Technische Universität München

MAX-PLANCK-INSTITUT FÜR PHYSIK

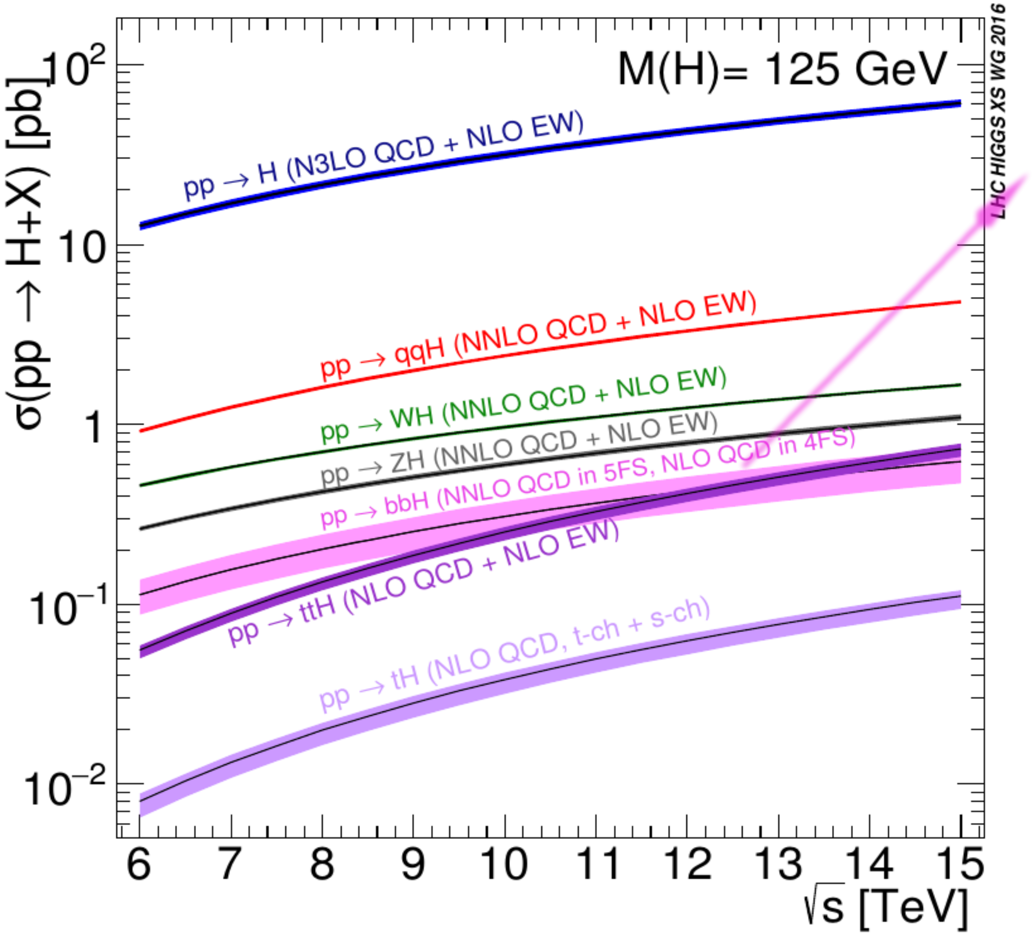
Precise predictions for $b\bar{b}H$ production at the LHC

Aparna Sankar

EPS-HEP 2025

PALAIS DU PHARO, Marseille, France, 7 July 2025

Higgs production in bottom quark fusion



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 (MSSM)

$b\bar{b}H$ enters as a **background** in other Higgs searches (notably **HH**)

Precise **simulation of the $b\bar{b}H$** also plays an important role in **constraining the light-quark Yukawa** couplings.

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

5 flavor scheme (5FS)

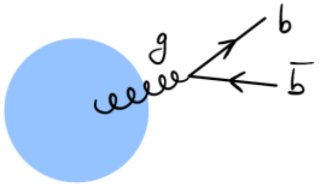
$$\mathbf{m_b = 0}$$

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

4 flavor scheme (4FS)

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

$$\mathbf{f_b = 0}$$



[Image courtesy : C. Biello]

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

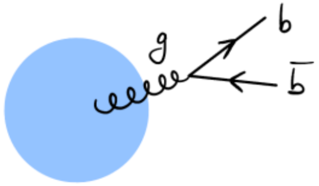
5 flavor scheme (5FS)

$$m_b = 0$$
$$f_b \neq 0$$

- **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

4 flavor scheme (4FS)

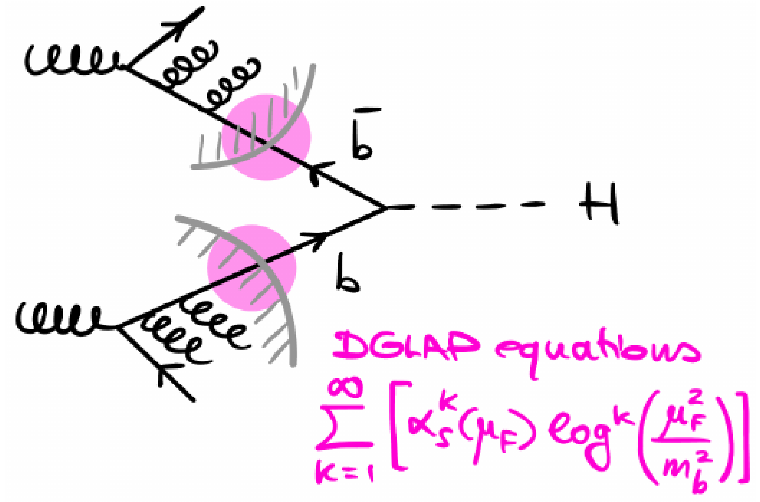
$$m_b \neq 0$$
$$f_b = 0$$



- 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]

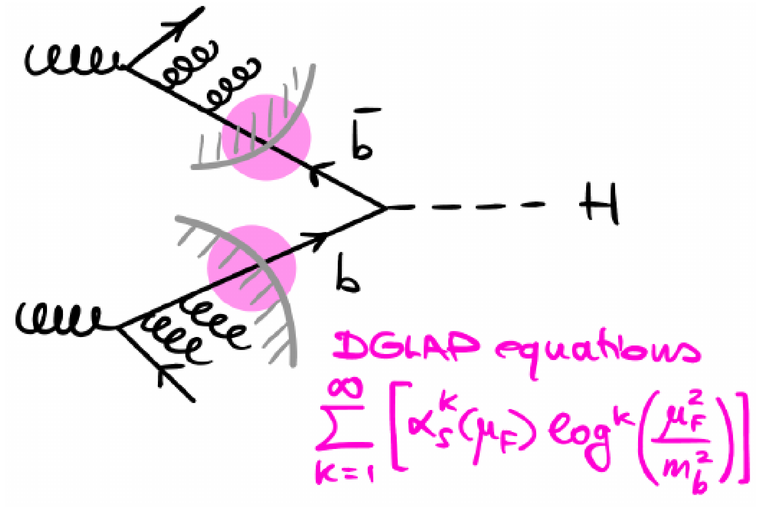
5FS



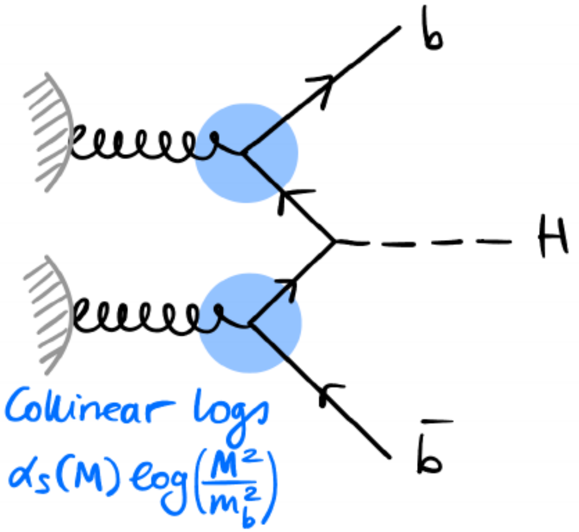
- ✔ Computing **higher orders** is **easier**
- ✔ The **DGLAP** evolution **resums** initial state collinear **logs** into the bottom PDFs
- **Neglects** power-suppressed terms of the **O(m_b/m_H)**

[Image courtesy : C. Biello]

5FS



4FS

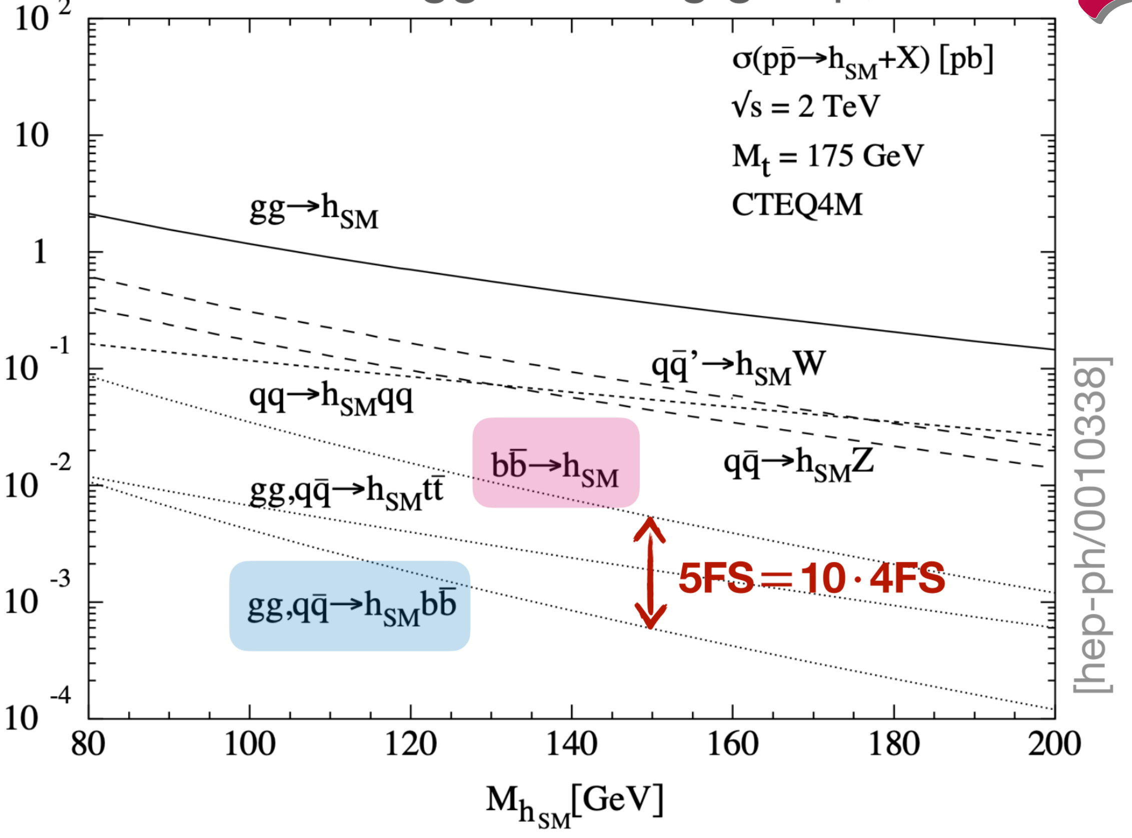


- ✔ Computing **higher orders** is **easier**
- ✔ The **DGLAP** evolution **resums** initial state collinear **logs** into the bottom PDFs
- • **Neglects** power-suppressed terms of the $\mathbf{O(m_b/m_H)}$

- • 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]

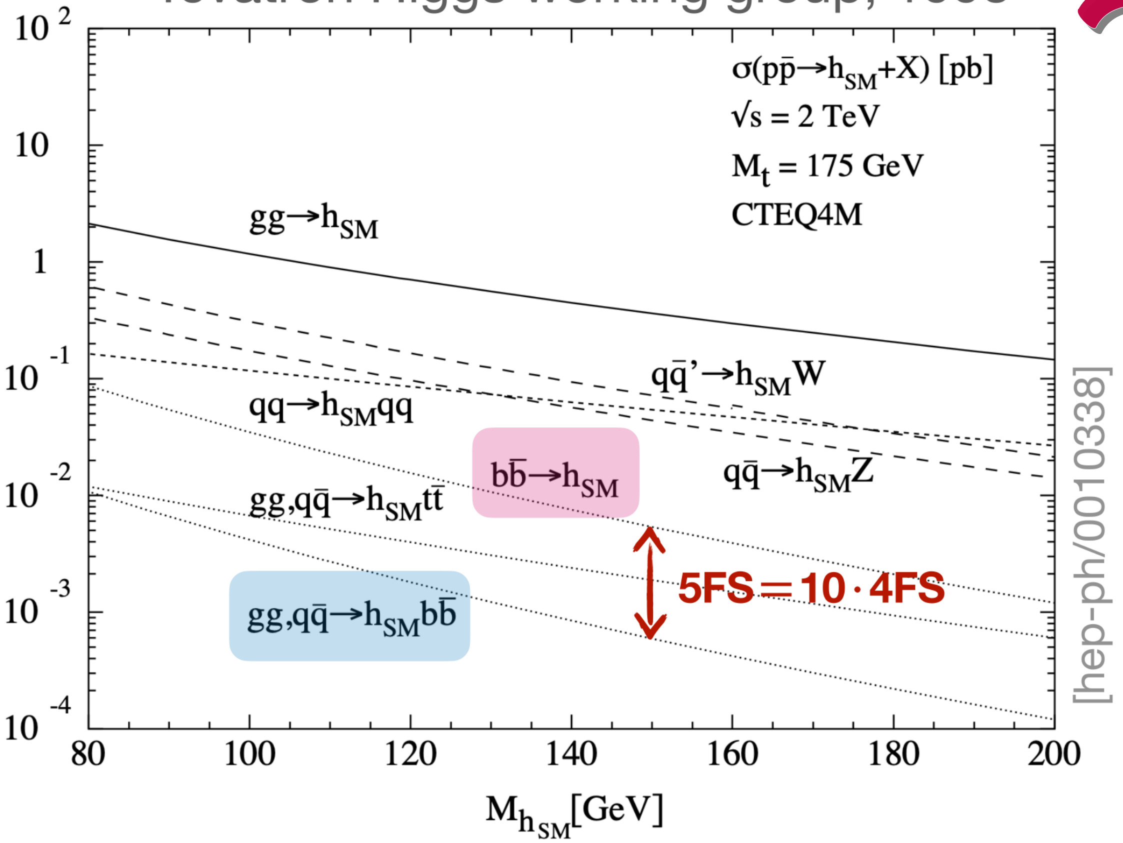
Tevatron Higgs working group, 1998



Large differences between 4FS and 5FS - cross-section predictions differ by up to a factor of ten.

Collinear logarithms have a strong effect!

Tevatron Higgs working group, 1998



Large differences between 4FS and 5FS - cross-section predictions differ by up to a factor of ten.

Collinear logarithms have a strong effect!

Scales	$\sigma(b\bar{b} \to h)$	$\sigma(gg \to b\bar{b}h)$	$\sigma(b\bar{b} \to h)/\sigma(gg \to b\bar{b}h)$
$\mu_F = \mu_R = m_h$	26.6 fb	3.1 fb	8.5
$\mu_F = \mu_R = m_h/4$	20.8 fb	9.2 fb	2.3

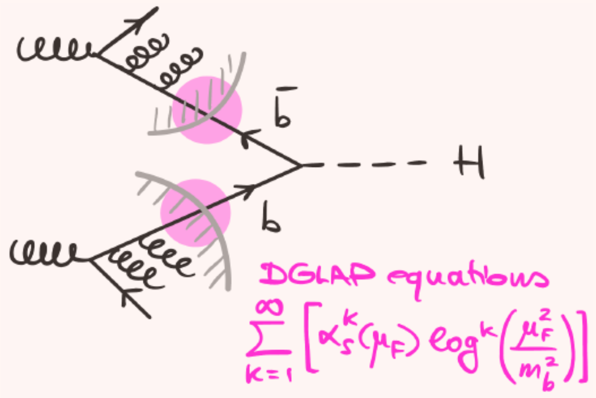
[Maltoni, Sullivan, Willenbrock (0301033)]

Tuning the renormalisation and, notably, the factorisation **scales reduces** the **difference**

Lower scales improved the **perturbative convergence**

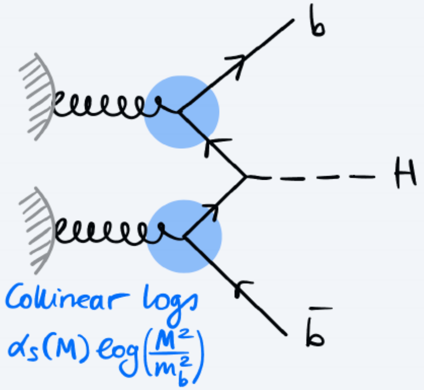
State-of-the-art

5FS



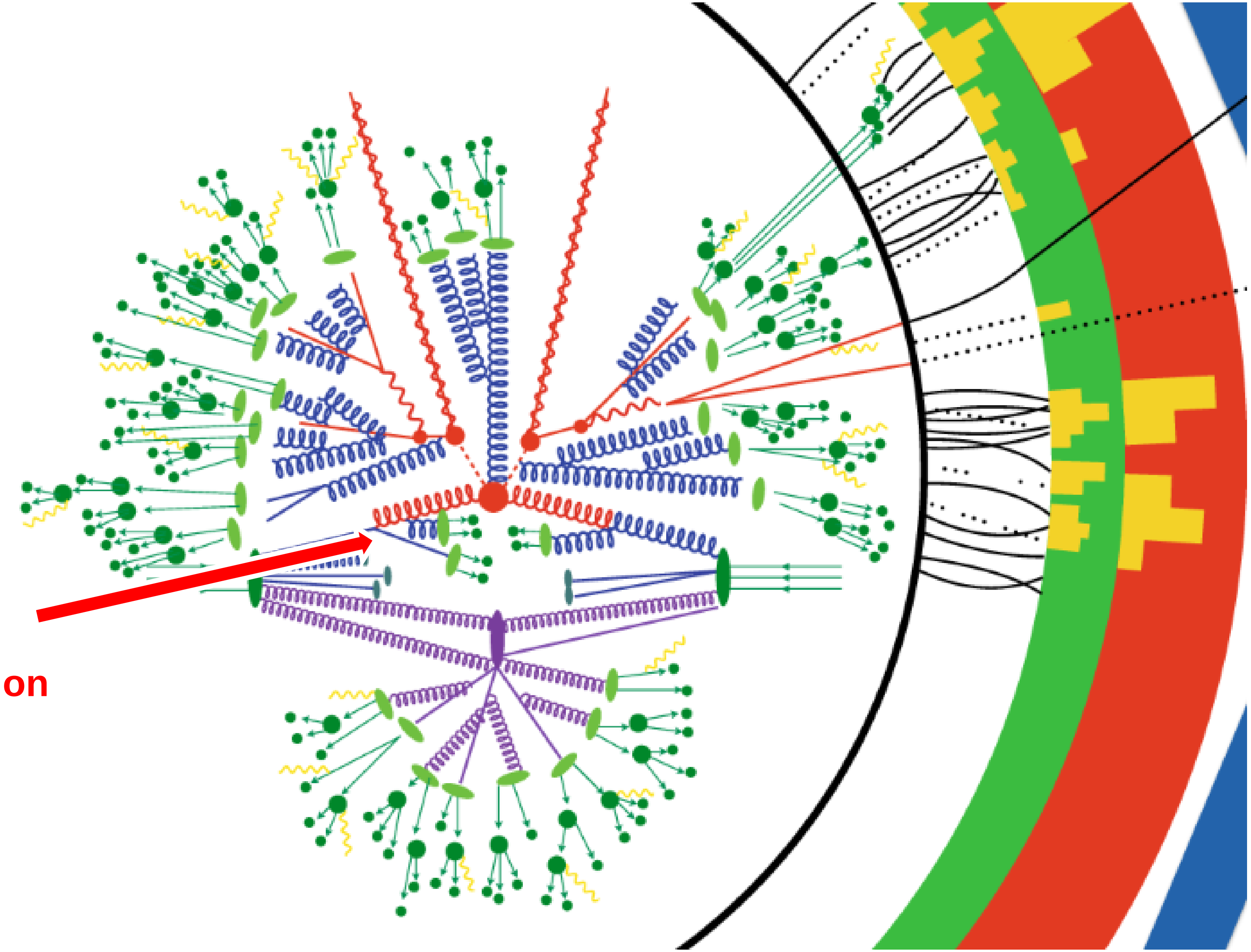
- Total cross-section @ N3LO-QCD
  [Duhr, Dulat, Mistlberger (1904.09990)]
- NNLO-QCD matched with Parton Shower (PS) — NEW — *This talk*
  [Biello, AS, Wiesemann, Zanderighi (2402.04025)]
  [Gavardi, Kuk, Lim (2505.14773)]

4FS



- Total cross-section @ NLO-QCD
  [Dittmaier, Krämer, Spira (0309204)]
- NLO-QCD+PS
  [Jäger, Reina, Wackeroth (1509.05843)]
  [Wiesemann, Frederix, Frixione, Hirschi, Maltoni, Torrielli (1409.5301)]
- NLO-QCD+PS combined with NLO-EW in the 4FS
  [Pagani, Shao, Zaro (2005.10277)]
- NNLO-QCD + PS with approximate 2-loop — NEW
  [Biello, Mazzitelli, AS, Wiesemann, Zanderighi (2412.09510)] *This talk*

Events at the LHC



Hard process

- N^xLO – High precision

Fixed order perturbation theory

Events at the LHC

Parton shower (PS)

- Realistic LHC event
- Resummation

Shower Monte Carlo (SMC)

Hard process

- N^xLO – High precision

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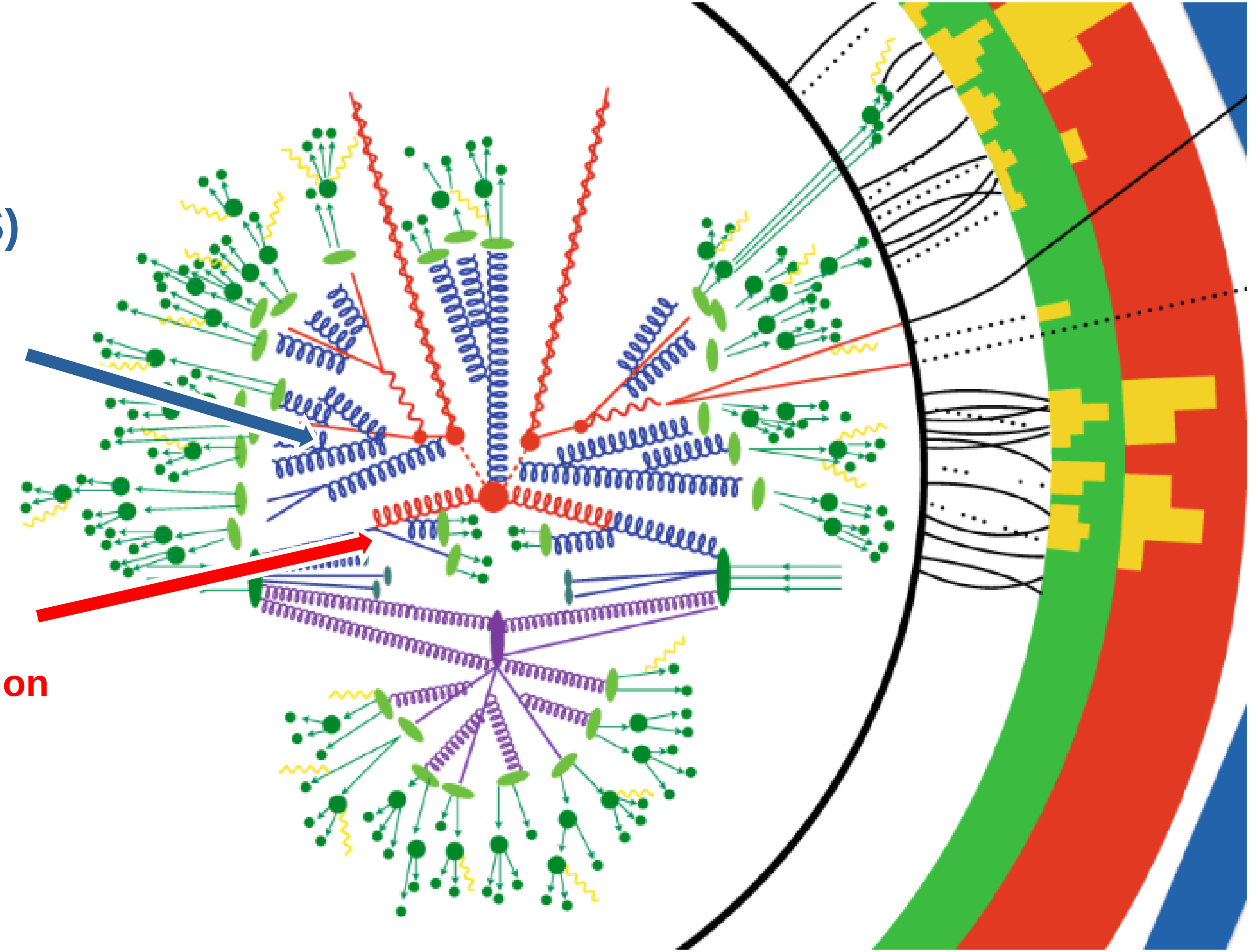

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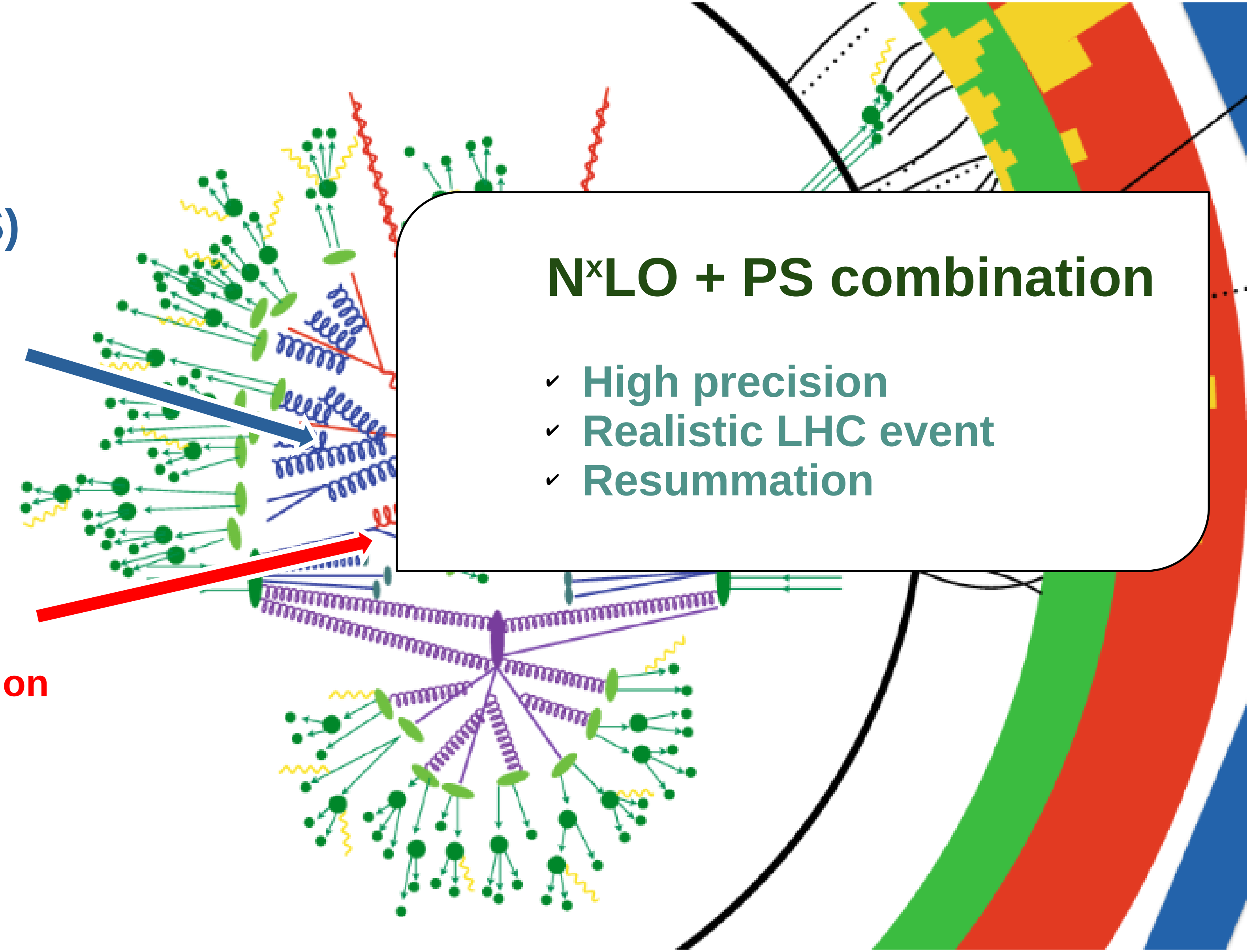

N^{x}LO + PS combination

- ✓ High precision
- ✓ Realistic LHC event
- ✓ Resummation

Events at the LHC

Parton shower (PS)

- Realistic LHC event
- Resummation

Shower Monte Carlo (SMC)

Hard process

- N^{x}LO – High precision

Fixed order perturbation theory

N^{x}LO + PS combination

- ✓ High precision
- ✓ Realistic LHC event
- ✓ Resummation

Current frontier : NNLO+PS accuracy

NNLO+PS | Methods

- **NNLOPS: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$_{PS}$

(embedded in **POWHEG** ([P. Nason (0409146)]) method)

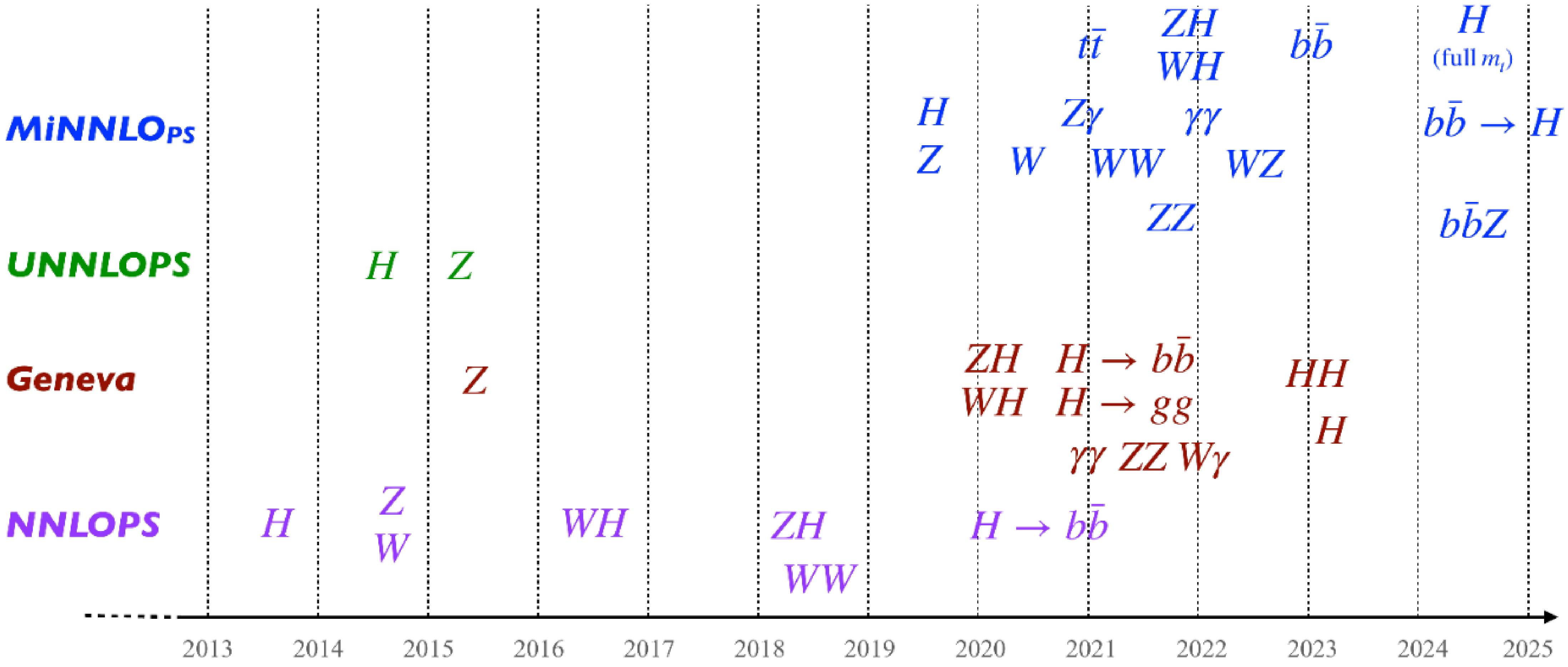
2->1 : [Monni, Nason, Re, Wisemann, Zanderighi (1908.06987)]
[Monni, Re, Wiesemann (2006.04133)]

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

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

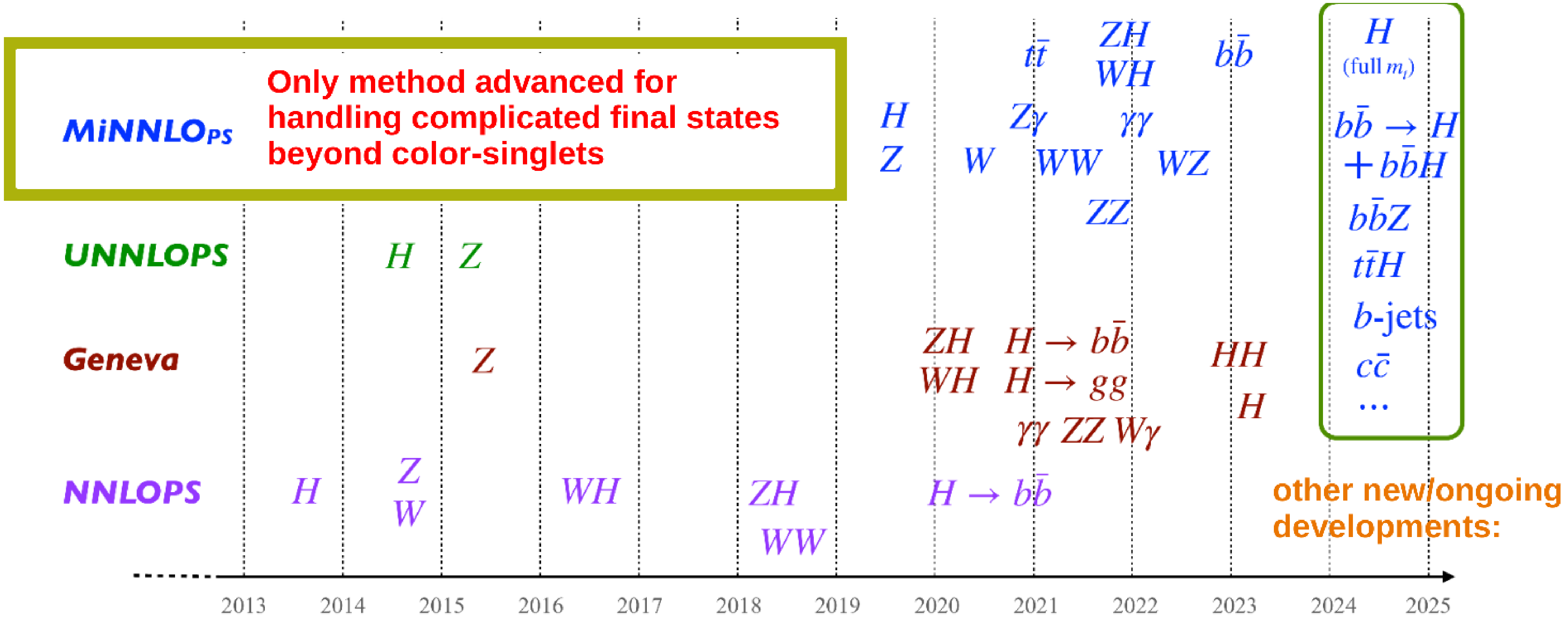
$b\bar{b}Z$: [Mazzitelli, Sotnikov, Wiesemann (2404.08598)]

NNLO+PS timeline



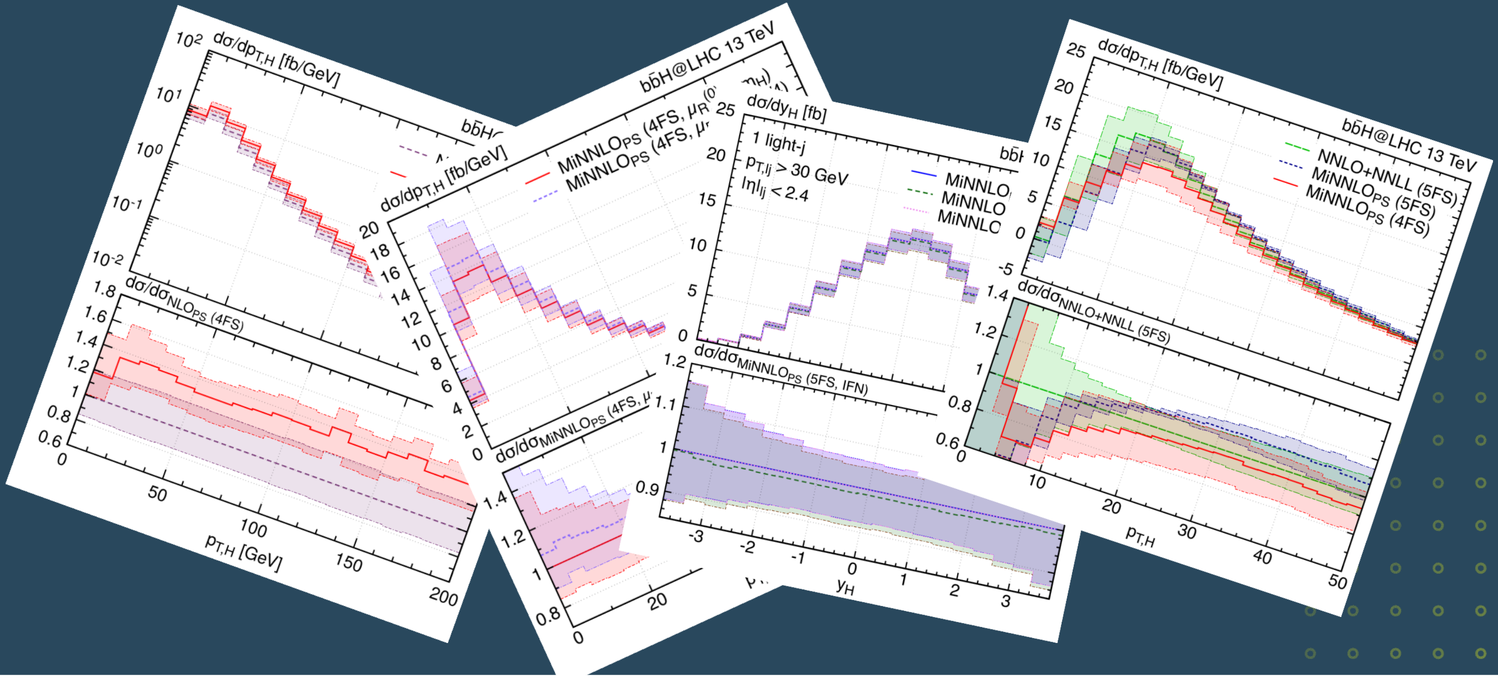
Slide from M. Wiesemann ATLAS-Subgroup Meeting 2024

NNLO+PS timeline



Slide from M. Wiesemann ATLAS-Subgroup Meeting 2024

$b\bar{b}H$ | Results



Flavour-scheme comparison

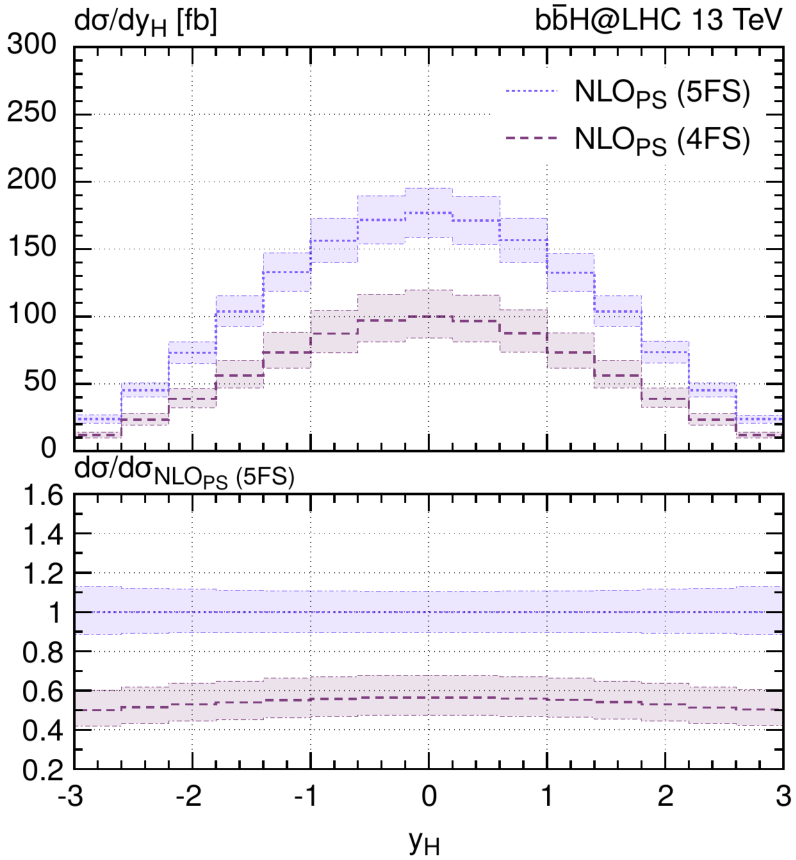
Setup
PDF: NNLO NNPDF4.0 set
Central scales: $\mu_R = \mu_F = m_H$

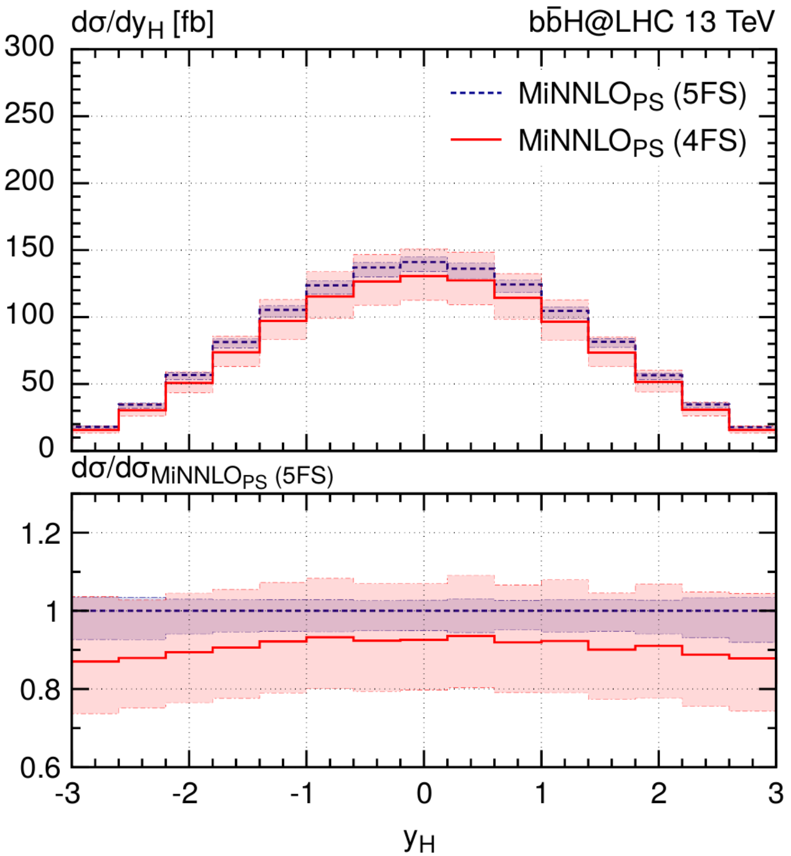
- **NNLO** corrections in the 4FS **resolve** the long-standing **discrepancy!**

- **At NNLO QCD**, 4FS and 5FS **agree** within their scale uncertainties **without** the need of any **ad hoc scaling** factors

5FS NLO+PS	$0.645(5)^{+11\%}_{-10\%}$
4FS NLO+PS	$0.354(6)^{+20\%}_{-16\%}$

5FS MiNNLOPS	$0.509(1)^{+2.9\%}_{-5.3\%}$
4FS MiNNLOPS	$0.466(0)^{+16\%}_{-14\%}$





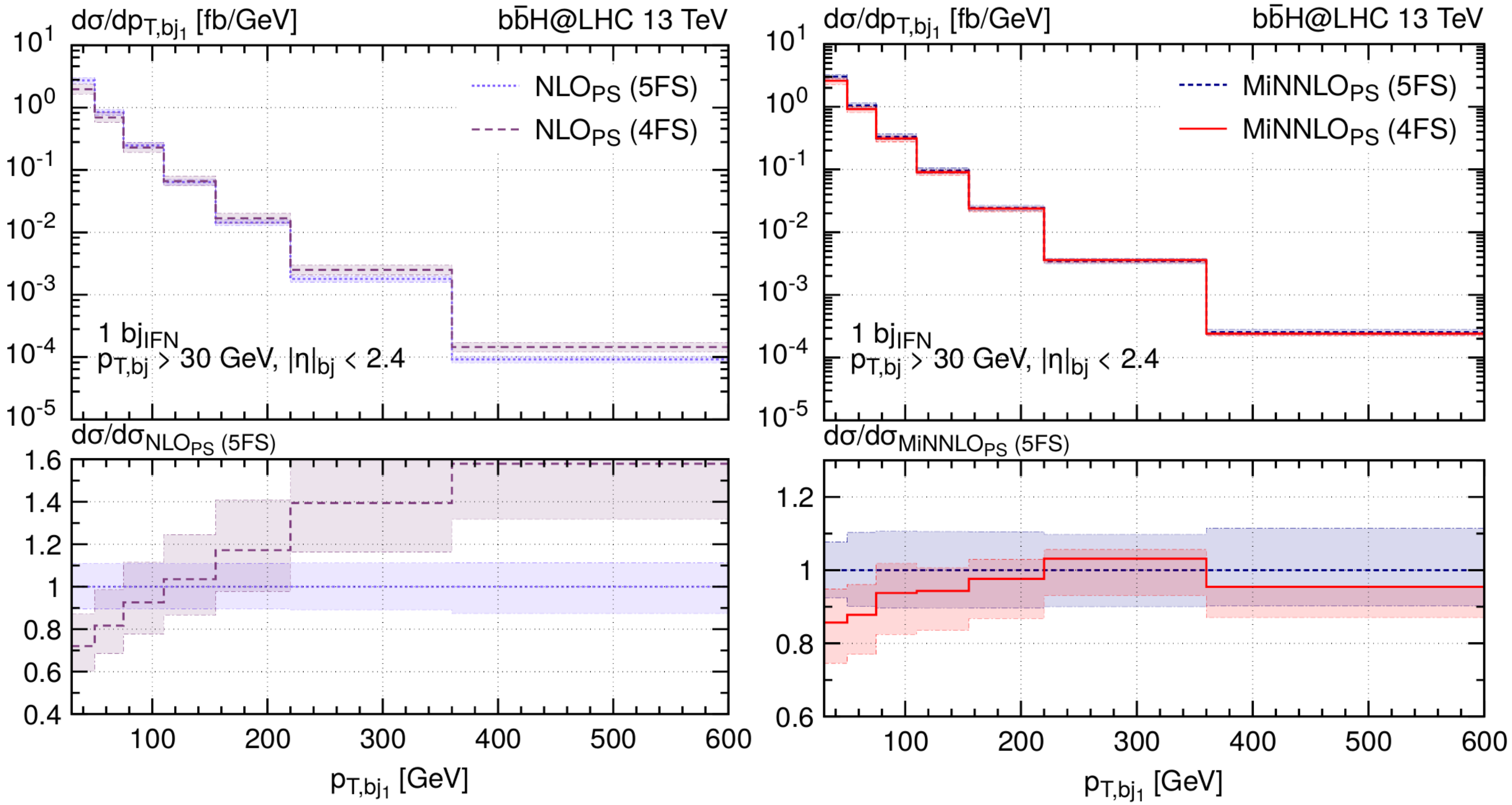
[Biello, Mazzitelli, AS, Wiesemann, Zanderighi (2412.09510)]

Flavour-scheme comparison

b-jet observables (4FS vs. 5FS) using **IRC-safe** Interleaved Flavour Neutralisation (**IFN**) tagging

IFN: [Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler (2306.07314)]

- **MiNNLO$_{PS}$** generators **significantly improve** 4FS/5FS **agreement**
- With NNLO corrections, 4FS and 5FS **shapes align** closely and have **smaller uncertainty** bands



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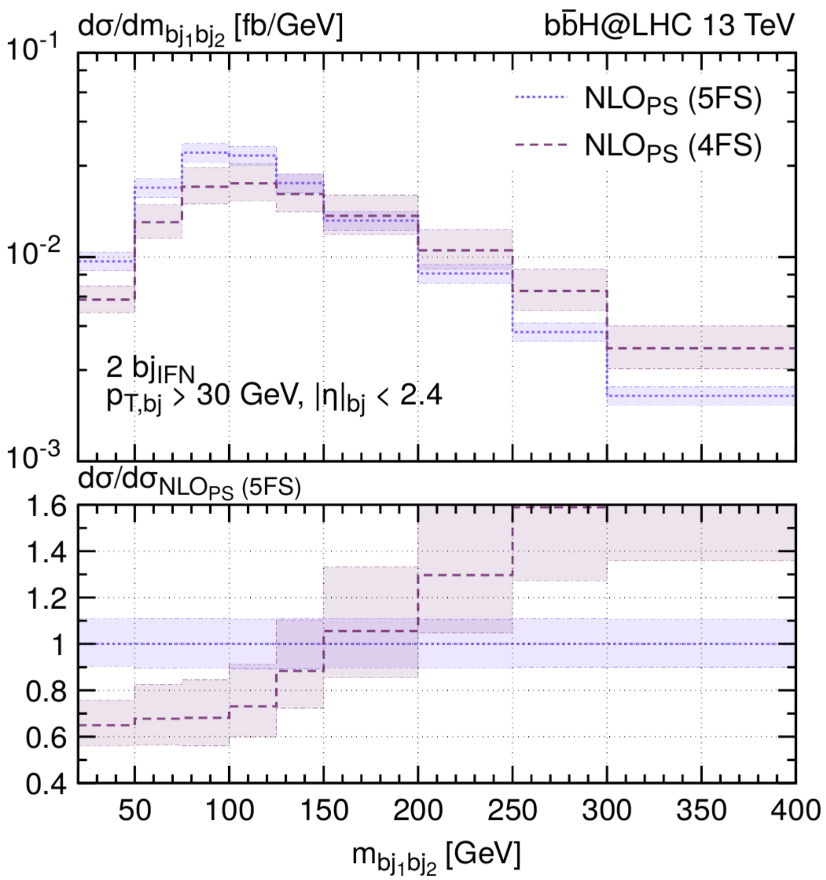
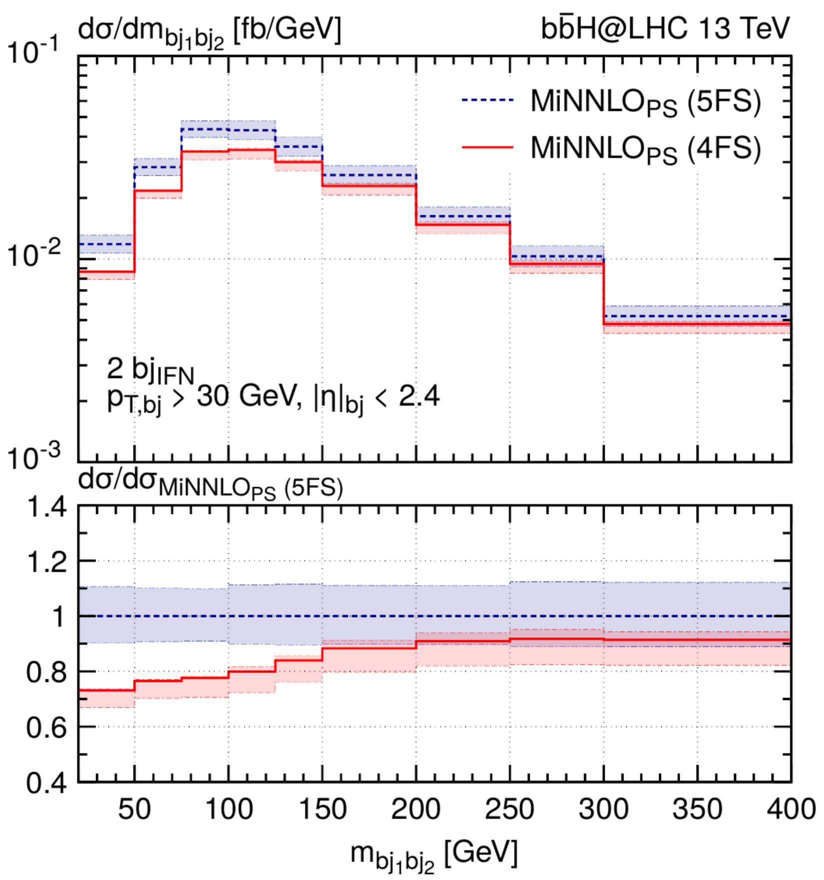
- **MiNNLO$_{PS}$** generators **improve agreement**, but below 150 GeV up to 30% differences remain outside scale bands
- **5FS** is effectively **LO+PS** (wide uncertainties) vs. **4FS NNLO+PS** (narrow uncertainties)





[Biello, Mazzitelli, AS, Wiesemann, Zanderighi (2412.09510)]

Background for HH searches in $b\bar{b}\gamma\gamma$ channel

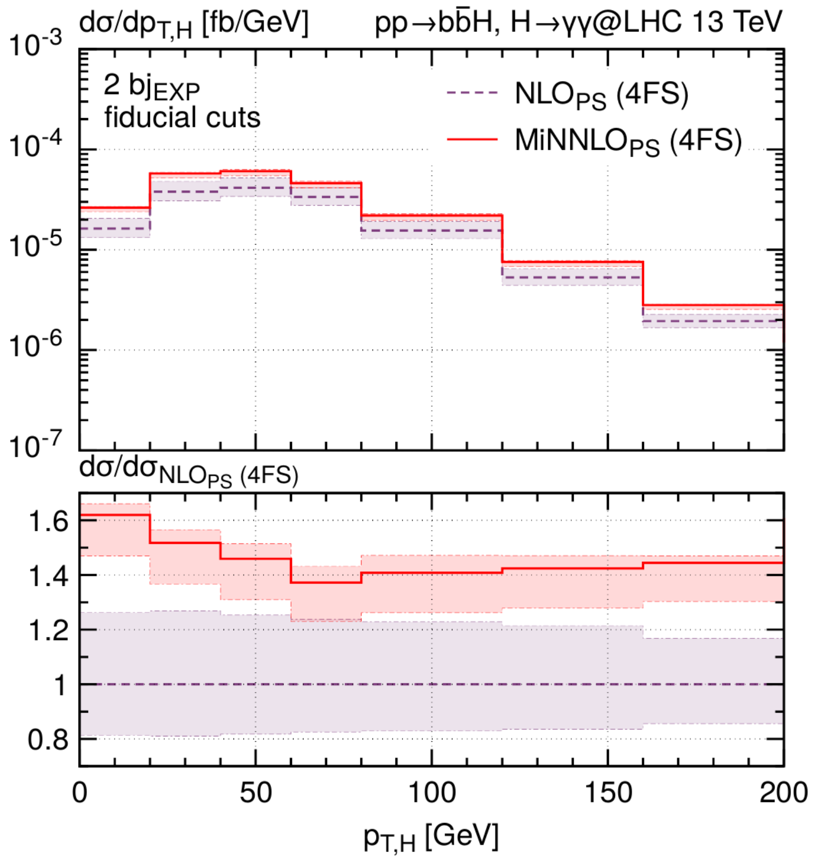
Fiducial cuts

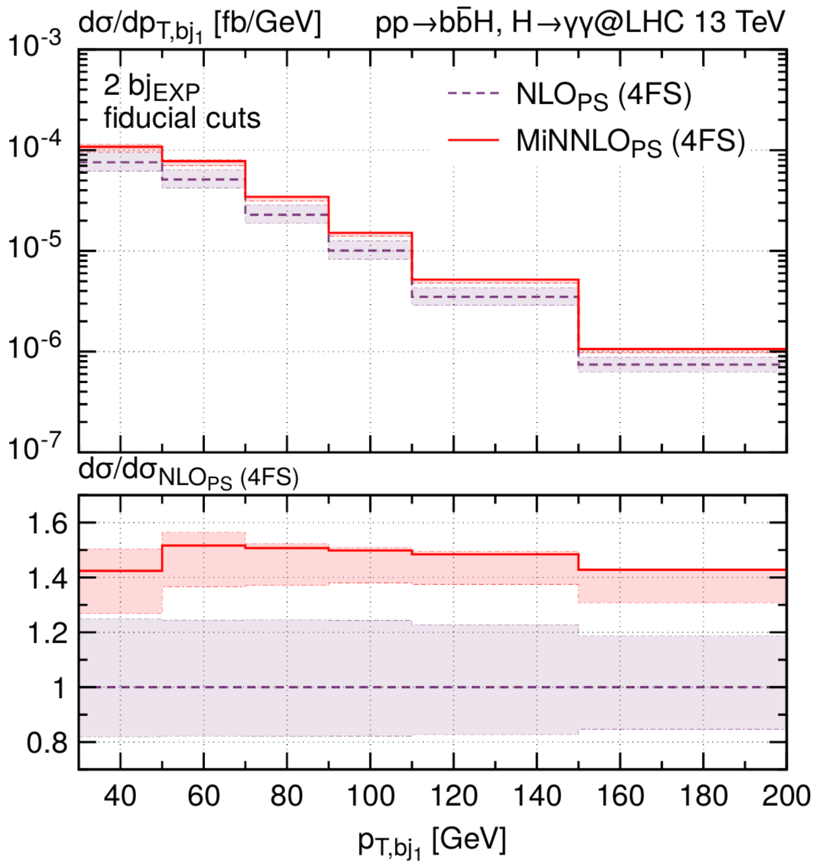
[ATLAS (2112.11876)]

$$p_T(b_i) > 25 \text{ GeV}, |\eta(b_j)| < 2.5$$
$$80 \text{ GeV} < m(b_1, b_2) < 140 \text{ GeV}$$

$$p_T(\gamma_1) > 0.35\, m(\gamma_1, \gamma_2)$$
$$p_T(\gamma_2) > 0.25\, m(\gamma_1, \gamma_2)$$
$$|\eta(\gamma_i)| < 2.37$$
$$105 \text{ GeV} < m(\gamma_1, \gamma_2) < 160 \text{ GeV}$$

- Anti-k_t jet clustering (R=0.4) with experimental **(EXP) b-tagging** criteria





- At **NNLO+PS**, positive corrections and **substantial reduction** in scale **uncertainties**.

[Biello, Mazzitelli, AS, Wiesemann, Zanderighi (2412.09510)]

5FS + 4FS combination

Only fully-inclusive matched results are known for $b\bar{b}H$ in different schemes to date:

- **Santander matching** [Harlander, Kramer, Schumacher (1112.3478)]
  - Uses a weighted average based on the logarithm of the ratio mH/mb
  - Now outdated
- **FONLL matching** [Forte, Napoletano, Ubiali (1508.01529, 1607.00389)]
  - Now applied @ N3LO(5FS)+NLO(4FS) [Duhr, Dulat, Hirschi, Mistlberger (2004.04752)]
- **NLO+NNLLpart+ybyt matching**

  [Bonvini, Papanastasiou, Tackmann (1508.03288, 1605.01733)]

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Rely on a systematic **expansion** of the **4FS parameters** and **PDFs** in the **5FS** ones and **different methods** to merge both schemes **to avoid double-counting** of common contributions.

Combining 5FS & 4FS (ongoing work)

Aim : First fully differential level flavour-scheme matching for $b\bar{b}H$ production

- **Methods**
  - **Power corrections isolation (PCI) method** [R. Gauld (2107.01226)]

    A massive variable flavour number scheme with **numerical extraction of power corrections**

$$\mathrm{d}\sigma^{M} = \mathrm{d}\sigma^{m=0,n_f} + \mathrm{d}\sigma^{\ln(m)} + \mathrm{d}\sigma^{pc}$$

Massive contributions	nf dependent massless contributions	Logarithmic contributions	Power correction contributions

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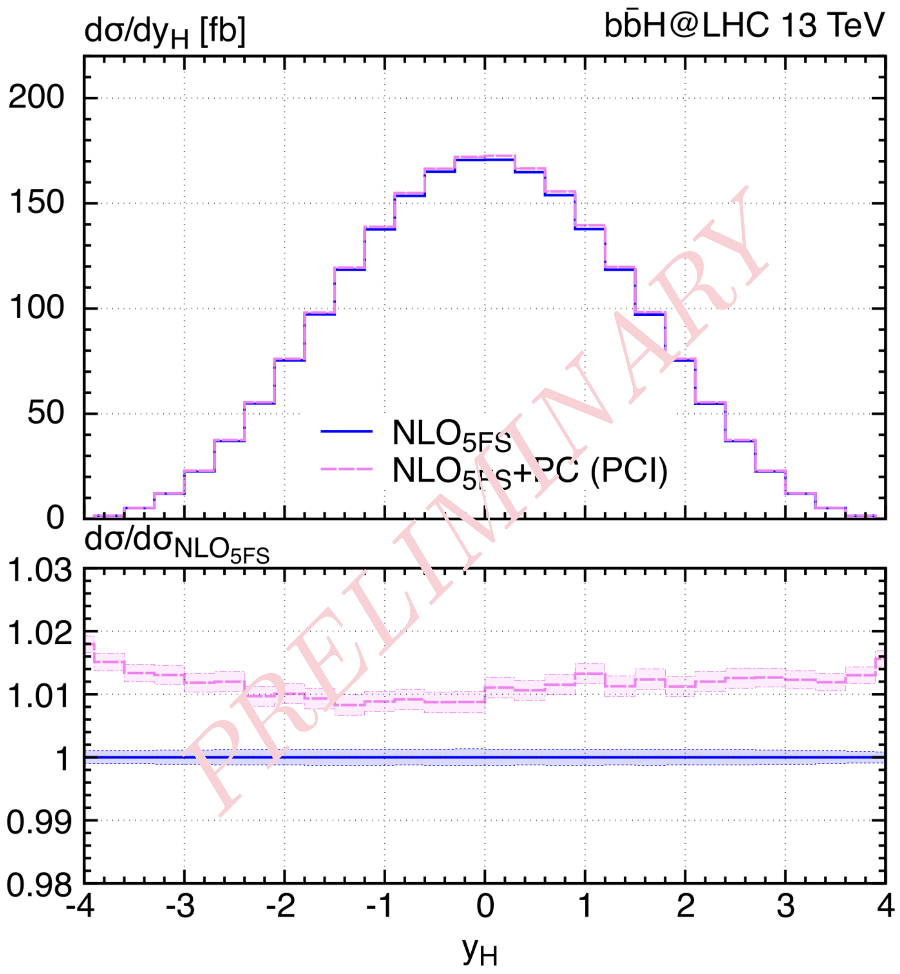
Massive contributions	nf dependent massless contributions	Logarithmic contributions	Power correction contributions

Combine the massless 5FS result—which resums logarithms—with the **power corrections** to form the PCI matching formula:

$$\mathrm{d}\sigma^{\mathrm{PCI}} = \mathrm{d}\sigma^{m=0} + \mathrm{d}\sigma^{pc}$$

PCI results at first order

Higgs boson rapidity



- **Power-suppressed** terms shift the NLO-5FS prediction by ≈ **1–2 %**, with **no visible shape distortion.**

Biello, Gauld, AS, Wiesemann, Zanderighi [in progress]

Simplified-ACOT (S-ACOT) method

[Guzzi, Nadolsky, Reina, Wackeroth, Xie (2410.03876)]

- Split into two channels:
  - **Flavour creation (FC)**: genuine 4FS diagrams, full **heavy-quark mass** dependence
  - **Flavour excitation (FE)**: bottom-initiated legs, **resums collinear logs**
  - **Subtract overlap** by removing FC computed with a perturbatively **subtracted bottom PDF** (fixed-order collinear logs)

$$\sigma^{\text{sACOT}} = \sigma^{\text{FC}} + \sigma^{\text{FE}} - \sigma^{\text{sub}}$$

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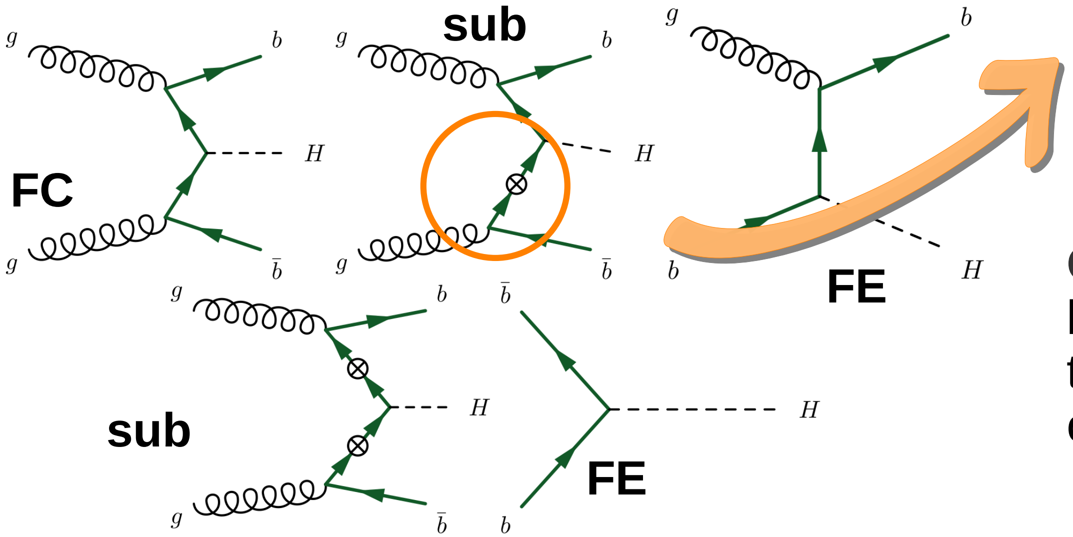
Diagramatically at first order:



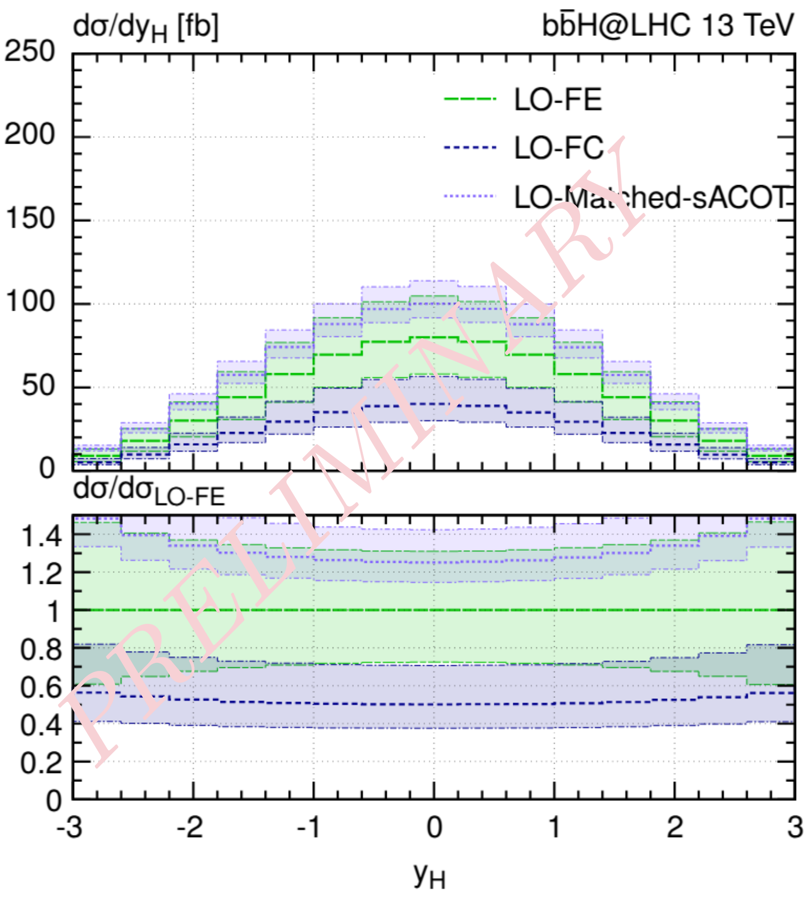
Insertion of bottom subtraction PDF

$$\tilde{f}_{\mathrm{b}}^{(1)} = a_s [A_{\mathrm{bg}}^{(1)} \lhd g]$$

Operator Matrix Elements (OMEs): kernels for $g \to b\bar{b}$ splitting that build the b-PDF from the g-PDF and encode collinear logs

S-ACOT results at first order

Higgs boson rapidity



- The **LO matched** curve is systematically **higher** than either **pure FC or FE**, it captures both production mechanisms while removing only the smaller double-counted region.
- Further, the **shape of the matched** distribution **remains consistent** with the individual FC and FE spectra.

Biello, Gauld, Guzzi, Nadolsky, AS, Wiesemann, Xie, Zanderighi [in progress]

Conclusions

- Presented the **first fully differential** predictions for **$b\bar{b}$H** process in **5FS and 4FS** at **NNLO+PS** using the **MiNNLO$_{PS}$** method

- The **novel NNLO** corrections in the **4FS resolves** the long-standing **4FS–5FS discrepancy**

- The **MiNNLO$_{PS}$ – 4FS** generator is **essential** for **accurate b-jet** observables, enabling **direct comparison** with **b-tagged** measurements.

- Presented two **different methods** (power correction isolation & simplified-ACOT matching) to **combine 5FS and 4FS** predictions.

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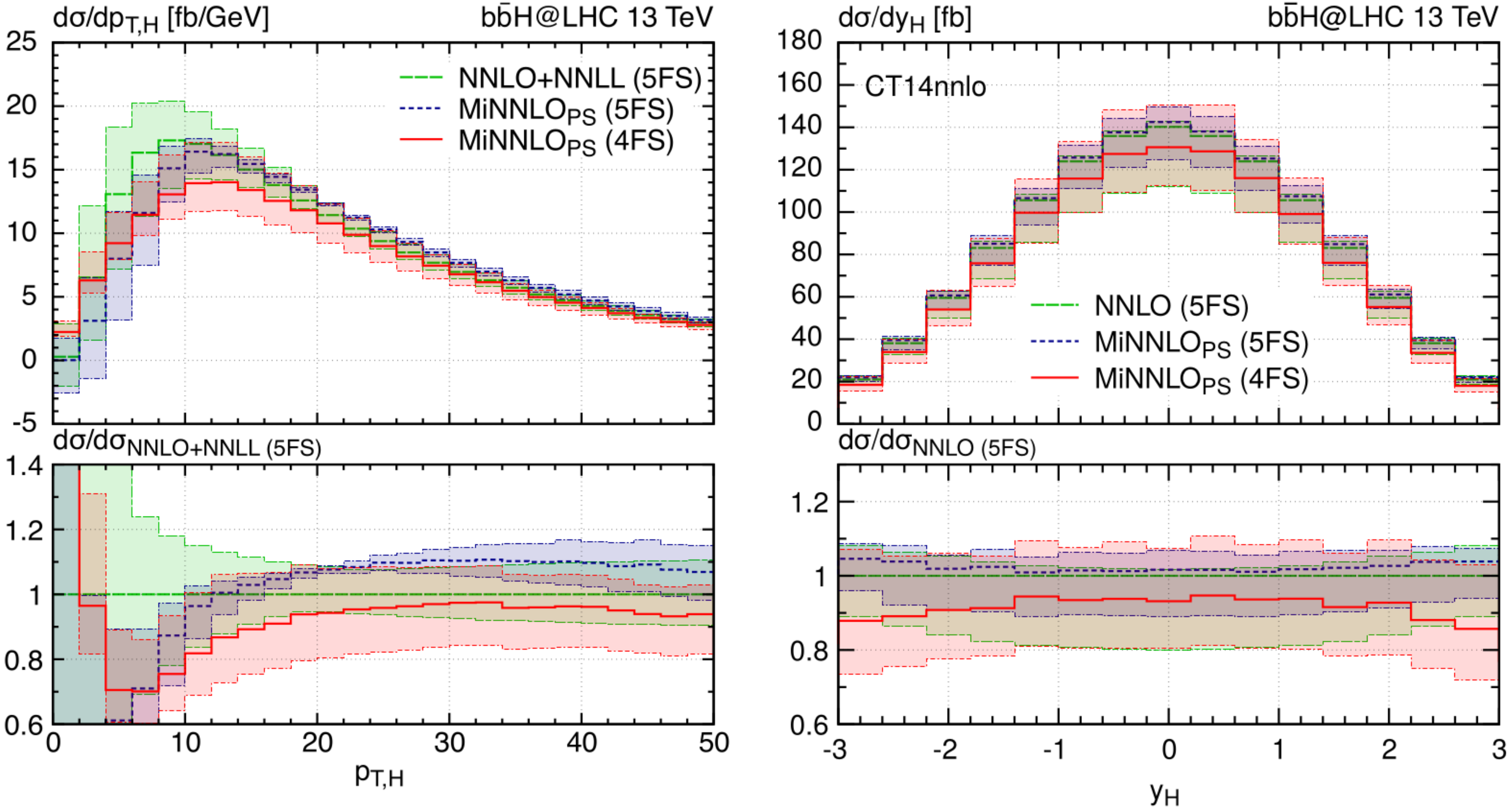
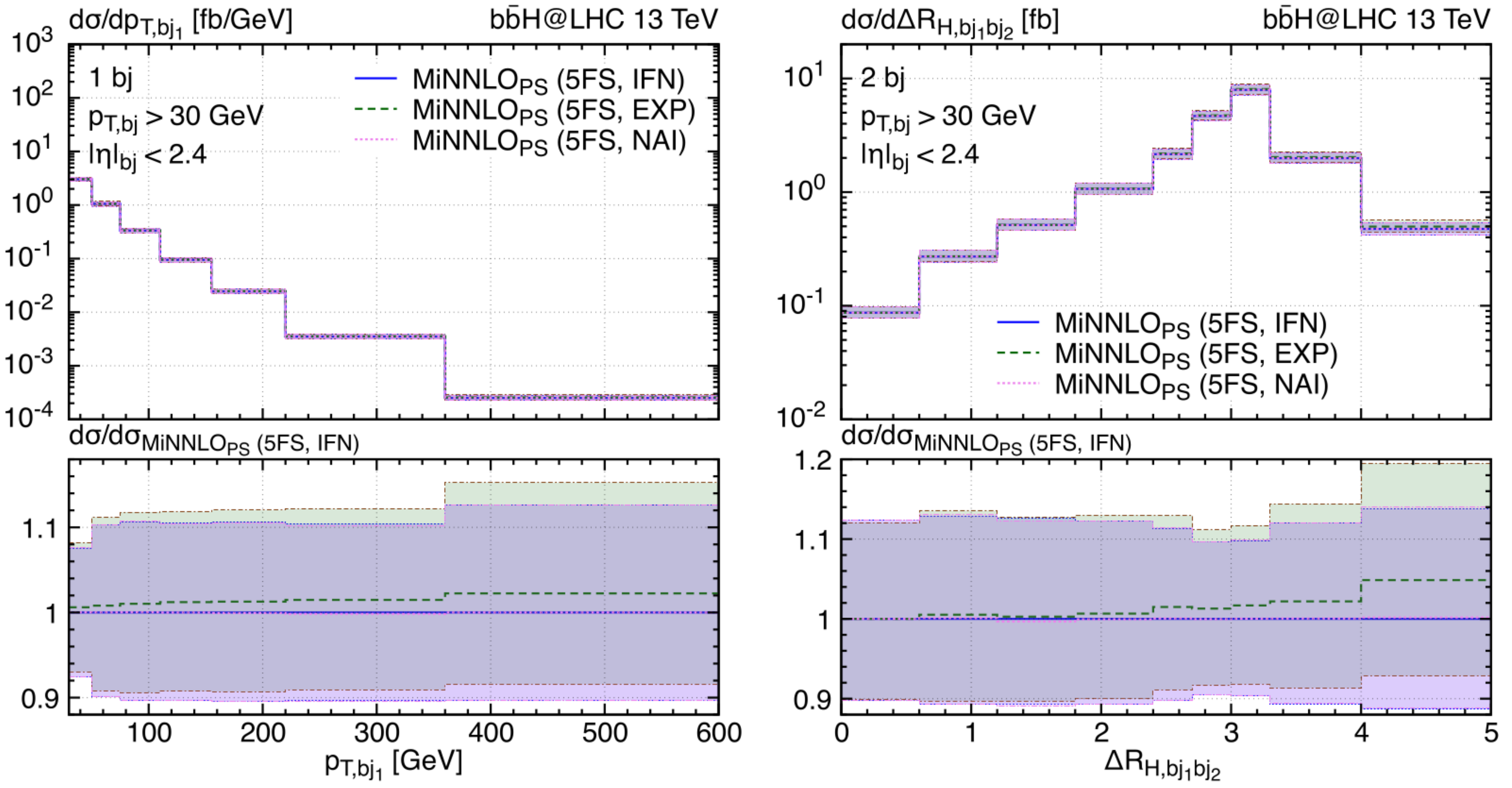
Thank You!

Backup slides


dσ/dp_T,H [fb/GeV]
bb̄H@LHC 13 TeV
NNLO+NNLL (5FS)
MiNNLO_PS (5FS)
MiNNLO_PS (4FS)
dσ/dσ_NNLO+NNLL (5FS)
p_T,H
dσ/dy_H [fb]
bb̄H@LHC 13 TeV
CT14nnlo
NNLO (5FS)
MiNNLO_PS (5FS)
MiNNLO_PS (4FS)
dσ/dσ_NNLO (5FS)
y_H


dσ/dp_T,bj1 [fb/GeV]
bb̄H@LHC 13 TeV
1 bj
p_T,bj > 30 GeV
|η|_bj < 2.4
MiNNLO_PS (5FS, IFN)
MiNNLO_PS (5FS, EXP)
MiNNLO_PS (5FS, NAI)
dσ/dσ_MiNNLO_PS (5FS, IFN)
p_T,bj1 [GeV]
dσ/dΔR_H,bj1bj2 [fb]
bb̄H@LHC 13 TeV
2 bj
p_T,bj > 30 GeV
|η|_bj < 2.4
MiNNLO_PS (5FS, IFN)
MiNNLO_PS (5FS, EXP)
MiNNLO_PS (5FS, NAI)
dσ/dσ_MiNNLO_PS (5FS, IFN)
ΔR_H,bj1bj2