MiNNLOPS level:
the two schemes now has a very similar shape and they are in agreement within the scale uncertainty.

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

Fiducial analysis with b-tagging

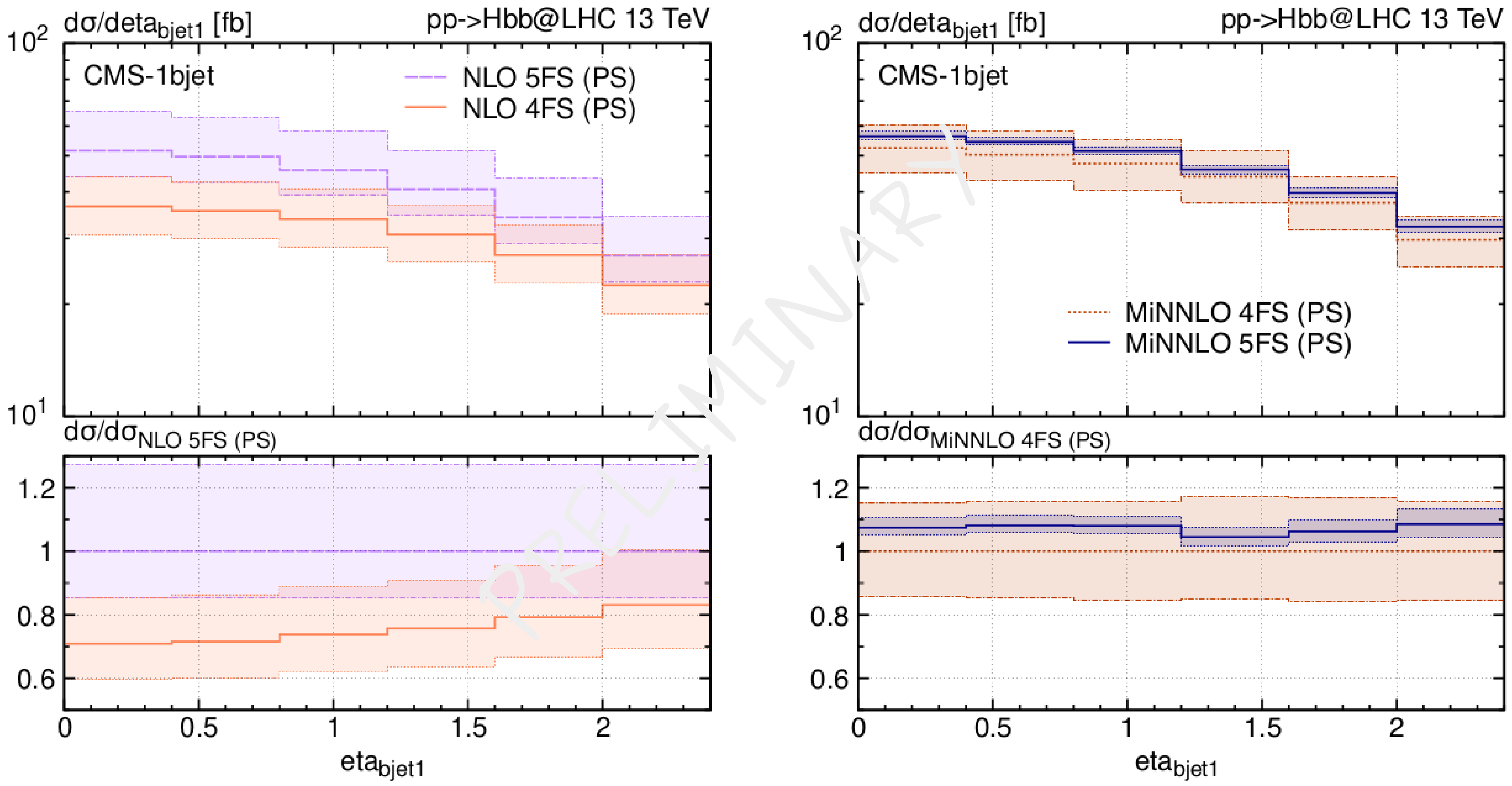


[Biello, Mazzitelli, **AS**, Wiesemann, Zanderighi (in progress)]

If we require at least 2 b-jets, the scheme comparison does not improve at MiNNLOPS.

At high $p_{T,H}$ there is a better agreement, but in general the agreement between flavour schemes is worse with an additional b-jet.

Fiducial analysis with b-tagging

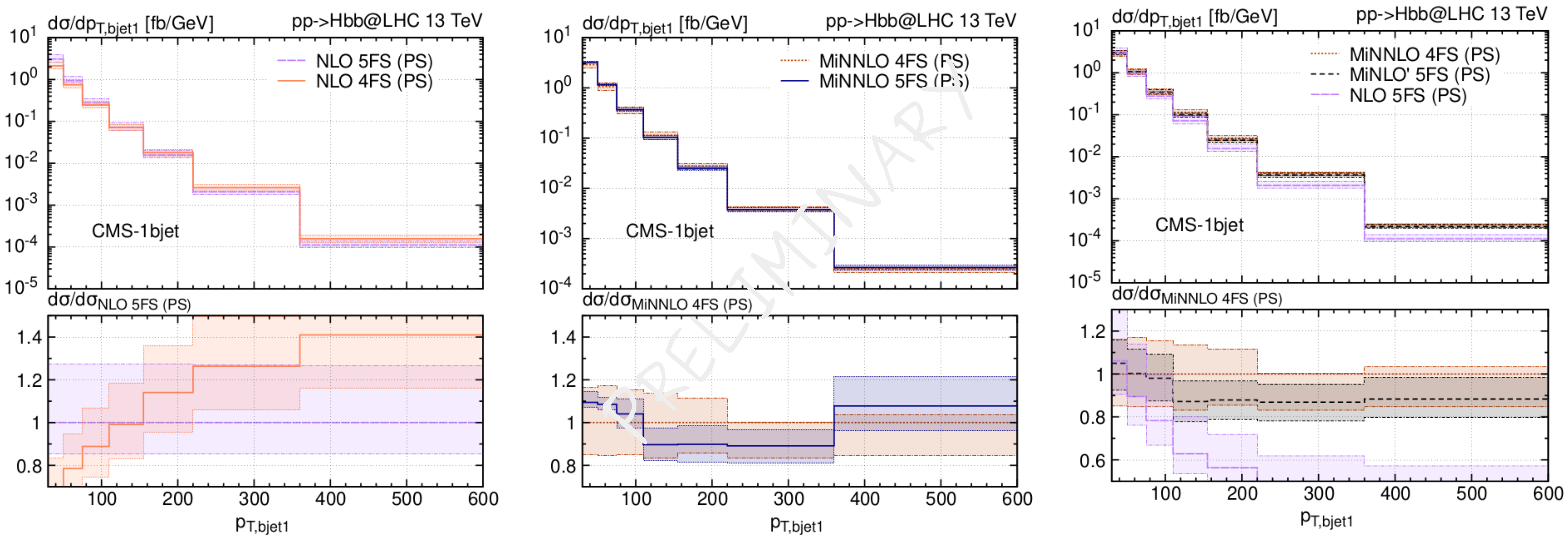


[Biello, Mazzitelli, **AS**, Wiesemann, Zanderighi (in progress)]

The two NLOPS generators are not in agreement while the MiNNLOPS predictions show a nice overlap.

The 5FS overestimates by an almost constant factor the 4FS prediction.

Fiducial analysis with b-tagging



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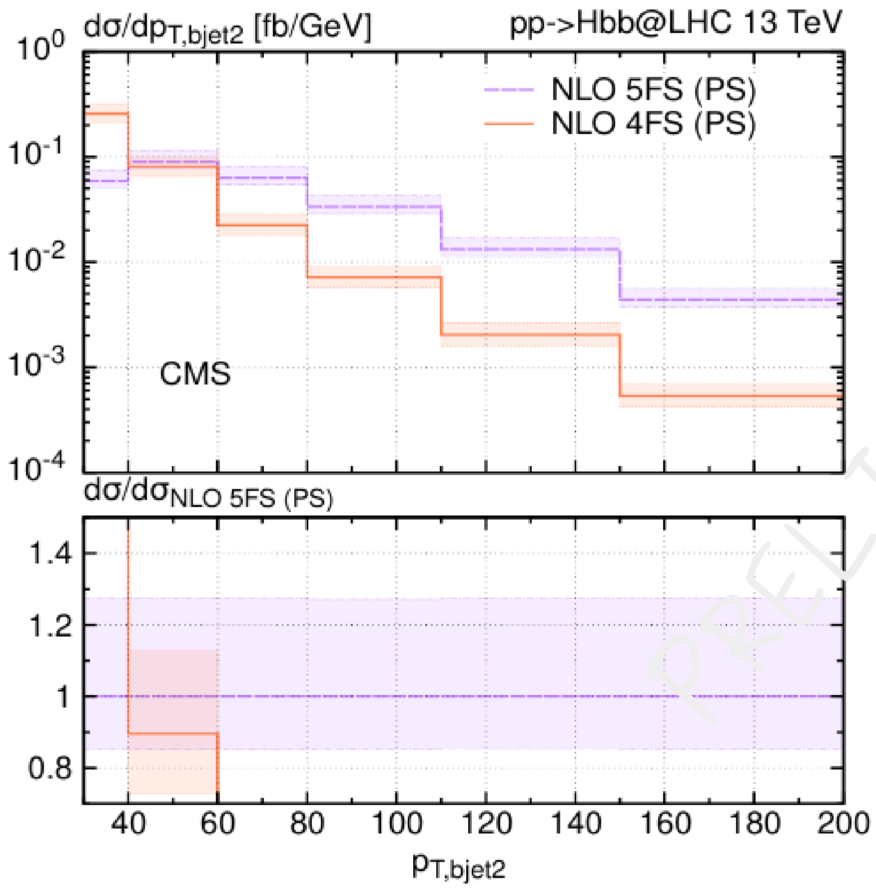

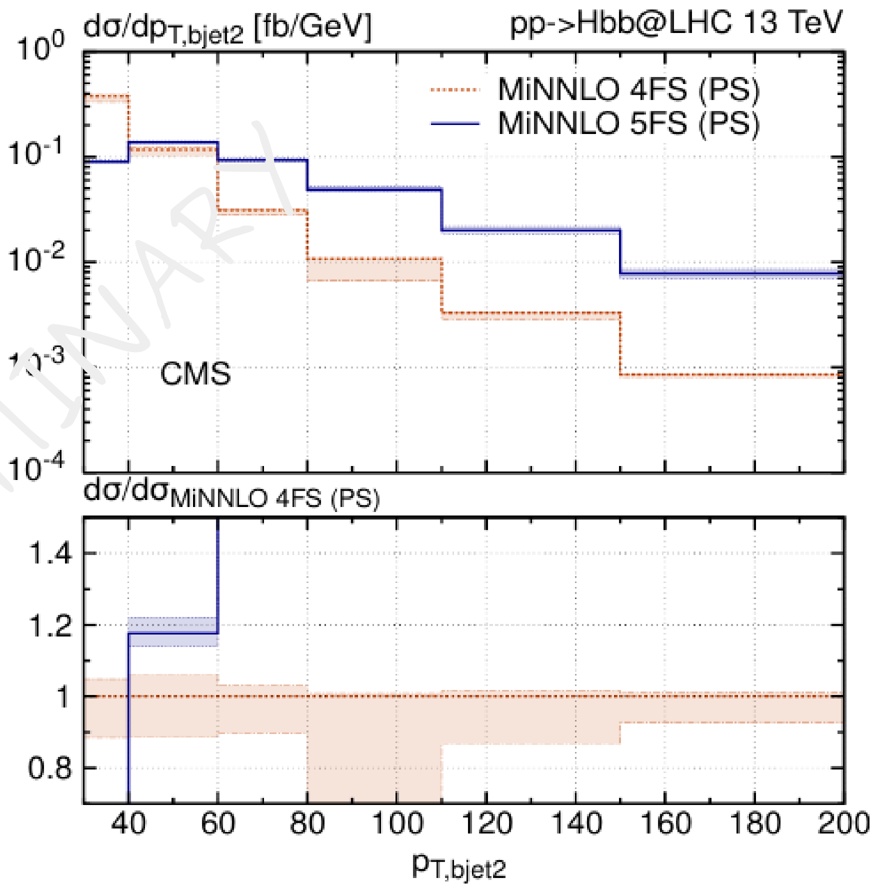

[Biello, Mazzitelli, **AS**, Wiesemann, Zanderighi (in progress)]

Summary & Outlook

- Discussed the **first NNLO+PS** computation for **$b\bar{b}H$** in both **5FS & 4FS** at the LHC by using **MiNNLO$_{\mathrm{PS}}$** method

- Extensive **validation of 5FS** predictions against **fixed-order results** from literature, showcasing **consistency** in relevant kinematical regions

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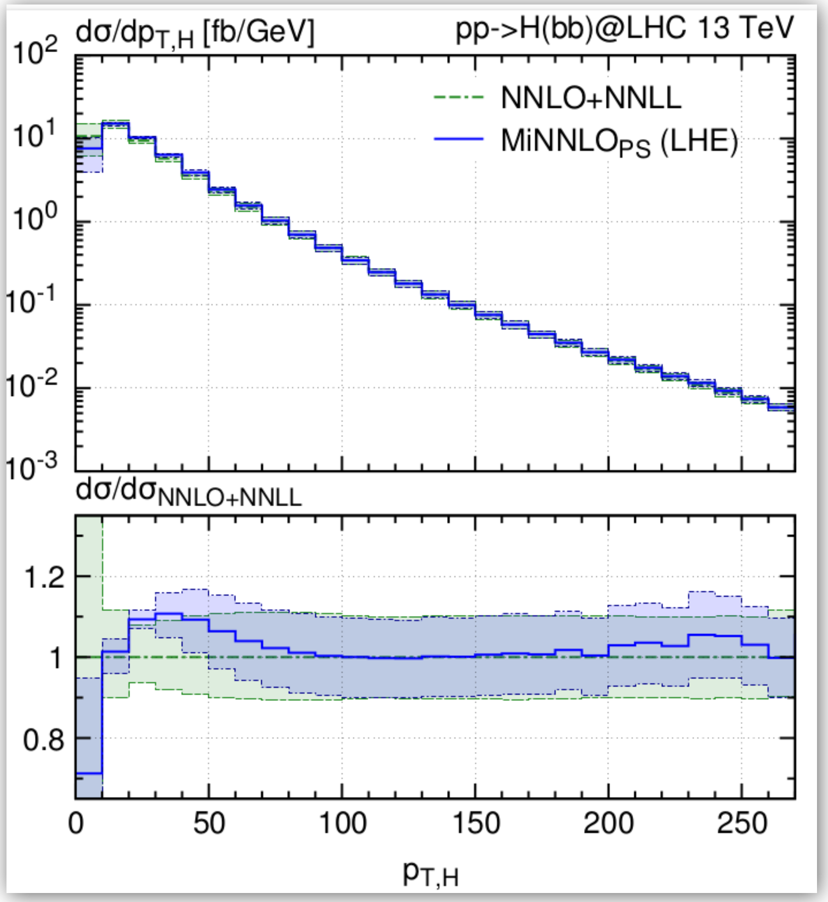
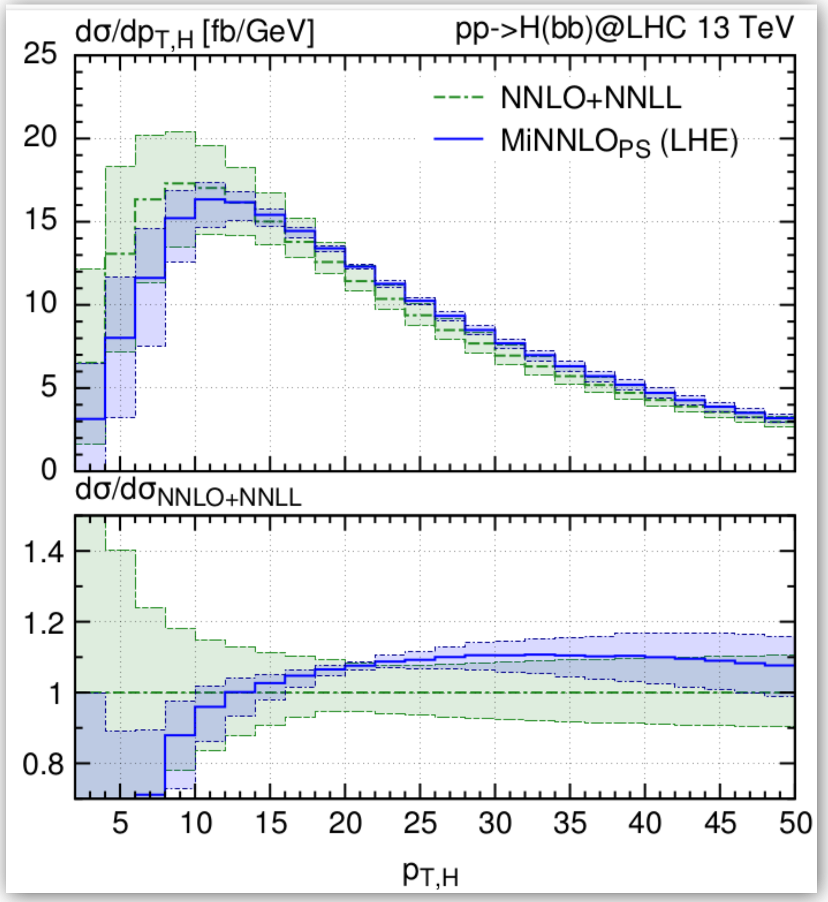
THANK YOU !

Backup slides.....

Comparison to NNLO+NNLL

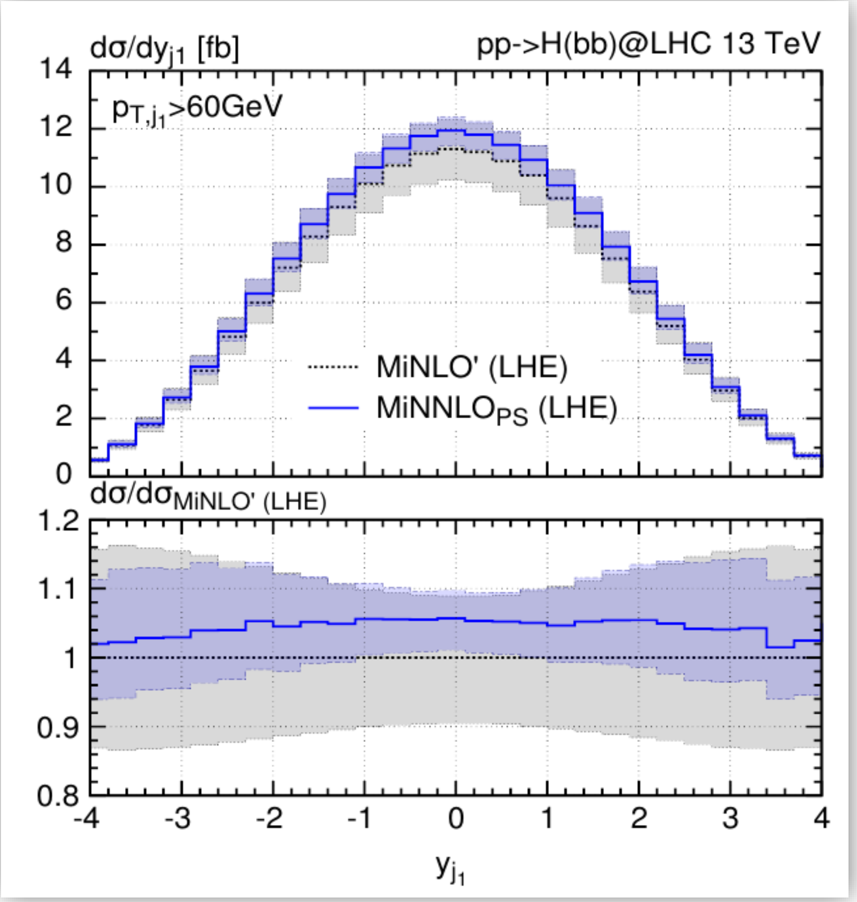


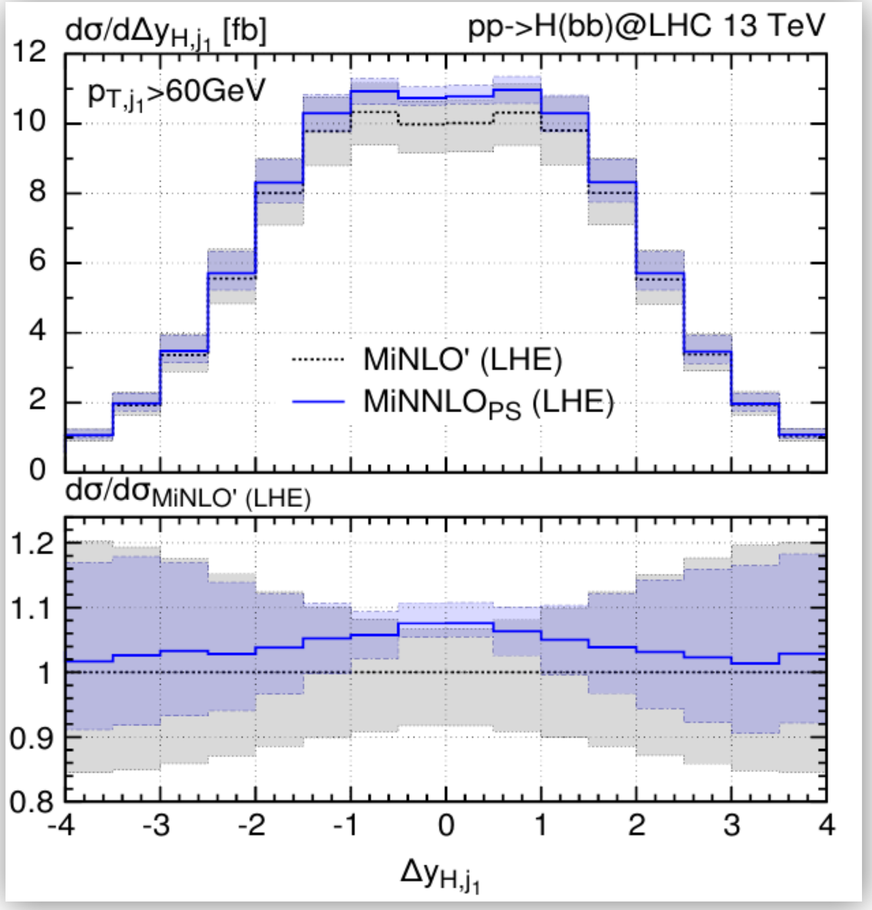


At high $p_{T,H}$:
they coincide again

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

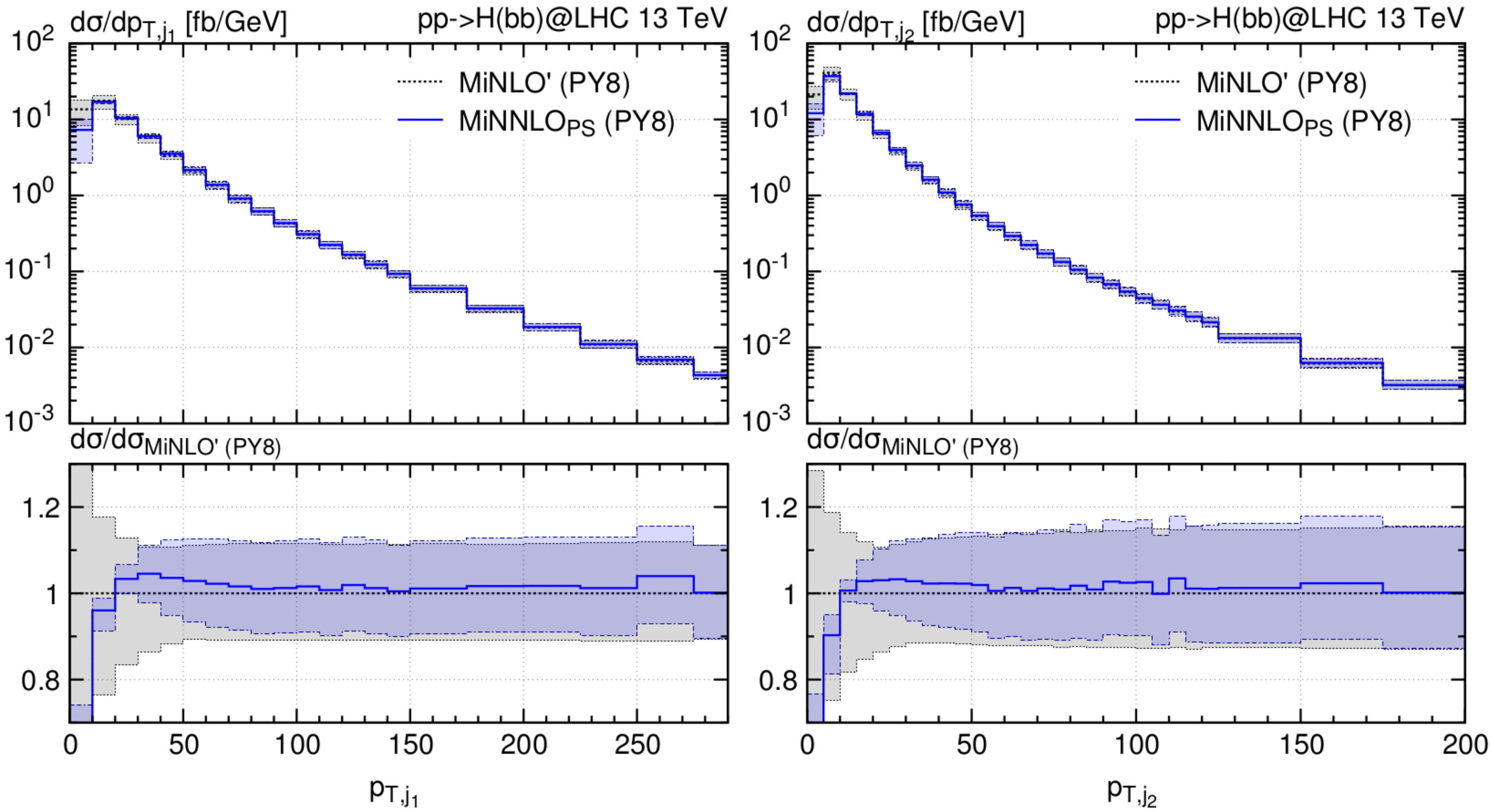
Comparison of MiNLO' & MiNNLO$_{PS}$





- ✓ 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 $m_b = 0$.

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

- 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 $\hat{p_{\bar{b}}}$ 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)]

Double virtual amplitude

Rescue precision system

For a stable numerical evaluation of the 2-loop: we used a trick from dimentional analysis.

Previously the library was computing the massless two-loop correction interfered with the tree-level by using the LHC-like PS points produced from Powheg ,

$$F^{(2)}(p_1^{\text{mless}}, p_2^{\text{mless}}, p_3^{\text{mless}}, p_4^{\text{mless}}, p_5^{\text{mless}}, \mu) = 2\Re A^{(2)}(\{p_i^{\text{mless}}\}, \mu) A^{(0)}(\{p_i^{\text{mless}}\})^\dagger.$$

For dimentional reasons, this finite reminder satisfy the relation

$$F^{(2)}(\{p_i^{\text{mless}}\}, \mu) = \frac{|A^{(0)}(\{p_i^{\text{mless}}\})|^2}{|A^{(0)}(\{p_i^{\text{resc}}\})|^2} F^{(2)}(\{p_i^{\text{resc}}\}, 1), \quad p_i^{\text{resc}} = \frac{p_i^{\text{mless}}}{\mu}$$

Double virtual amplitude

Since μ is the invariant mass of Hbb̄ in our case, we essentially compute the two-loop amplitude with momenta of order of 1 instead of the typical energy at the LHC.

We verified that for stable PS point both the approaches give the same results, while we saw differences for pathological PS points in the gluon channel. This had a clear improvement in the stability.

We implemented this rescue system together with the evaluation of the coefficients in quadruple precision, while the pentagon functions in quadruple precision only when the gram determinant >0,

$$\Delta = \det(s_{ij}) \text{ with } 1 \leq i, j \leq 4, \text{ via } \Delta = (\mathrm{tr}_5)^2.$$

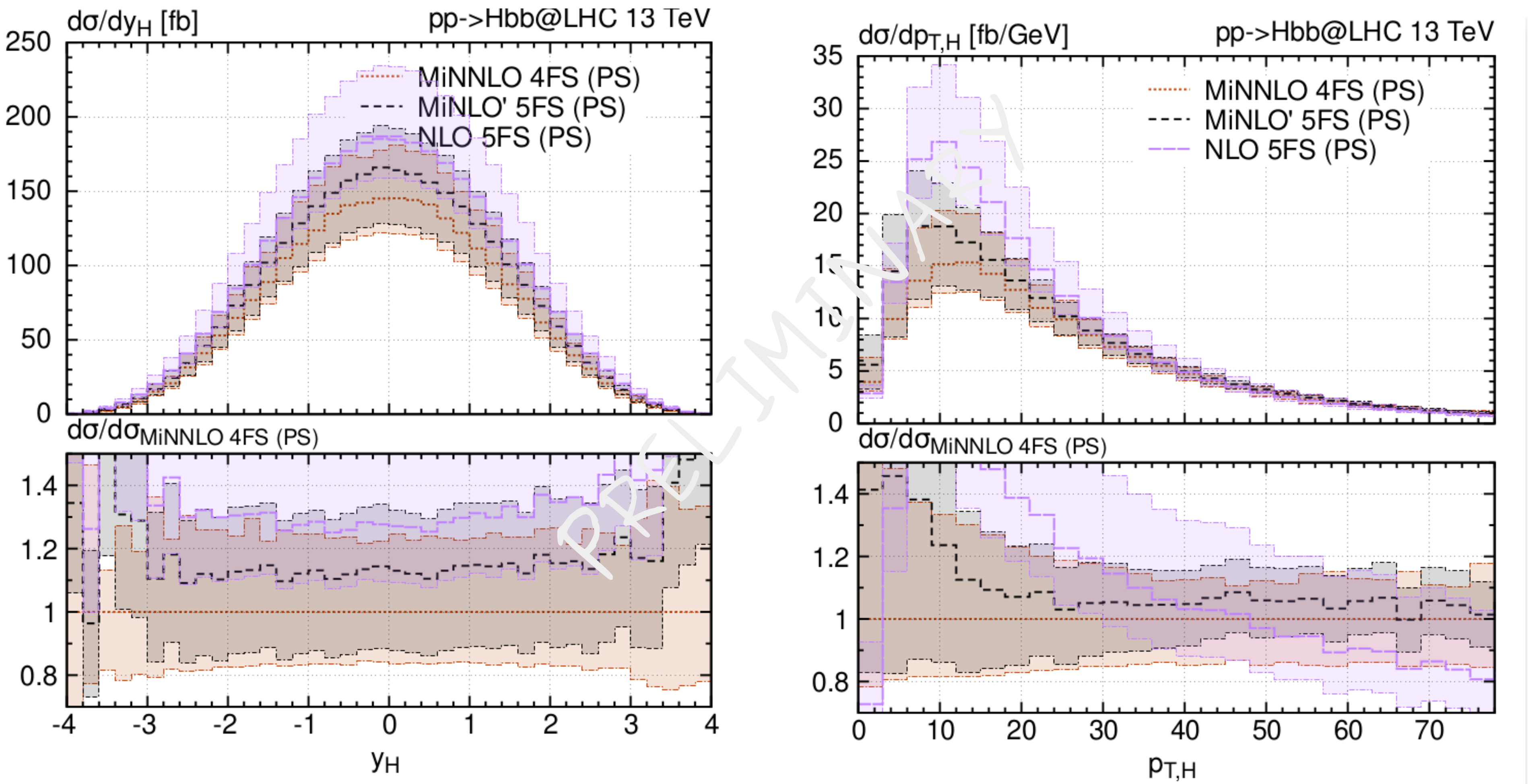
$$\mathrm{tr}_5 = 4i\epsilon_{\mu\nu\rho\sigma} p_1^\mu p_2^\nu p_3^\rho p_4^\sigma = [12]\langle 23\rangle[34]\langle 41\rangle - \langle 12\rangle[23]\langle 34\rangle[41]\,.$$

$$\Delta_5 = (s_{12}(s_{15} - s_{23}) - s_{15}s_{45} + s_{34}(s_{23} + s_{45} - m_H^2))^2 + 4s_{23}s_{34}s_{34}(s_{12} + s_{15} - s_{34} - m_H^2),$$

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

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


dσ/dy_H [fb]
pp->Hbb@LHC 13 TeV
MiNNLO 4FS (PS)
MiNLO' 5FS (PS)
NLO 5FS (PS)
dσ/dσ_MiNNLO 4FS (PS)
y_H
dσ/dp_T,H [fb/GeV]
pp->Hbb@LHC 13 TeV
MiNNLO 4FS (PS)
MiNLO' 5FS (PS)
NLO 5FS (PS)
dσ/dσ_MiNNLO 4FS (PS)
p_T,H
PRELIMINARY