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

Aparna Sankar

In collaboration with
C. Biello, M. Wiesemann, G. Zanderighi + (J. Mazzitelli)

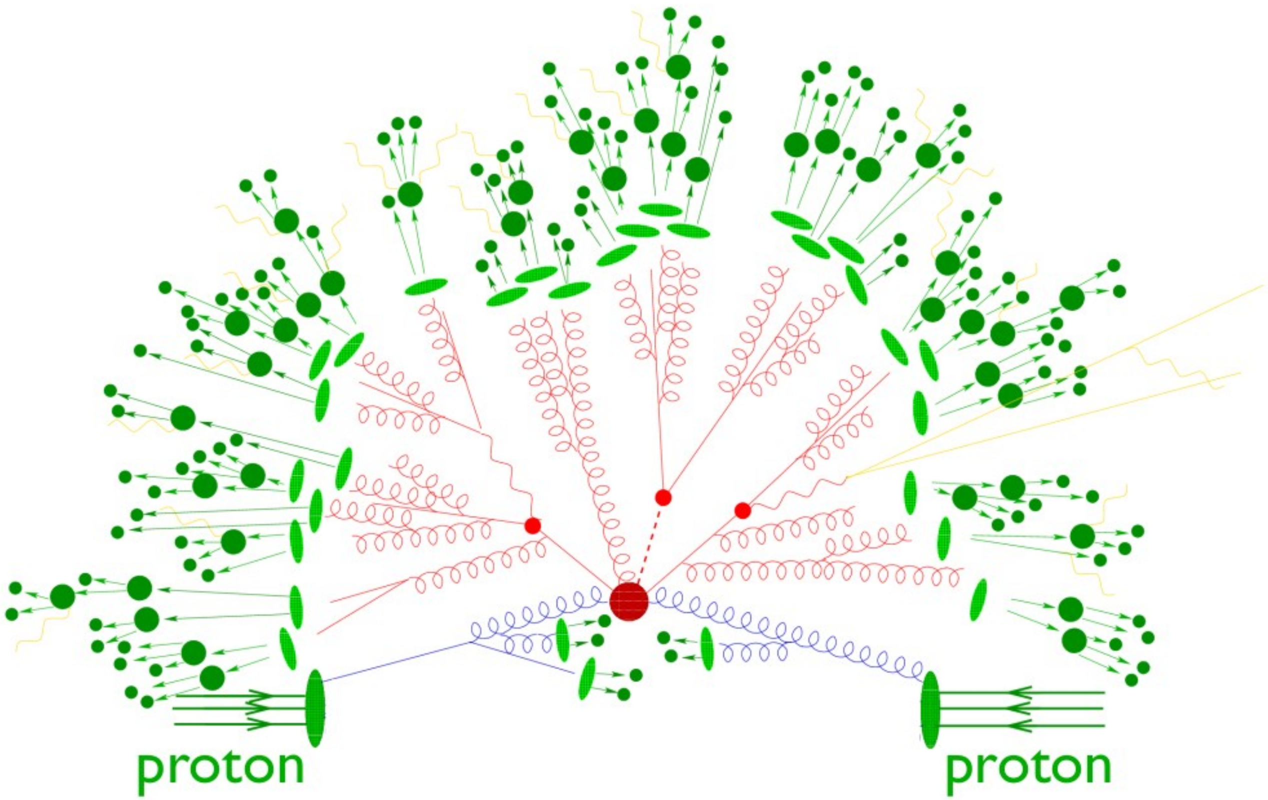
MAX-PLANCK-INSTITUT
FÜR PHYSIK

Technische Universität München

HEP Theory Seminar
BCTP, University of Bonn, 3 June 2024

Events at the LHC

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



[Sherpa’s artistic view]

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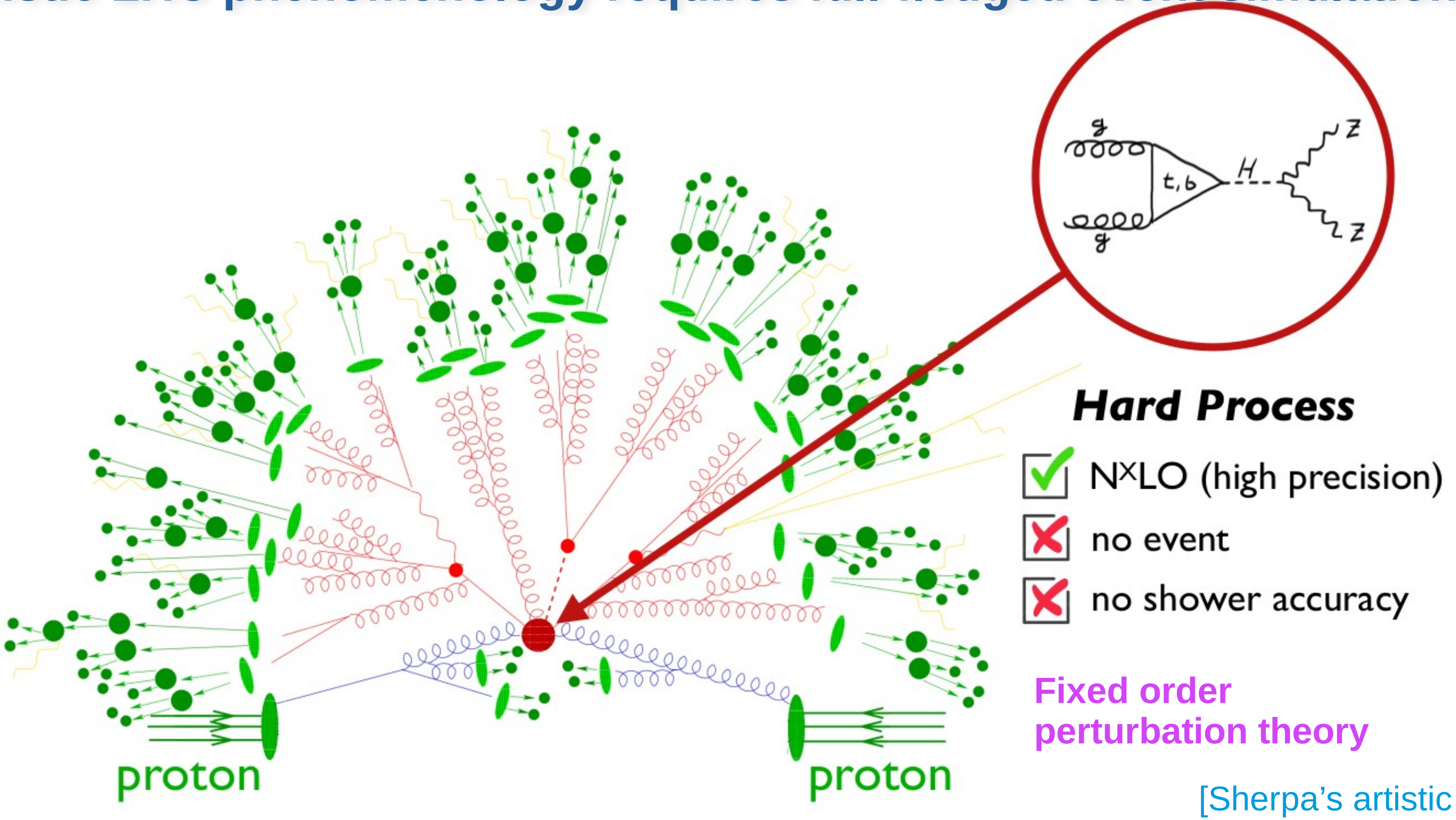

Hard Process

- ☑ $N^{x}LO$ (high precision)
- ☒ no event
- ☒ no shower accuracy

Fixed order perturbation theory

[Sherpa's artistic view]

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Parton Shower (PS)
+
Hadronization

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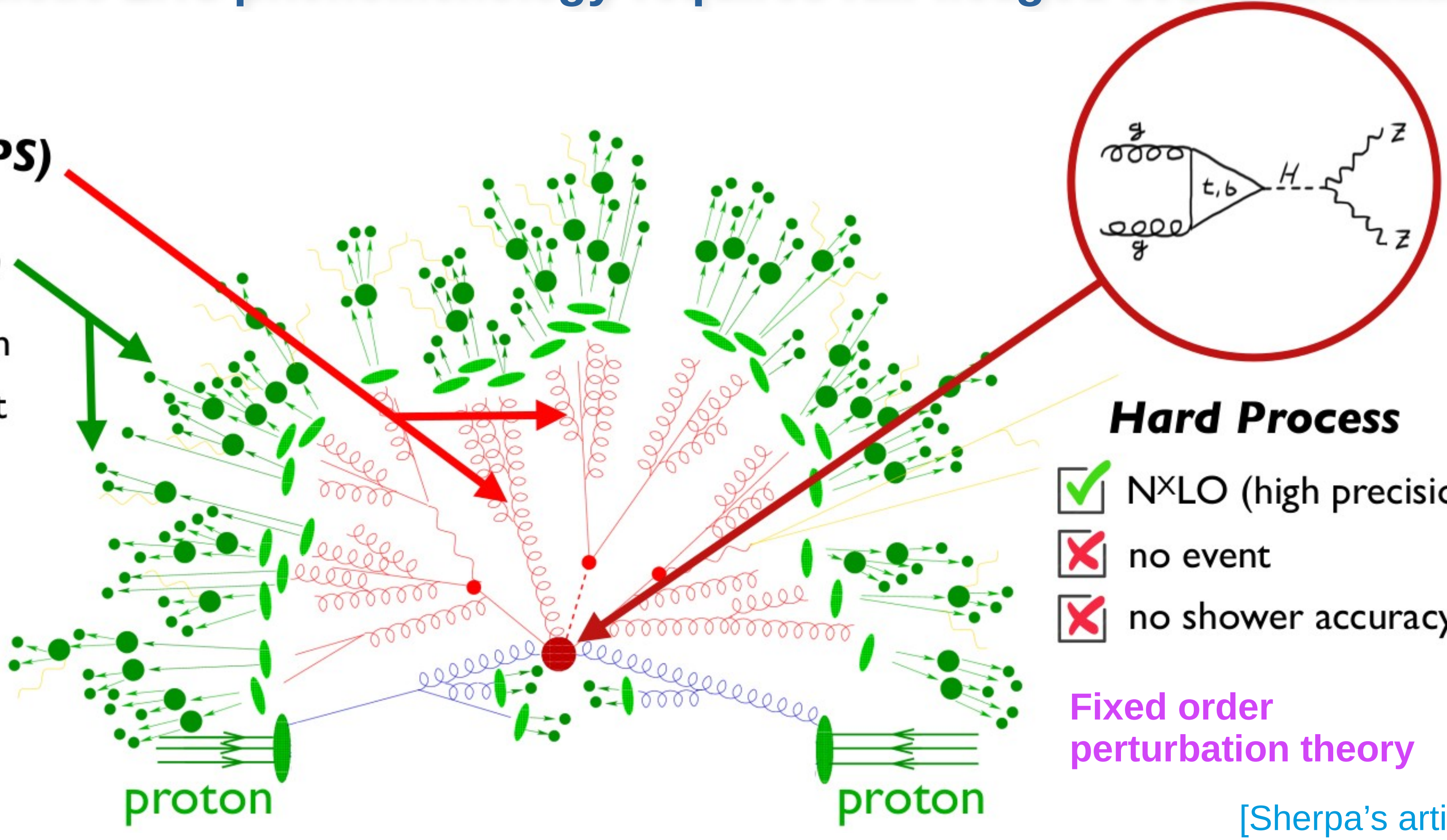
- ☑ shower accuracy (low precision)

Shower Monte Carlo (SMC)



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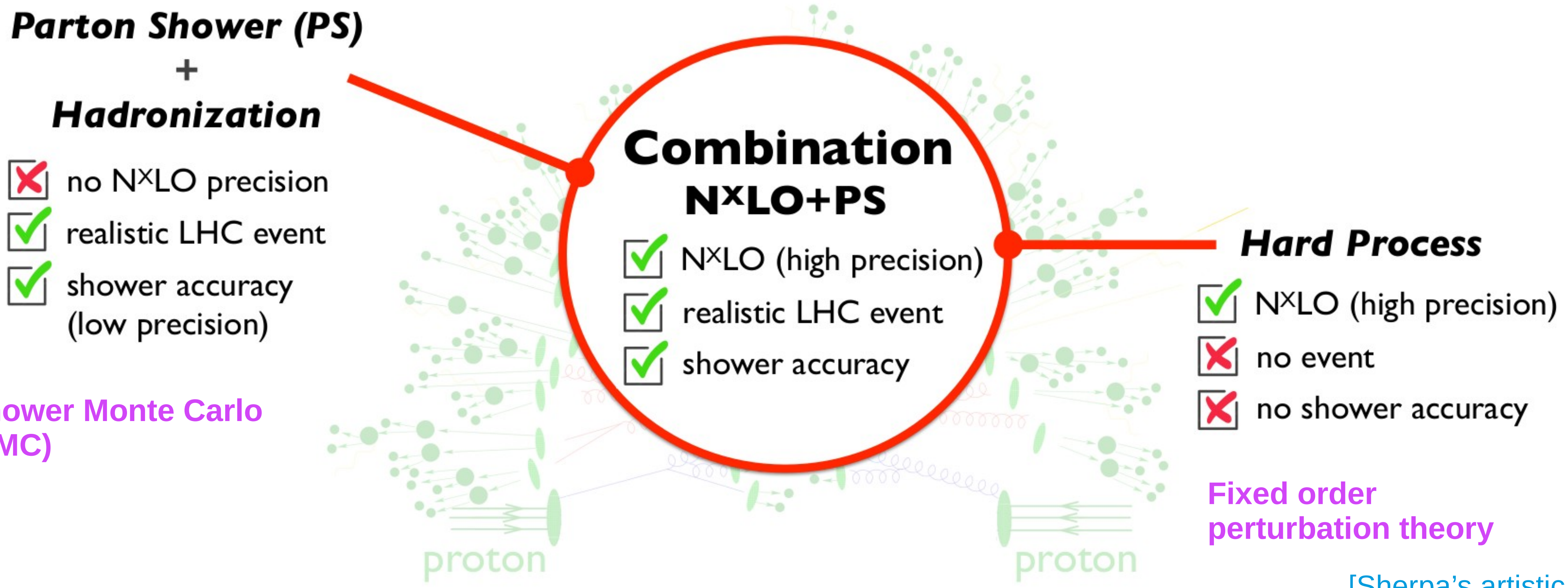

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Combination
$\mathrm{N^xLO+PS}$

- ☑ $\mathrm{N^xLO}$ (high precision)
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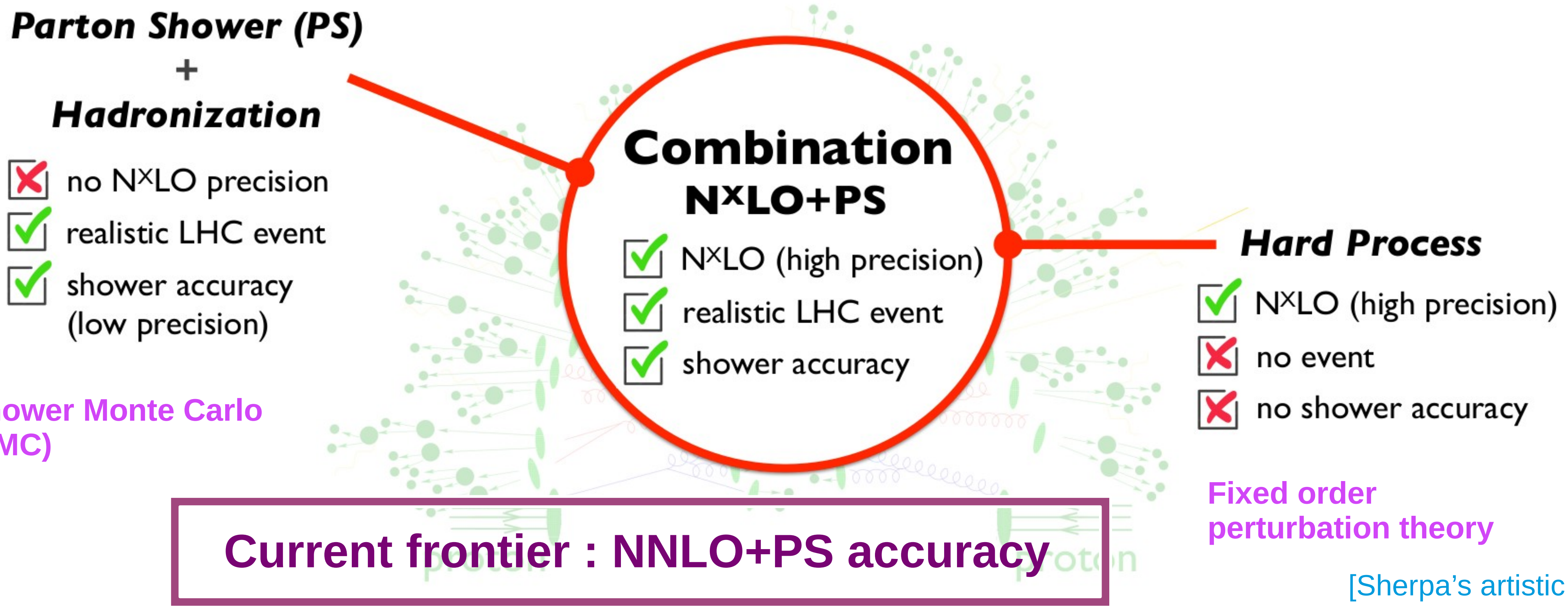

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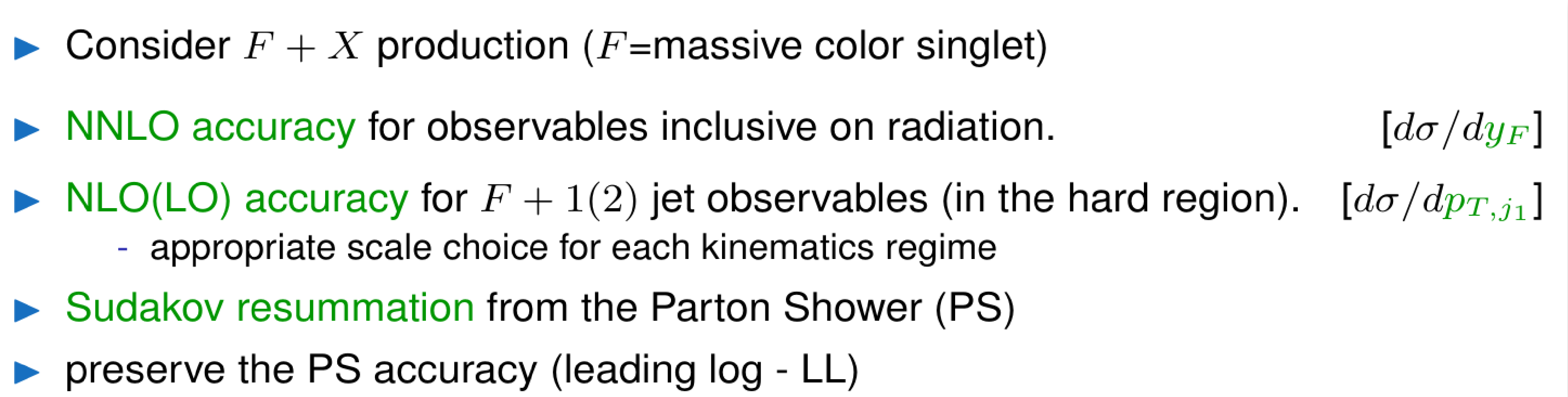
Fixed order perturbation theory

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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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)]

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

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

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

NNLO+PS: methods

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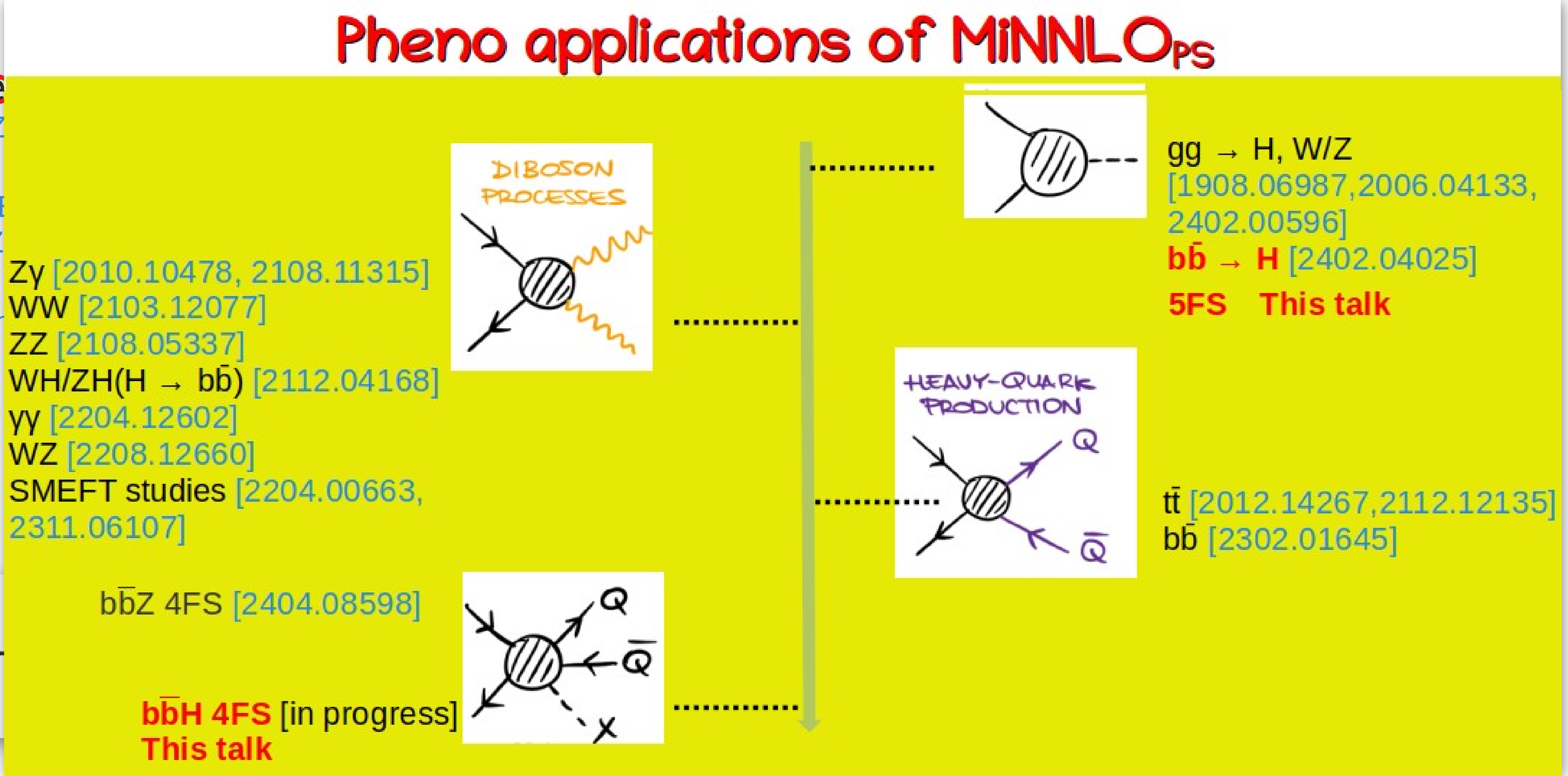

Pheno applications of MiNNLO$_{PS}$

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

$b\bar{b}$Z 4FS [2404.08598]

$b\bar{b}$H 4FS [in progress]
This talk

gg → H, W/Z [1908.06987,2006.04133, 2402.00596]
$b\bar{b}$ → H [2402.04025]
5FS This talk

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

POWHEG

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

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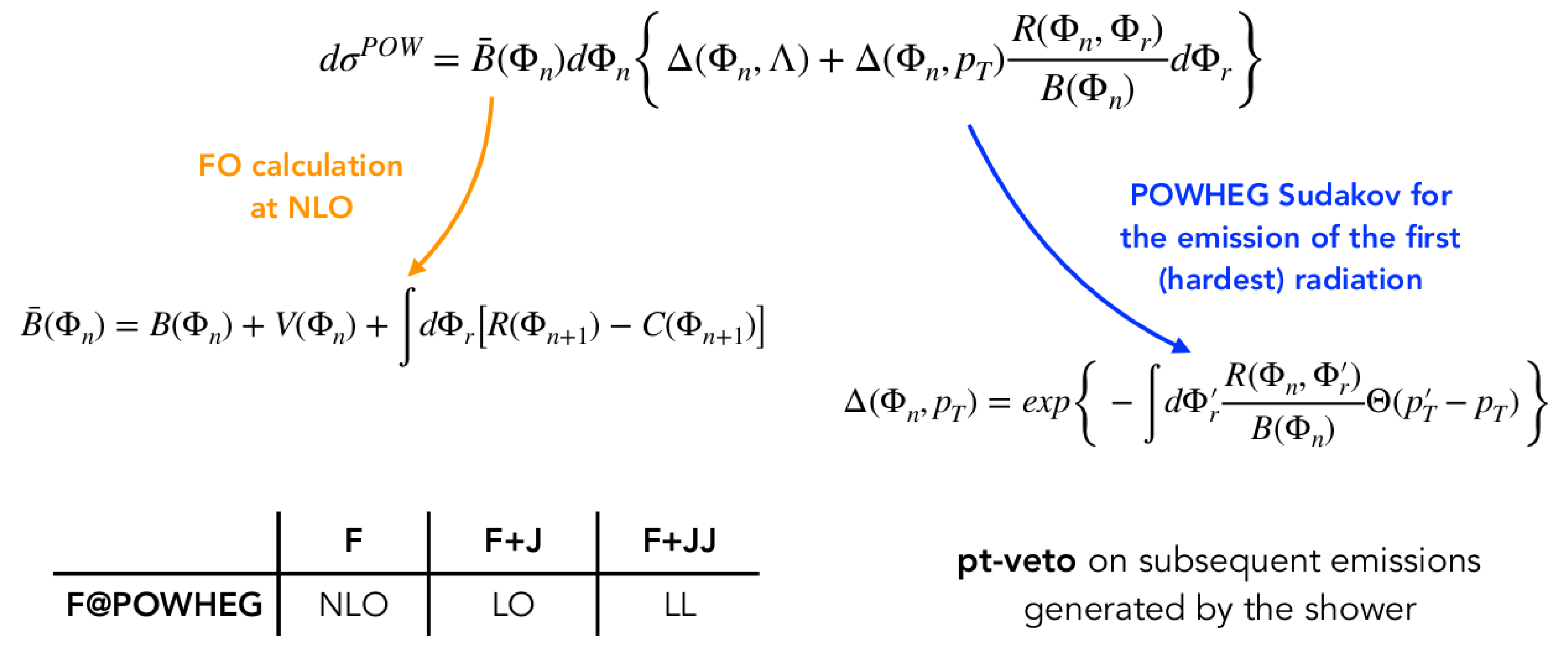


$$d\sigma^{POW} = \bar{B}(\Phi_n)d\Phi_n\left\{\Delta(\Phi_n,\Lambda) + \Delta(\Phi_n,p_T)\frac{R(\Phi_n,\Phi_r)}{B(\Phi_n)}d\Phi_r\right\}$$

FO calculation at NLO

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

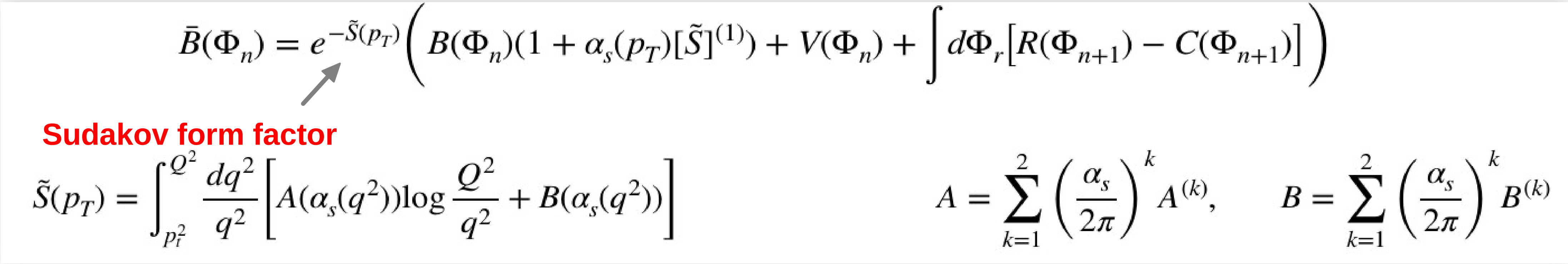
POWHEG Sudakov for the emission of the first (hardest) radiation

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

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

pt-veto on subsequent emissions generated by the shower

MiNLO’

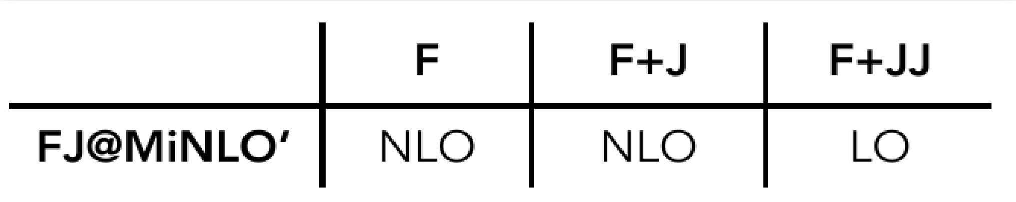


$$\bar{B}(\Phi_n) = e^{-\tilde{S}(p_T)}\left(B(\Phi_n)(1+\alpha_s(p_T)[\tilde{S}]^{(1)}) + V(\Phi_n) + \int d\Phi_r\left[R(\Phi_{n+1}) - C(\Phi_{n+1})\right]\right)$$

Sudakov form factor

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

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



	F	F+J	F+JJ
FJ@MiNLO’	NLO	NLO	LO

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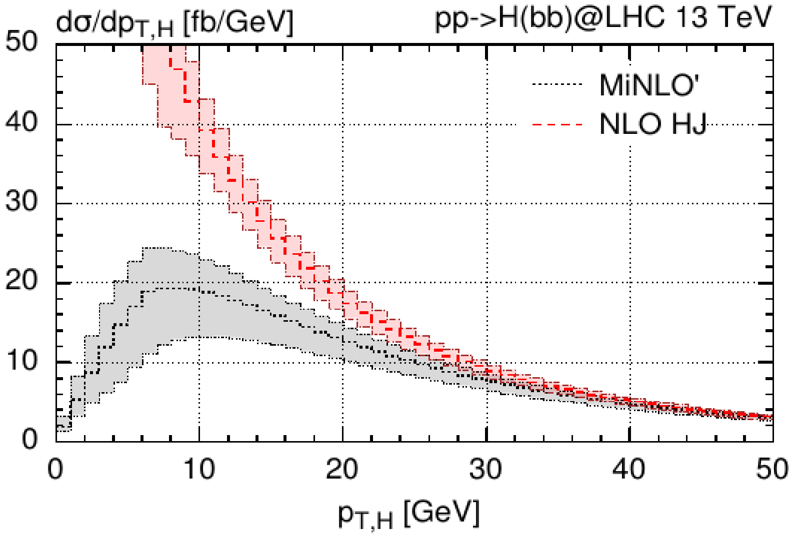
- **Finite result** for F+J production when the **jet is unresolved**
- Prescription in the **choice of the scales** μ_R and μ_F ($\mu_R = \mu_F \sim p_T$)
- **NLO** accuracy for observables inclusive in F and F+J

	F	**F+J**	**F+JJ**
FJ@MiNLO’	NLO	NLO	LO



MiNNLO$_{\text{PS}}$

- ✦ starting equation:

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

Hard function

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

Luminosity (symbolically)

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

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

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- expanded up to $\alpha_s^3(p_T)$ we have: (resummation scheme: $\mu_{\mathrm{R}} = \mu_{\mathrm{F}} \sim p_T$)

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

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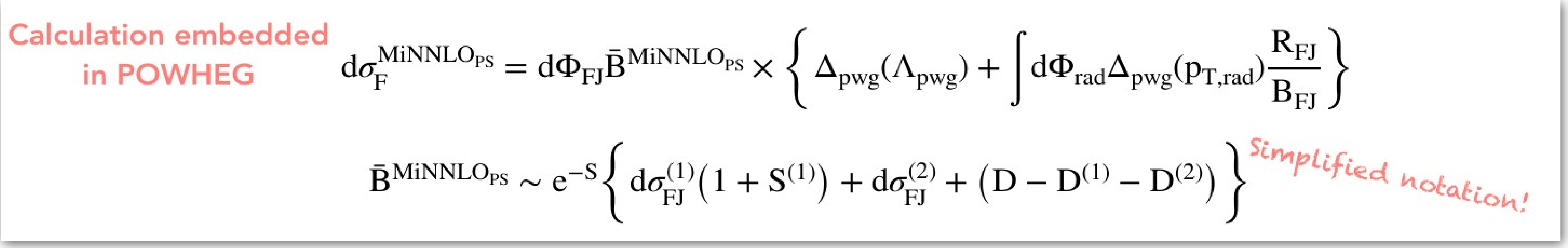
$$d\sigma_F^{\rm MiNNLO} \sim e^{-S}\left\{\boxed{\underbrace{d\sigma_{FJ}^{(1)}}_{\sim\alpha_s(p_T)}\Big(1+\underbrace{S^{(1)}\Big)+d\sigma_{FJ}^{(2)}}_{\sim\alpha_s^2(p_T)}} + \boxed{\underbrace{\Big(D-D^{(1)}-D^{(2)}\Big)}_{\sim\alpha_s^3(p_T)}} + \boxed{\text{regular}}\right\}$$

MiNLO' **NNLO corrections** **Beyond accuracy**

MiNNLO$_{\mathrm{PS}}$



Calculation embedded in POWHEG

$$\mathrm{d}\sigma_{\mathrm{F}}^{\mathrm{MiNNLO_{PS}}} = \mathrm{d}\Phi_{\mathrm{FJ}}\bar{\mathrm{B}}^{\mathrm{MiNNLO_{PS}}} \times \left\{ \Delta_{\mathrm{pwg}}(\Lambda_{\mathrm{pwg}}) + \int \mathrm{d}\Phi_{\mathrm{rad}}\Delta_{\mathrm{pwg}}(\mathrm{p}_{\mathrm{T,rad}})\frac{\mathrm{R}_{\mathrm{FJ}}}{\mathrm{B}_{\mathrm{FJ}}} \right\}$$

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

Simplified notation!

MiNNLO$_{\mathrm{PS}}$

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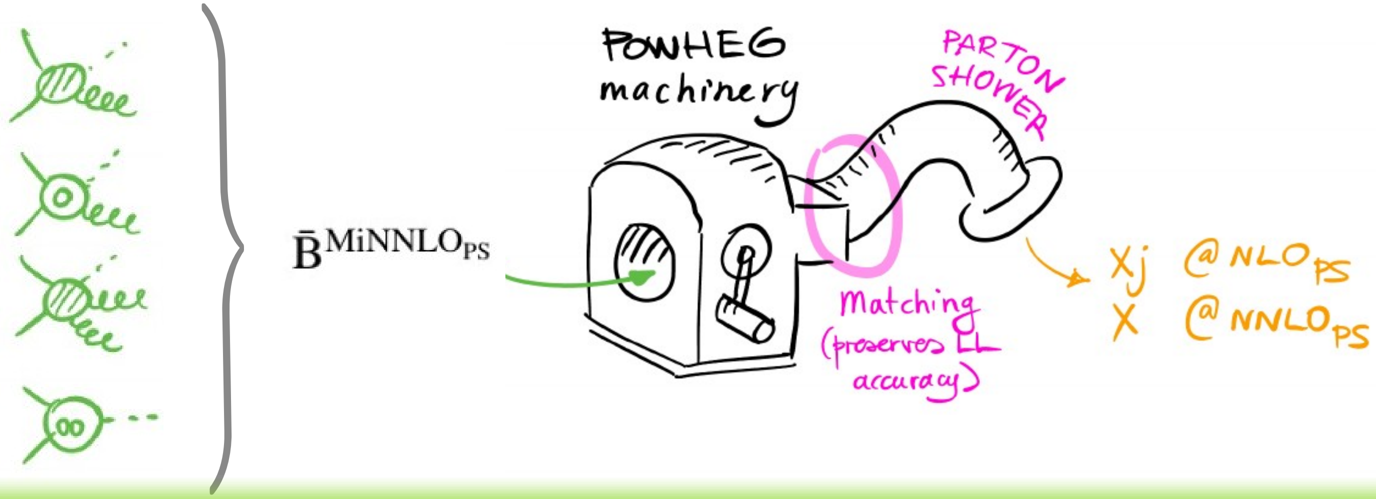
In summary:



[Image courtesy : C. Biello]

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

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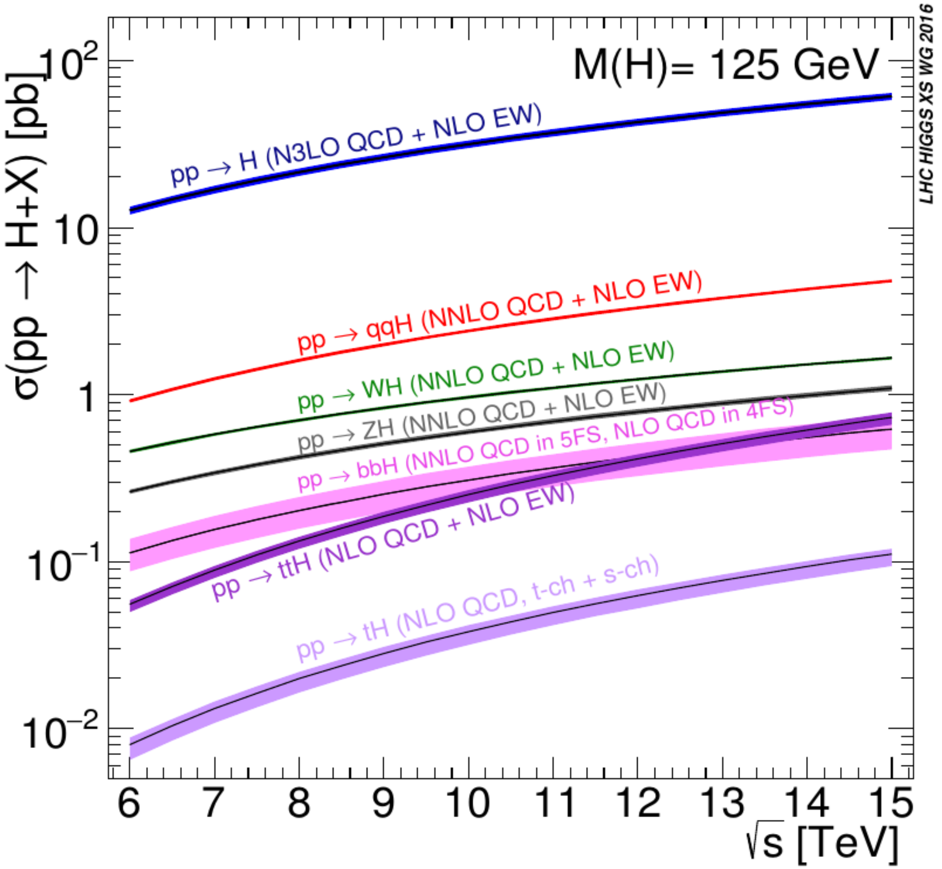

[LHC HIGGS XS WG 2016]

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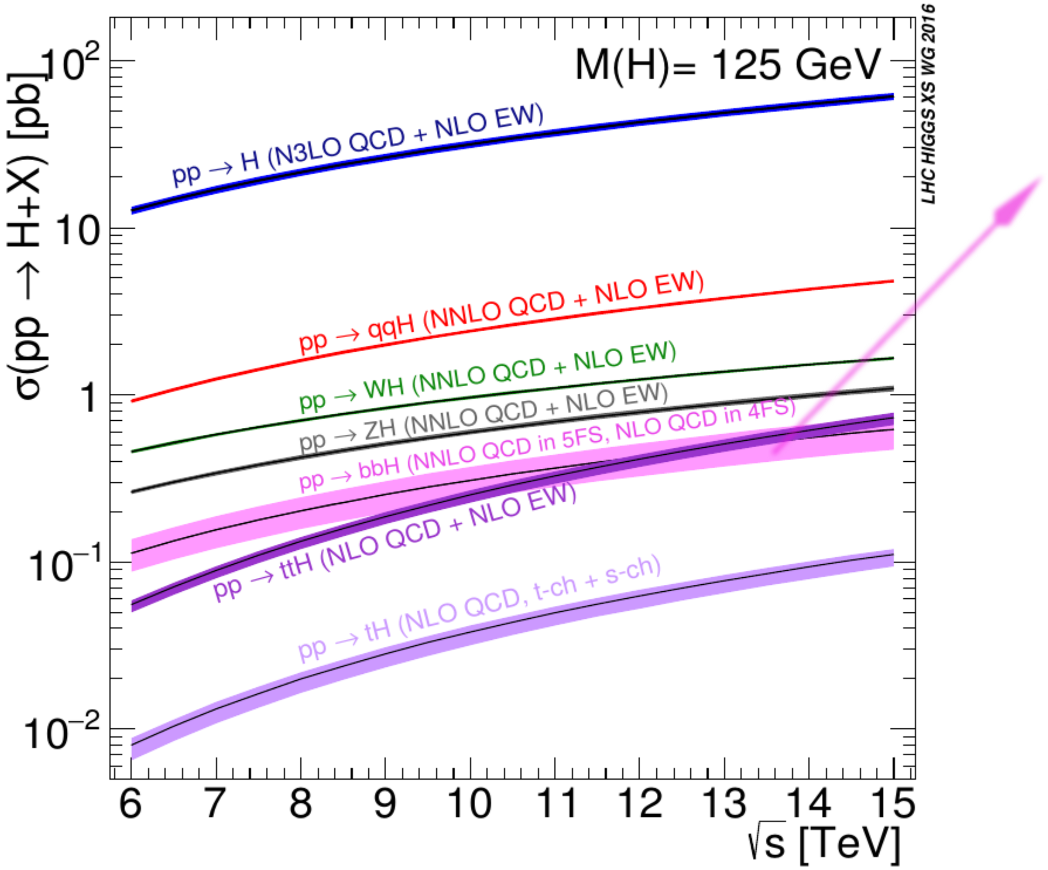

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- Although it is a **subdominant channel,** its cross section is **large enough.**

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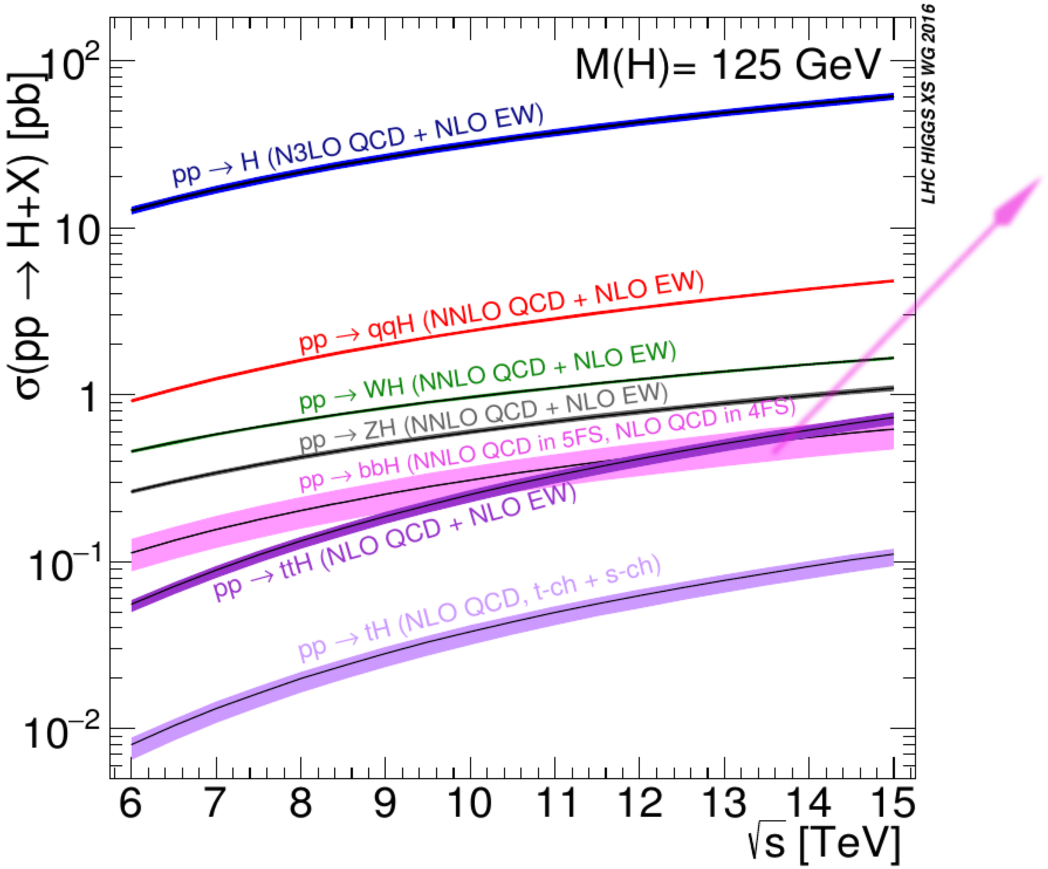

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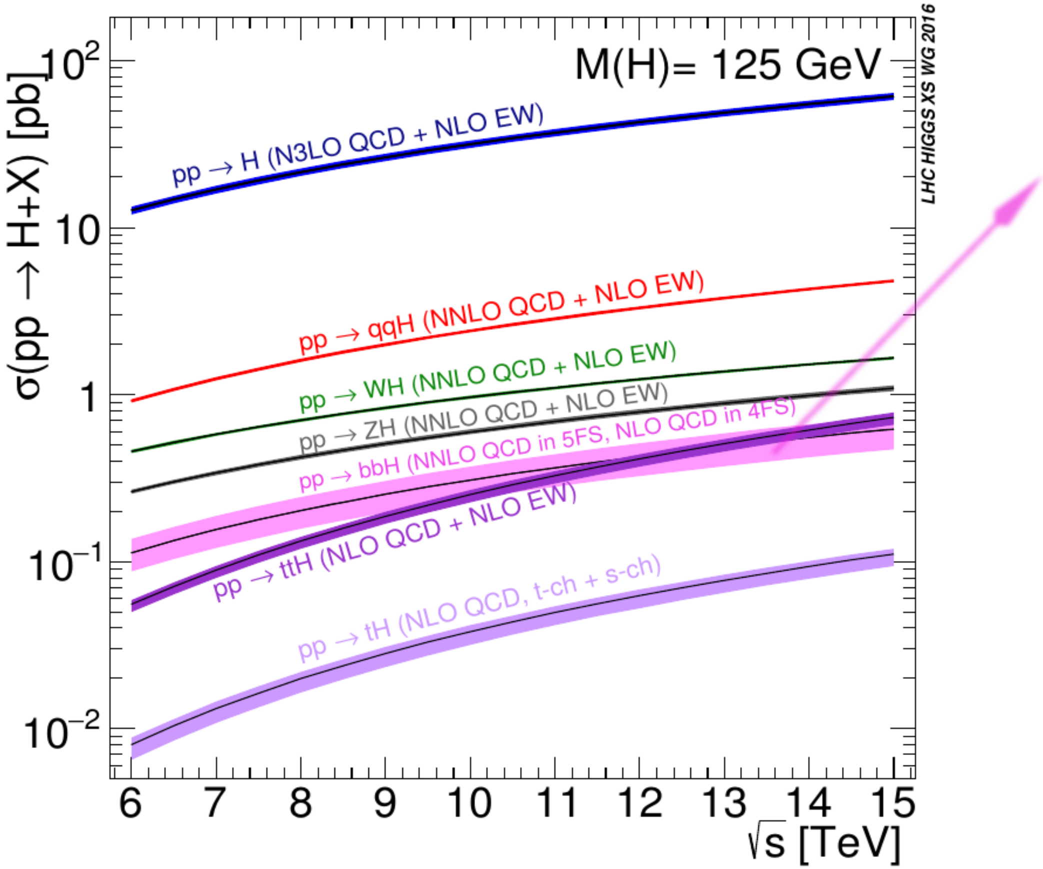

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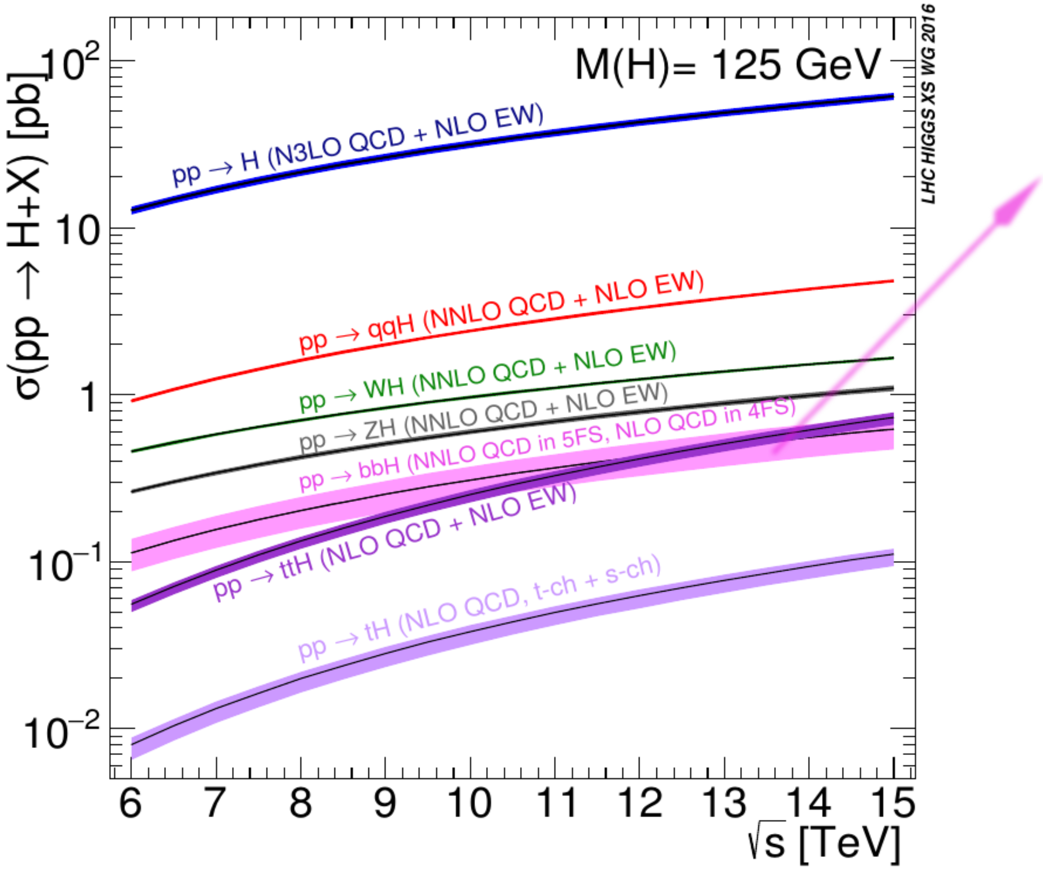

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- Direct probe of **Higgs couplings to the bottom quark** (**y_b**) in production
- **Bottom Yukawa coupling**: Important due to its **enhancement in New Physics models** like minimal supersymmetric extensions of the SM
- $b\bar{b}H$ enters as a **background**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

4 flavor scheme (4FS)

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

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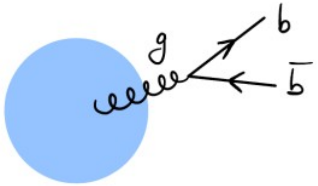

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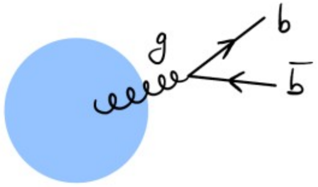

- **Active parton** inside the proton.
- **Included** in the parton distribution functions (**PDFs**) of the proton.
- It is taken to be **massless except** in the **Yukawa** coupling

[Image courtesy : C. Biello]

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

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

5 flavor scheme (5FS)

4 flavor scheme (4FS)

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

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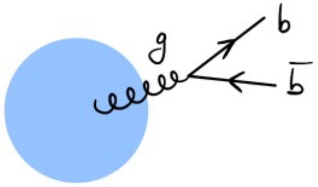
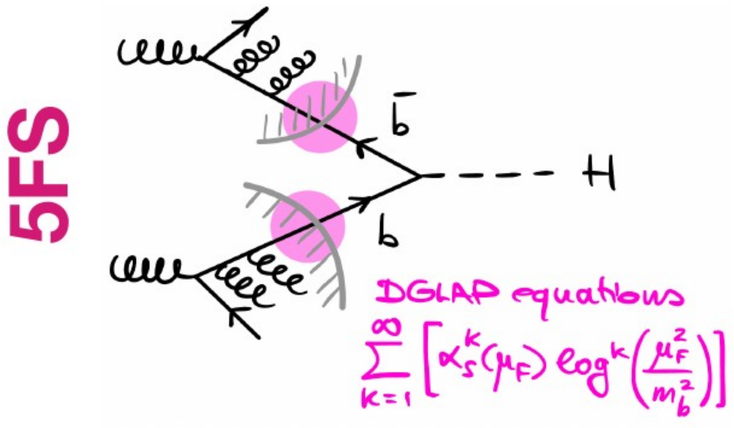


- Considered as a **heavy quark**
- The bottom quark's contribution is **neglected** in the **PDFs**.
- A **massive** bottom quark is produced from **gluon splitting**

[Image courtesy : C. Biello]

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

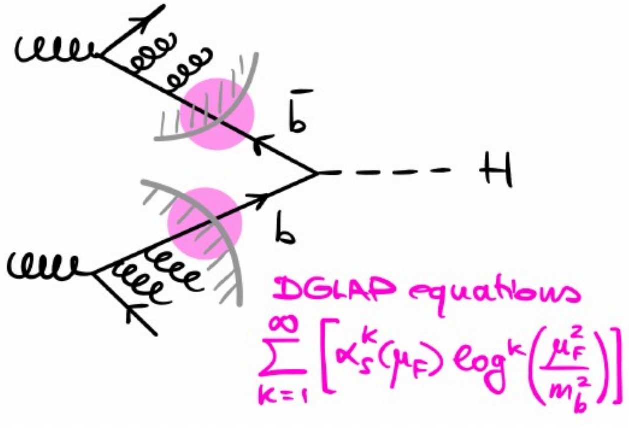


- ✓ Computing **higher orders** is **easier**
- ✓ The **DGLAP** evolution **resums** initial state collinear **logs** into the bottom PDFs
- Neglects power-suppressed terms of the $O(m_b/m_H)$

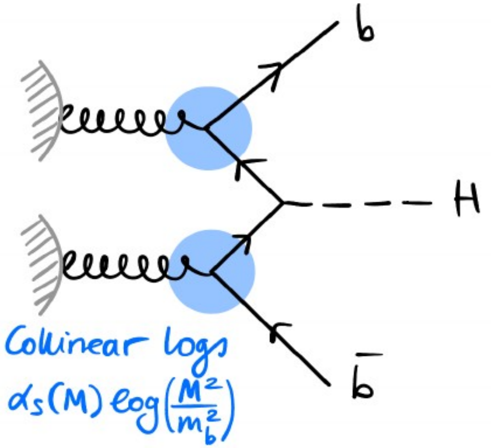
[Image courtesy : C. Biello]

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

5FS



4FS



- ✓ 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)]
- **N3LO+** threshold resummation at **N3LL** in the **5FS** [AH, Chakraborty, Das, Mukherjee, Ravindran (1905.03771)]
- **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)]

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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.

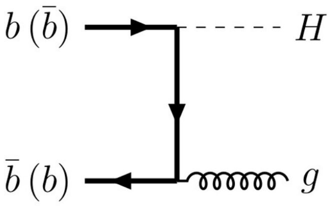
The computation (5FS)

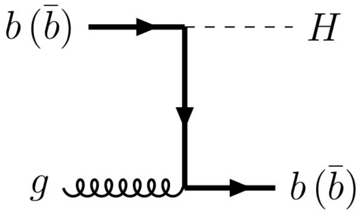
- **`MiNNLO`$_{\text{PS}}$ $b\bar{b}$ → H** generator implemented in the **`Powheg-Box-Res`**

[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)]





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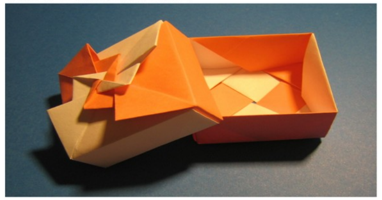

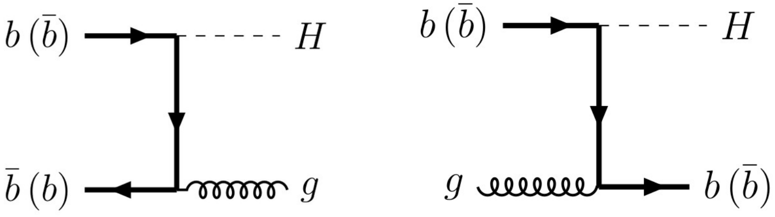

- Tree-level amplitudes of the **HJ & HJJ** : **`OPENLOOPS`**

[F. Buccioni, S. Pozzorini and M. Zoller (1710.11452), F. Buccioni et al (1907.13071)]

- **Virtual** corrections : A**`nalytic results`**

substantially improve the numerical performance of the code

[R.V. Harlander et al (1007.5411)]

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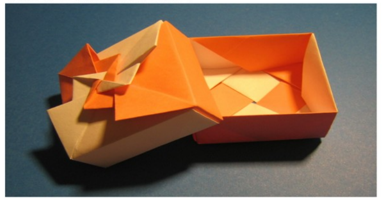

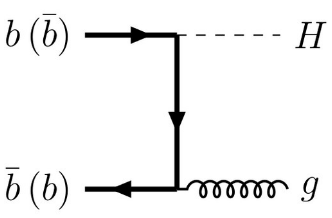

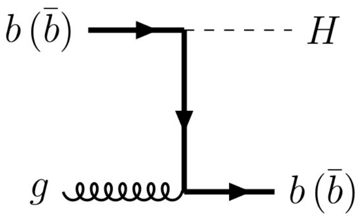

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  substantially improve the numerical performance of the code

- In a second step, we extended the **HJ NLO+PS** implementation to **NNLO+PS accuracy** through the **`MiNNLOPS`** 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** [$Y_b(m_b{=}4.18\ \text{GeV}) \rightarrow Y_b(m_H) = 2.79$].

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

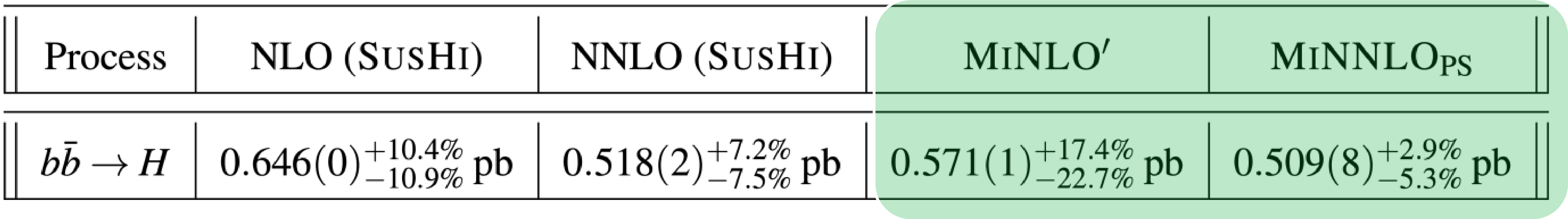
- **Matching to Parton Shower:**
  - Predictions matched to parton shower using **`Pythia8`** with **leading-log (LL)** accuracy.

- **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)]

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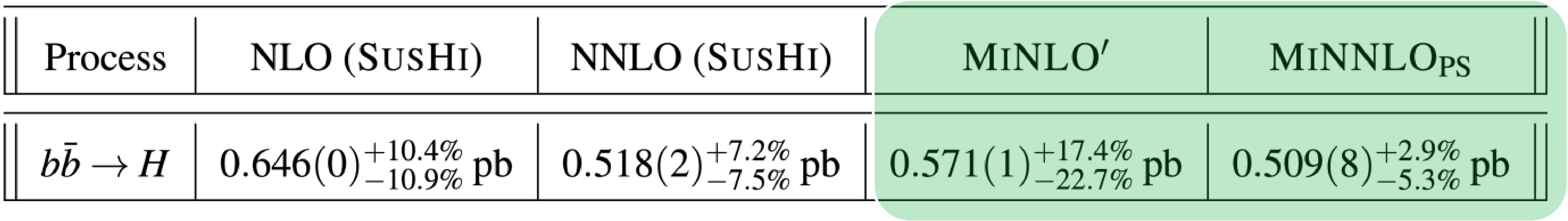

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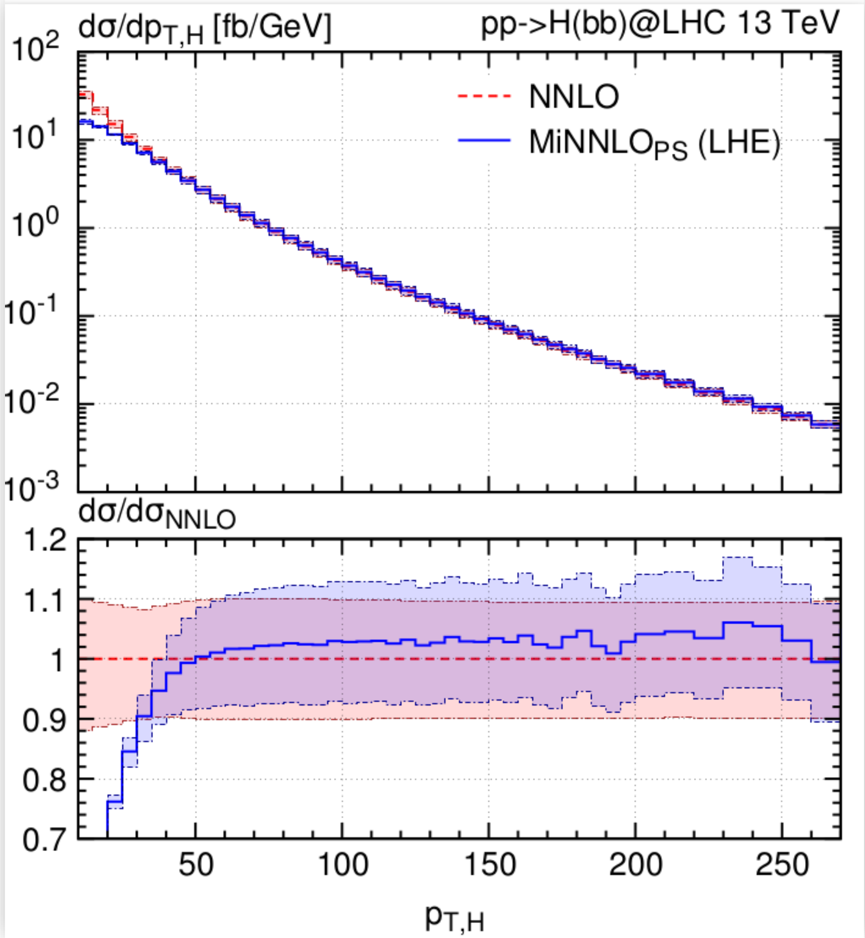
[Biello, **AS**, Wiesemann, Zanderighi (2402.04025)]

- NNLO QCD corrections **reduce cross section** by > 10%
- Scale **uncertainities** significantly **reduced** with NNLO QCD corrections
- Our **MiNNLO$_{\text{PS}}$** 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)]

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

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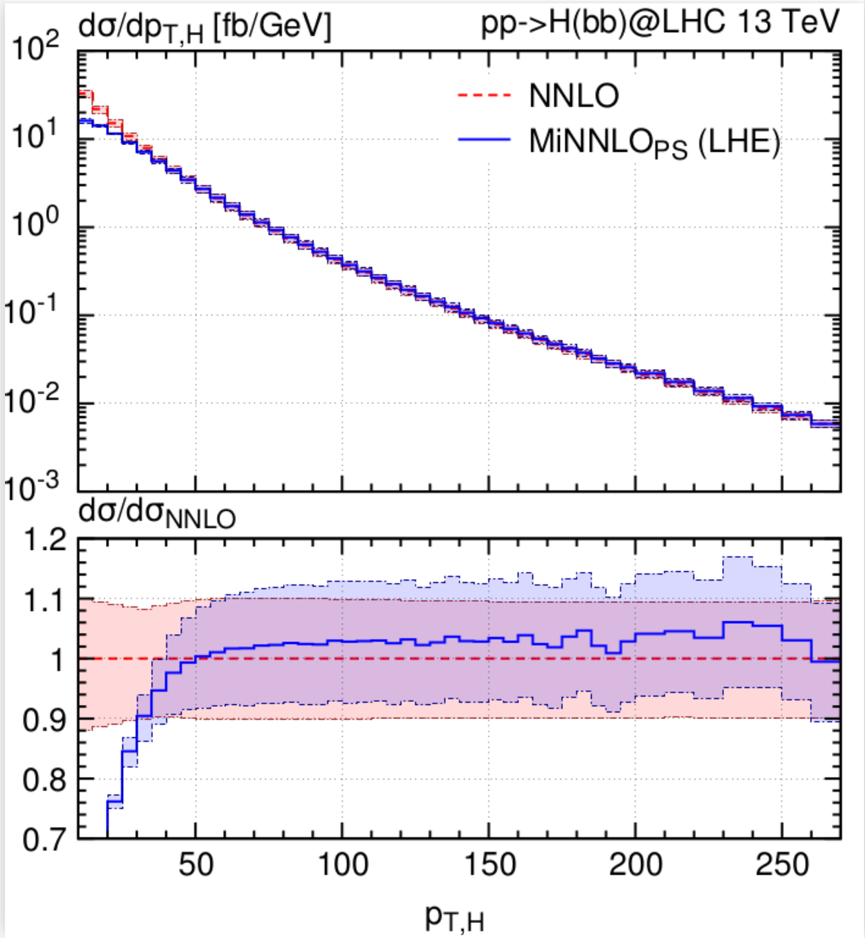


- **Full agreement** in **large $p_{T,H}$** regime with fixed-order predictions within quoted uncertainities

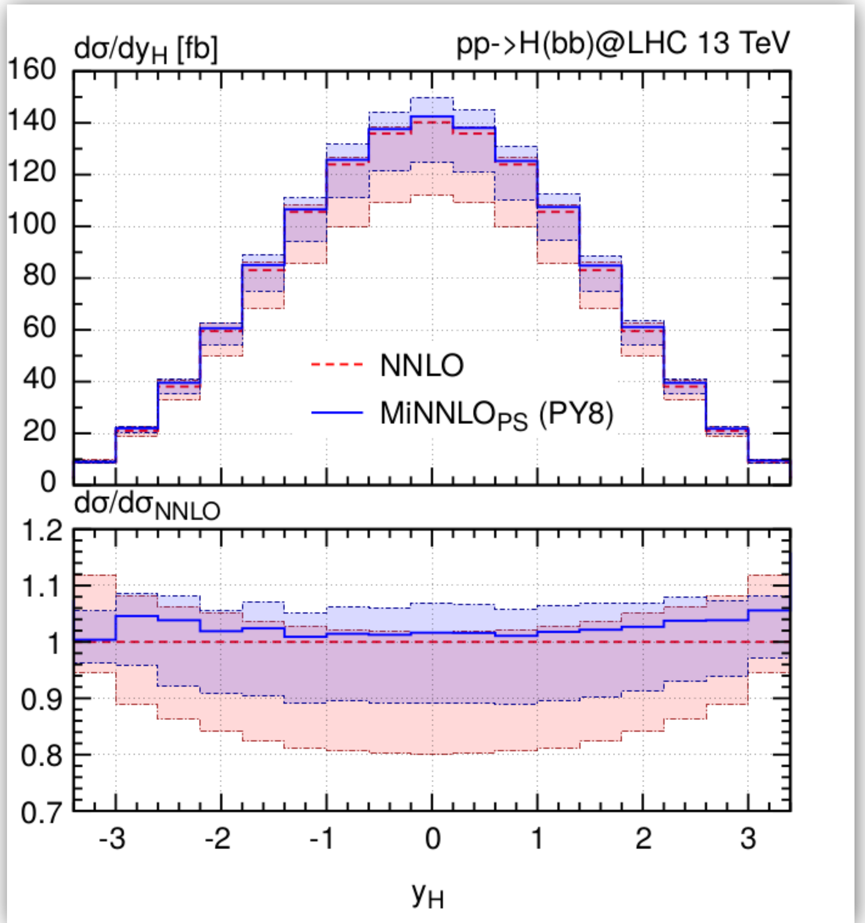
- Fixed-order calculations diverge for $p_{T,H} \rightarrow 0$ **MiNNLO_{PS}** prediction remains **finite**

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

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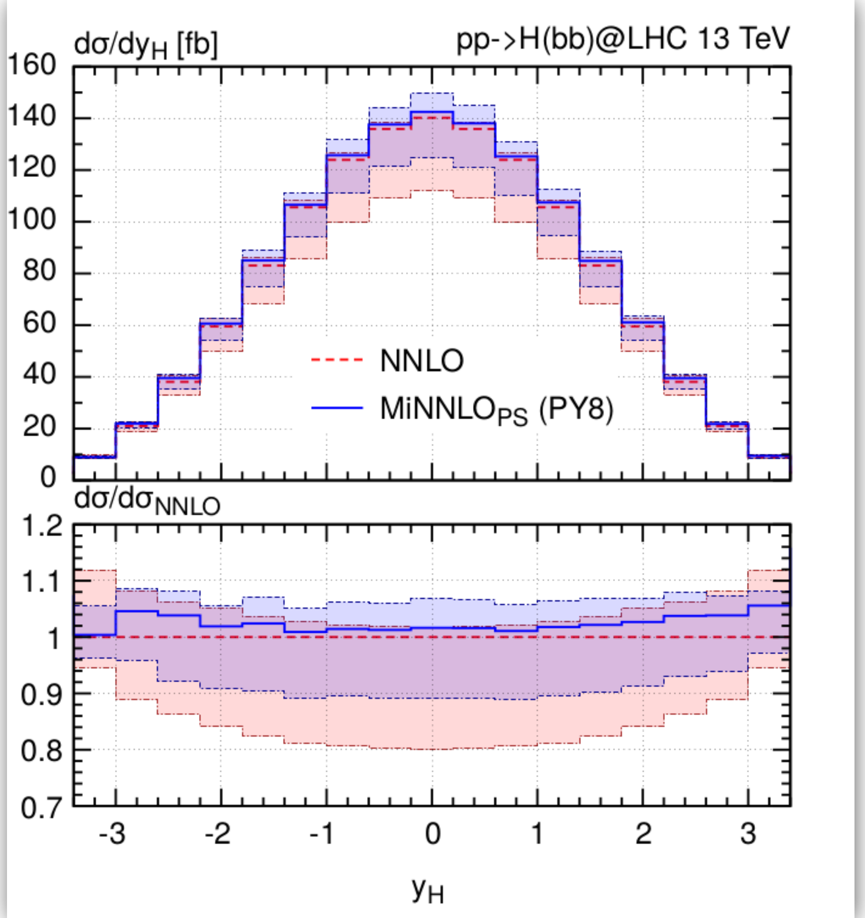
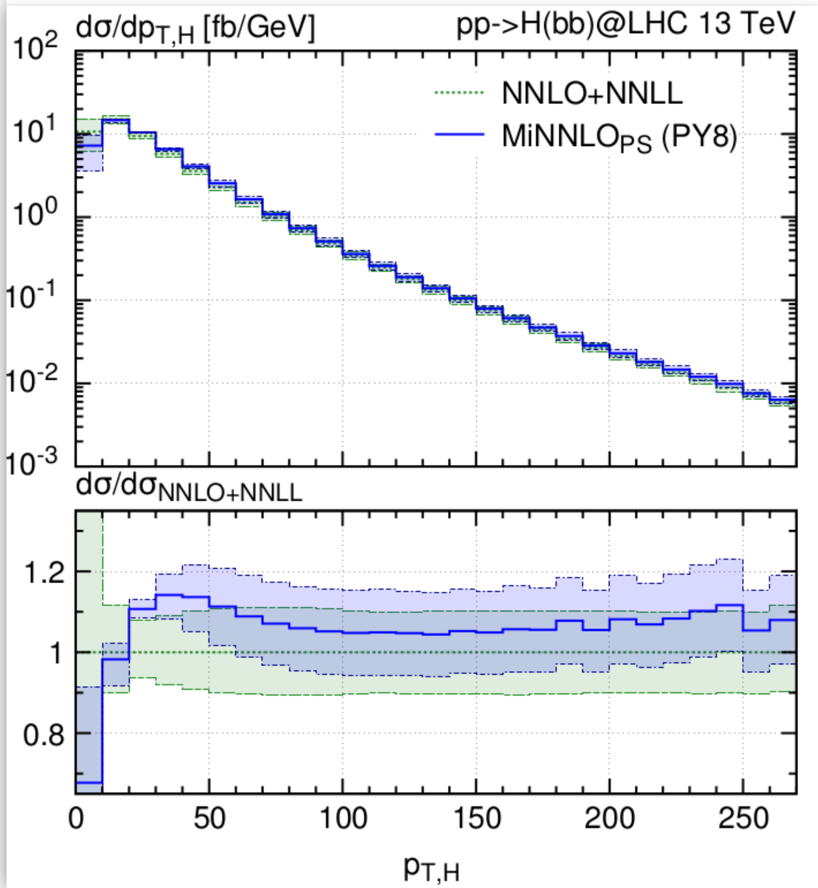
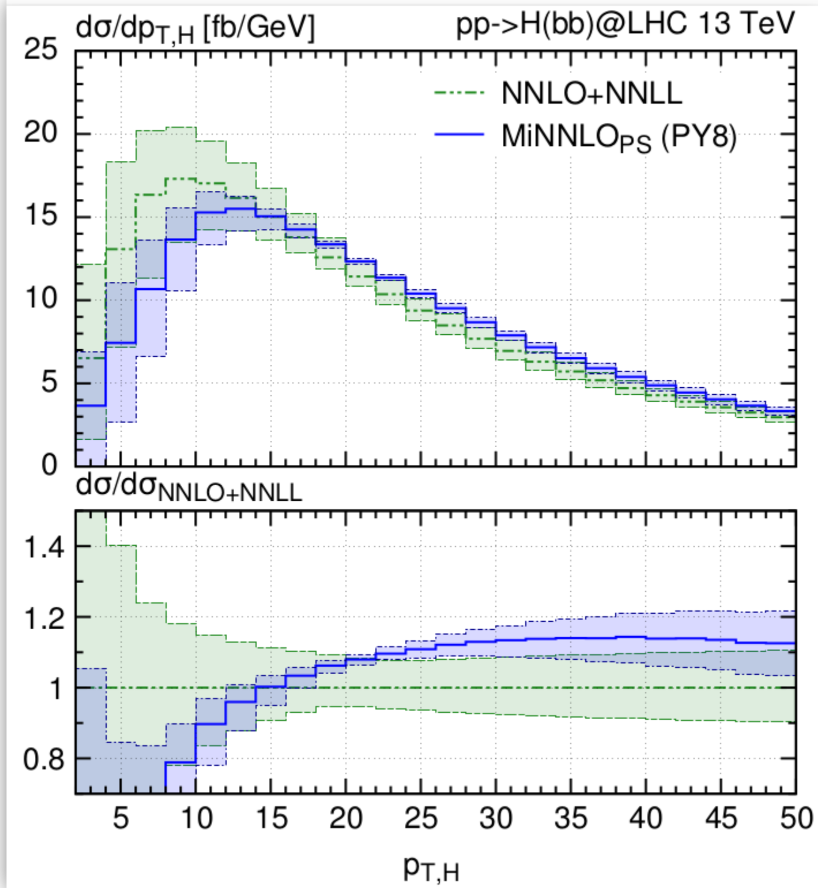


- A **good agreement**, both in terms of normalization and in terms of shape, between the two central predictions.
- The **bands** of **MiNNLO$_{PS}$** result are **more symmetric** & slightly **smaller** than the **NNLO** ones.

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

Comparison to NNLO+NNLL





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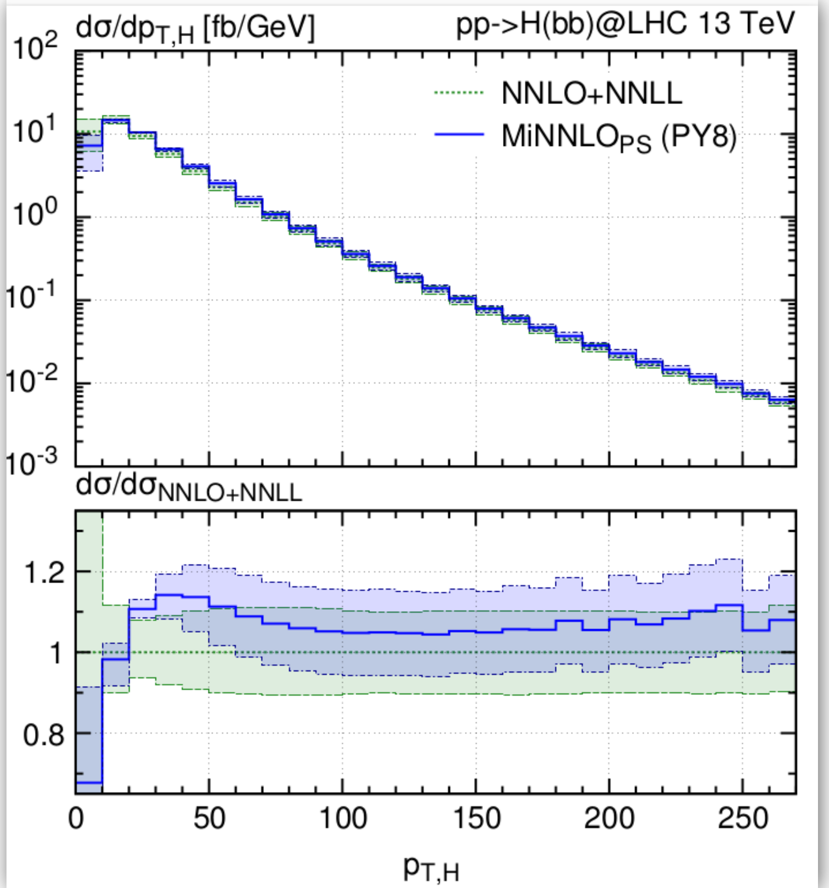
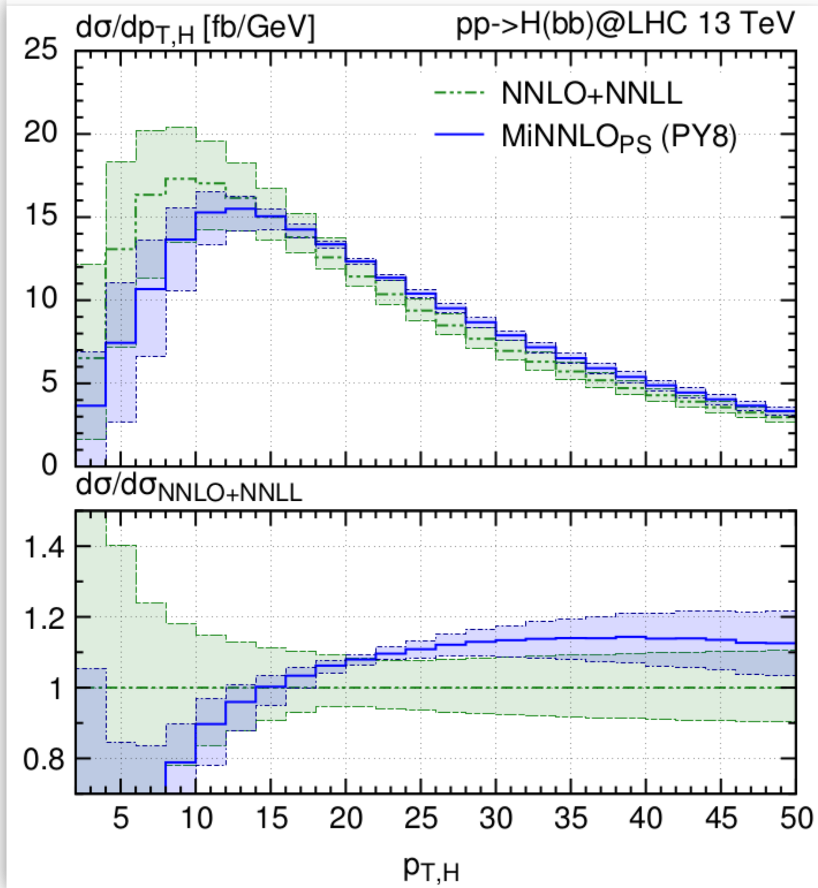
Comparison to NNLO+NNLL





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

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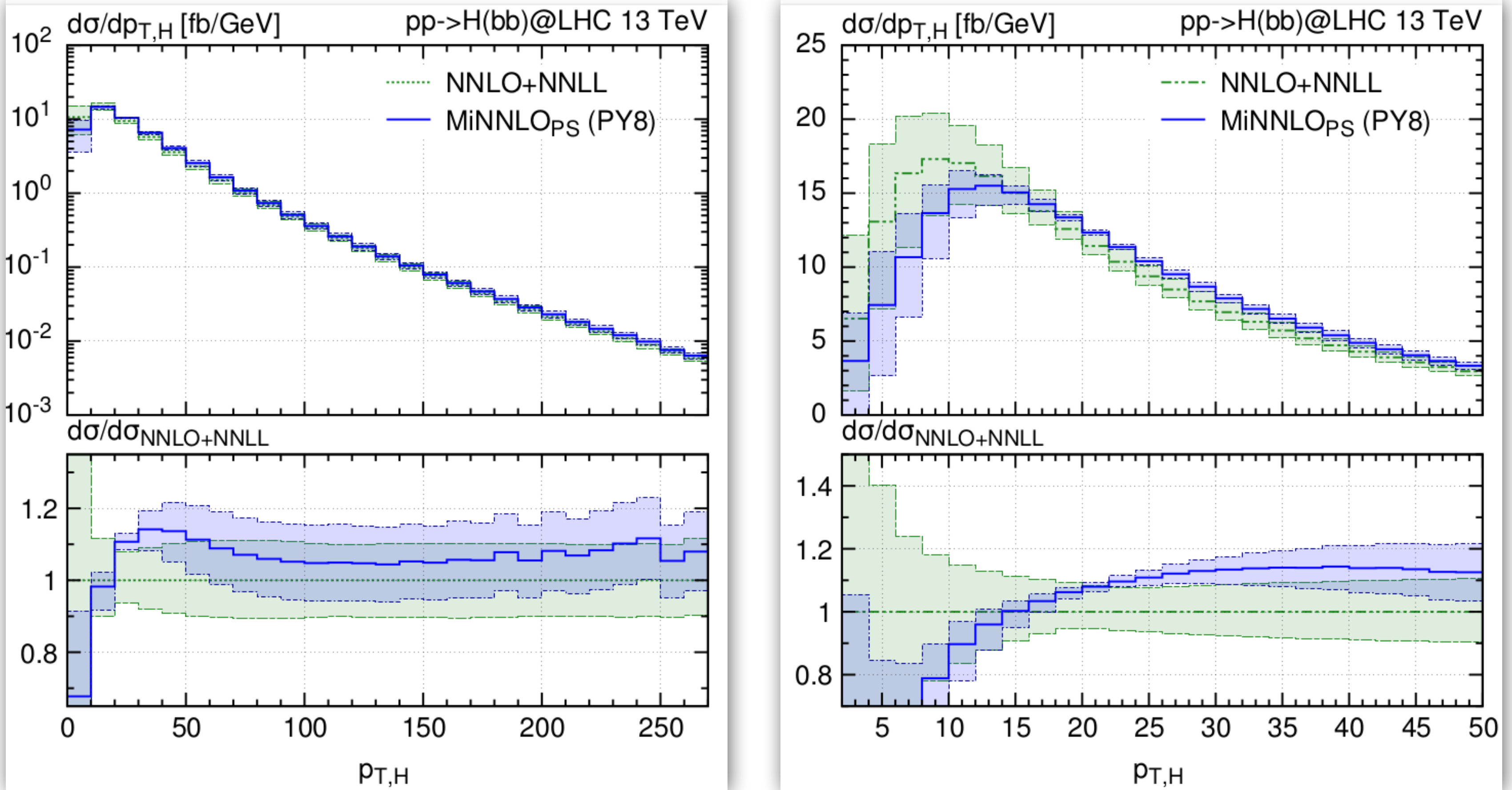
MiNNLO$_{PS}$ [Biello, **AS**, Wiesemann, Zanderighi (2402.04025)]

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.**

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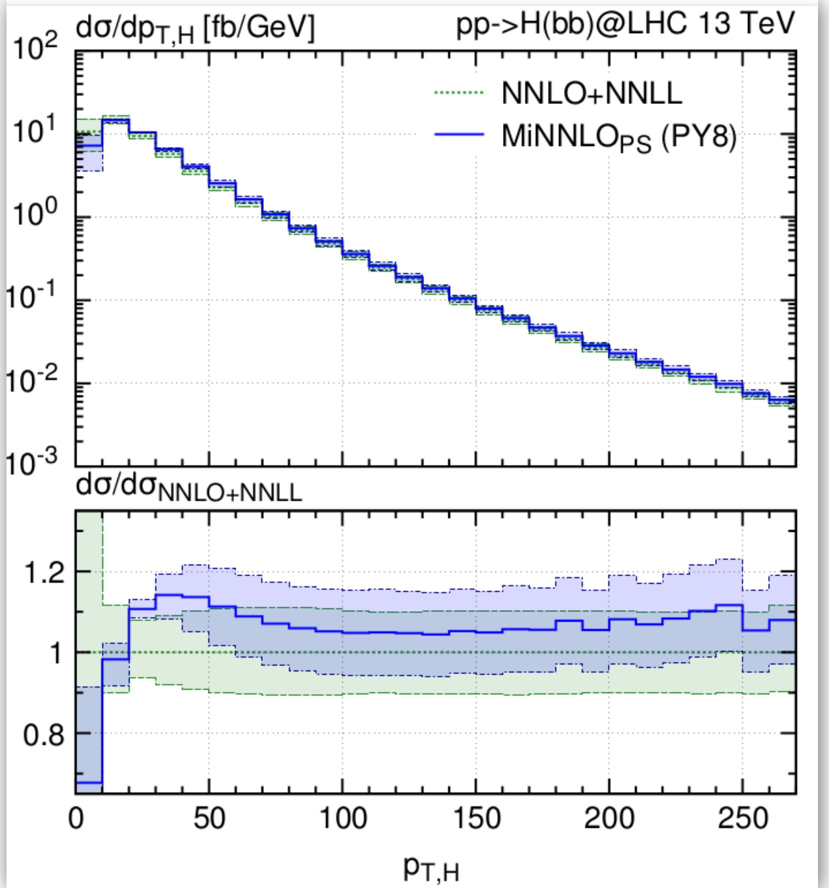
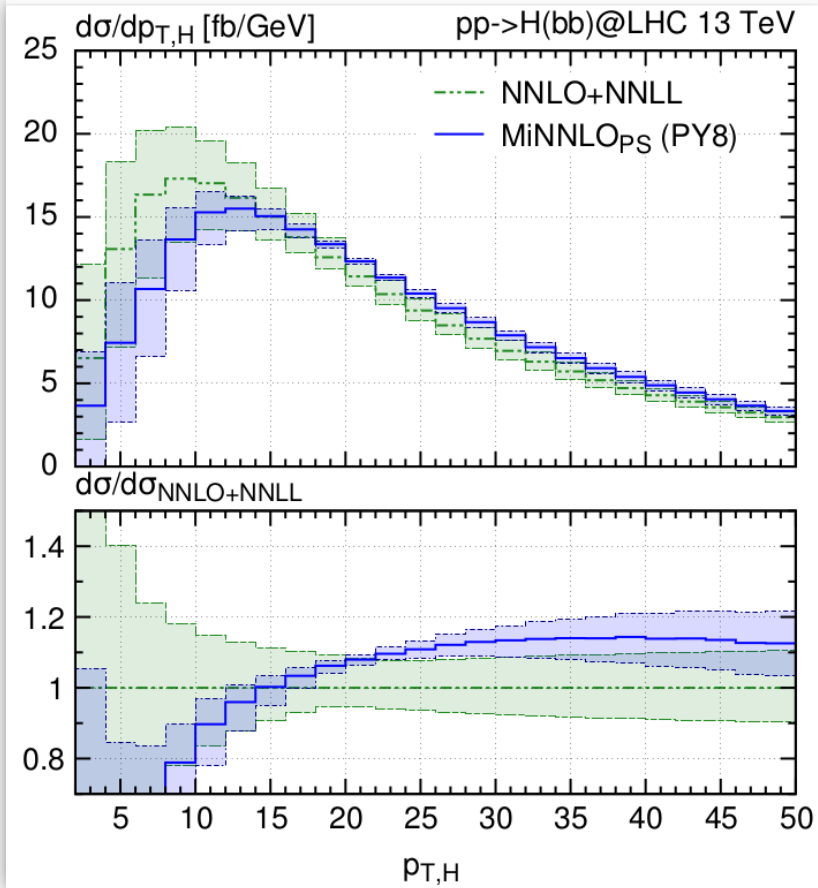
Comparison to NNLO+NNLL





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- **At small $p_{T,H}$**:
  slightly worsen the agreement. **MiNNLO$_{PS}$** uncertainities are **underestimated.**

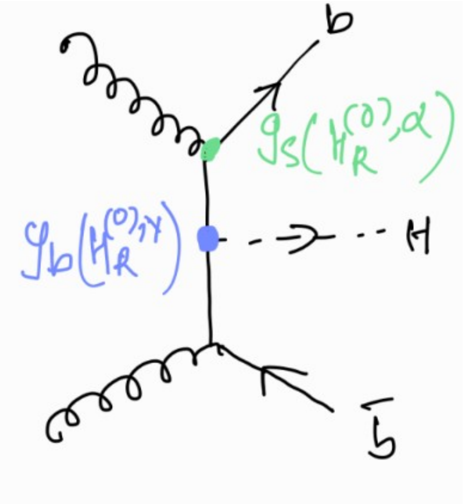
- **Massless** approximation **misses** potentially **relevant mass effects at small p_T** , need to **combine** with **massive 4FS** calculation.

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



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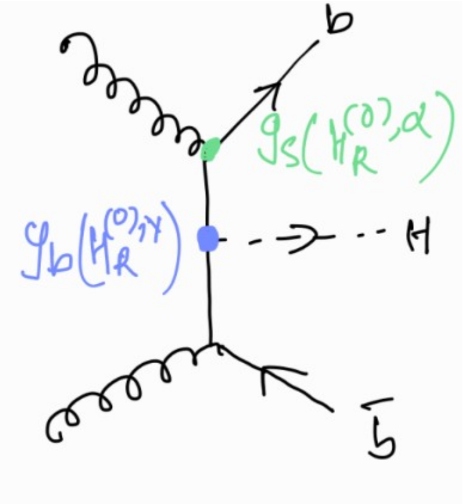
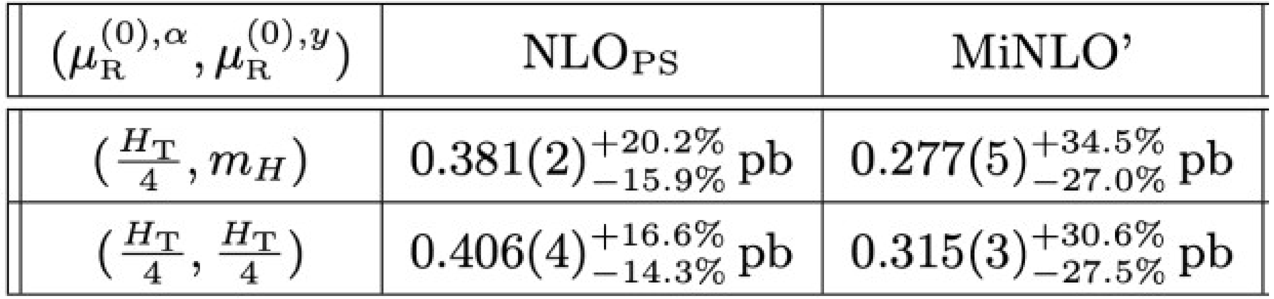




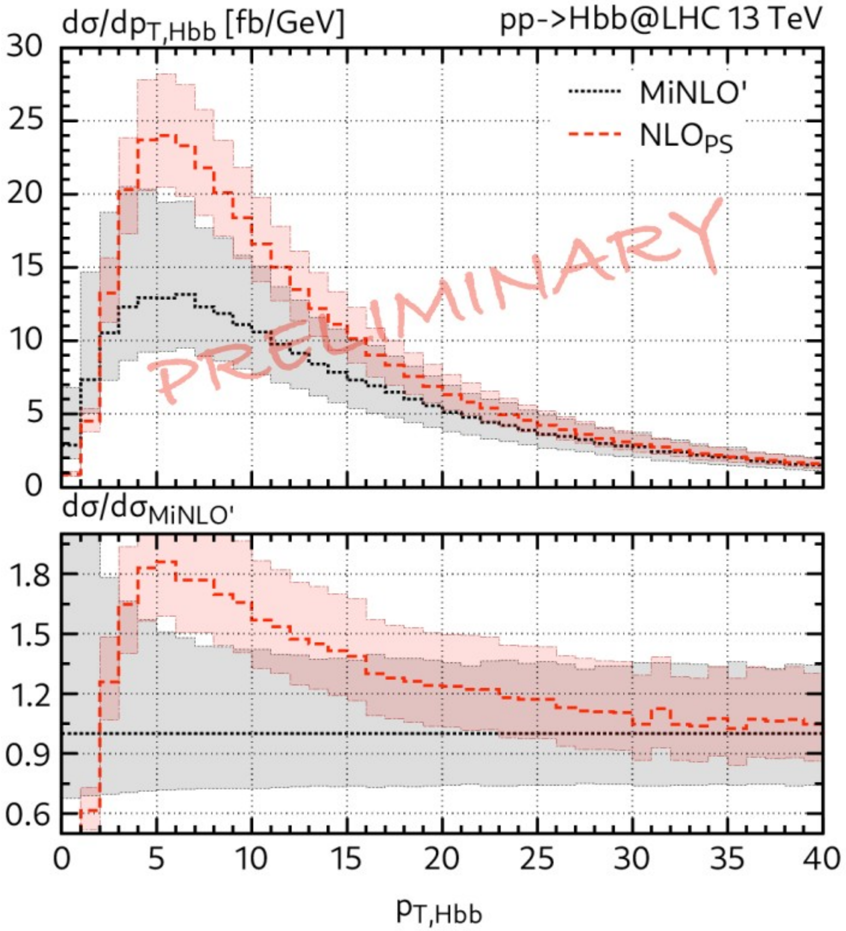
$(\mu_R^{(0),\alpha}, \mu_R^{(0),y})$	NLO$_{\rm PS}$	MiNLO'
$(\frac{H_T}{4}, m_H)$	$0.381(2)^{+20.2\%}_{-15.9\%}$ pb	$0.277(5)^{+34.5\%}_{-27.0\%}$ pb
$(\frac{H_T}{4}, \frac{H_T}{4})$	$0.406(4)^{+16.6\%}_{-14.3\%}$ pb	$0.315(3)^{+30.6\%}_{-27.5\%}$ pb

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

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

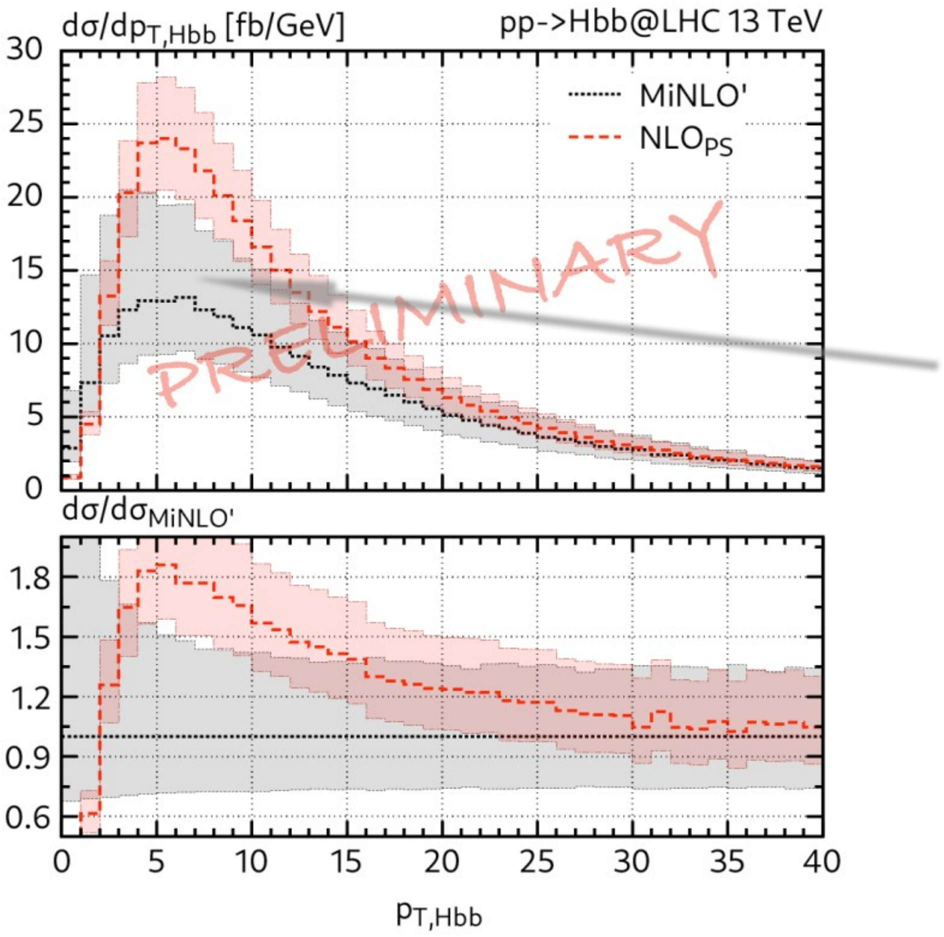
MiNLO' more than 20% less than NLO

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



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

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



- 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

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

Double virtual Amplitude

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Collinear poles in 5FS

Logs of m_b in 4FS

$b\bar{b}H$ 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**

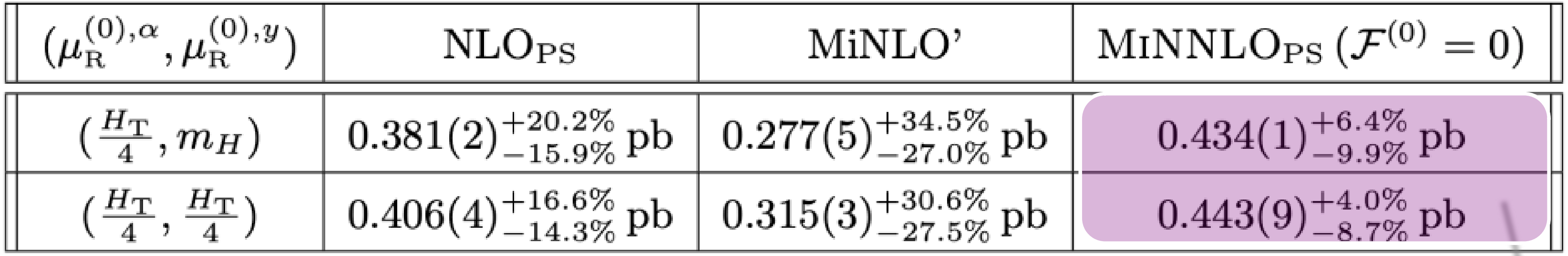
$$\mathscr{A}^{(2)} = \underbrace{\log(m_b)\text{-terms} + \text{const.}}_{\mathscr{F}^{(2)}\,\mathscr{A}^{(0)}_{m_b=0} + \mathscr{F}^{(1)}\,\mathscr{A}^{(1)}_{m_b=0} + \mathscr{F}^{(0)}\,\boxed{\mathscr{A}^{(2)}_{m_b=0}}} + \mathcal{O}\left(\frac{m_b}{Q}\right)$$

Massification coefficients

Massless double virtual amplitude

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

Double virtual Amplitude

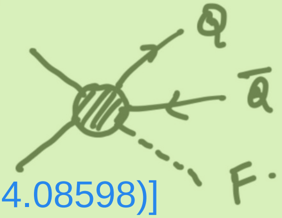


$(\mu_{\mathrm{R}}^{(0),\alpha}, \mu_{\mathrm{R}}^{(0),y})$	NLO$_{\mathrm{PS}}$	MiNLO'	MiNNLO$_{\mathrm{PS}}$ $(\mathcal{F}^{(0)} = 0)$
$(\frac{H_{\mathrm{T}}}{4}, m_H)$	$0.381(2)^{+20.2\%}_{-15.9\%}$ pb	$0.277(5)^{+34.5\%}_{-27.0\%}$ pb	$0.434(1)^{+6.4\%}_{-9.9\%}$ pb
$(\frac{H_{\mathrm{T}}}{4}, \frac{H_{\mathrm{T}}}{4})$	$0.406(4)^{+16.6\%}_{-14.3\%}$ pb	$0.315(3)^{+30.6\%}_{-27.5\%}$ pb	$0.443(9)^{+4.0\%}_{-8.7\%}$ pb

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

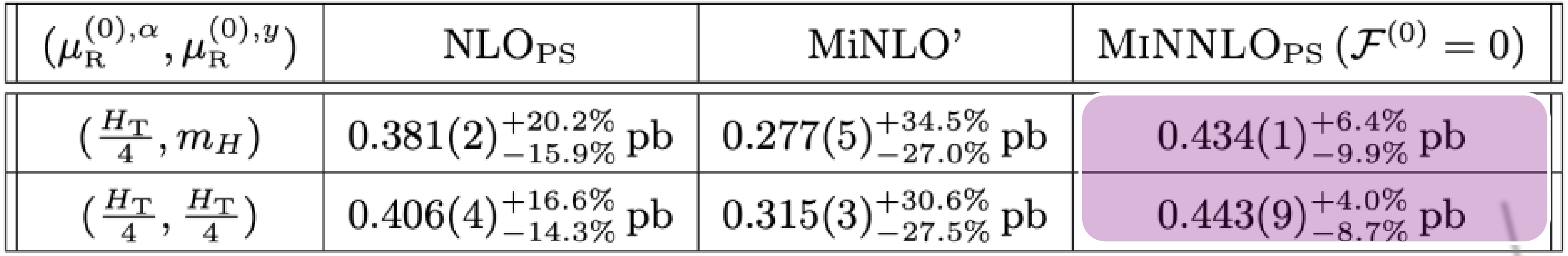
Predictions using recent extension of **MiNNLO$_{\mathrm{PS}}$ for Q$\bar{\mathrm{Q}}$F**

[Mazzitelli, Sotnikov, Wiesemann (2404.08598)]



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

Double virtual Amplitude



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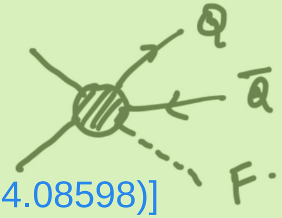
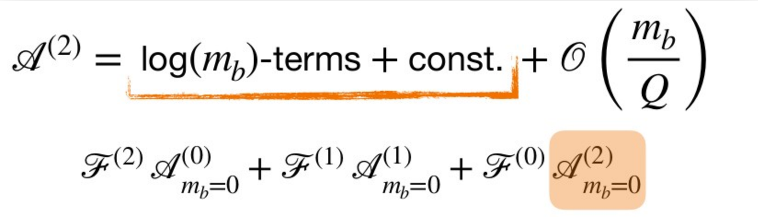




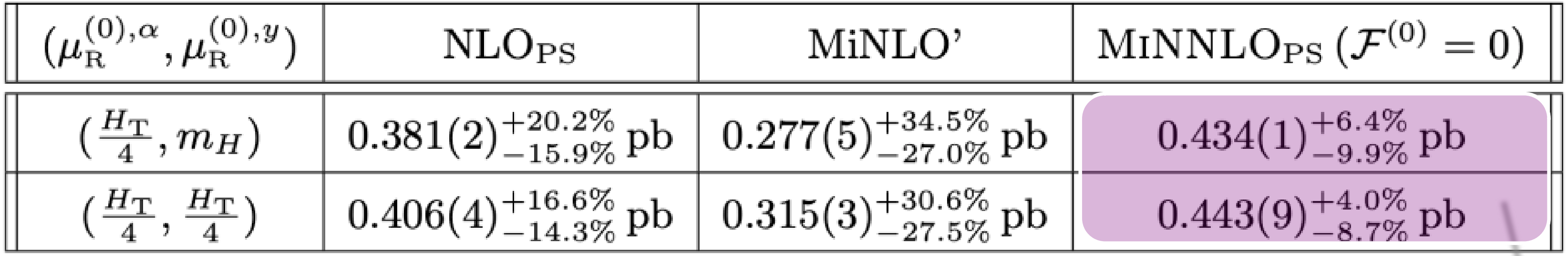
$$\mathscr{A}^{(2)} = \underbrace{\log(m_b)\text{-terms} + \text{const.}} + \mathcal{O}\left(\frac{m_b}{Q}\right)$$

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

MiNNLOPS with **only logarithmic** contributions in the 2-loop predicts a total cross-section **bigger** than the **NLO+PS** one.

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

Double virtual Amplitude



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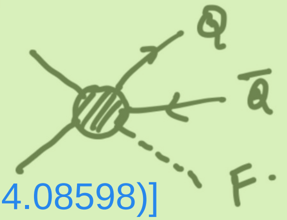

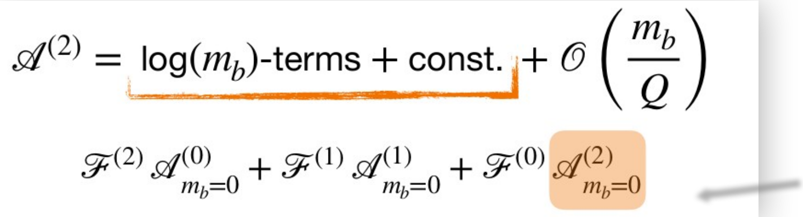

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$$\mathscr{F}^{(2)}\mathscr{A}^{(0)}_{m_b=0} + \mathscr{F}^{(1)}\mathscr{A}^{(1)}_{m_b=0} + \mathscr{F}^{(0)}\boxed{\mathscr{A}^{(2)}_{m_b=0}}$$

What about the 2-loop?

MiNNLOPS with **only logarithmic** contributions in the 2-loop predicts a total cross-section **bigger** than the **NLO+PS** one.

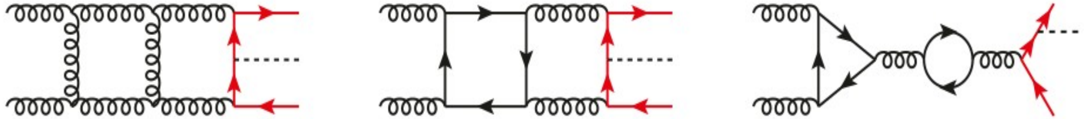
$b\bar{b}H$ in the 4FS

Double virtual Amplitude

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

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

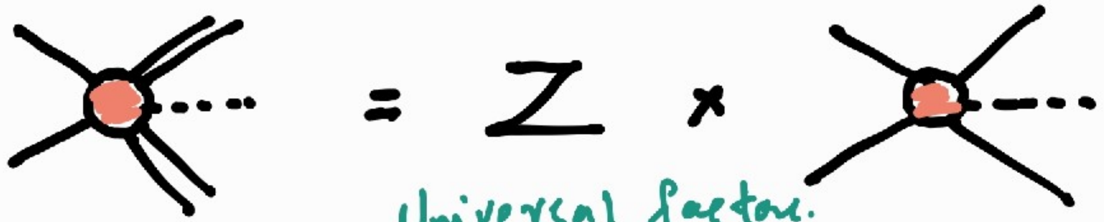
[Badger, Hartanto, Kryś, Zoia (2107.14733)]



- 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)



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

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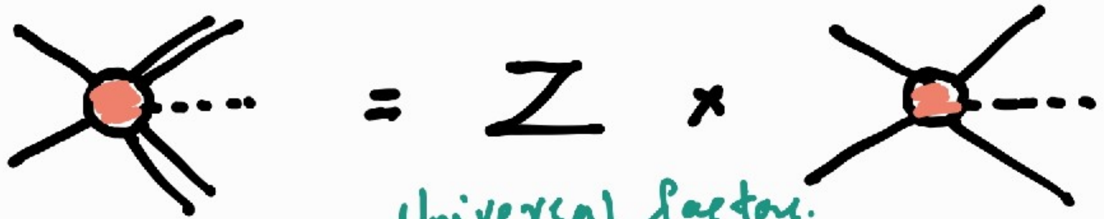
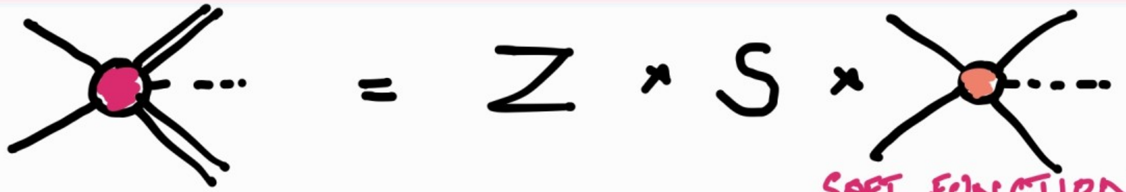


$$|A_{massive}\rangle = \prod_i \overbrace{\left[Z_i(\{m_q\})\right]}^{\text{Universal factor.}}{}^{1/2} \; |A_{massless}\rangle$$

- 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 qq̄ → QQ̄ [Czakon, Mitov, Moch (0705.1975)]

Massification procedure

Generalised massification (GM)

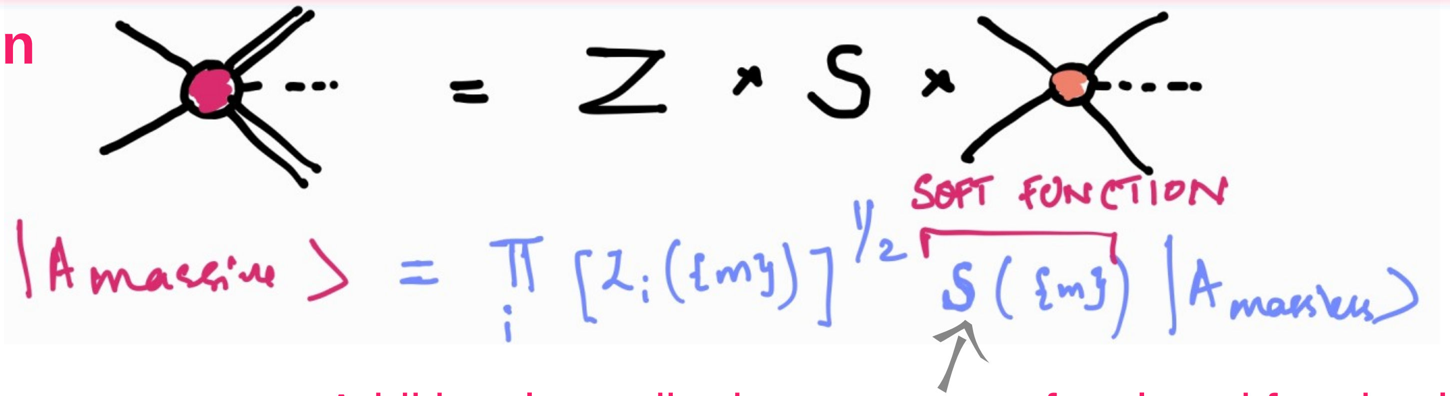


$$|A_{\text{massive}}\rangle = \prod_i \left[Z_i(\{m\})\right]^{1/2} \overbrace{S(\{m\})}^{\text{SOFT FUNCTION}} |A_{\text{massless}}\rangle$$

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 $m_b = 0$.

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

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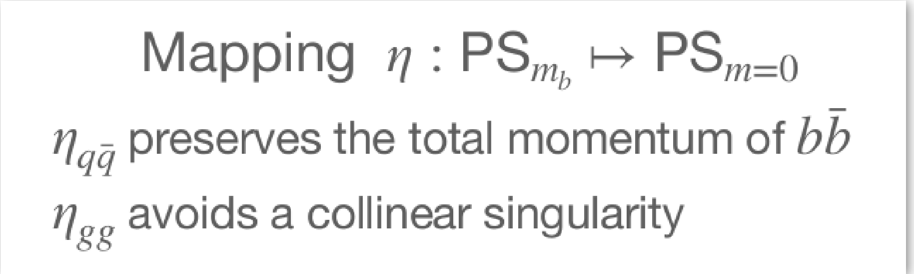
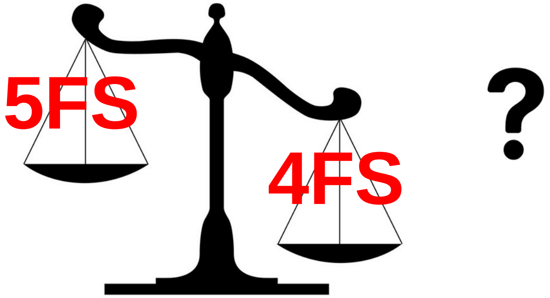


Mapping $\eta : \mathrm{PS}_{m_b} \mapsto \mathrm{PS}_{m=0}$

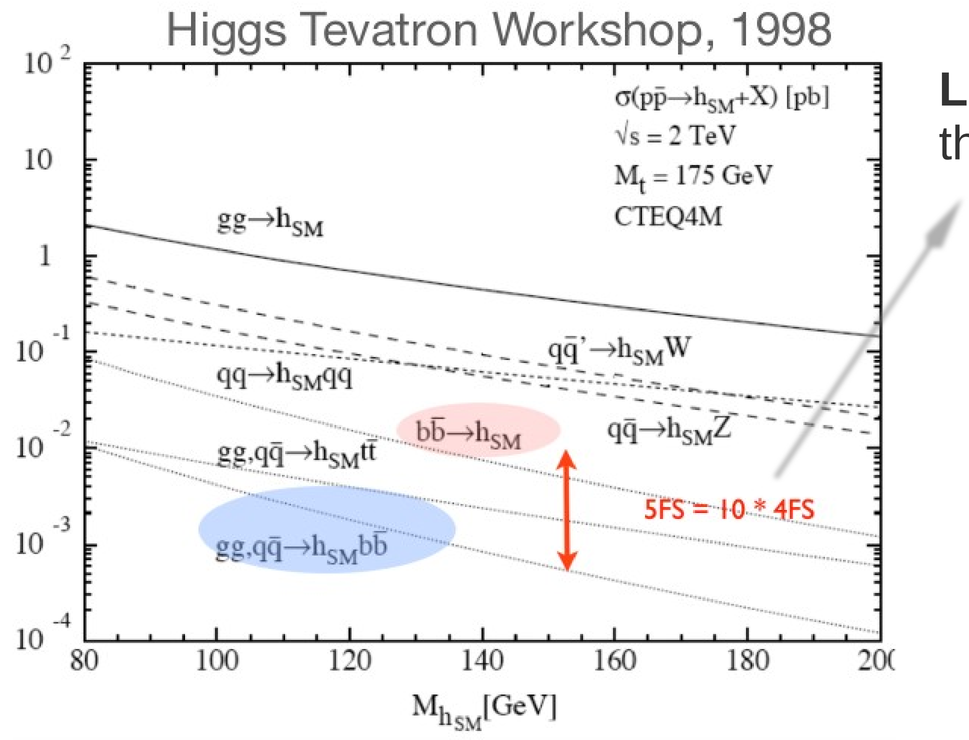
$\eta_{q\bar{q}}$ preserves the total momentum of $b\bar{b}$

η_{gg} avoids a collinear singularity

Flavour scheme comparisons

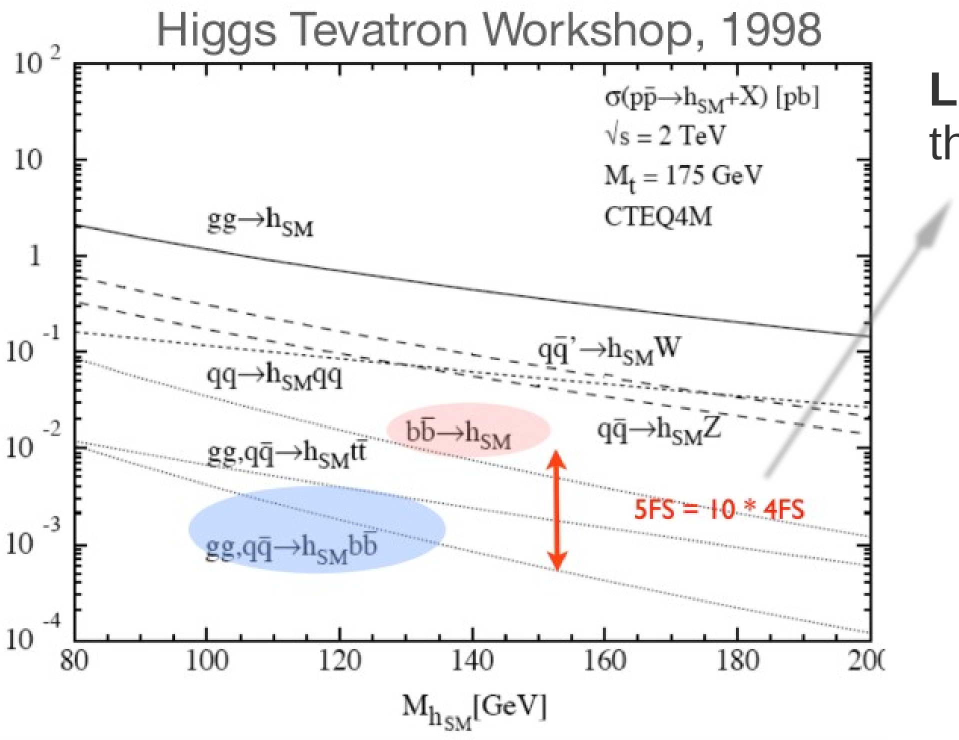


Total cross-section



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

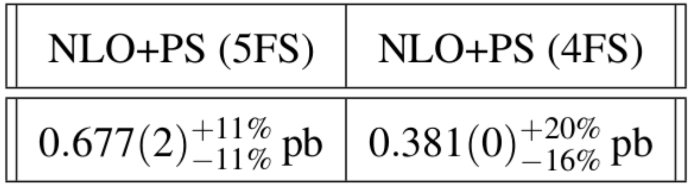
Total cross-section


Higgs Tevatron Workshop, 1998

5FS = 10 * 4FS

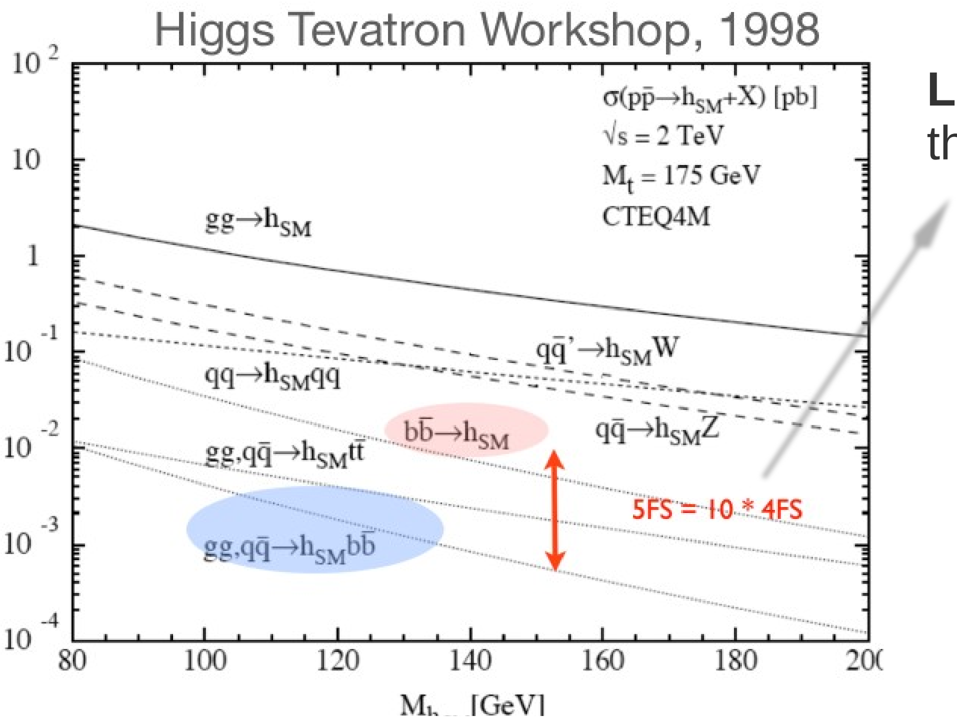
Large differences in the predictions were first observed at the **LO**: the effect of collinear resummation is extremely large.

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



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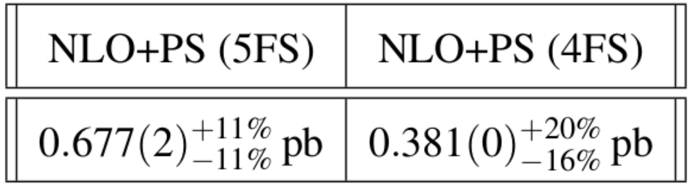

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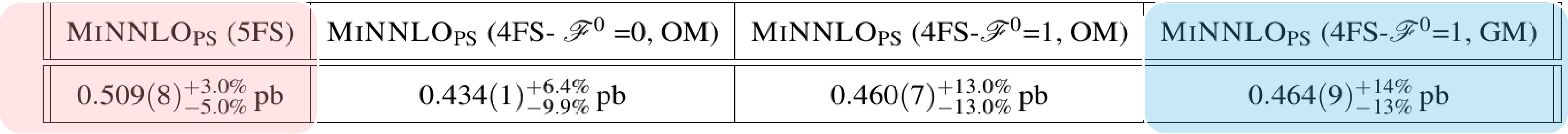
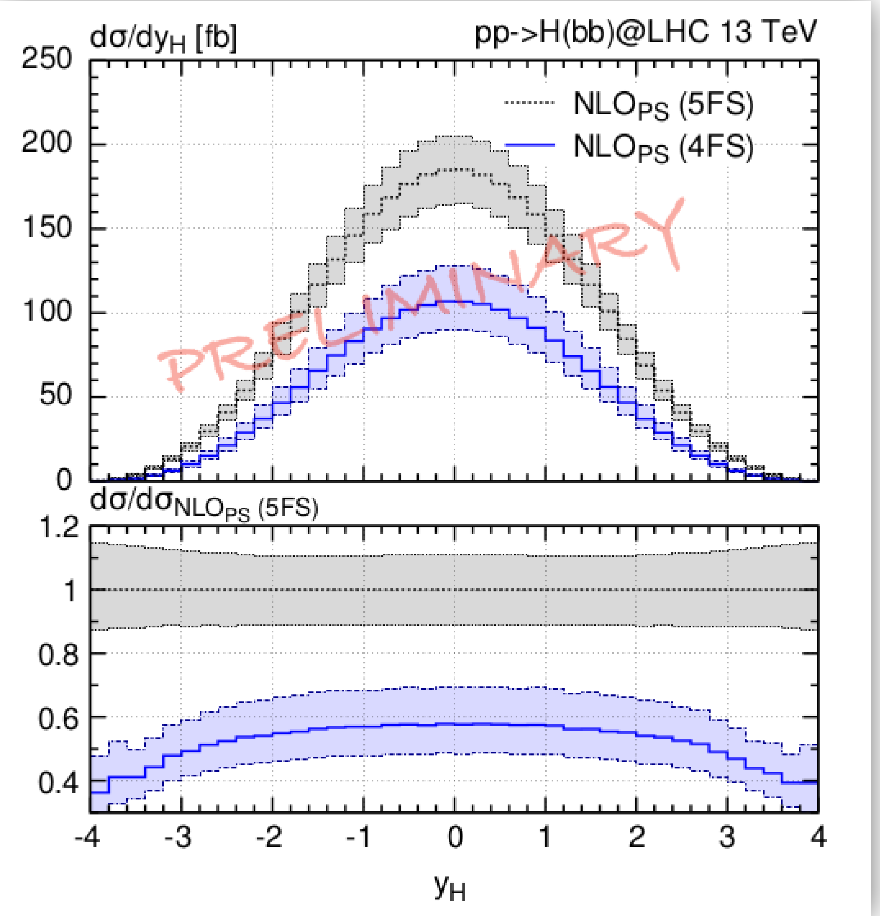
NNLO : 5FS = 1.09 * 4 FS : The best prediction till today..

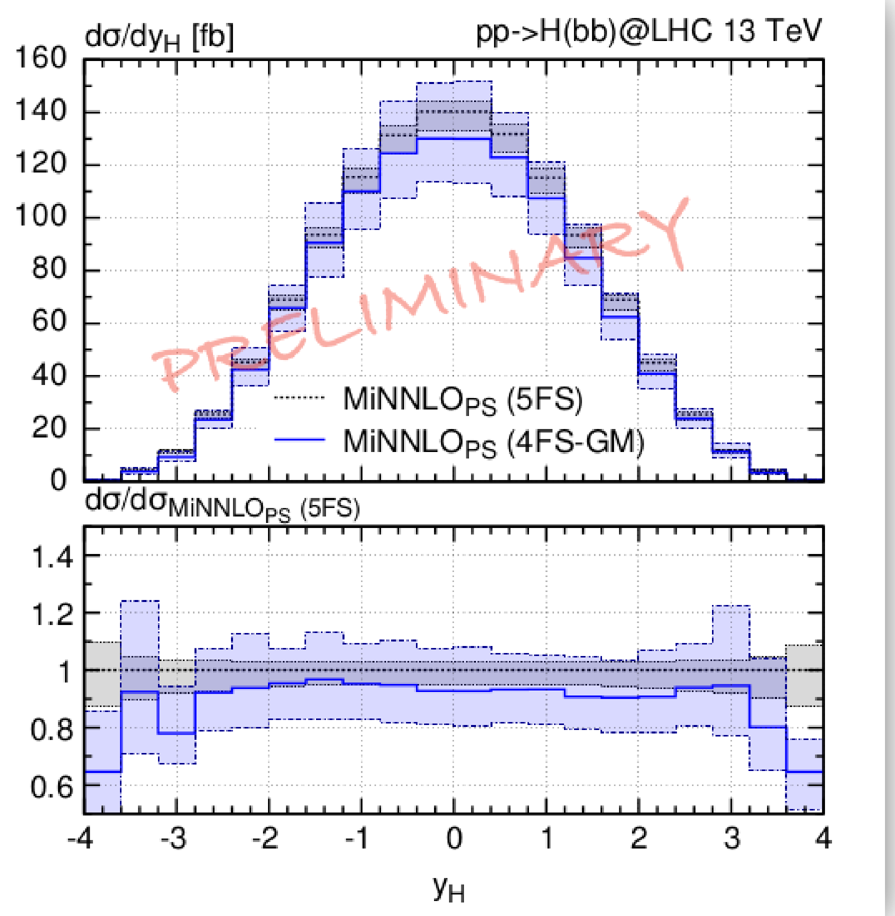


MiNNLO$_{\rm PS}$ (5FS)	MiNNLO$_{\rm PS}$ (4FS- $\mathscr{F}^0$ =0, OM)	MiNNLO$_{\rm PS}$ (4FS-$\mathscr{F}^0$=1, OM)	MiNNLO$_{\rm PS}$ (4FS-$\mathscr{F}^0$=1, GM)
$0.509(8)^{+3.0\%}_{-5.0\%}$ pb	$0.434(1)^{+6.4\%}_{-9.9\%}$ pb	$0.460(7)^{+13.0\%}_{-13.0\%}$ pb	$0.464(9)^{+14\%}_{-13\%}$ pb

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

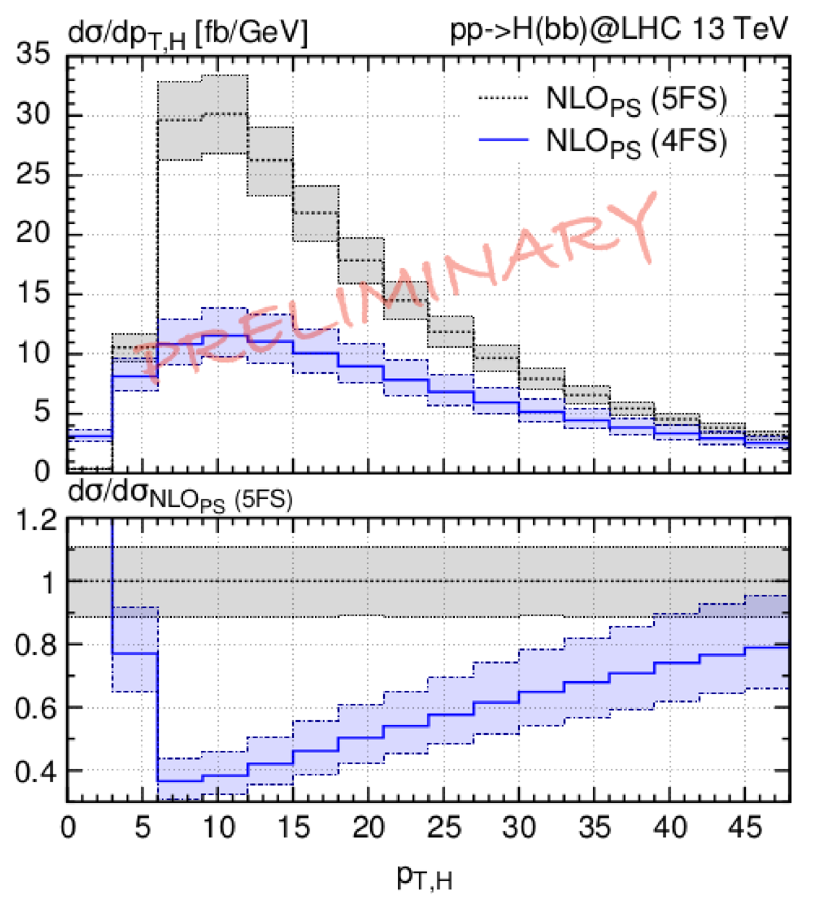
Higgs rapidity

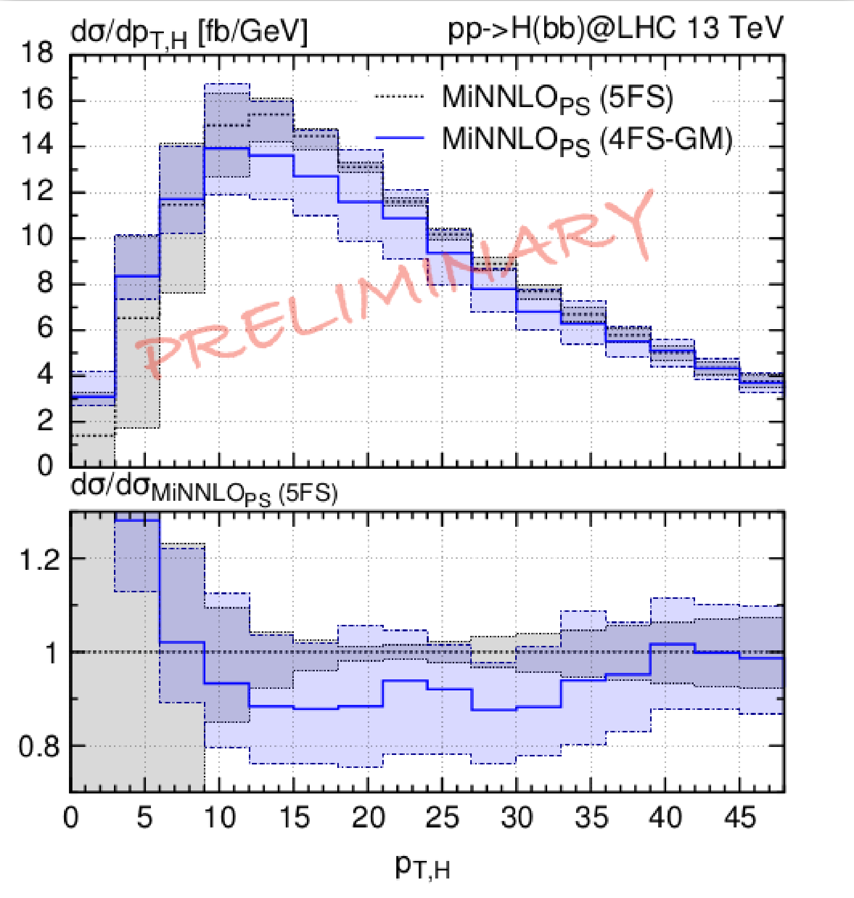




[Biello, Mazzitelli, **AS**, Wiesemann, Zanderighi (in progress)]

Higgs p_T spectrum





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

Summary & Outlook

- **NNLO+PS** is required for p**recise** & **realistic LHC phenomenology.**

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

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

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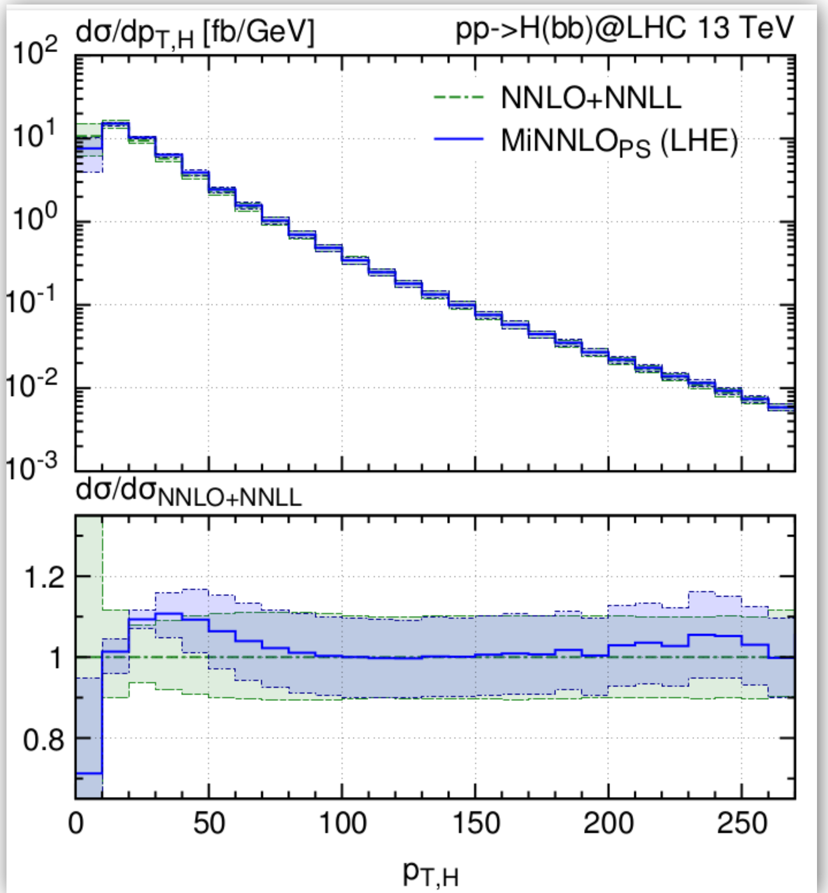
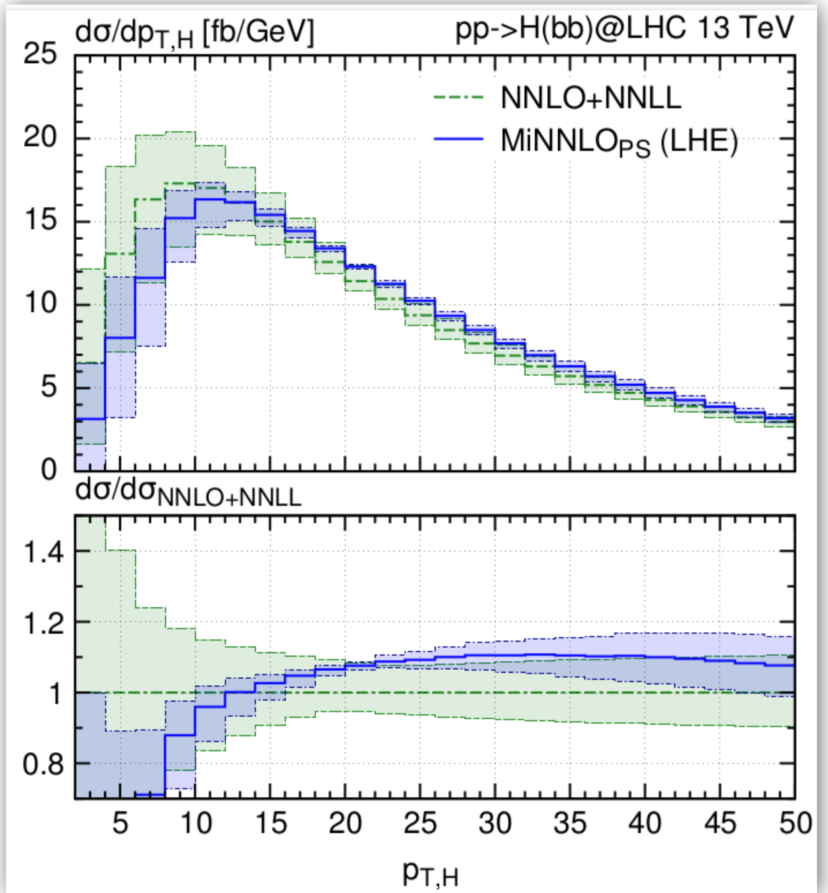
THANK YOU !

Backup slides.....

Comparison to NNLO+NNLL

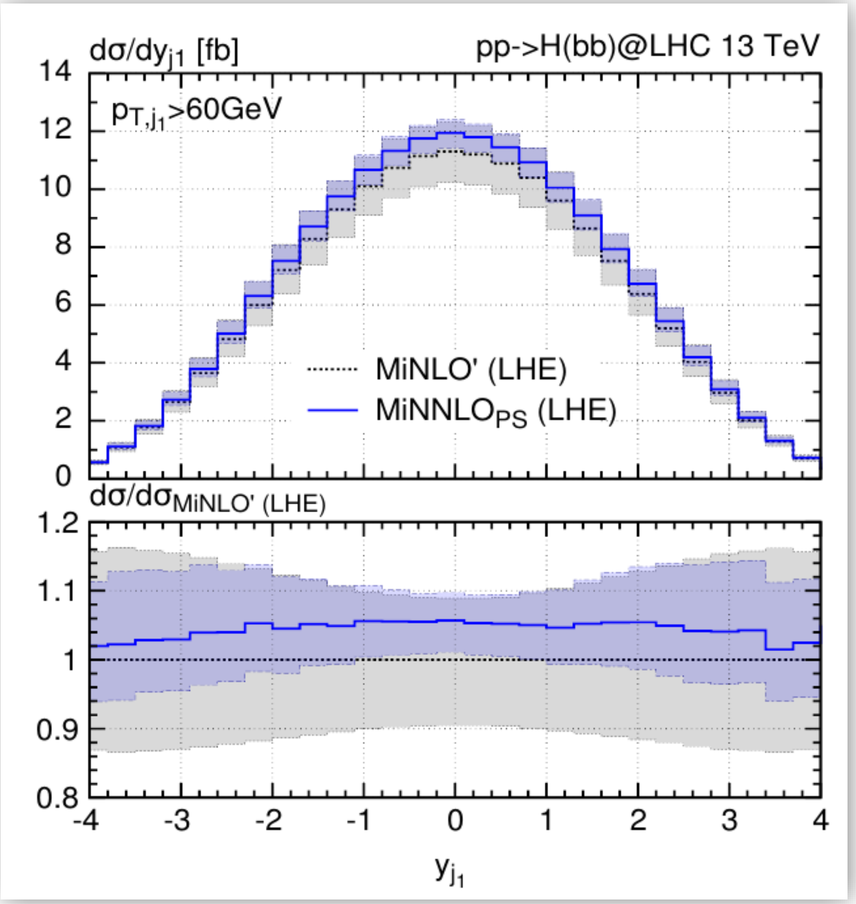


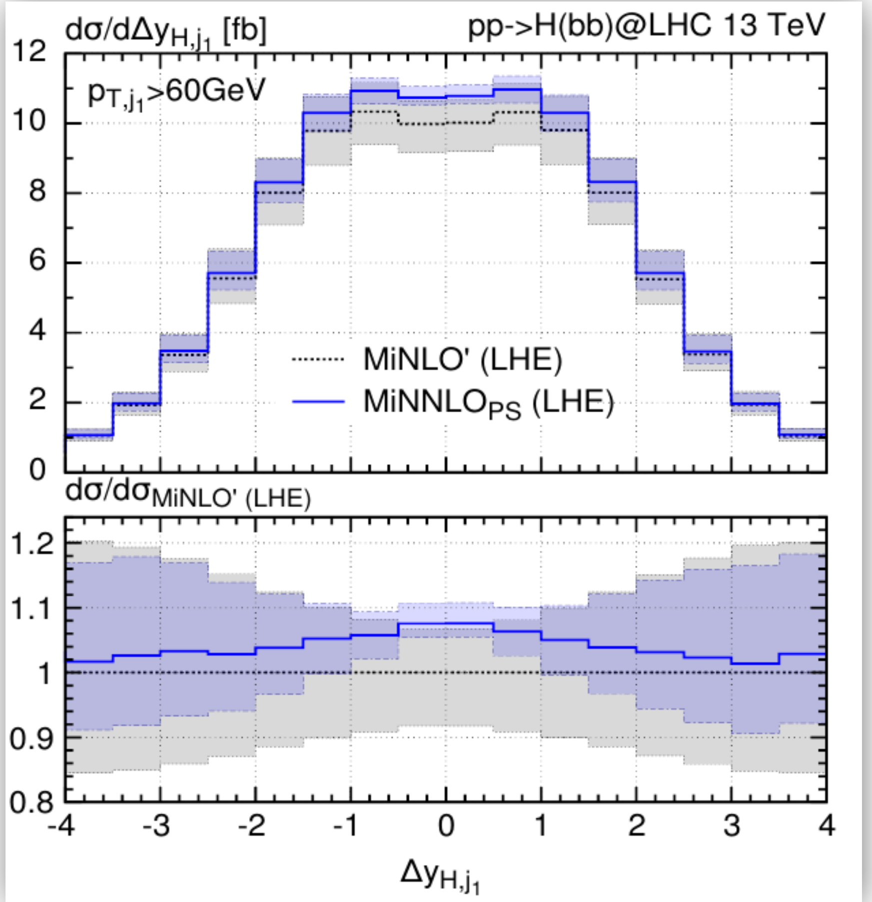


At high $p_{T,H}$:
they coincide again

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

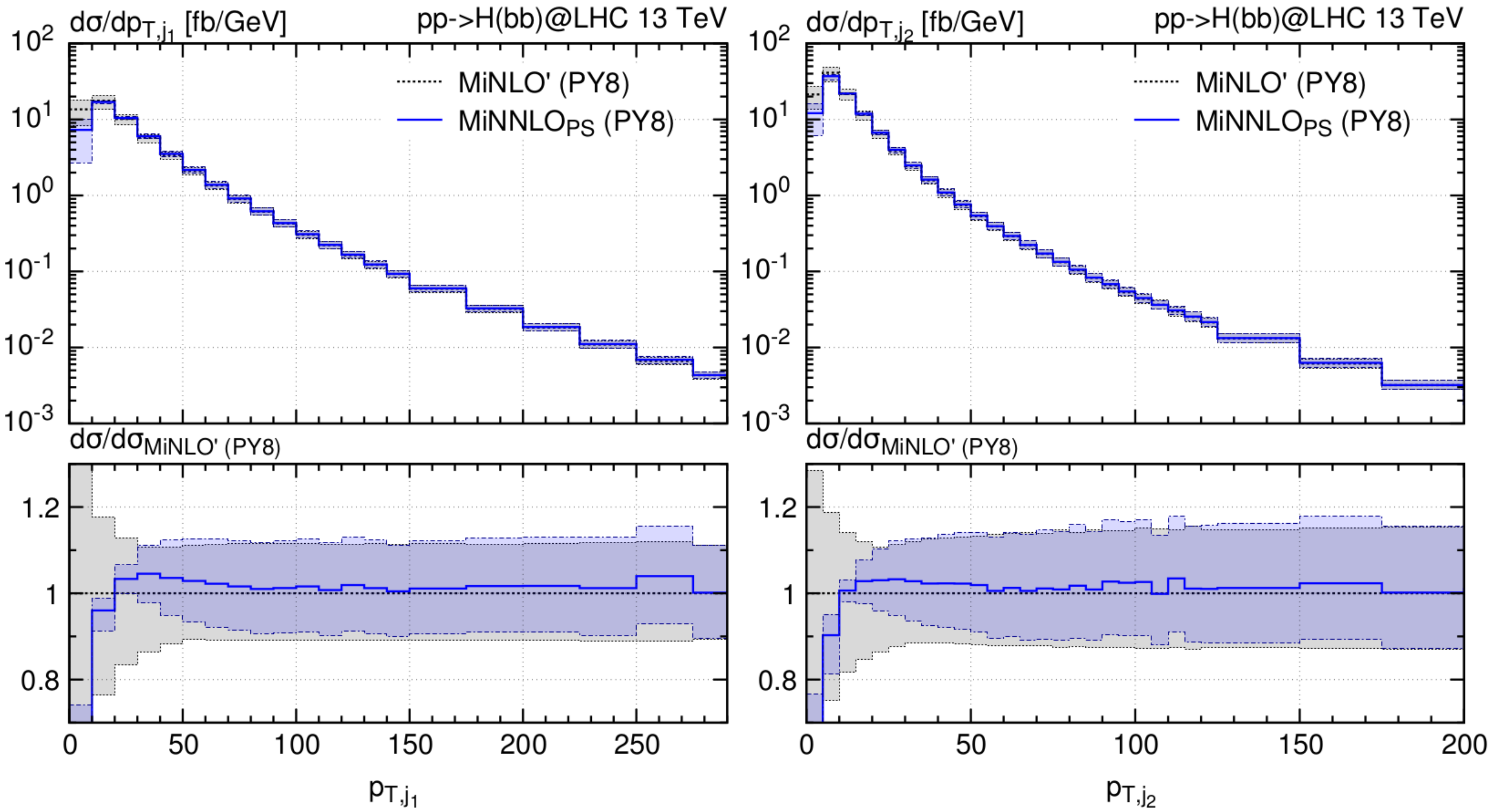
Comparison of MiNLO’ & MiNNLO$_{PS}$





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

Comparison of `MiNLO'` & `MiNNLO`$_{\mathrm{PS}}$



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 $\eta(P) = P_0 + O(m_b / m_H)$.

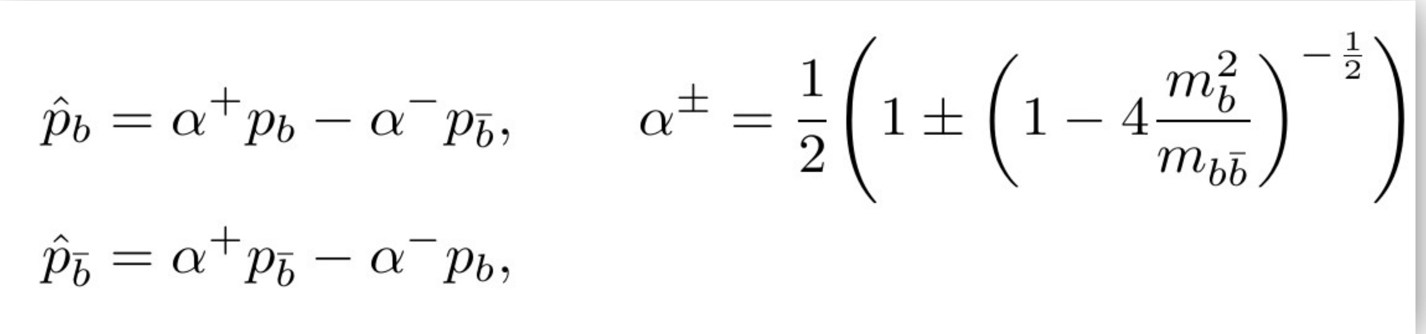
- We have to ensure that η does not cause amplitudes to be evaluated near their singularities.

- 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 → $b\bar{b}$ 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:

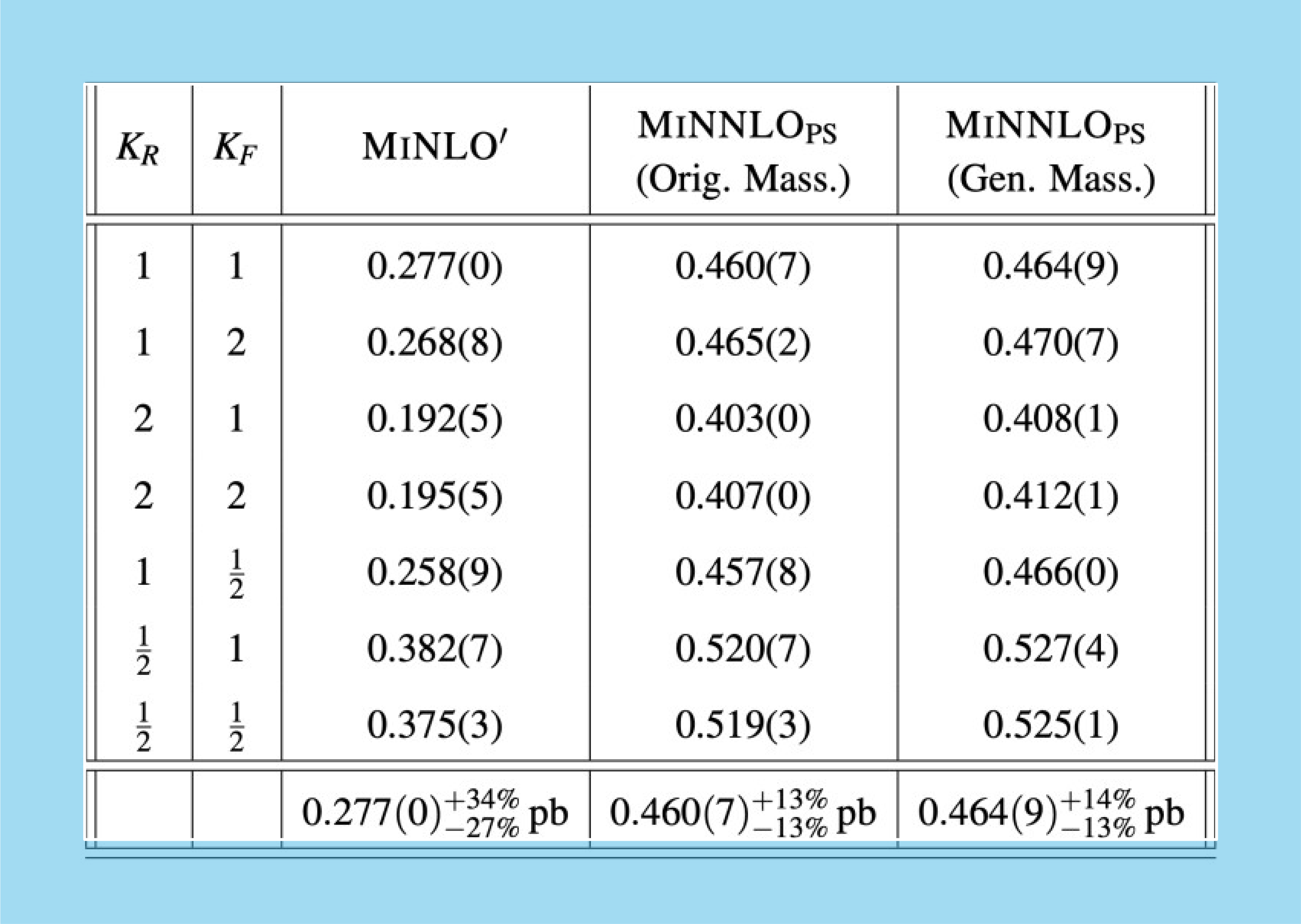
1. We redistribute $\Delta p_{b\bar{b}} = p_b + p_{\bar{b}} - \hat{p}_b - \hat{p}_{\bar{b}}$ into $\hat{p}_1$ and $\hat{p}_2$, such that $\hat{p}_{12} = \hat{p}_1 + \hat{p}2 = p1 + p2 - \Delta p_{b\bar{b}}$, by performing a Lorentz boost on p_1 and p_2 in the direction $-\hat{p}_{12}$ followed by rescaling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

OR

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

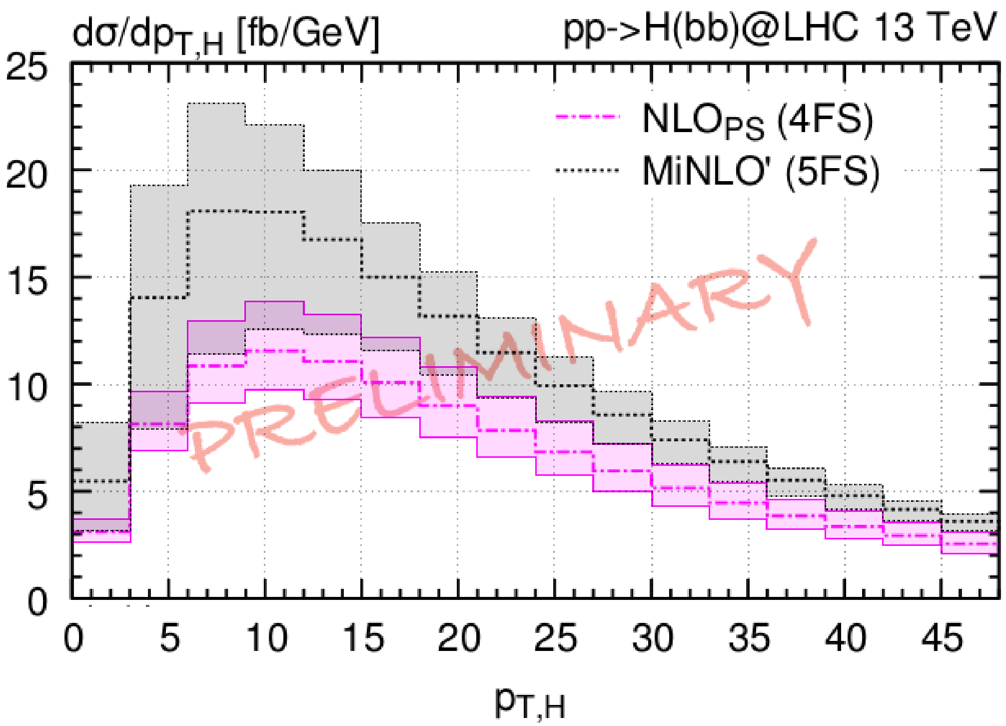
[Mazzitelli, Sotnikov, Wiesemann (2404.08598)]

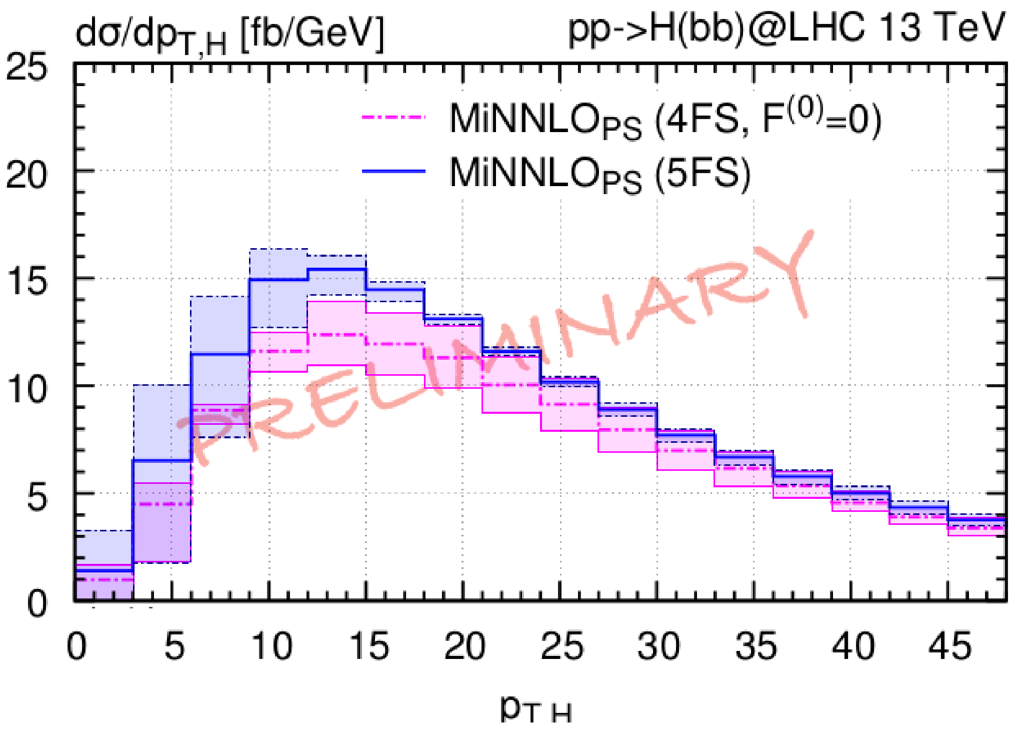
Cross-section details (4FS)

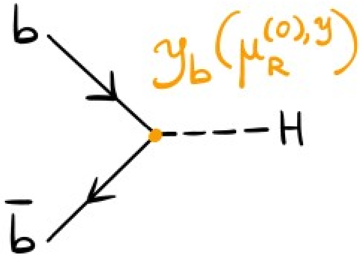


K_R	K_F	MiNLO′	MiNNLO$_{\text{PS}}$ (Orig. Mass.)	MiNNLO$_{\text{PS}}$ (Gen. Mass.)
1	1	0.277(0)	0.460(7)	0.464(9)
1	2	0.268(8)	0.465(2)	0.470(7)
2	1	0.192(5)	0.403(0)	0.408(1)
2	2	0.195(5)	0.407(0)	0.412(1)
1	$\frac{1}{2}$	0.258(9)	0.457(8)	0.466(0)
$\frac{1}{2}$	1	0.382(7)	0.520(7)	0.527(4)
$\frac{1}{2}$	$\frac{1}{2}$	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

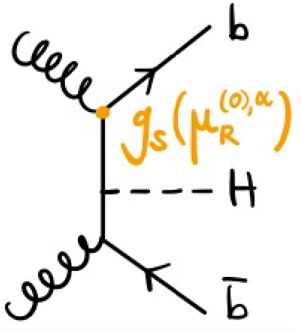
Before the two-loop | 4FS



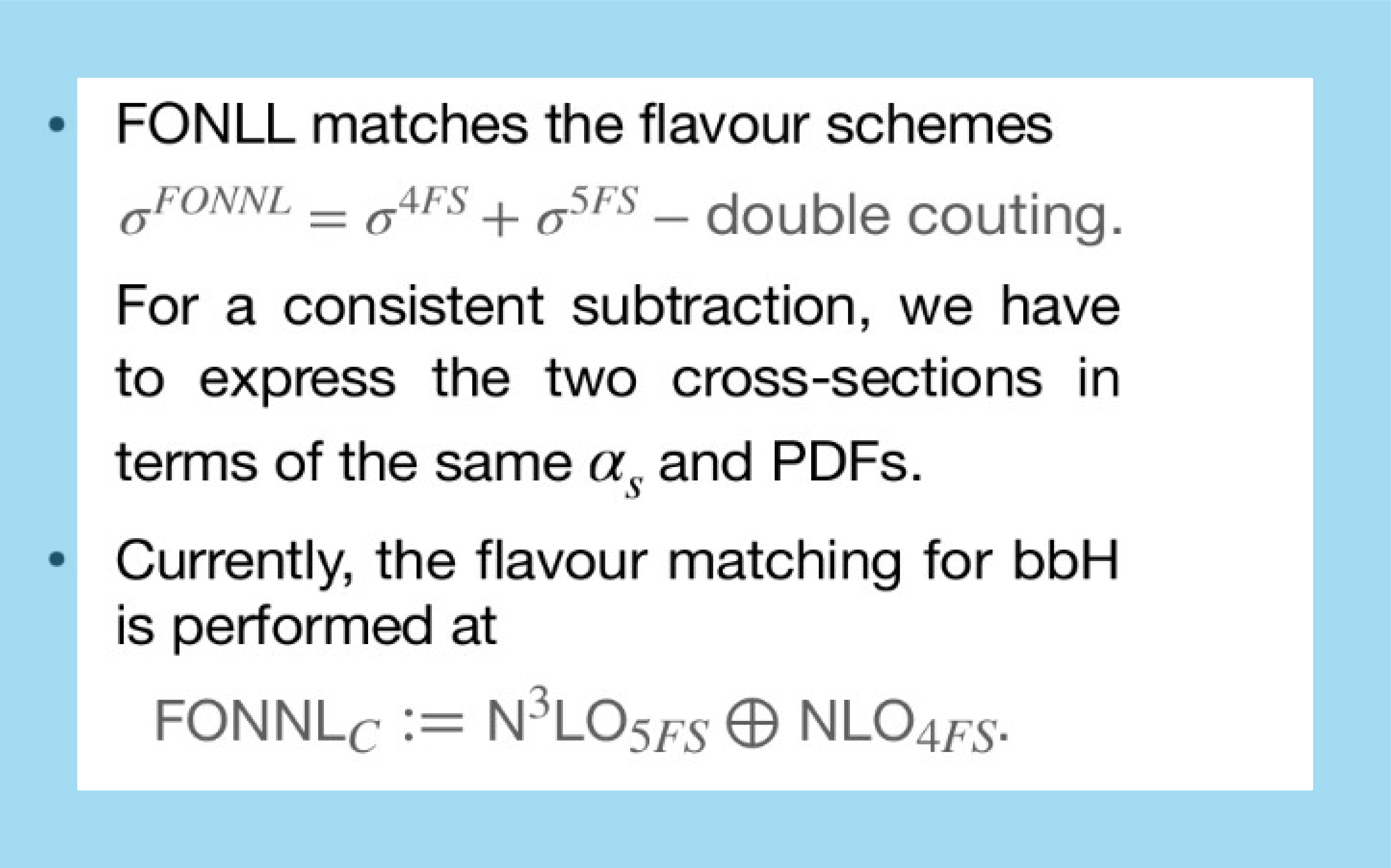




$(\mu_R^{(0),\alpha}, \mu_R^{(0),y})$	NLO$_{\text{PS}}$ (5FS)	NLO$_{\text{PS}}$ (4FS)	MiNNLO$_{\text{PS}}$ (5FS)	MiNNLO$_{\text{PS}}$ (4FS, $\mathscr{F}^{(0)} = 0$)
$(\frac{1}{4}H_T, m_H)$	$0.646(0)^{+10.4\%}_{-10.9\%}$ pb	$0.381(2)^{+20.2\%}_{-15.9\%}$ pb	$0.509(8)^{+2.9\%}_{-5.3\%}$ pb	$0.434(1)^{+6.4\%}_{-10.0\%}$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

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