MAX-PLANCK-INSTITUT
FÜR PHYSIK

Recent Event Simulations for Higgs processes at NNLO+PS

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Garching, Munich, Germany

Standard Model at the LHC 2025
Durham, UK
April 9th, 2025

LHC event

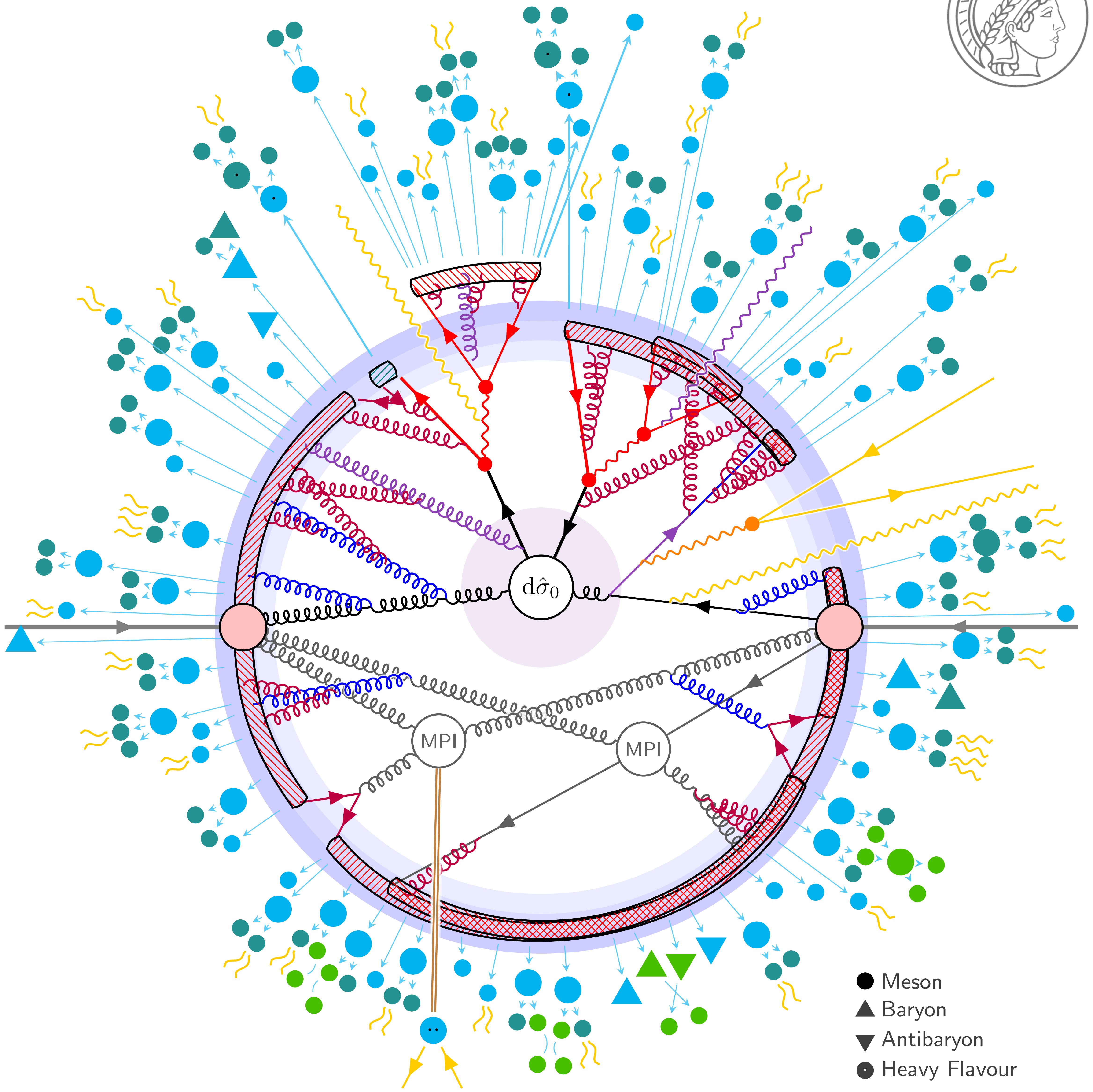

Image credit: PYTHIA 8.3 [2203.11601]

LHC event

α_s^3 N^3LO

α_s^2 $NNLO$

α_s^1 NLO

α_s^0 LO

Hard Process N^xLO

☑ High precision

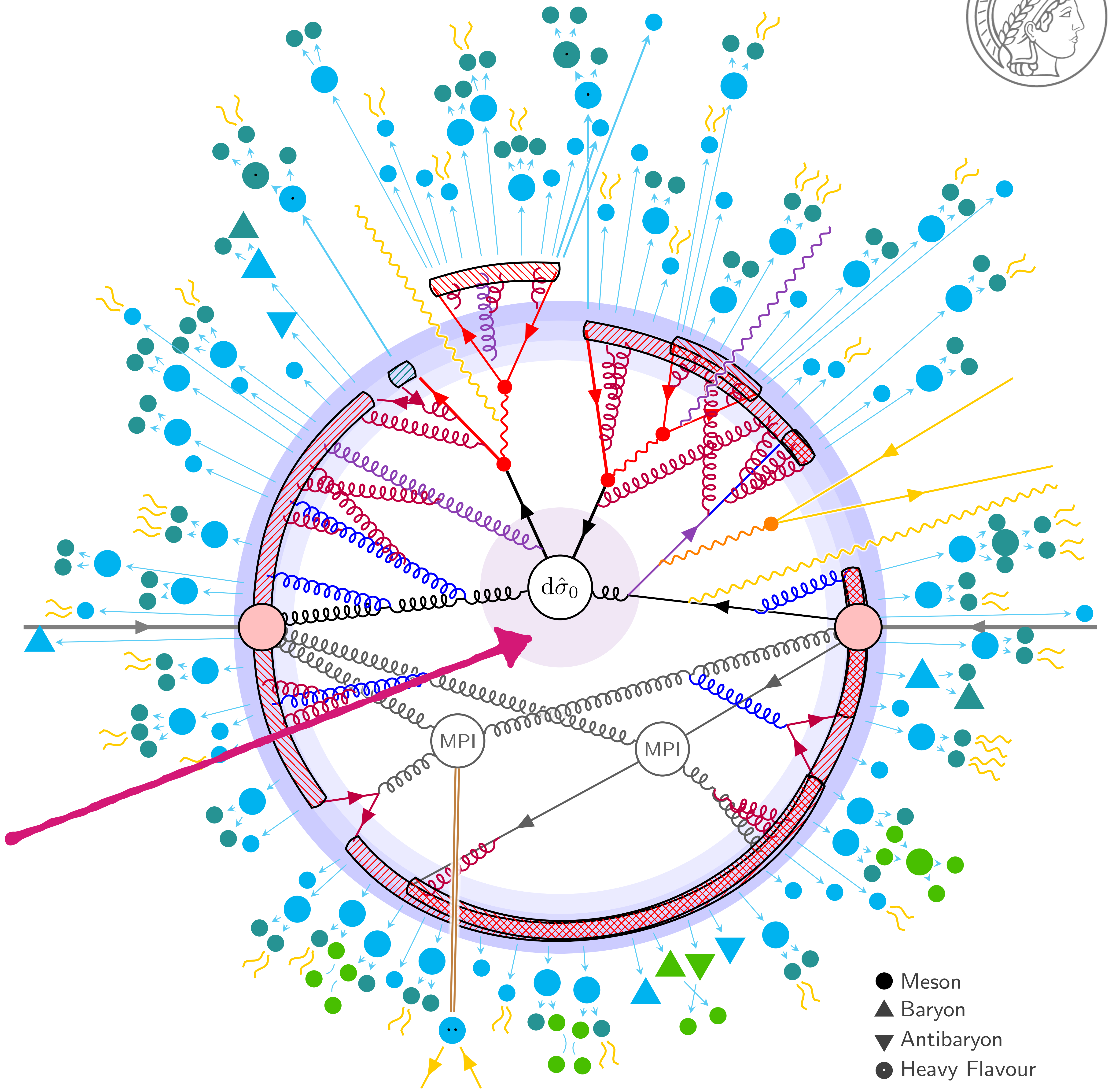

Image credit: PYTHIA 8.3 [2203.11601]

LHC event

$\alpha_s^n \log^{n-1}$ — $NNLL$

$\alpha_s^n \log^n$ — NLL

$\alpha_s^n \log^{n+1}$ — LL

α_s^3 — N^3LO

α_s^2 — $NNLO$

α_s^1 — NLO

α_s^0 — LO

Parton shower PS_{N^yLL} and hadronisation

- ☑ Realistic description
- ☑ N^yLL resummation

Hard Process N^xLO

- ☑ High precision

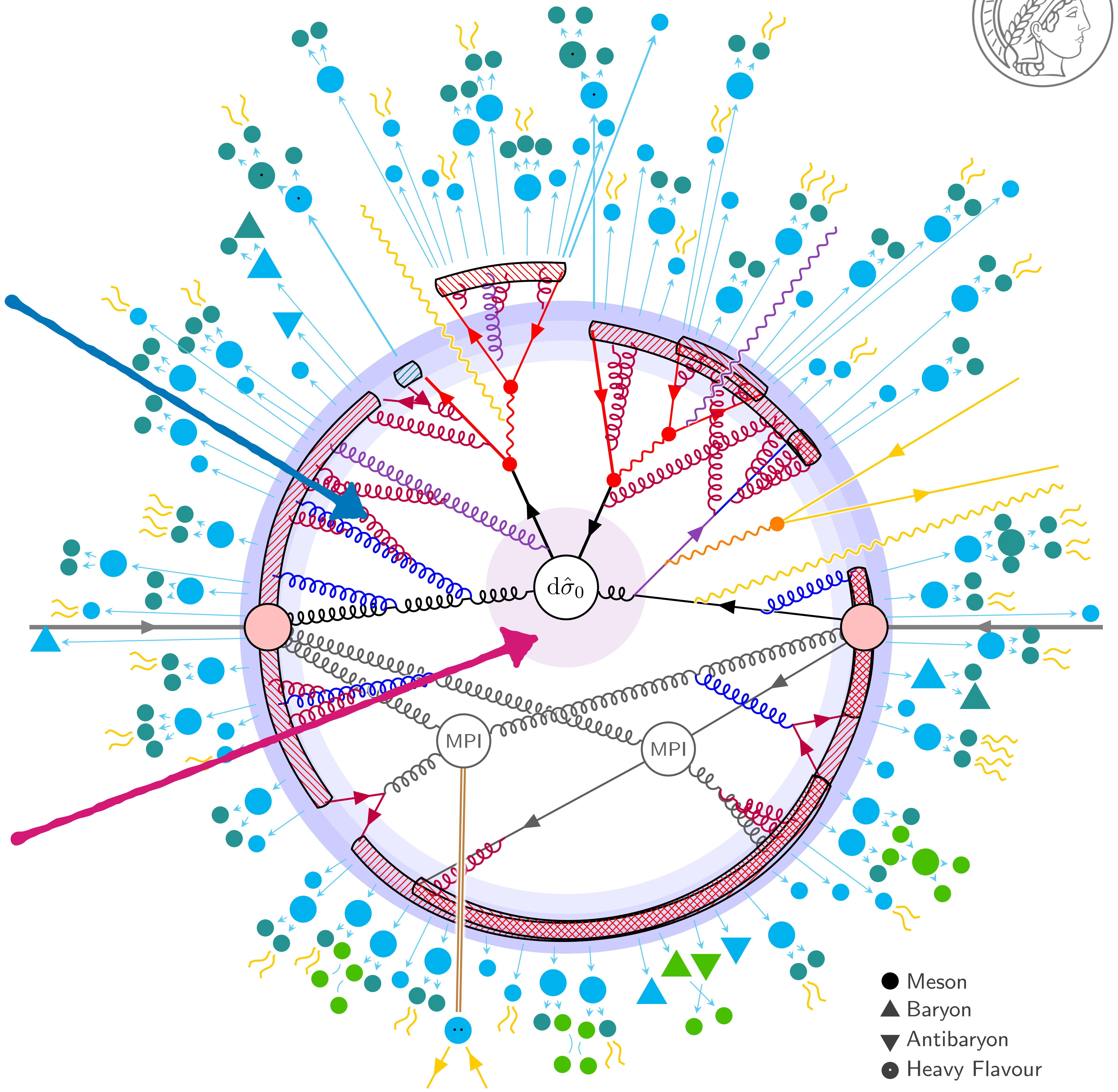

Image credit: PYTHIA 8.3 [2203.11601]

LHC event

$\alpha_s^n \log^{n-1}$ — *NNLL*

$\alpha_s^n \log^{n}$ — *NLL*

$\alpha_s^n \log^{n+1}$ — *LL*

α_s^3 — N^3LO

α_s^2 — *NNLO*

α_s^1 — *NLO*

α_s^0 — *LO*

Parton shower PS_{N^yLL} and hadronisation

- ☑ Realistic description
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- ☑ High precision

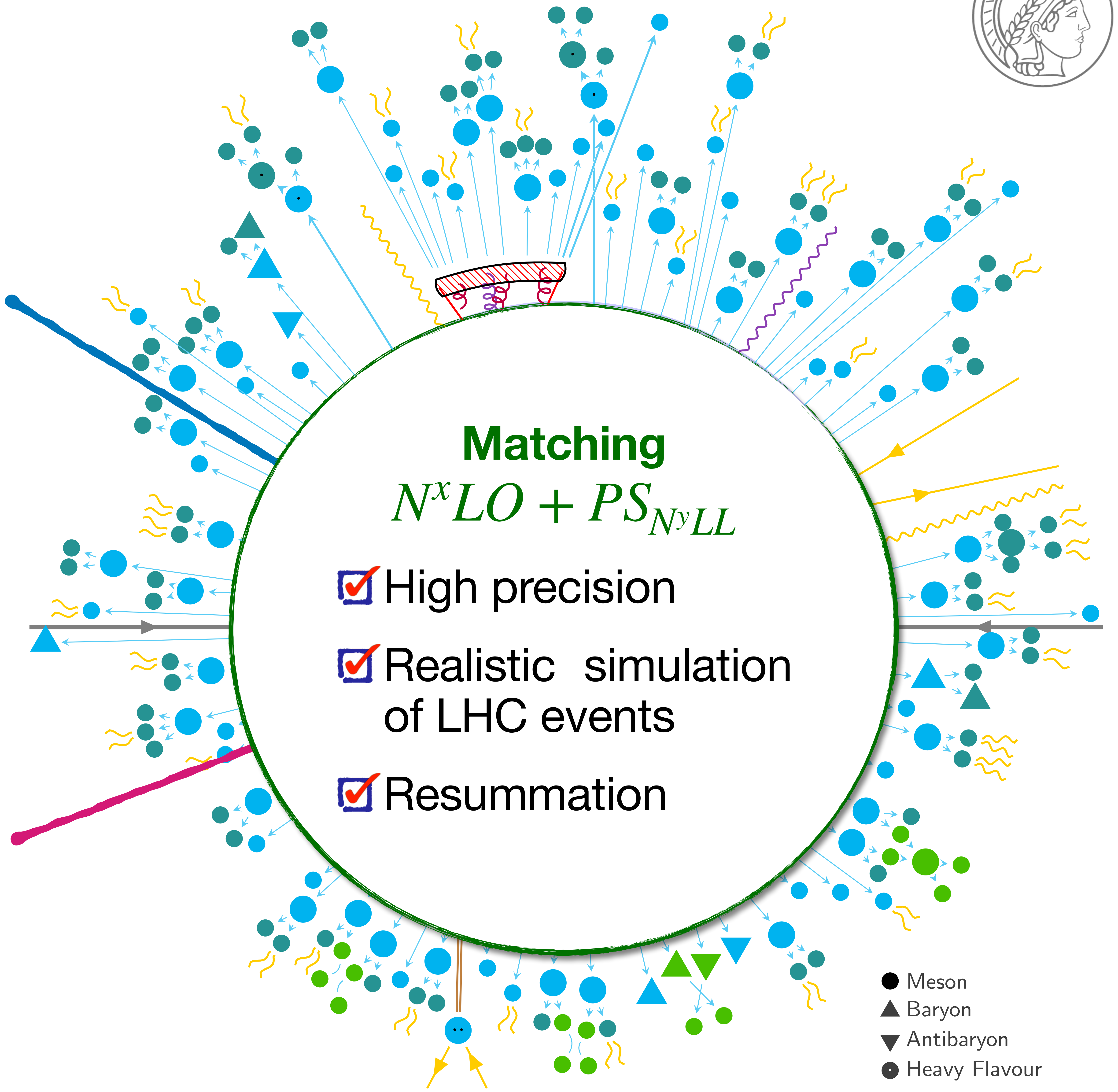


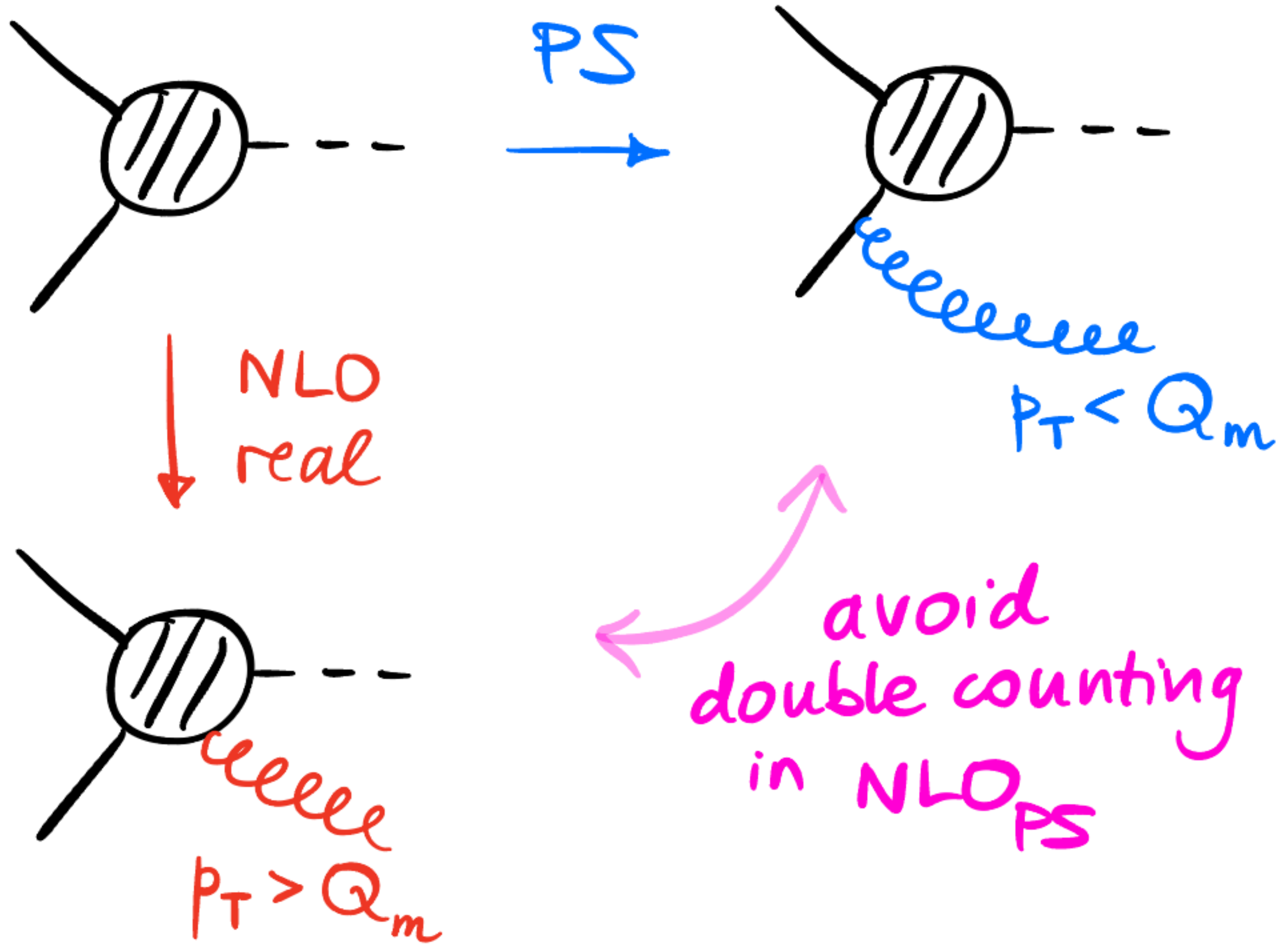
Image credit: PYTHIA 8.3 [2203.11601]

NLO+PS_{LL}

Solved problem for long time.
Completely understood and fully automated.

Two main approaches:

- **POWHEG** [0409146, 0709.2092, 1002.2581]
- **MC@NLO** [0204244]



Problem: Match fixed-order predictions with Parton Shower avoiding an unphysical matching scale.

POWHEG idea: implement a Monte Carlo generator that produces just one emission (the hardest one) which alone gives the correct NLO result.

Nason [hep-ph/0409146]

NNLO+PS$_{LL}$

State-of-the-art for precision LHC phenomenology.

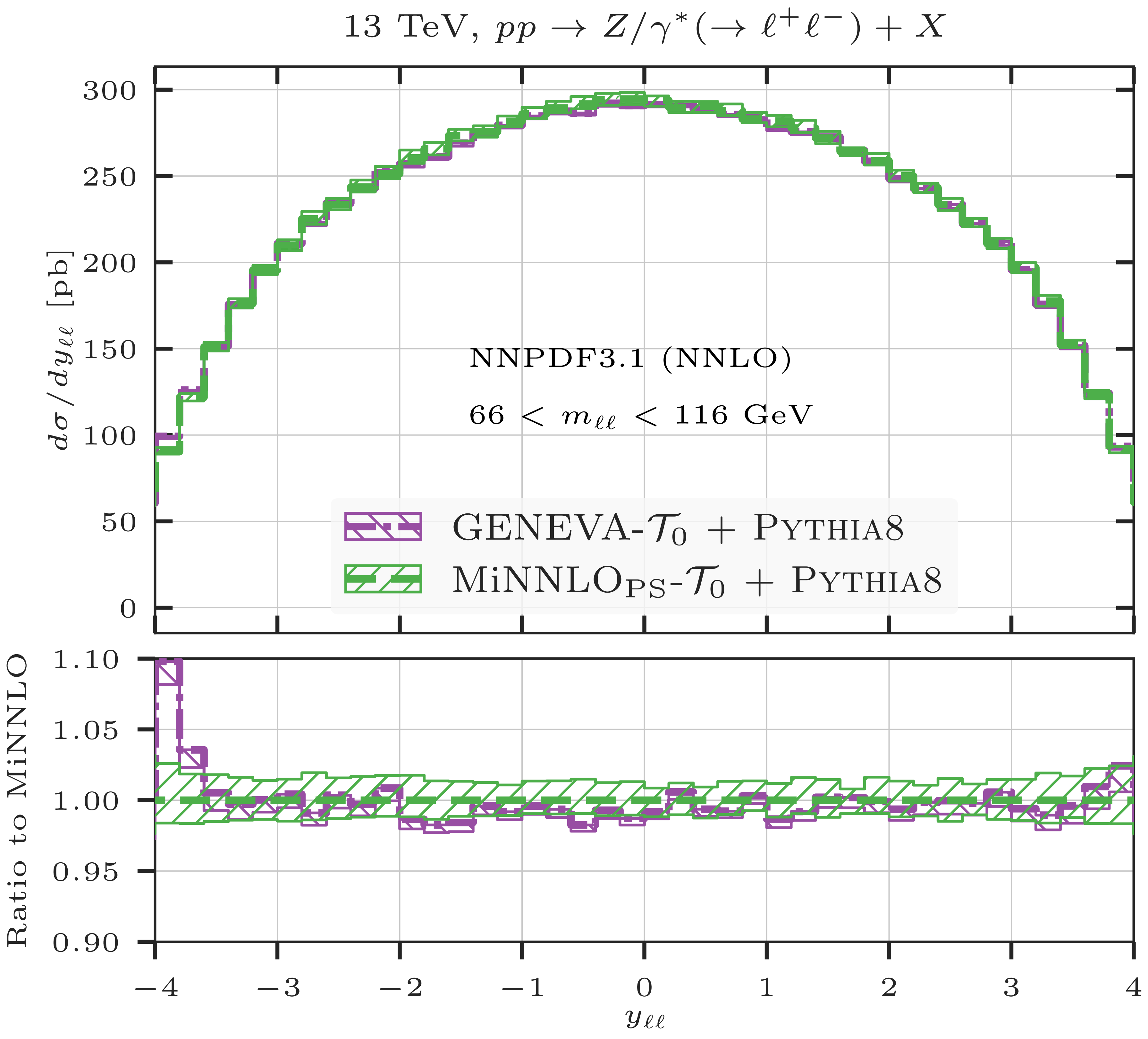
Lots of ongoing efforts. **Many processes** already implemented, beyond the color-singlet production.

Two main approaches:

- **MiNNLOPS** [1908.06987]
  - A modification of MiNLO' in the POWHEG framework [1212.4504]
  - Avoid the posteriori reweithing of **NNLOPS** [1309.0017]
- **GENEVA** [1311.0286]

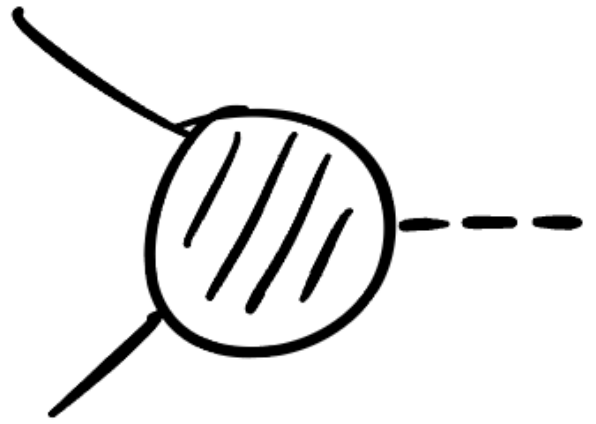
See also the work on

- **UNNLOPS** [1405.3607]
- Sector matching with Vincia [2108.07133]



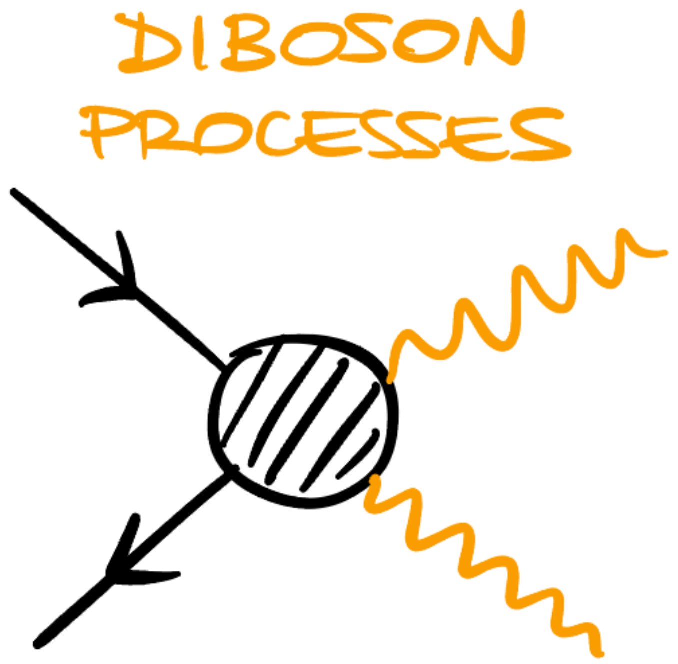
Ebert, Rottoli, Wiesemann, Zanderighi, Zanoli [2402.00596]

Classes of processes in MiNNLOPS



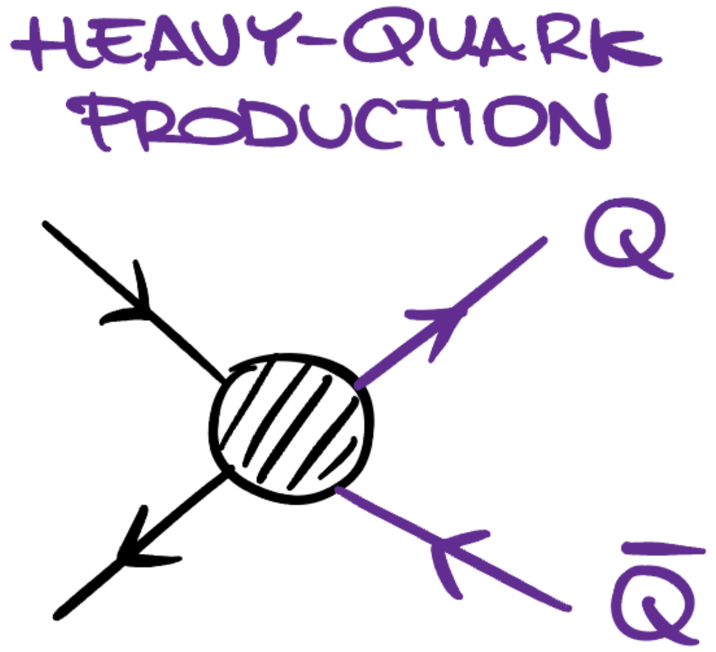
$gg \to H, W/Z$ [1908.06987, 2006.04133, 2402.00596, 2407.01354]

$b\bar{b} \to H$ [2402.04025]



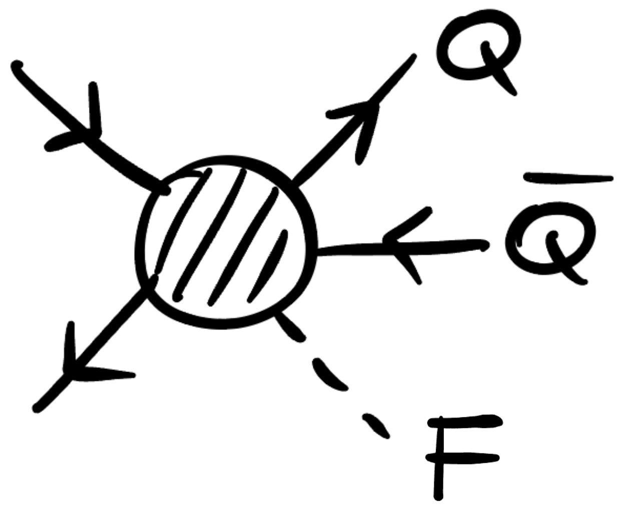
$Z\gamma$ [2010.10478, 2108.11315]
WW [2103.12077]
ZZ [2108.05337]
$WH/ZH(H \to b\bar{b})$ [2112.04168]
$\gamma\gamma$ [2204.12602]
WZ [2208.12660]
SMEFT studies [2204.00663, 2311.06107]

first (and currently only) NNLO+PS method for heavy-quark final states



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

$b\bar{b}Z$ [2404.08598]
$b\bar{b}H$ [2412.09510]



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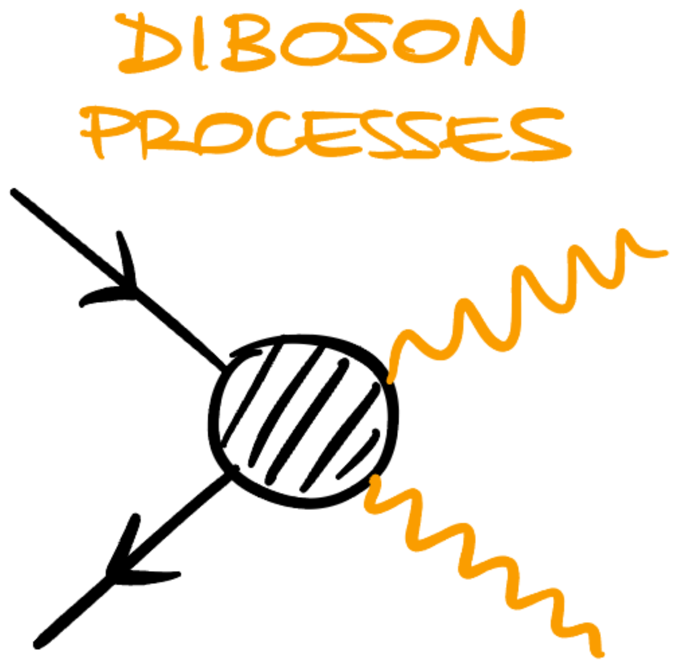

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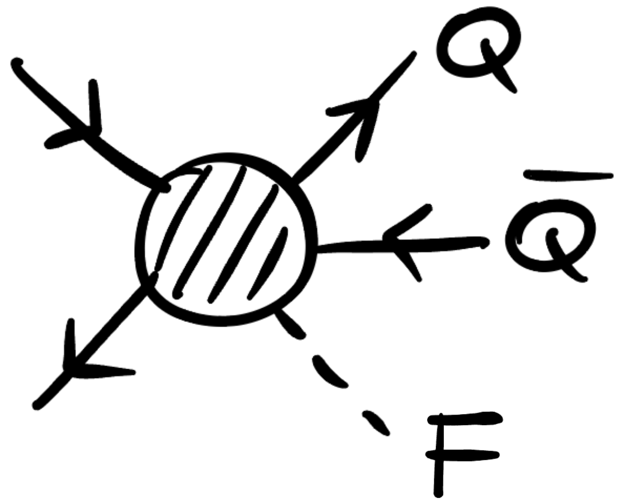

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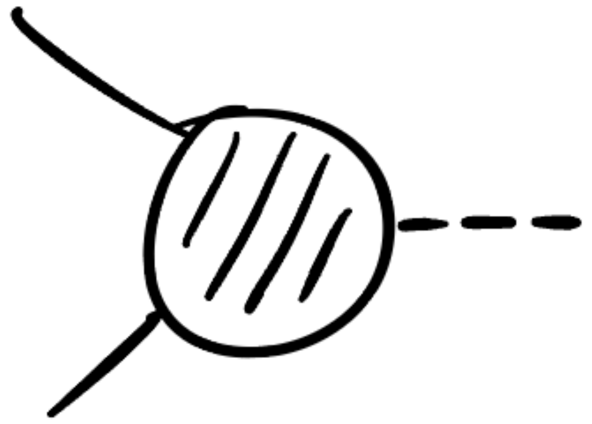

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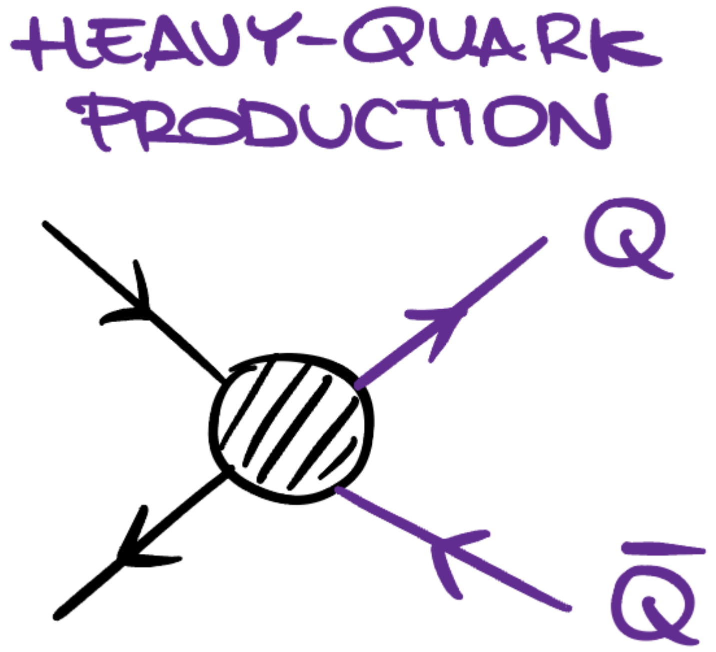


$t\bar{t}$ [2012.14267,2112.12135]
$b\bar{b}$ [2302.01645]

Higgs resent results discussed in this talk

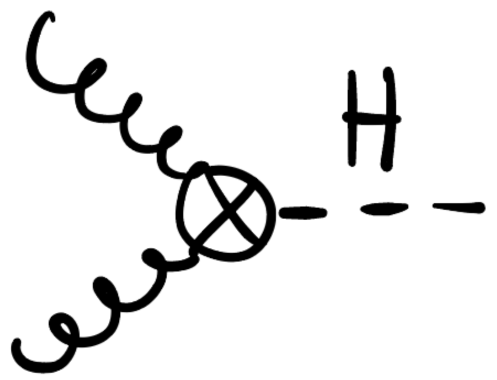
Full top dependence

ggF H

Niggetiedt, Wiesemann [2407.01354]

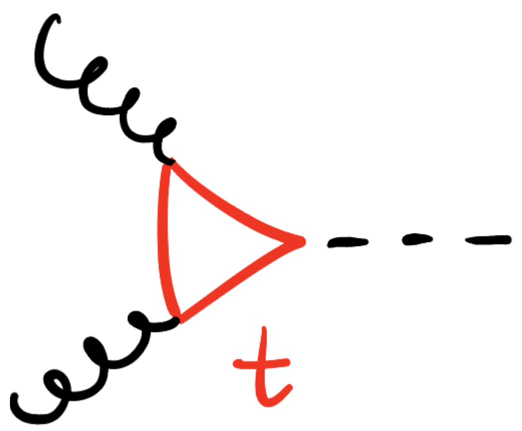
Why? Increasing precision calls for reducing theoretical uncertainty, like heavy-quark mass effects!

The Higgs production via gluon fusion with **exact top-quark mass** dependence has been recently implemented in the MiNNLOPS generator.



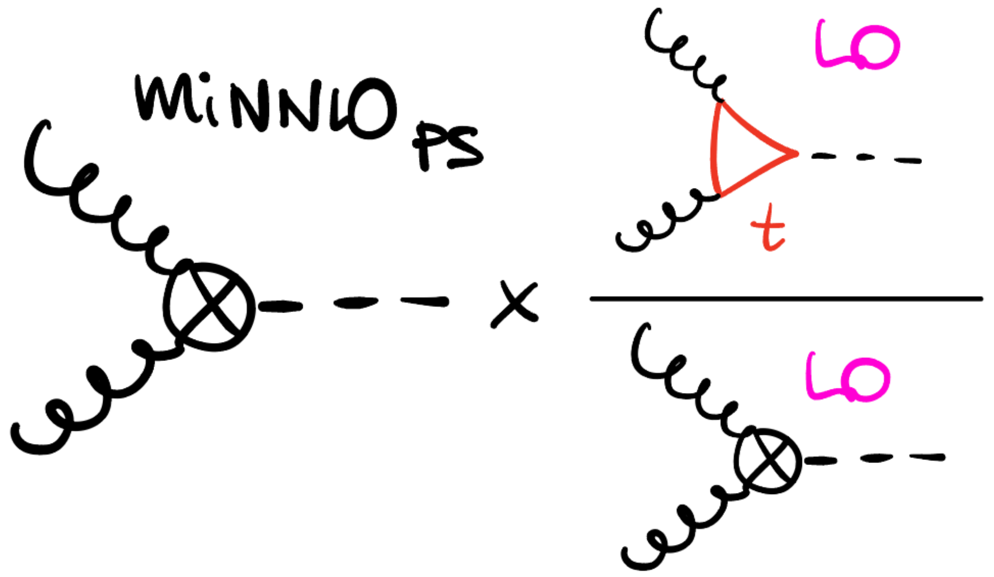
MiNNLO$_{PS}$ HTL

$$39.55(1)^{+11.0\%}_{-10.5\%}\ pb$$



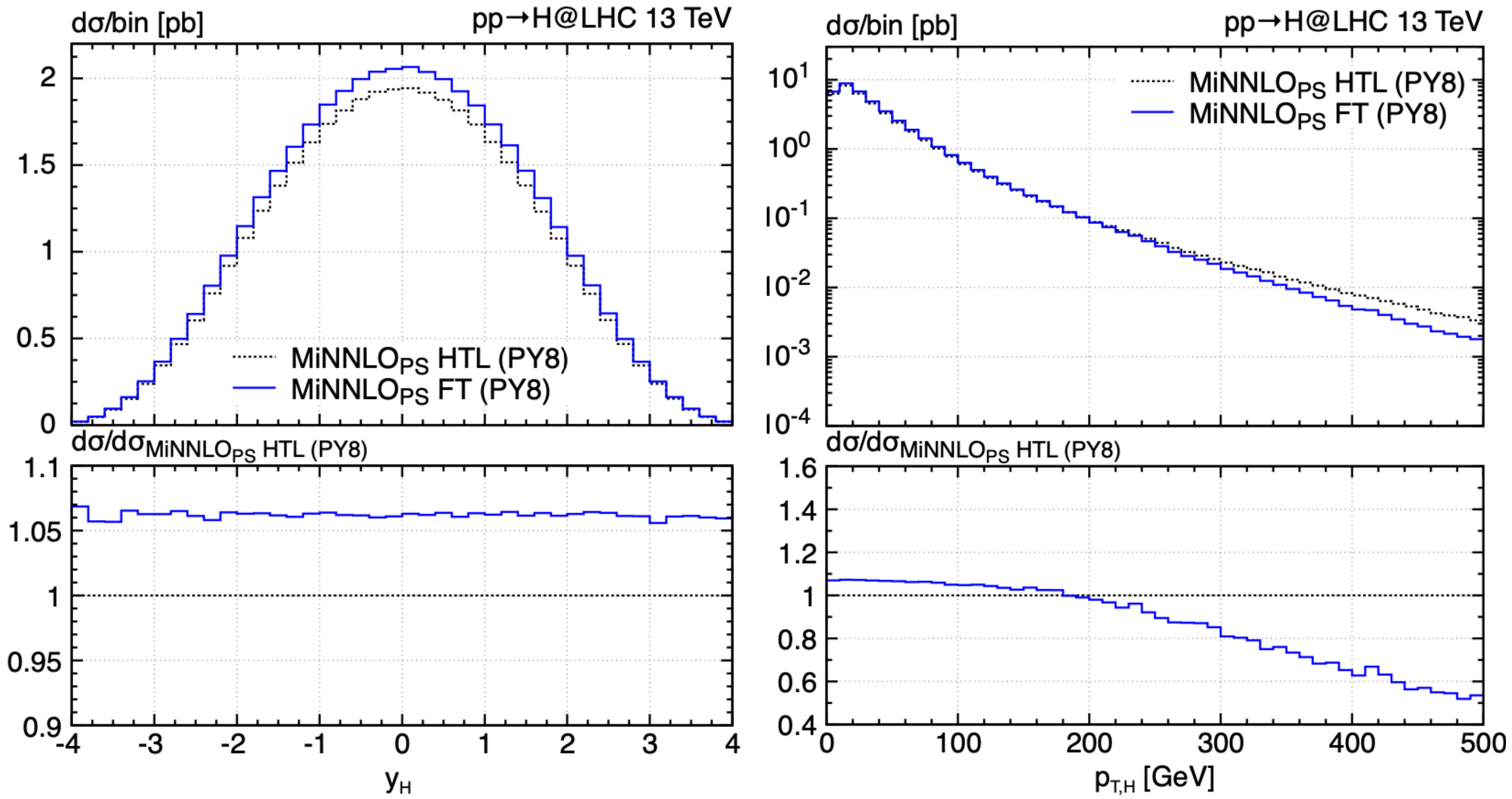
MiNNLO$_{PS}$ FT

$$42.01(1)^{+11.2\%}_{-10.6\%}\ pb$$



$$= 42.13(1)^{+11.0\%}_{-10.5\%}\ pb$$

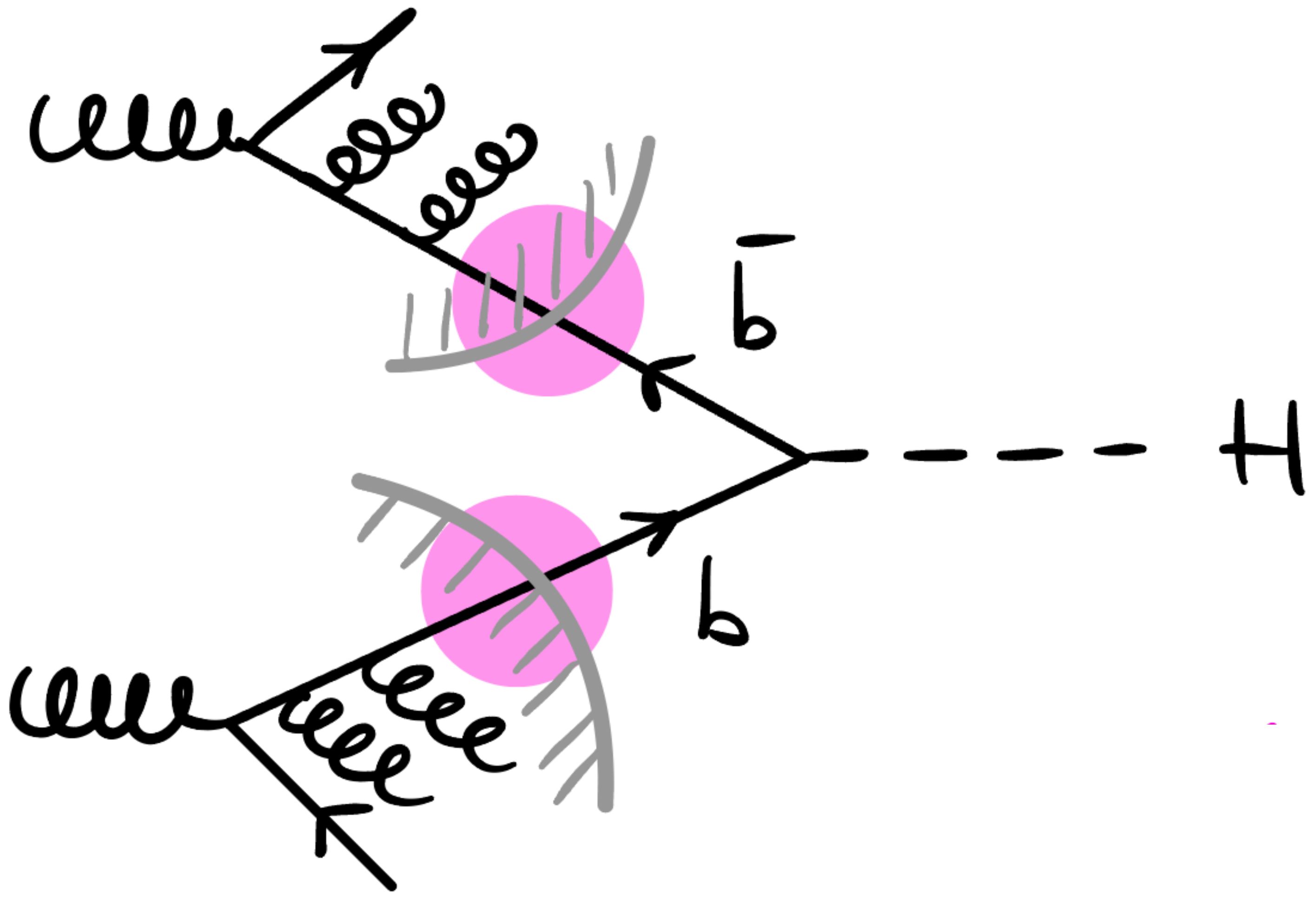
Captures almost all mass effects



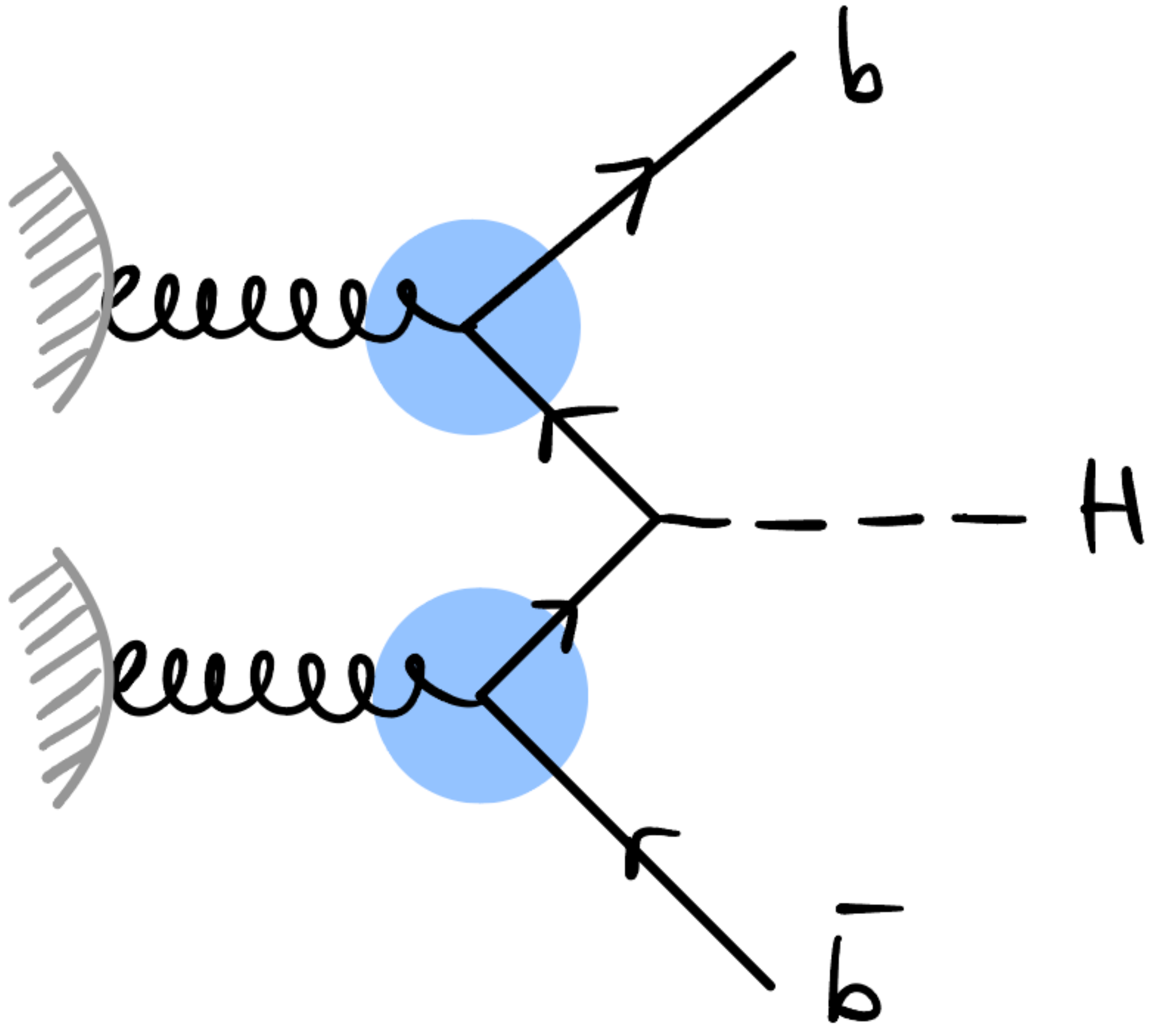
See next talk by René on quark mass effects!

bbH: a rare but interesting channel

5FS



4FS



massless scheme

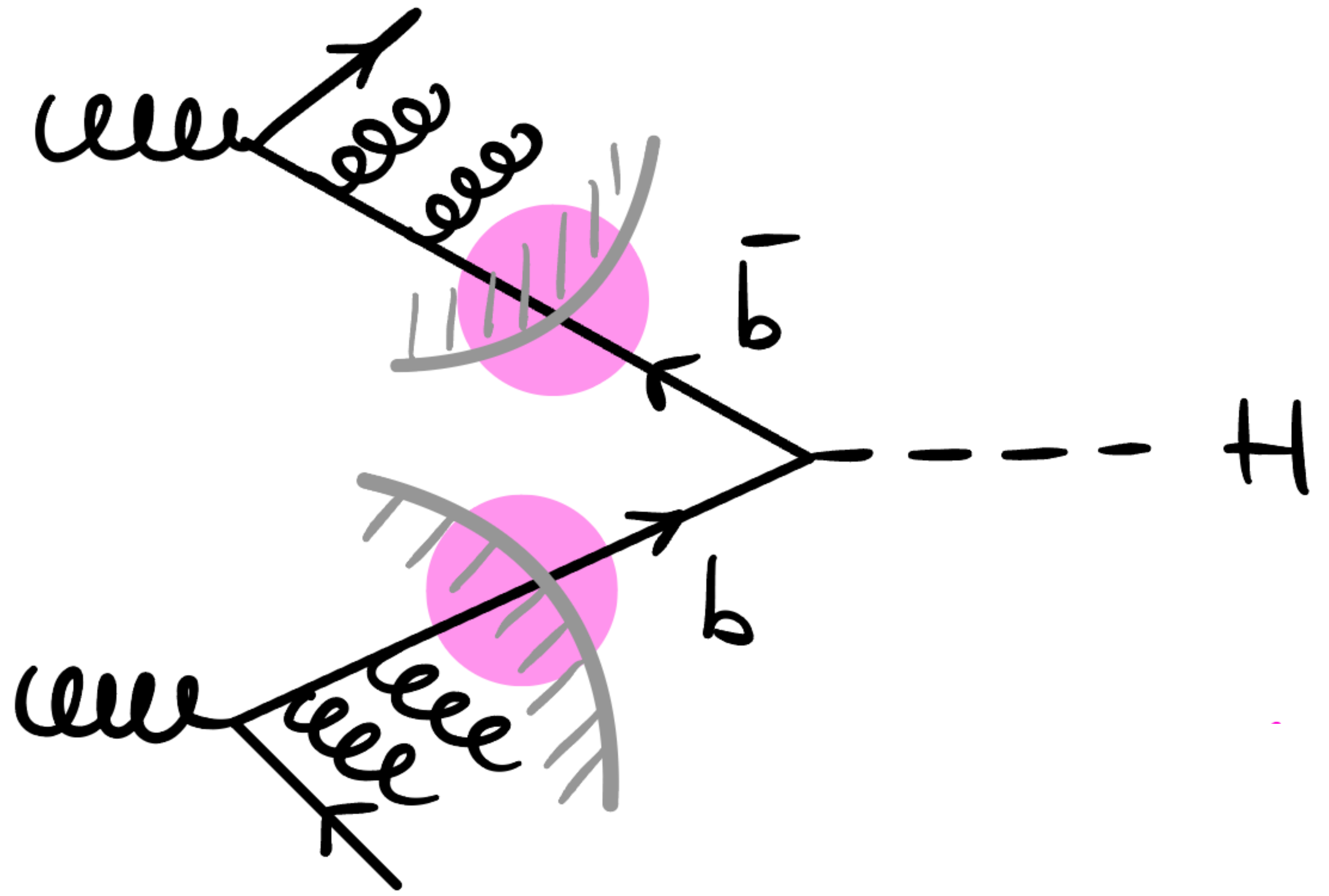
- ✓ DGLAP evolution resums initial-state logs into f_b
- ✓ Low multiplicity at Born level
- • Neglecting $O(m_b/m_H)$ yields less accurate description of bottom kinematic distribution

decoupling/massive scheme

- • It does not resum possibly large collinear logs
- • Computing higher orders is more difficult due to higher multiplicity
- ✓ Mass effects $O(m_b/m_H)$ appear order by order in perturbative QCD

Fixed order + parton shower state-of-the-art

5FS



- Cross-section FO @N^{3}LO

  Duhr, Dulat, Mistlberger [1904.09990]

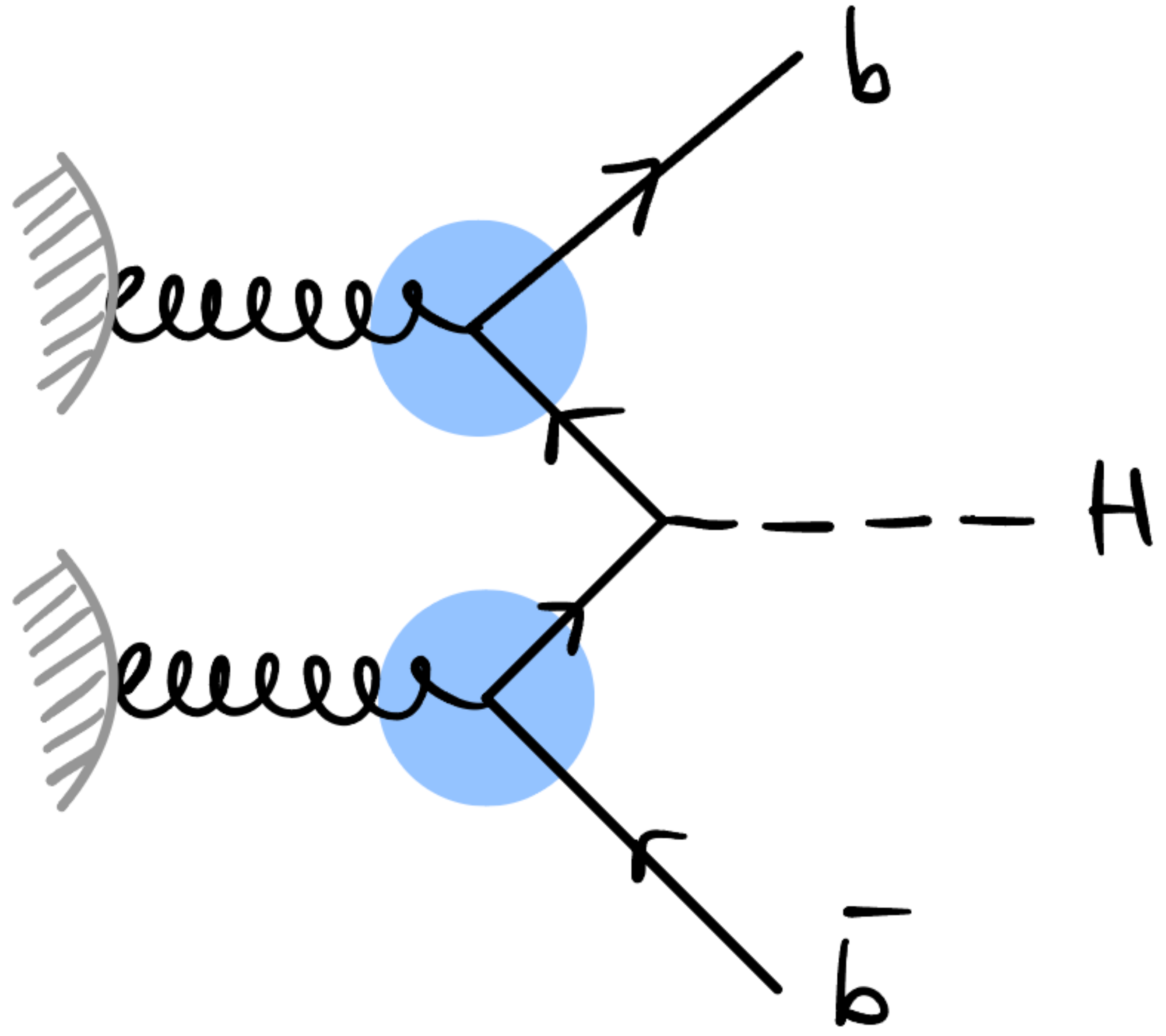
- Merged 0,1,2-jet at NLO and 3-jet at LO

  Krauss, Napoletano, Schumann [1612.04640]

- NNLO$_{QCD}$ + PS

  CB, Sankar, Wiesemann, Zanderighi [2402.04025]

4FS



- Cross-section FO @NLO

  Dittmaier, Krämer, Spira [hep-ph/0309204]

- NLO$_{QCD}$ + PS

  Wiesemann, Frederix, Frixione, Hirschi, Maltoni, Torrielli [1409.5301]
  Jäger, Reina, Wackeroth [1509.05843]

- NLO$_{QCD}$ + PS combined with NLO$_{EW}$

  Pagani, Shao, Zaro [2005.10277]

- NNLO$_{QCD}$ + PS **without double-virtual m_b power corrections**

  CB, Mazzitelli, Sankar, Wiesemann, Zanderighi [2412.09510]

Flavour-scheme comparison

central scales

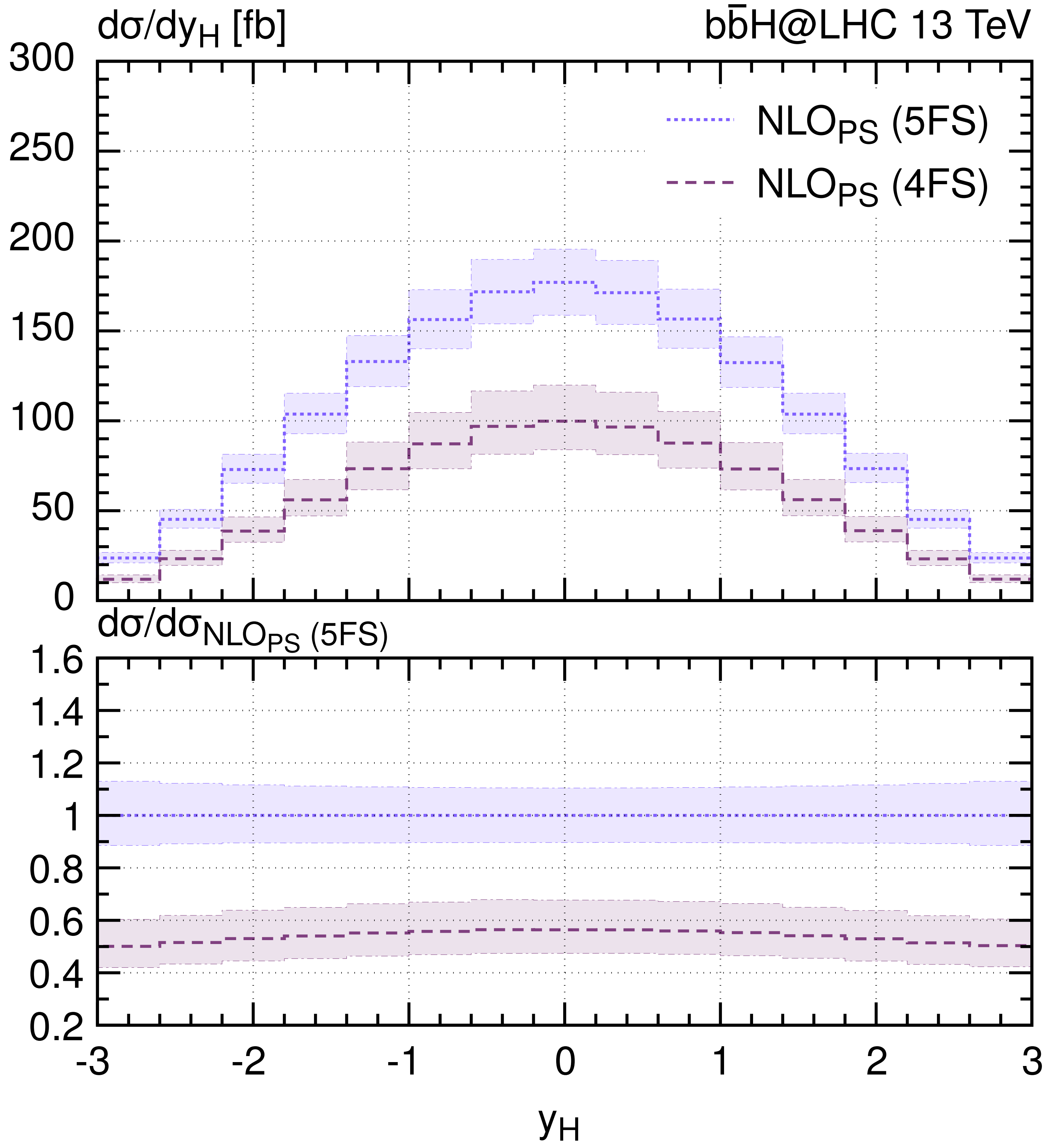
$$\mu_R^{(0),\alpha_s} = \mu_R^{(0),y_b} = \mu_R = \mu_F = m_H$$

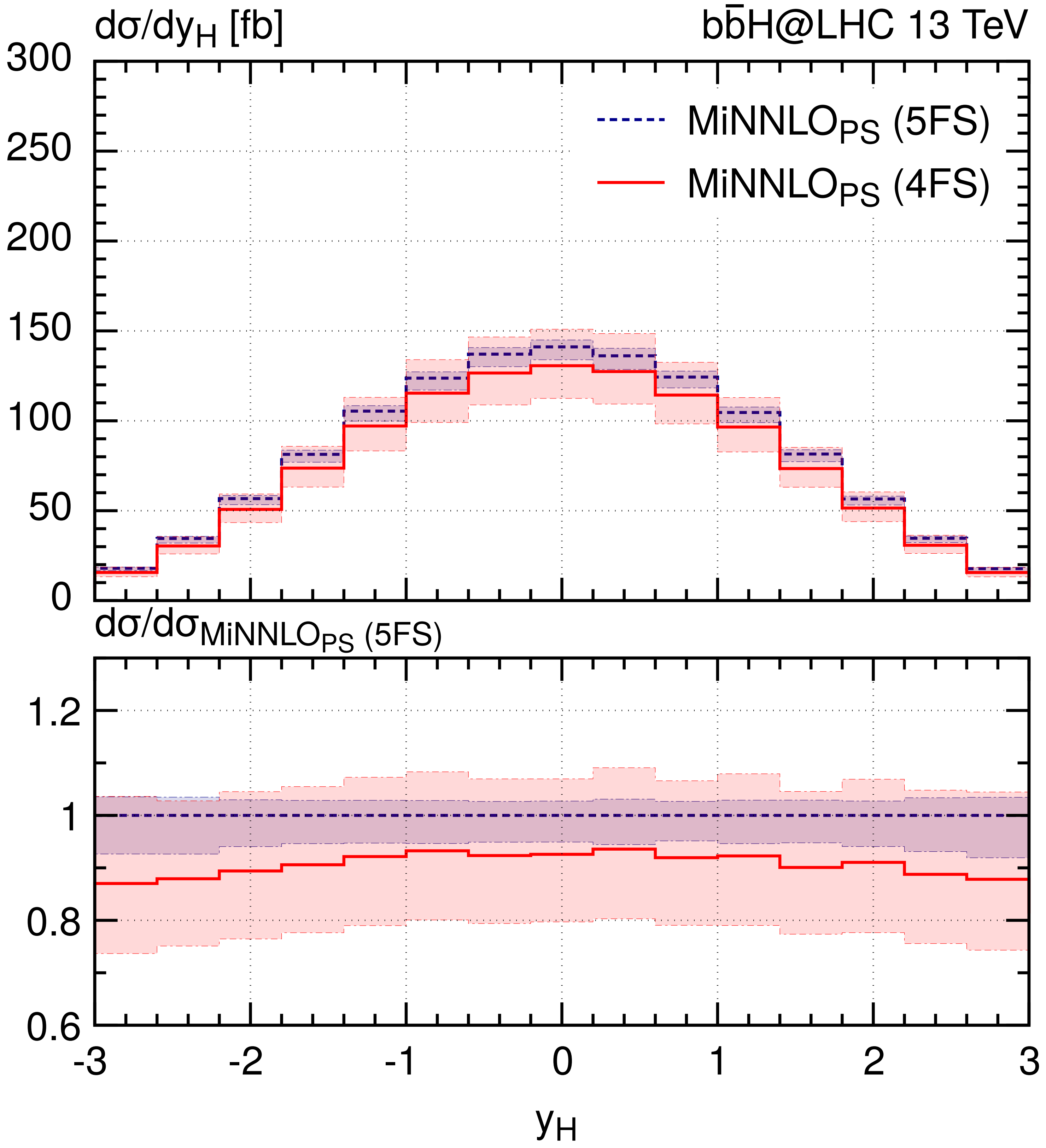
5FS NLO+PS	$0.645(5)^{+11\%}_{-10\%}$
4FS NLO+PS	$0.354(6)^{+20\%}_{-16\%}$

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

NNLO corrections solve the FS issue.

At NNLO QCD, the two predictions agree within the scale variation when using the most natural choice (m_H) as the central scale, without the need for artificial factors to improve the comparison.





CB, Mazzitelli, Sankar, Wiesemann, Zanderighi [2412.09510]

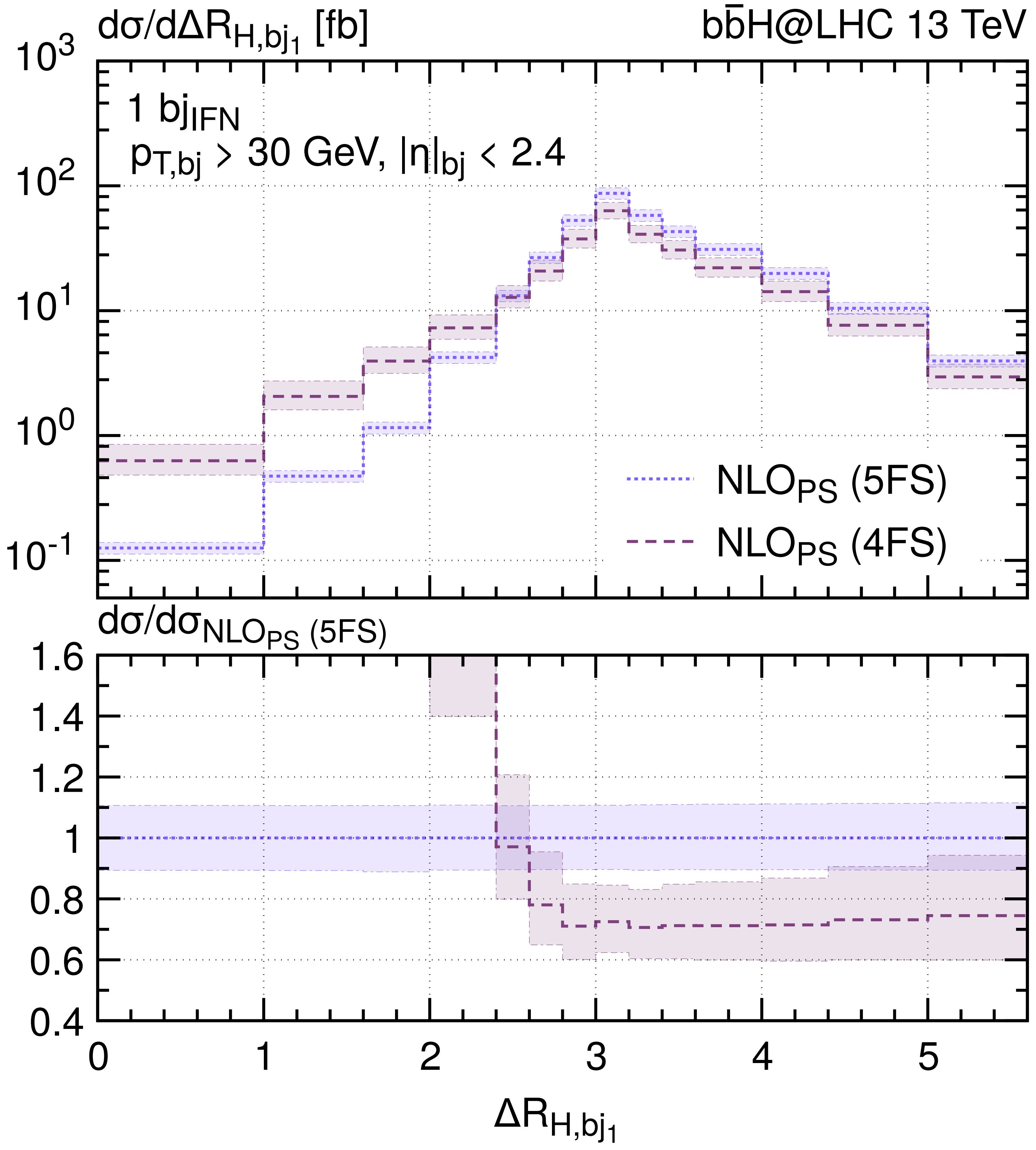
Flavour-scheme comparison

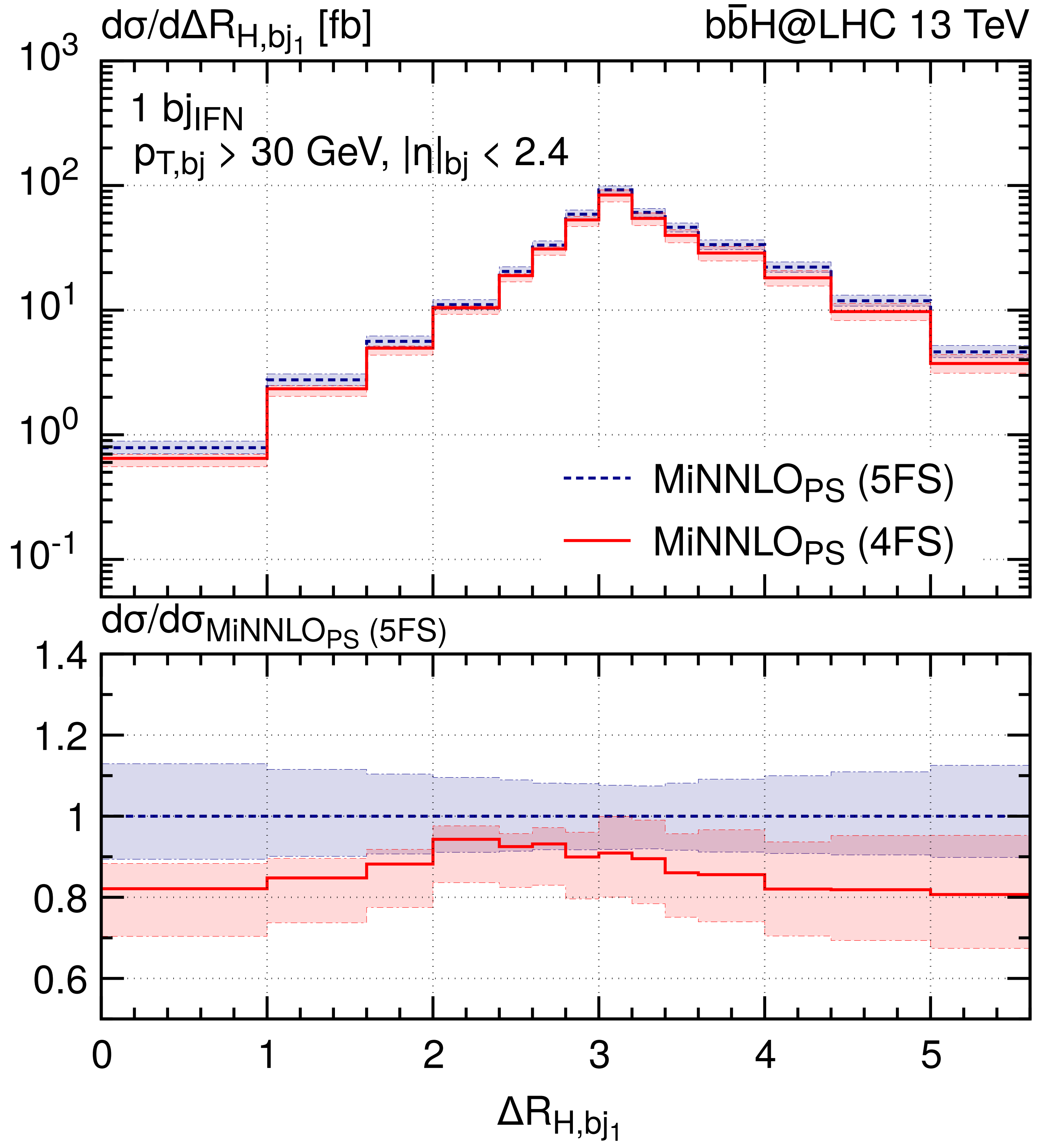
Properties of b-jet observables are investigated using the 4FS and 5FS generators with IR-safe b-tagging (IFN).

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

Higher-order five-FS corrections bring the shape closer to that of the 4FS, while NNLO 4FS corrections further enhance compatibility.

In 2b-jet regions, bigger tensions are observed and the 4FS generator is more trustable.





CB, Mazzitelli, Sankar, Wiesemann, Zanderighi [2412.09510]

A phenomenological application: $b\bar{b}\gamma\gamma$

$$m^*_{2b2\gamma} = m(b_1, b_2, \gamma_1, \gamma_2) - m(b_1, b_2) - m(\gamma_1, \gamma_2) + 2m_H$$

We require two b-jets satisfying experimental b-tagging criteria, along with

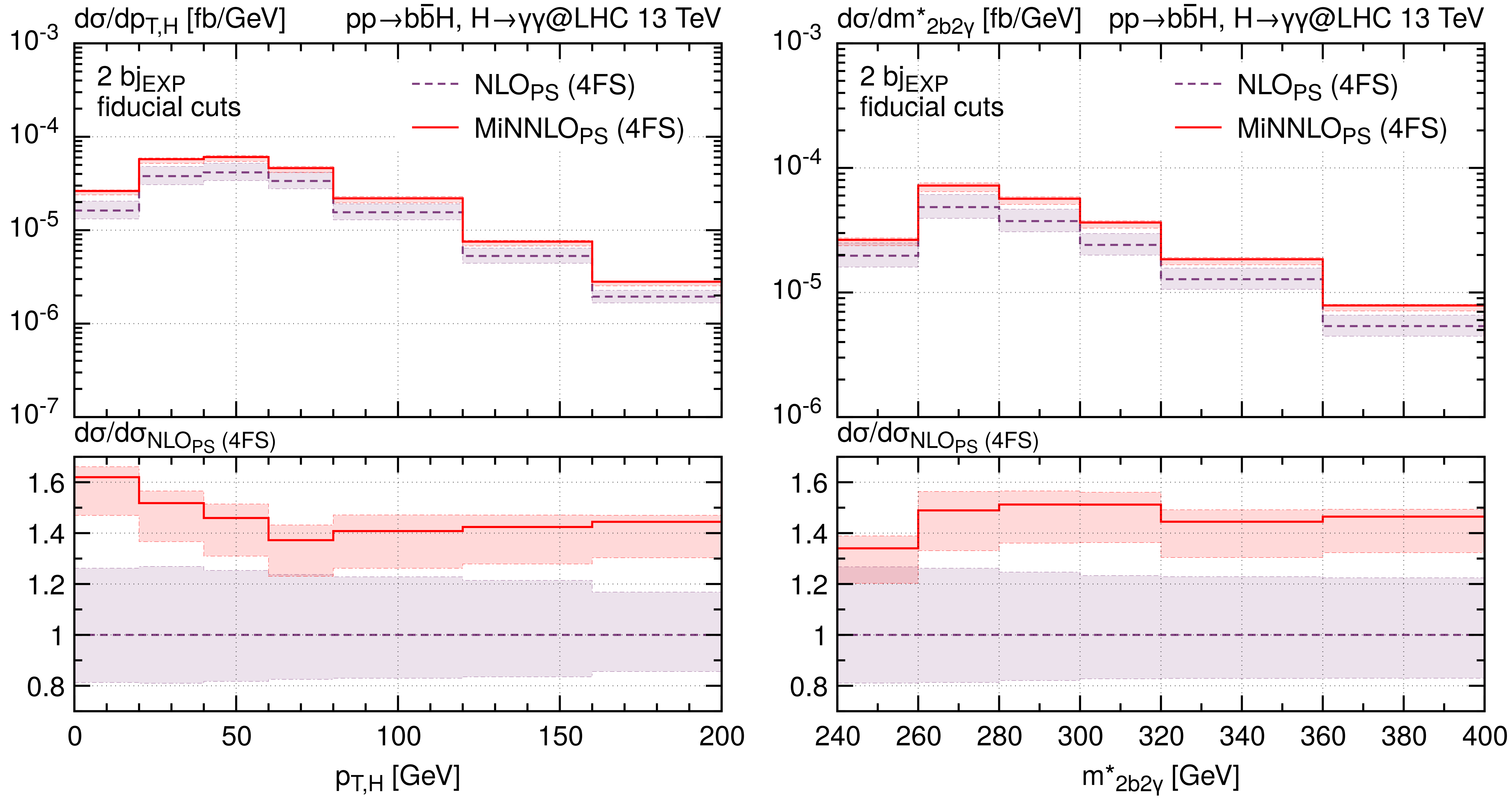
$$p_T(b_i) > 25\text{ GeV}, |\eta(b_j)| < 2.5$$
$$80\text{ GeV} < m(b_1, b_2) < 140\text{ GeV}$$

and two photons with

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

ATLAS [2112.11876]

The NNLO corrections are positive and associated with a reduced scale uncertainty.

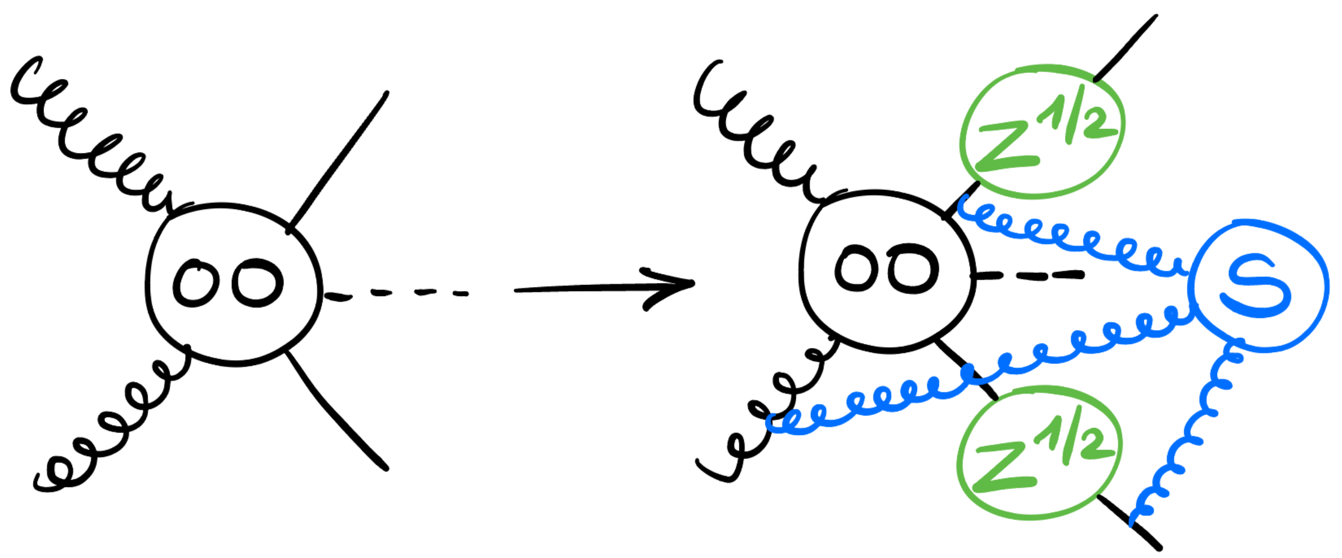


CB, Mazzitelli, Sankar, Wiesemann, Zanderighi [2412.09510]

Refining the generators…

The double-virtual correction relies on a massification approximation

Mitov, Moch [0612149]



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

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

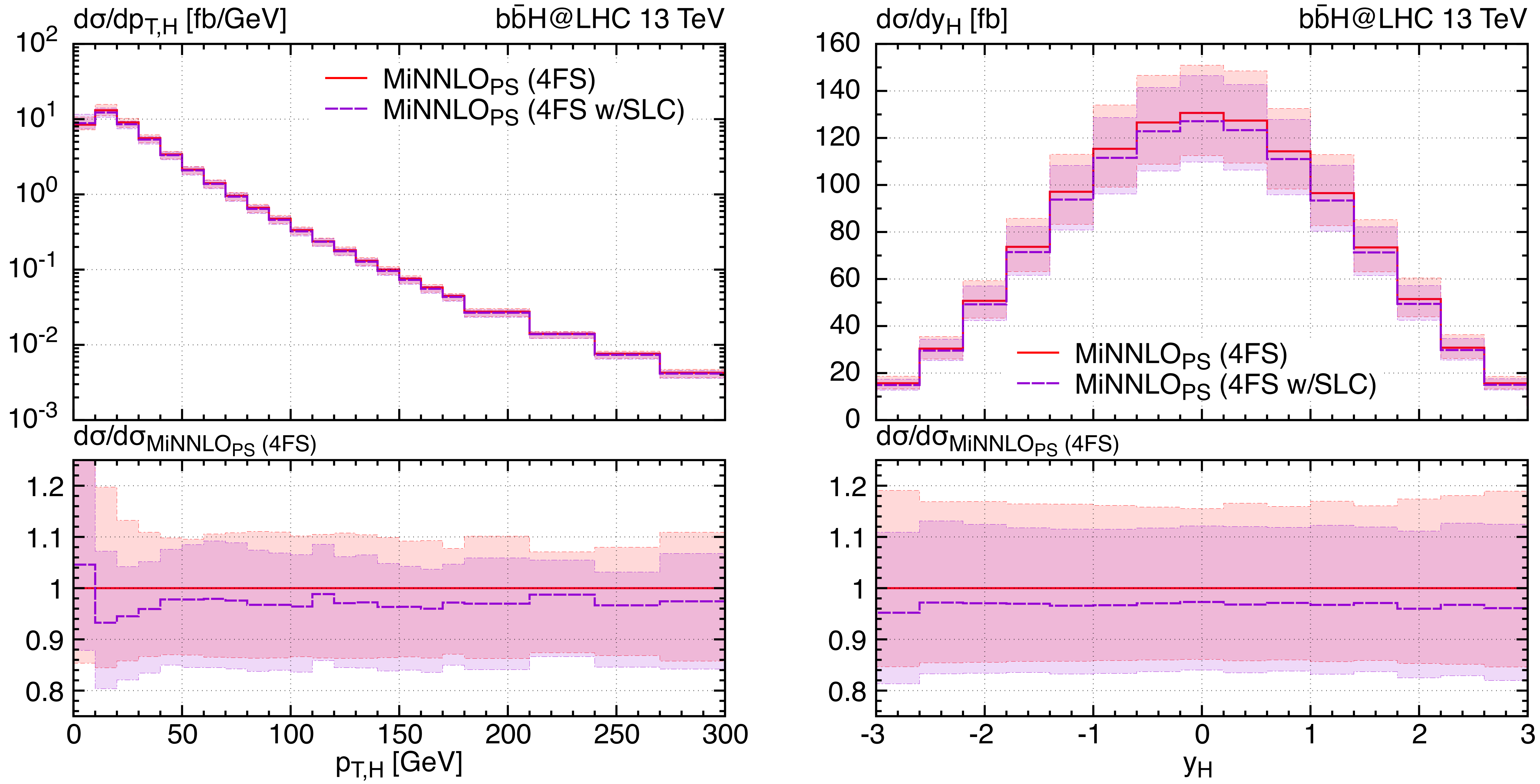
See the talk by Chiara on ttH predictions!

The first implementation was based on the two-loop amplitude in the **leading colour (LC) approximation**

Badger, Hartanto, Kryś, Zoia [2107.14733]

A recent calculation and numerical implementation of the **two-loop in full-colour (LC+SLC)** has been incorporated in MiNNLOPS via **LHE reweighting**

Badger, Hartanto, Poncelet, Wu, Zhang, Zoia [2412.06519]

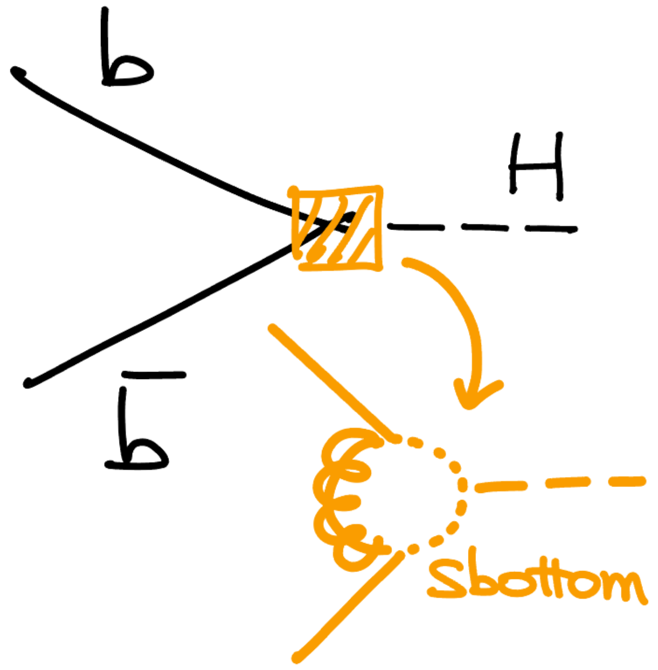


CB, Mazzitelli, Sankar, Wiesemann, Zanderighi [2412.09510v2]

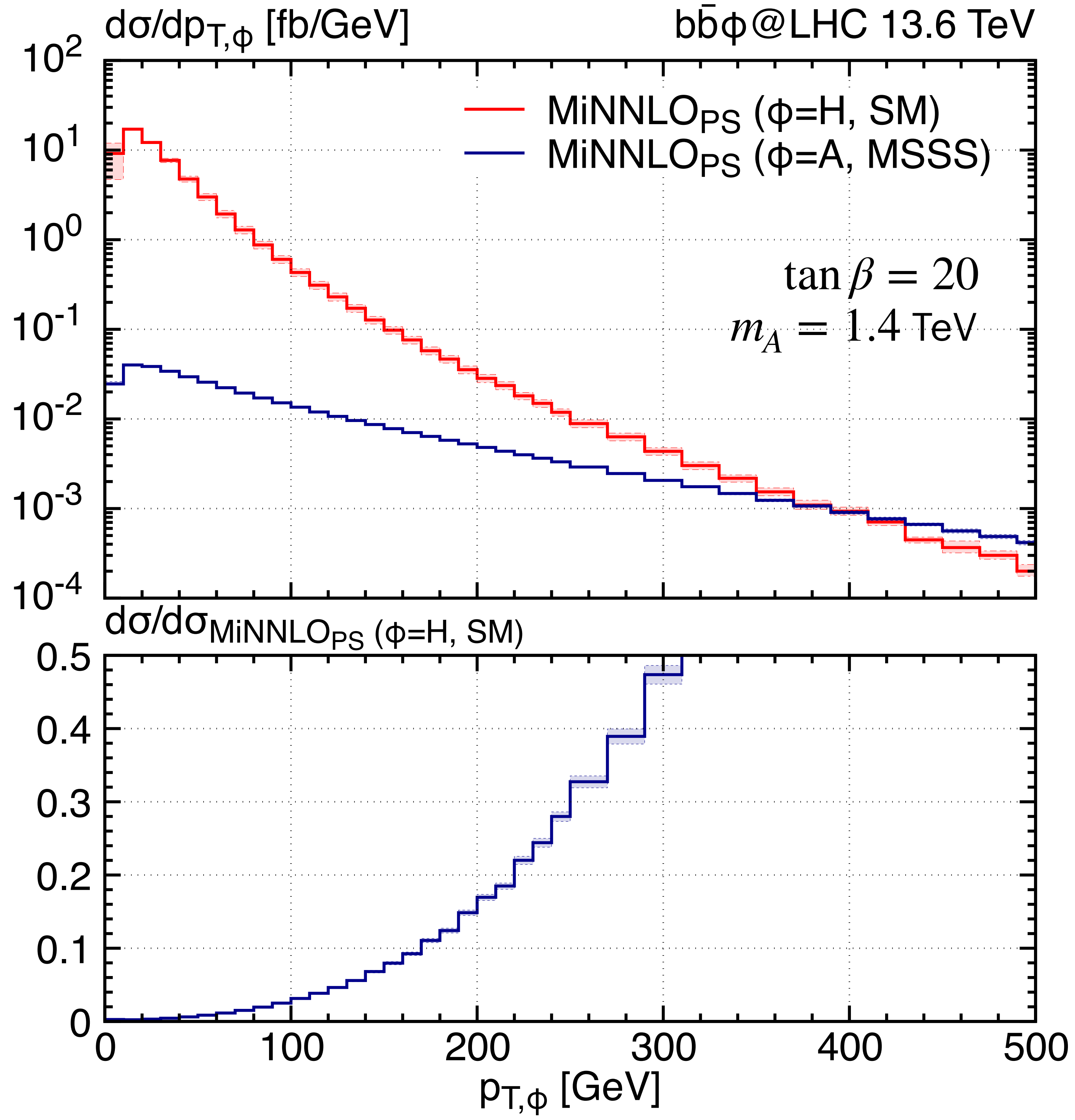
Refining the generators…

The 5FS MiNNLOPS generator has been recently extended to perform:

BSM Higgs

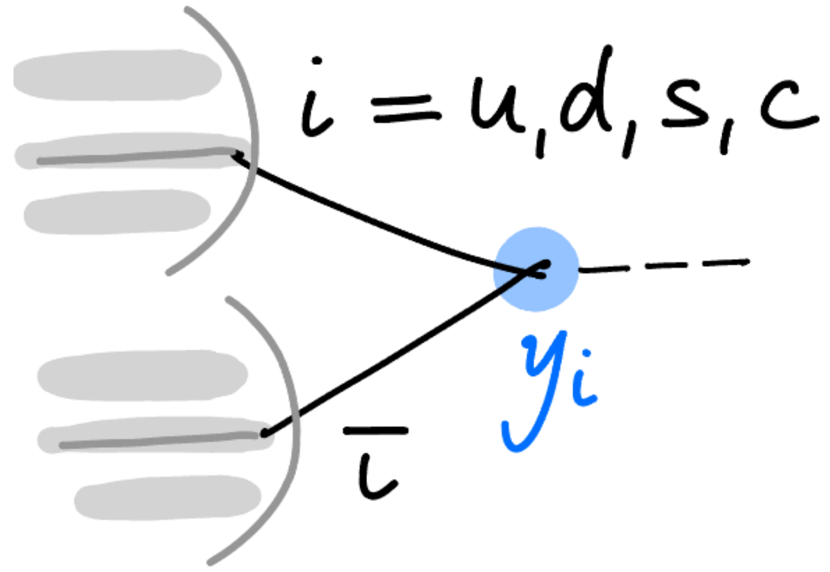


We have considered the m_{125} scenario in MSSM [1808.07542]



CB et al. [Report 5]

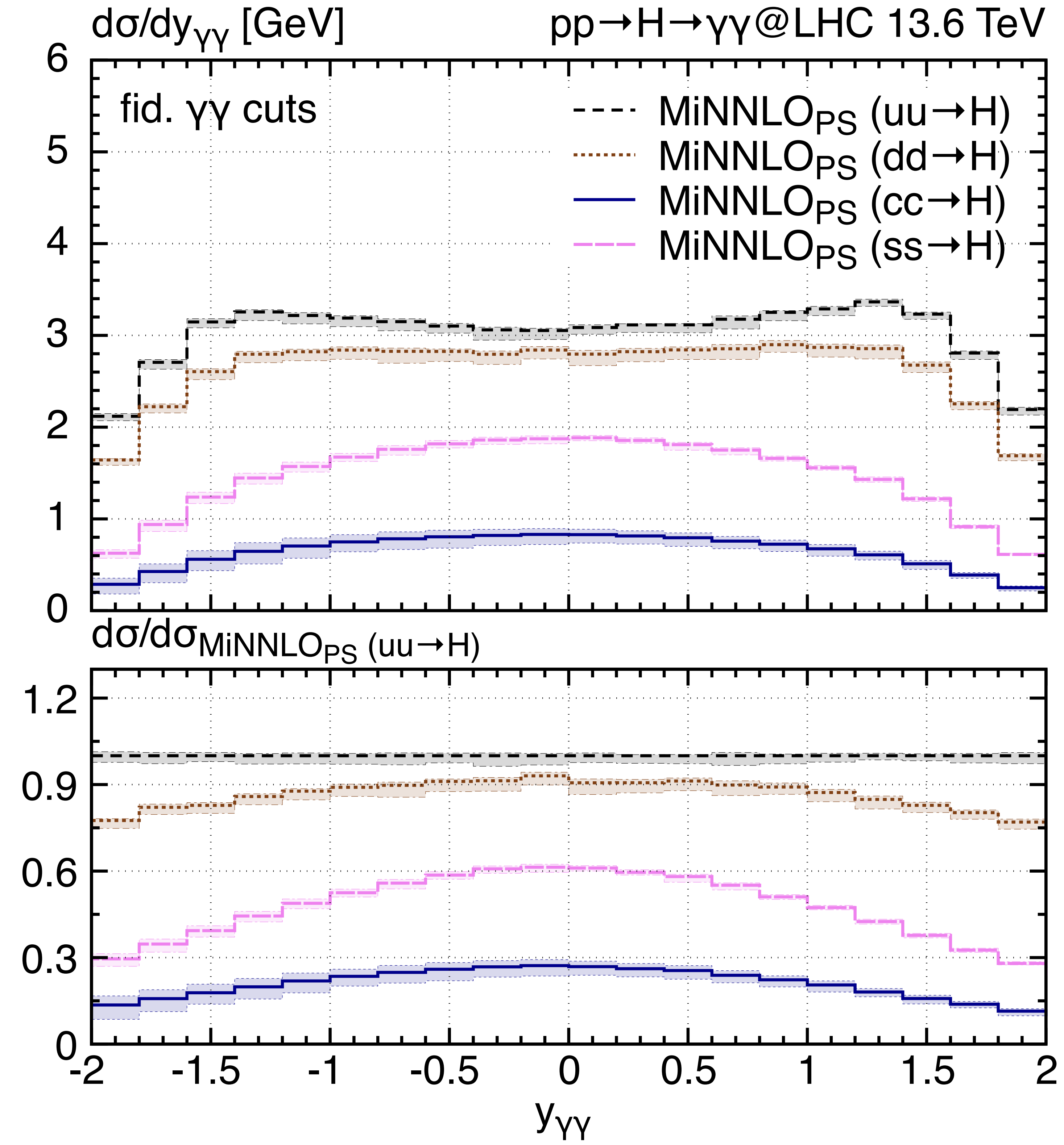
Light-parton fusion

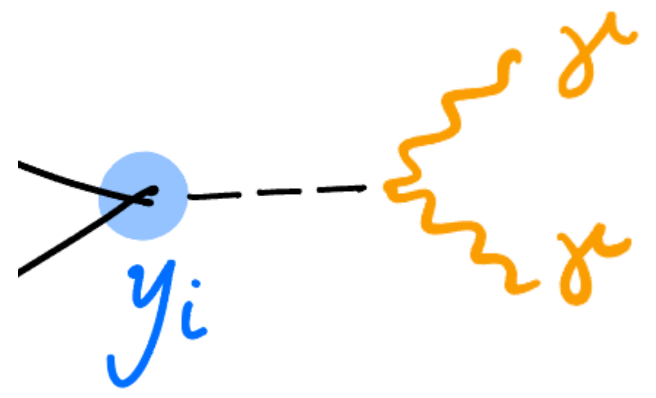


First insights on light-quark Yukawa interactions at NNLO+PS with

$$\kappa_i = \frac{y_i(m_h)}{y_b(m_h)} = 1$$

A mass reweighting is needed for SM predictions!





$$p_T(\gamma_1) > 0.35\, m(\gamma_1, \gamma_2)$$
$$p_T(\gamma_2) > 0.25\, m(\gamma_1, \gamma_2)$$
$$|\eta(\gamma_i)| < 2.37$$

Conclusions

MiNNLOPS has proven to be a flexible and adaptive NNLO+PS method, providing precise and accurate predictions in Higgs phenomenology.

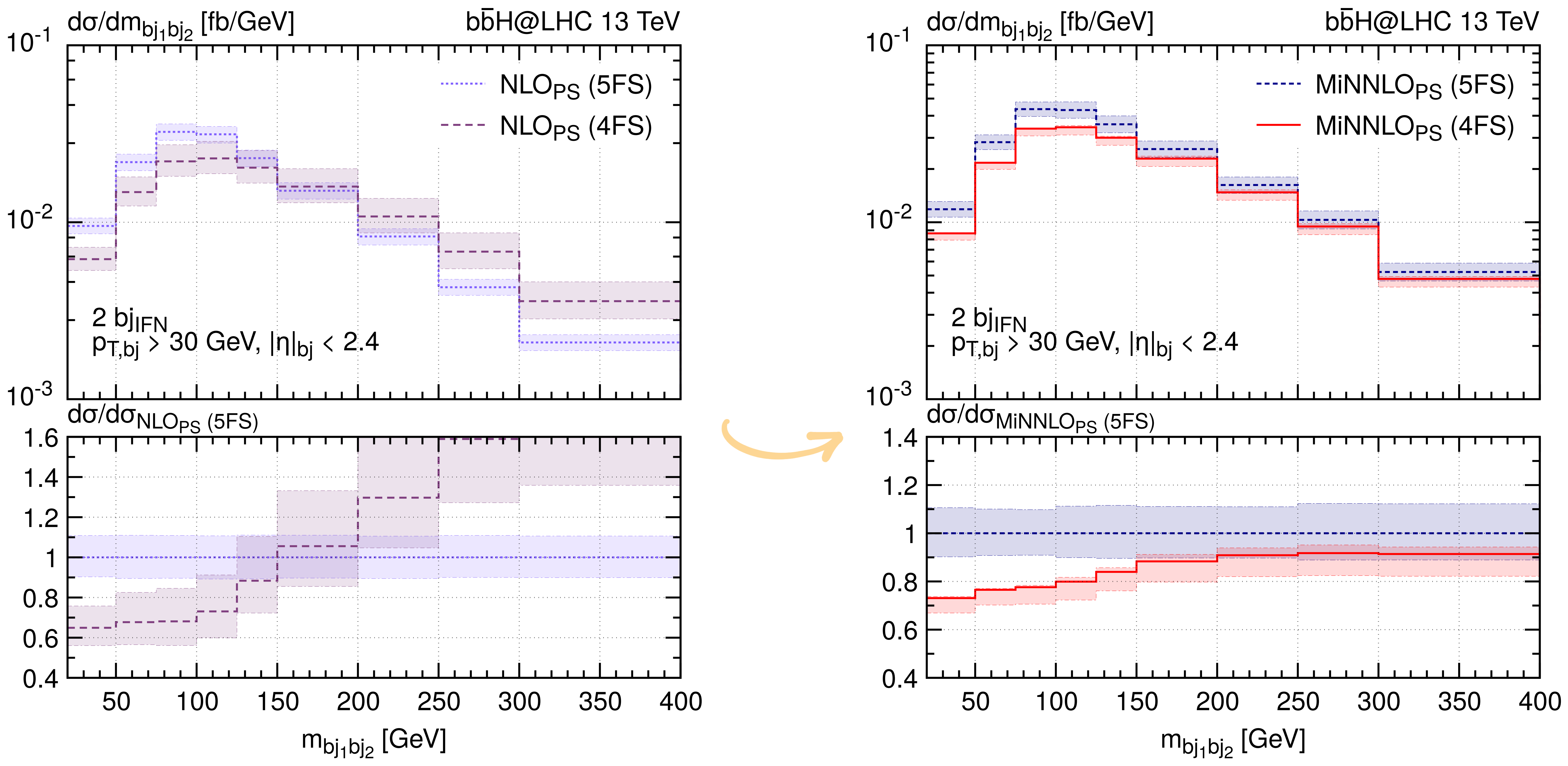
- The ggF includes exact top-quark mass corrections
- The bbH mode has been studied in two different flavour schemes
  - MiNNLOPS 5FS provides precise predictions for inclusive Higgs observables, with extensions to BSM scenarios and light-parton fusion
  - MiNNLOPS 4FS shows sizable NNLO corrections, reduces flavour-scheme tension, and yields accurate b-jet predictions, including for HH backgrounds studies

Thank you for the attention!

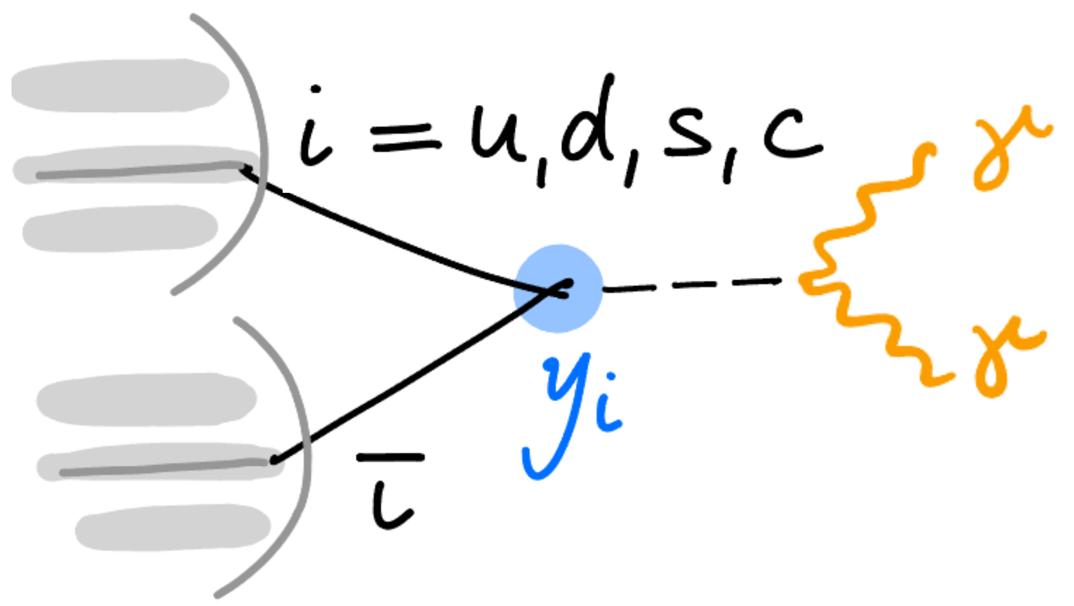
Backup slides:
bbH with MiNNLO$_{PS}$

Flavour-scheme comparison: 2 bjet bin

In 2b-jet regions, bigger tensions are observed, and the 4FS generator is more trustable.



CB, Mazzitelli, Sankar, Wiesemann, Zanderighi [2412.09510]



$$\kappa_i = \frac{y_i(m_h)}{y_b(m_h)} = 1$$

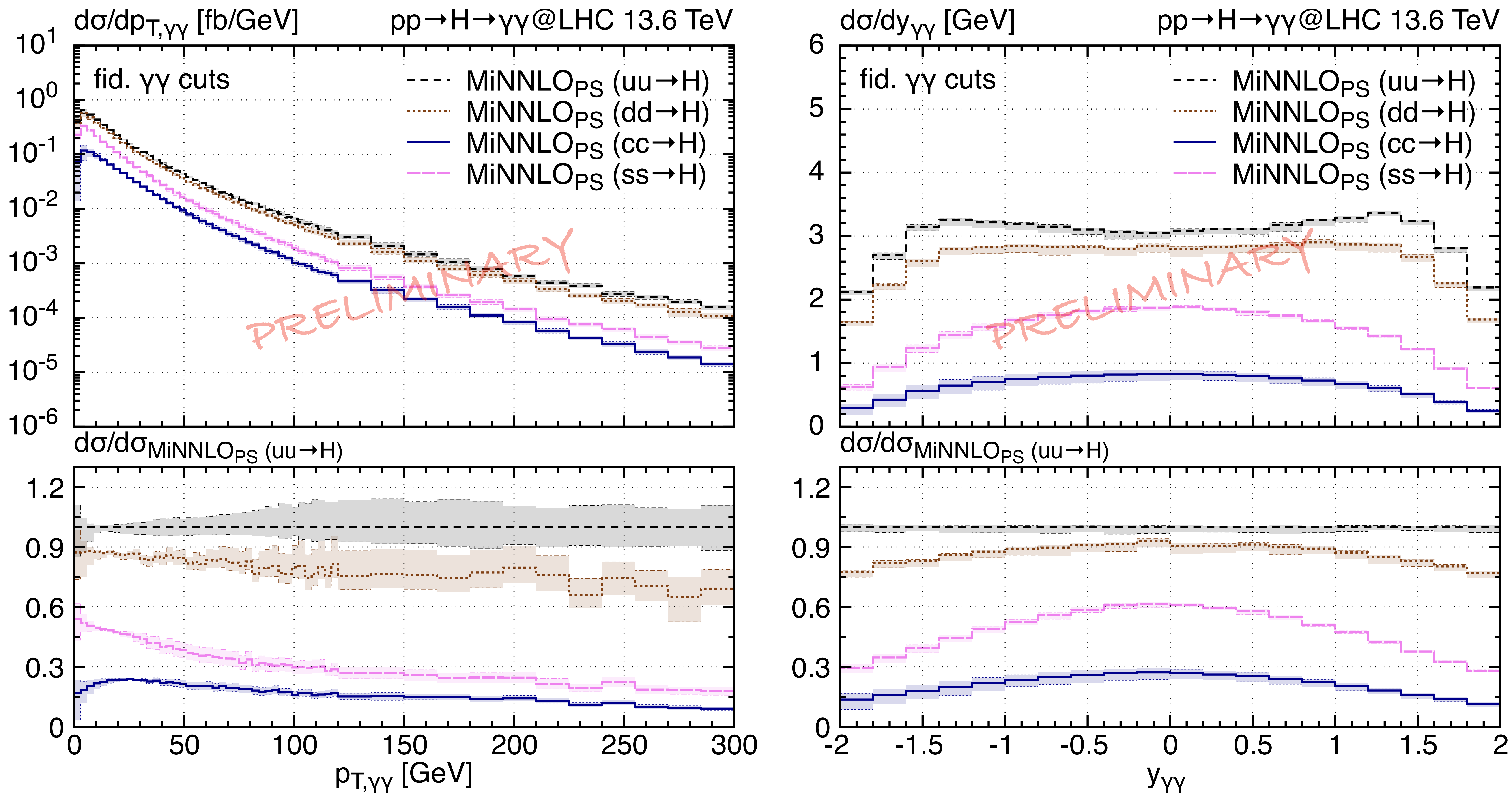
Refining the generators…

LHC Higgs Working Group

We require two photons satisfying the constraints:

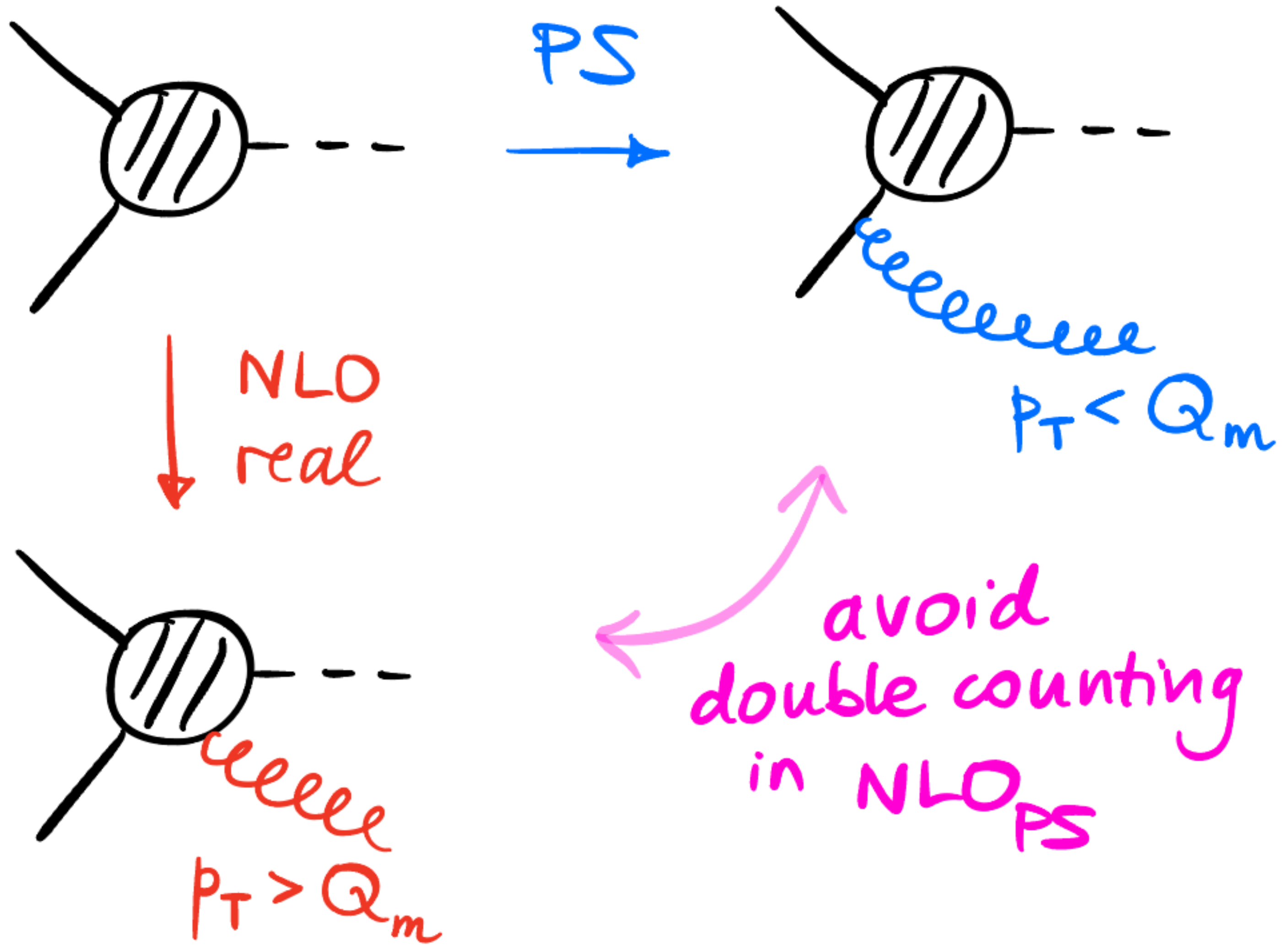
$$p_T(\gamma_1) > 0.35\, m(\gamma_1, \gamma_2)$$
$$p_T(\gamma_2) > 0.25\, m(\gamma_1, \gamma_2)$$
$$|\eta(\gamma_i)| < 2.37$$
$$105 \text{ GeV} < m(\gamma_1, \gamma_2) < 160 \text{ GeV}$$

Due to the different parton luminosity, the shape of the predictions is different in the flavour channels.



CB et al. [in preparation for Report 5]

Matching



Problem: Match fixed-order predictions with Parton Shower avoiding an unphysical matching scale.

POWHEG idea: implement a Monte Carlo generator that produces just one emission (the hardest one) which alone gives the correct NLO result.

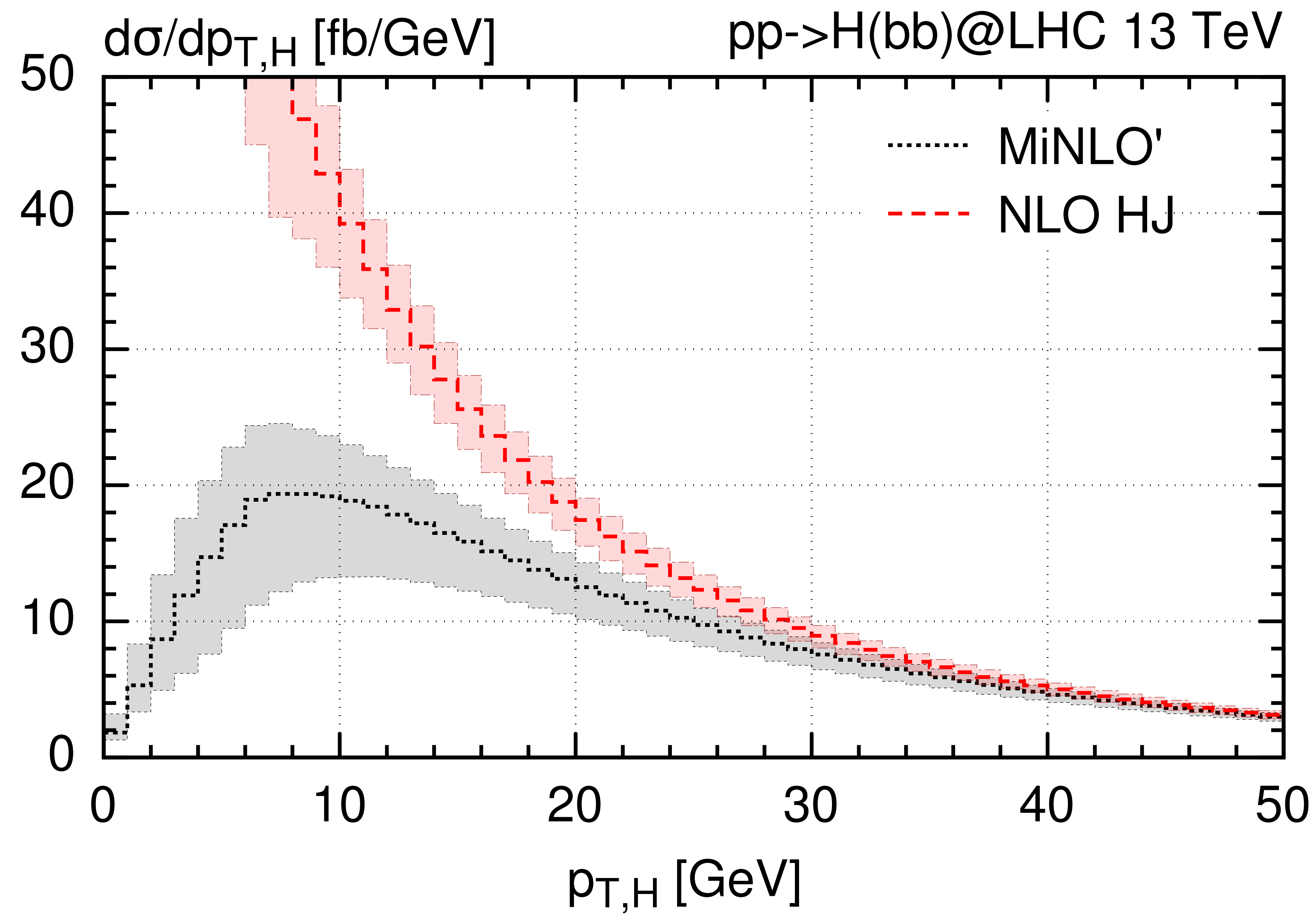
Nason [hep-ph/0409146]

Merging

Problem: Merge different multijet calculations without any unphysical merging scale.

MiNLO' idea: Start from a FO X+1jet prediction matched with PS and obtain inclusive predictions through particular scale choices and inclusion of a Sudakov form factor.

Hamilton, Nason, Zanderighi [1206.3572]
Hamilton, Nason, Oleari, Zanderighi [1212.4504]



MiNNLOPS in a nutshell

NLO Xj → NNLO X

MiNNLOPS is an extension of MiNLO' to achieve NNLO+PS accuracy for inclusive observables.

Monni, Nason, Re, Wiesemann, Zanderighi [1908.06987]

The modified POWHEG function is

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

Sudakov form factor

MiNLO' structure

Extra term:
it ensures NNLO accuracy.
F^{corr} encodes the spreading upon the full Φ_{XJ}.

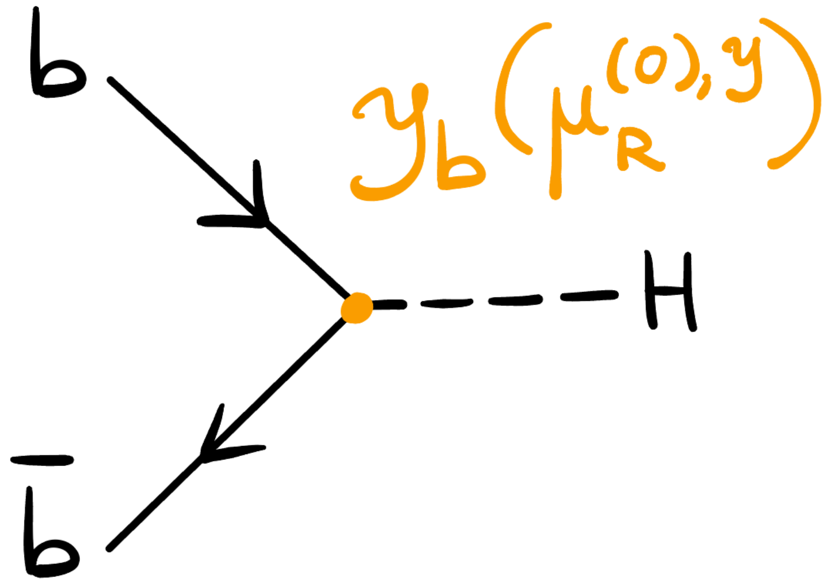
The QCD scales must be $\mu_F \sim \mu_R \sim p_T$ in the singular region.

Yukawa in MiNNLOPS

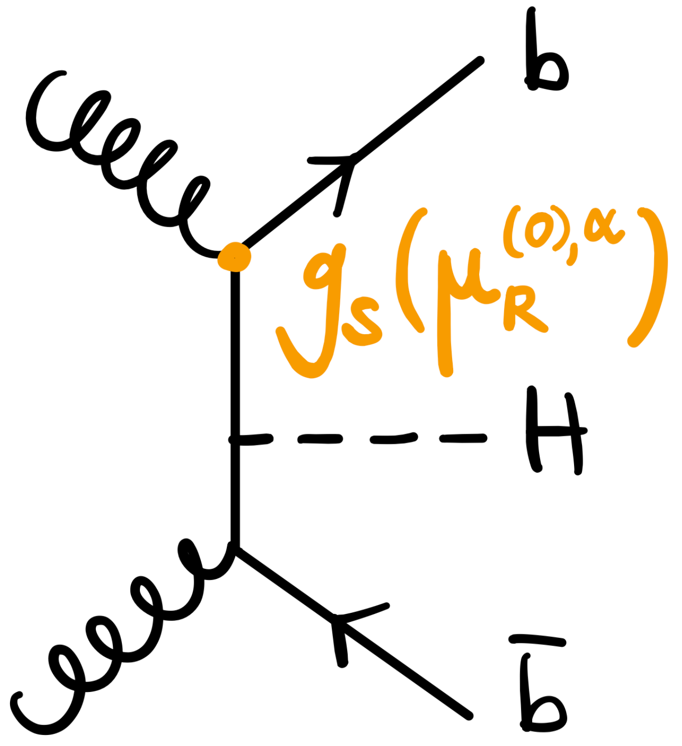
The $\overline{\text{MS}}$ running of these Born couplings

$$\sigma_{LO} \sim \alpha_s^{n_B}(\mu_R^{(0),\alpha})\, y^{m_B}(\mu_R^{(0),y})$$

requires some adaptations.



$(n_B = 0, m_B = 2)$



$(n_B = 2, m_B = 2)$

$H^{(1)} \supset$ single $\log(\mu_R^{(0),y})$

$H^{(2)} \supset$ single and double $\log(\mu_R^{(0),y})$ and mixed terms $\sim n_B m_B \log \mu_R^{(0),\alpha} \log \mu_R^{(0),y}$

$\tilde{B}^{(2)} \supset H^{(1)} \supset$ single $\log(\mu_R^{(0),y})$

The Yukawa scale has an interplay with the renormalisation and resummation scale factors

$$\alpha_s(p_T) \to \alpha_s\left(\frac{K_R}{K_Q} p_T\right)$$

$H^{(2)} \supset \log K_R \log \mu_R^{(0),y}$ and $\log K_Q \log \mu_R^{(0),y}$

Two-loop approximation in NNLO-4FS

The double virtual correction for massive bottoms is not known.

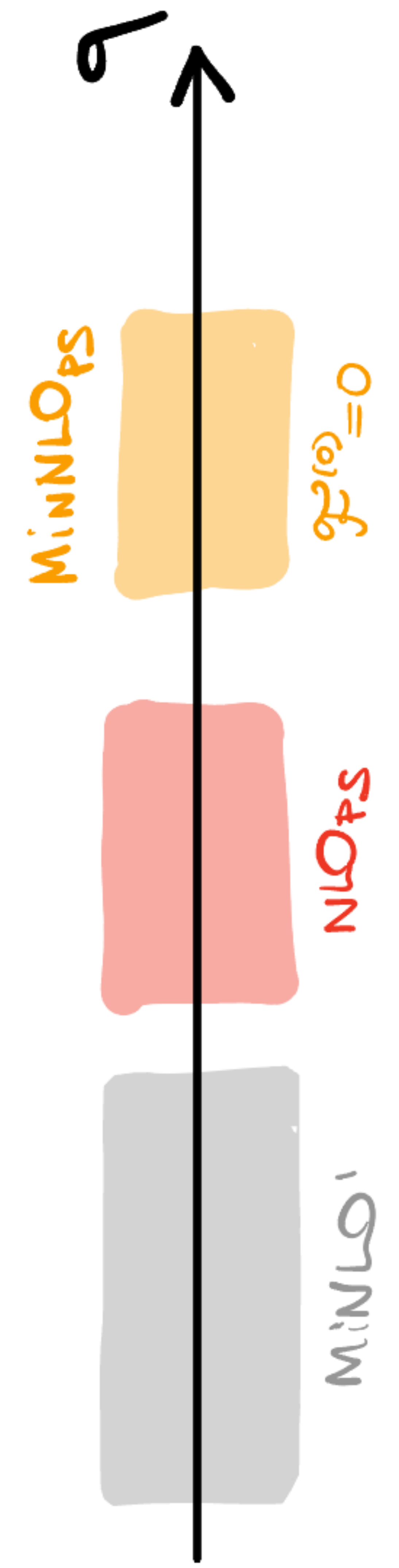
Approximation by retaining all the log-enhanced contributions through the massification procedure.

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

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

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

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

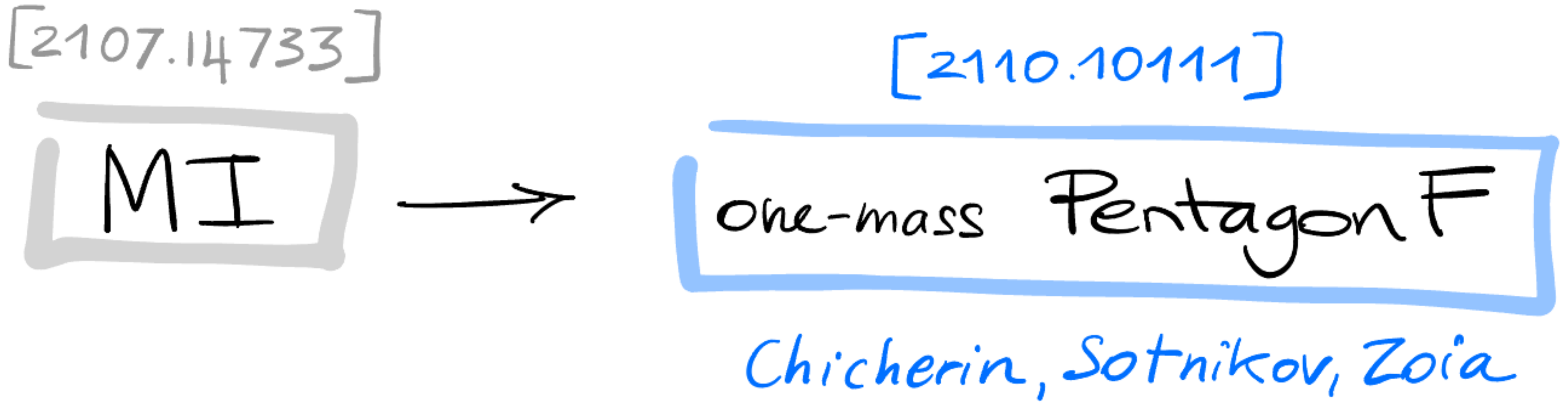


4FS massless two-loop library

We used analytic two-loop amplitudes for massless bottoms computed in the leading colour approximation.

Badger, Hartanto, Kryś, Zoia [2107.14733]

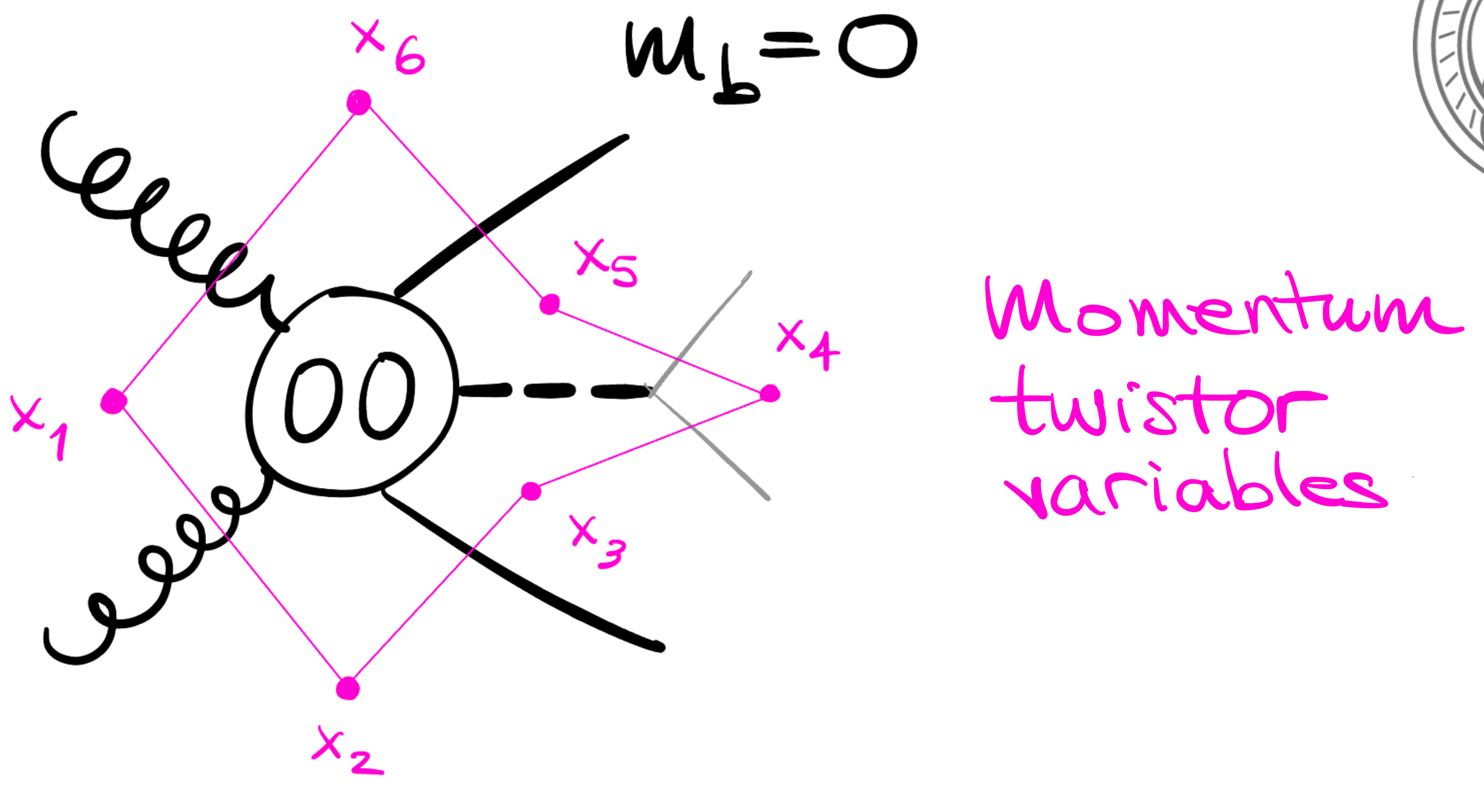
For fast numerical evaluation, we derived a mapping for the MIs in order to use the `PentagonFunctions` library [2009.07803, 2110.10111]



C++ code interfaced with POWHEG:
~ 3 sec for each PS point in double precision

Cross-checked with an independent implementation from UZH

Devoto, Grazzini, Kallweit, Mazzitelli, Savoini [2411.15340]



$$\sum_j \mathrm{coeff}_j(x_i)\cdot \mathrm{MI}_j$$

IR SCHEME in the library

$$\mathcal{A}^{\text{catani}} = (1 - I)\,\mathcal{A}^{\text{UV-ren}}$$ [hep-ph/9802439]

$$\mathcal{A}^{\text{SCET}} = Z^{-1}\,\mathcal{A}^{\text{UV-ren}}$$ [0901.0722]

$$\mathcal{A}^{\text{SCET}} = Z^{-1}(1 - I)^{-1}\,\mathcal{A}^{\text{catani}}$$

output of the library — Badger et al.

Original massification for bbH-4FS

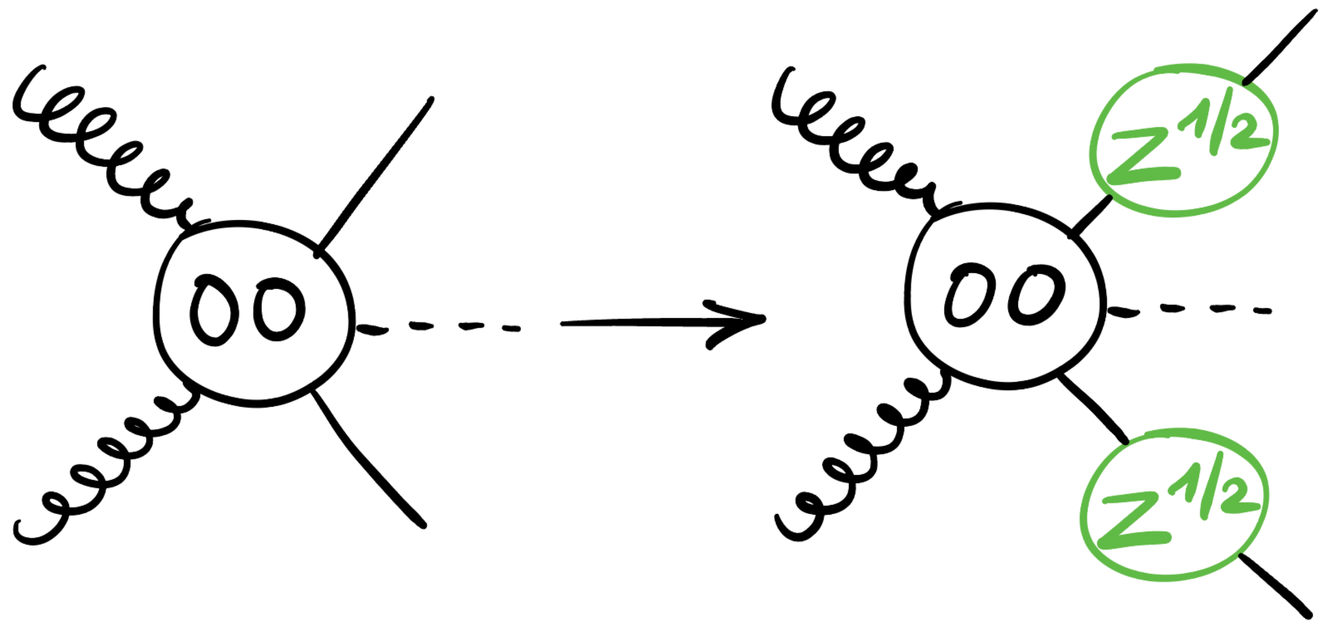
First two-loop massification in Bhabha scattering — Penin [hep-ph/0508127]

Extension for non-abelian theories from factorisation principles — Mitov, Moch [hep-ph/0612149]

Universal factors

$$|\mathcal{A}(m_i,\epsilon)\rangle = \prod_{i\,=\,\text{massive external legs}} \left(Z_i\left(\frac{m^2}{\mu^2}, \alpha_s(\mu^2), \epsilon\right)\right)^{1/2} |\mathcal{A}(m_i=0,\epsilon)\rangle$$

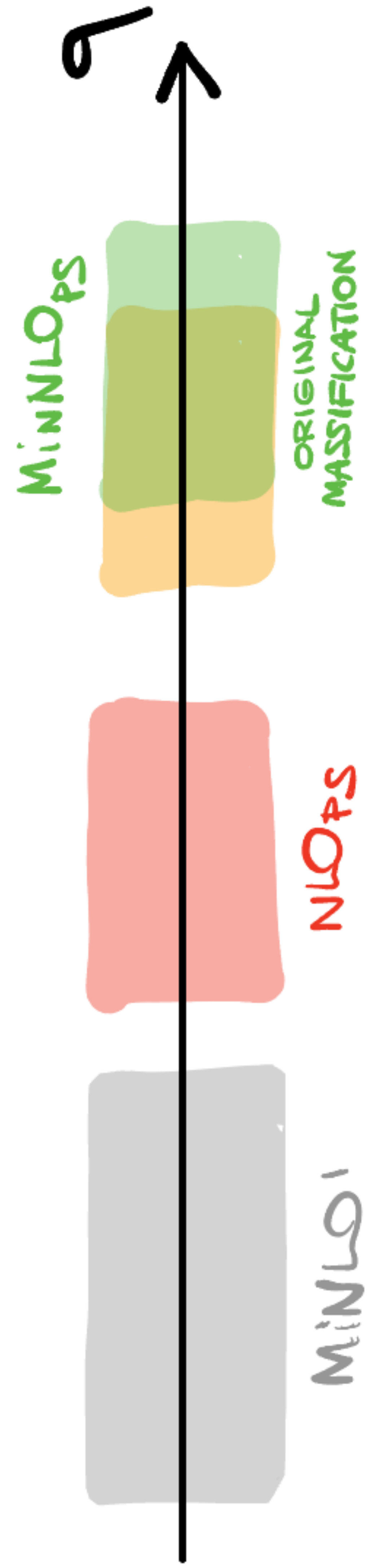
First check in $q\bar{q} \to Q\bar{Q}$
Czakon, Mitov, Moch [0705.1975]



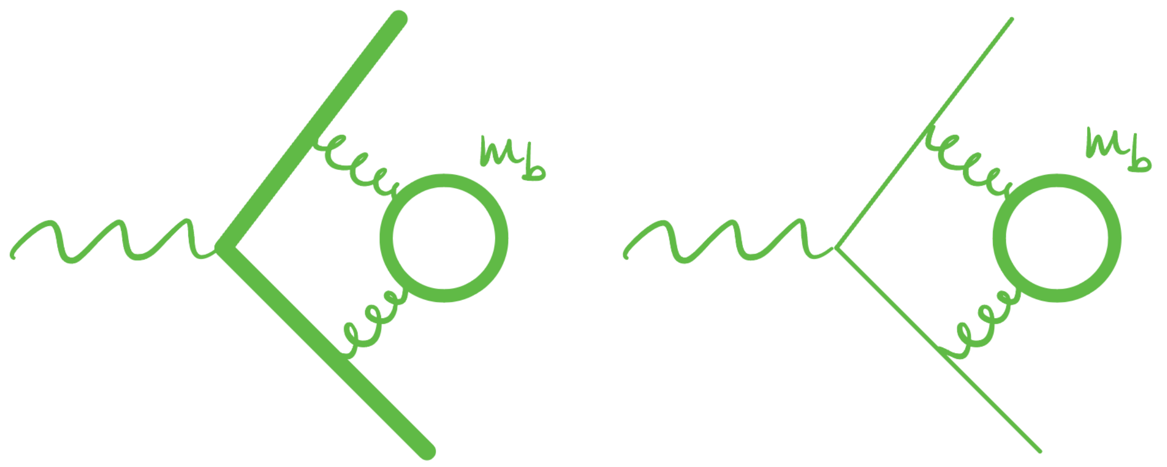
Mapping $\eta : \mathrm{PS}_{m_b} \mapsto \mathrm{PS}_{m=0}$

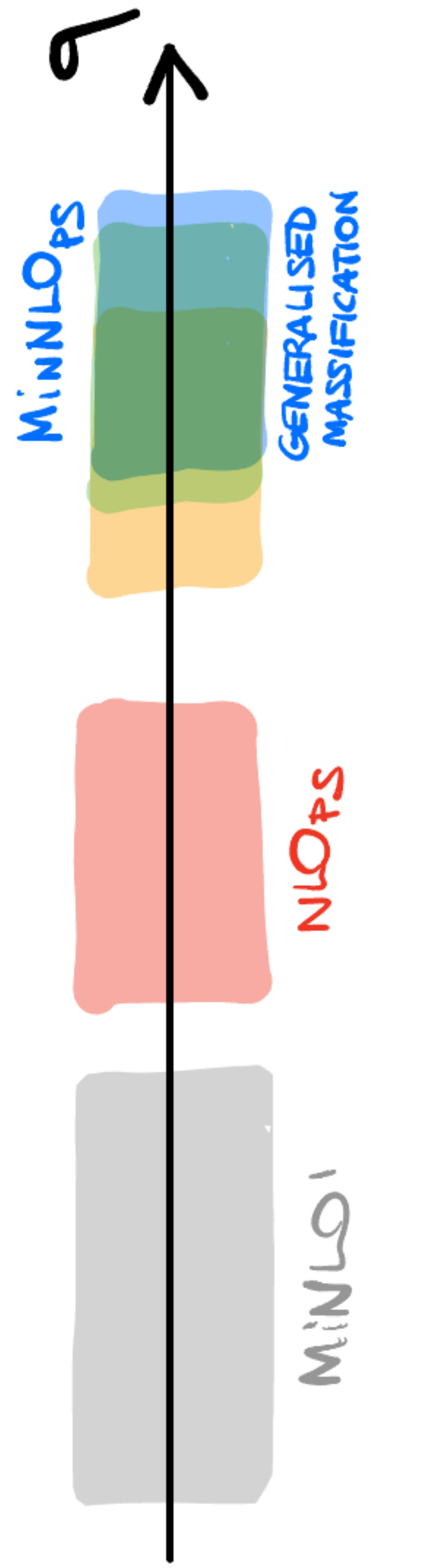
$\eta_{q\bar{q}}$ preserves the total momentum of $b\bar{b}$

η_{gg} avoids a collinear singularity



Generalised massification





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]

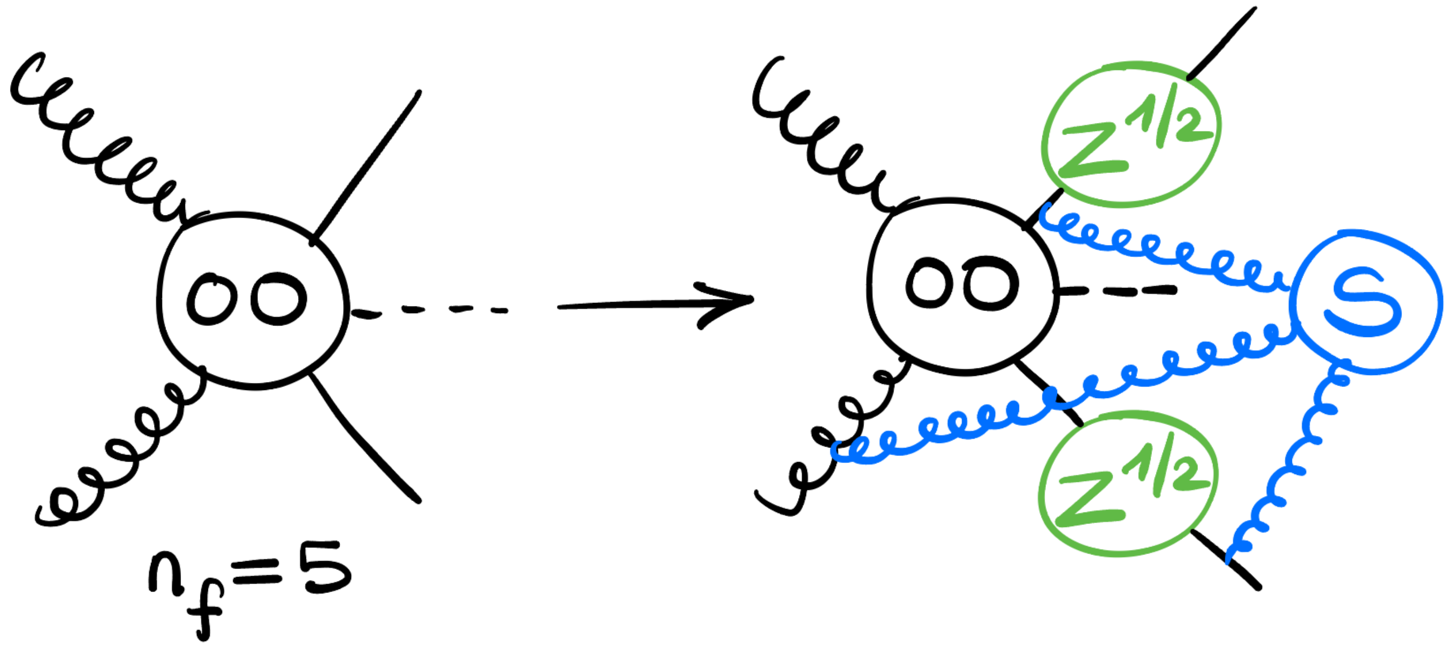
$$|\mathcal{A}_{\text{massive}}\rangle = \prod_i \left(Z_i(\{m\})\right)^{1/2} S(\{m\}) \, |\mathcal{A}_{\text{massless}}\rangle$$

with massive loop effects

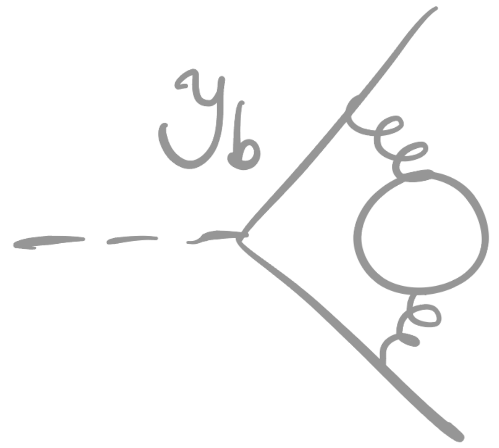
SOFT FUNCTION

$\mathcal{O}(\alpha_s^2)$ effects

$T_i \cdot T_j$



We applied decoupling relations for α_s and $\overline{\text{MS}}$ Yukawa



$$y_b^{(n+1)}(\mu) = y_b^{(n)}(\mu)\left(1 + \alpha_s^2(\mu) \cdot \text{logs}\right)$$

$$\bar{\mathcal{F}}^{(2)} \to \bar{\mathcal{F}}^{(2)} + \text{logs}$$