

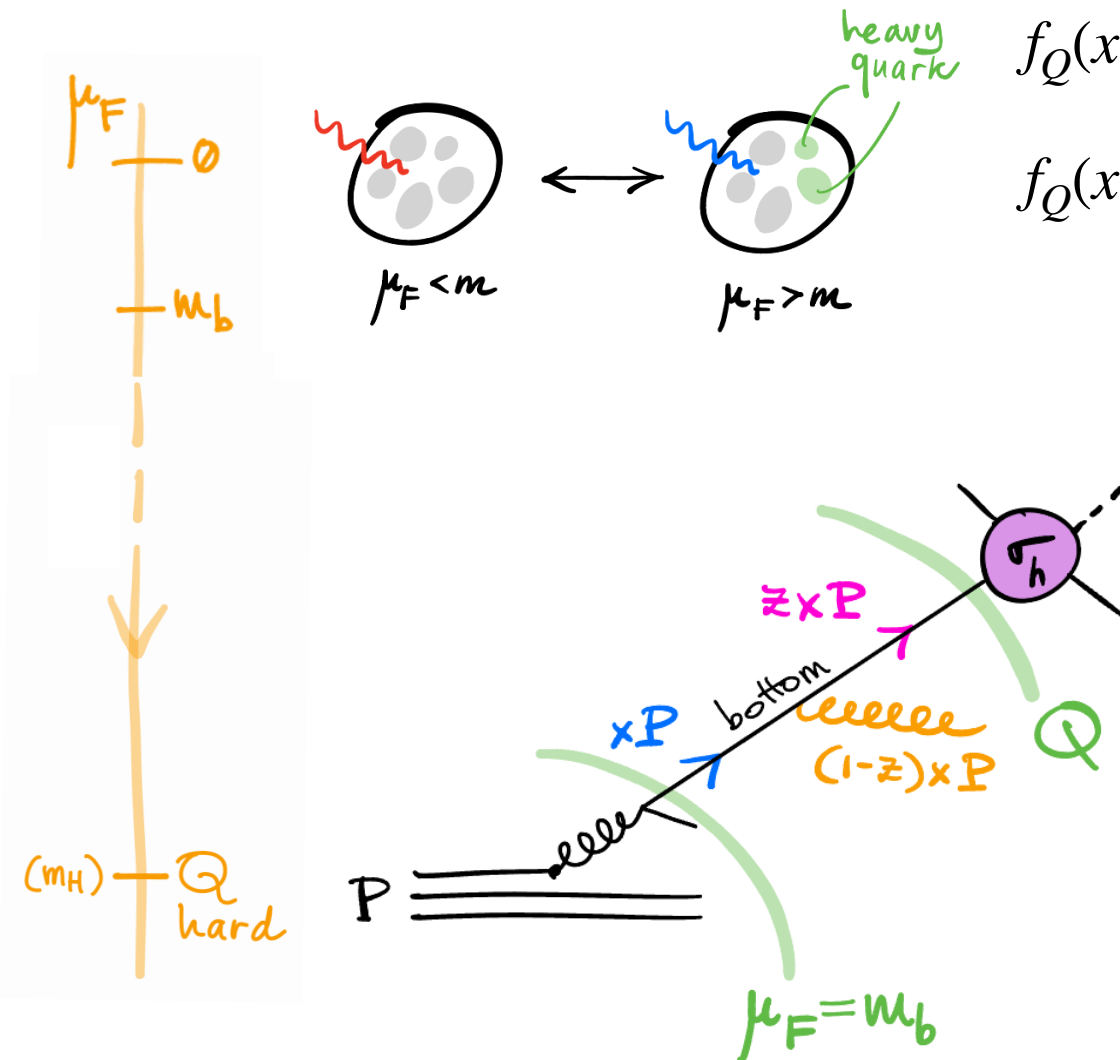
Matching flavour schemes via isolation of heavy-quark mass power corrections

Christian Biello
ITP ETH Zürich

in collaboration with
Rhorry Gauld, Aparna Sankar, Marius Wiesemann, Giulia Zanderighi
[in preparation]

QCD@LHC 2026
01.10.2026, Oxford

All you need is collinear factorisation Collins [hep-ph/9806259]



$$f_Q(x, \mu_F^2) = 0, \quad \mu_F < m_Q$$

$$f_Q(x, \mu_F^2) = \frac{\alpha_s}{2\pi} f_g(x, \mu_F^2) \otimes P_{Qg}^{(0)} \ln \frac{\mu_F^2}{m_Q^2} + \mathcal{O}(\alpha_s^2), \quad \mu_F \rightarrow m_Q^+$$

Gluon splitting into heavy-quarks

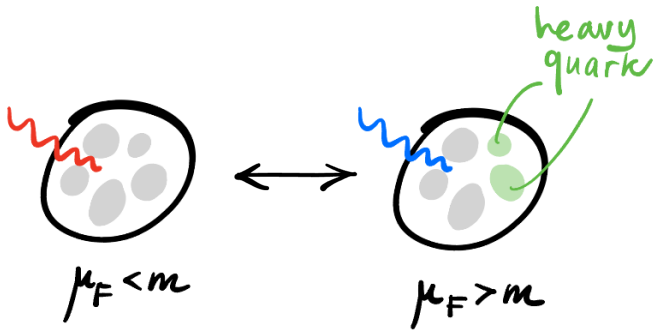
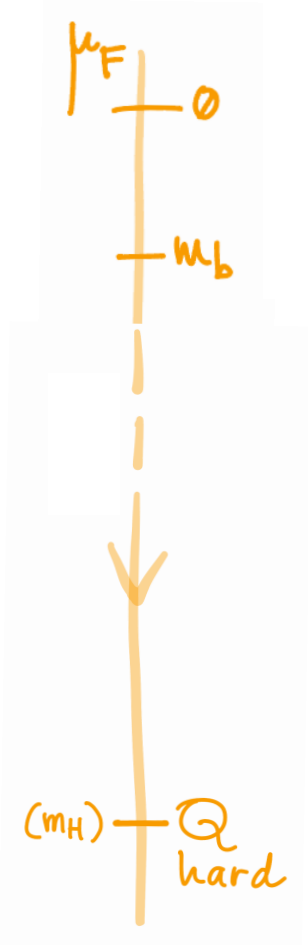


Enhancement of high-order contributions, during parton evolution, associated with multiple small-angle parton emissions

$$f_Q(x, m_b^2) \rightarrow f_Q(x, Q^2) \subset \sum \alpha_s^i(Q^2) \ln^j \frac{m_Q^2}{Q^2}$$

**Resummation
via DGLAP evolution**

All you need is collinear factorisation Collins [hep-ph/9806259]



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OME⁽¹⁾

Crossing the heavy-quark threshold in the variable-flavor number scheme (VFNS) requires matching conditions.

$$\alpha_s^{(n_f+1)}(x, \mu_F^2) = \zeta^{(n_f+1)}(\alpha_s) \alpha_s^{(n_f)},$$

$$f_i^{(n_f+1)}(x, \mu_F^2) = A_{ij}^{(n_f+1)}(\alpha_s) \otimes f_j^{(n_f)}$$

See Blümlein's talk
this afternoon

Space-like threshold matching conditions

They admit a perturbative expansion in α_s

NNLO and N3LO matching conditions are known using the formalism of OMEs

Buza et al. [9612398]

Ablinger, Behring, Blümlein et al. [2019-2024]

Massless or massive?

massless/0MVFNS scheme

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

N3LO: Duhr, Dulat, Mistlberger [1904.09990]

NNLO+PSLL: MiNNLOPS and Geneva [2402.04025, 2505.14773]

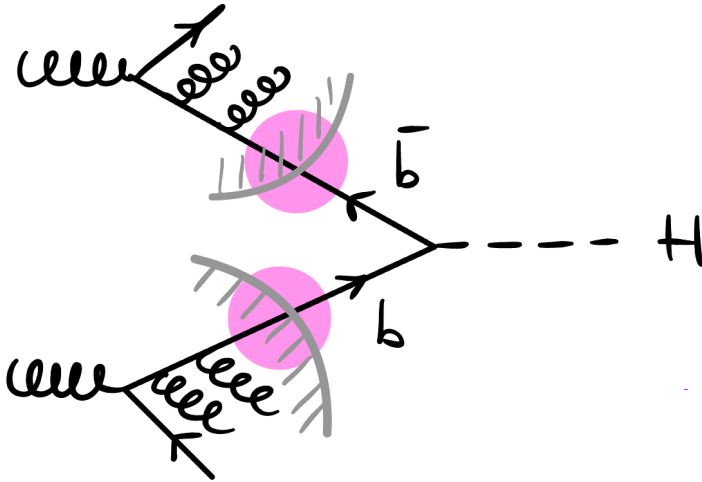
massive/decoupling scheme

- It does not resum possibly large collinear logs
- Computing higher orders is more difficult due to higher multiplicity
- ✓ Power corrections effects $\mathcal{O}(m_b)$ appear order by order in perturbative QCD

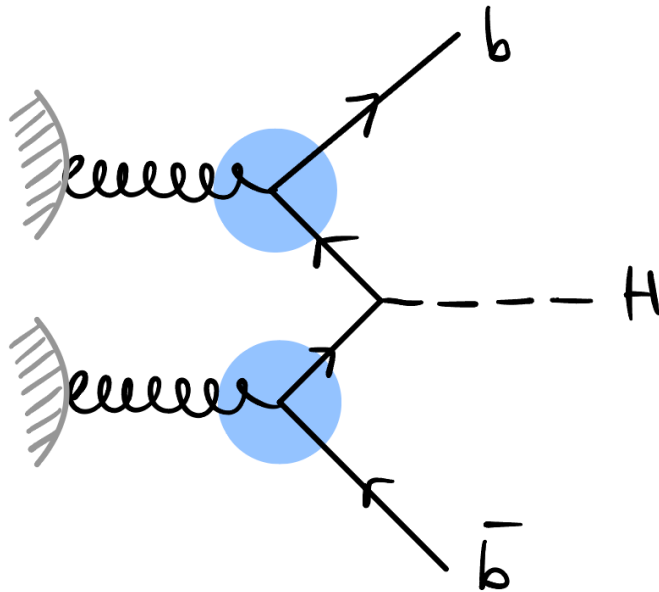
NLO: Dittmaier, Krämer, Spira [hep-ph/0309204]

NNLO+PSLL (high-energy two-loop approx): MiNNLOPS [2412.09510]

5FS



4FS



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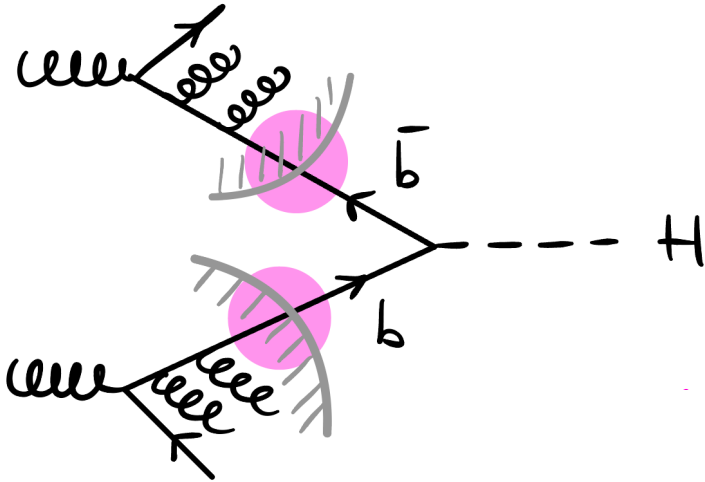
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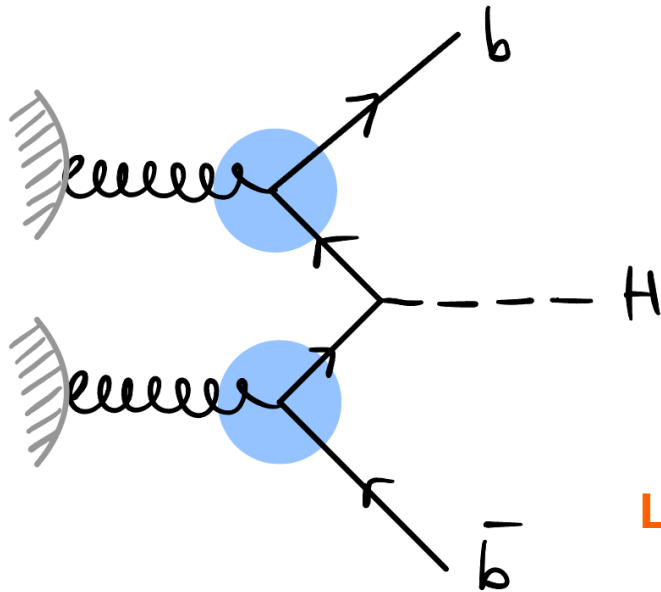
NNLO+PSLL (high-energy two-loop approx): MiNNLOPS [2412.09510]

Let's isolate them!

5FS



4FS



Matching flavour schemes

The fully-integrated methods

Santander matching

Harlander, Kramer, Schumacher [1112.3478]

ad-hoc *combination* as weighted average

no longer in use by LHCHWG

FONLL matching

Forte, Napoletano, Ubiali
[1508.01529, 1607.00389]

Proper matching with subtraction of double counting

now applied @ $N^3LO^{5FS} + NLO^{4FS}$

Duhr, Dulat, Hirschi, Mistlberger [2004.04752]

NLO+NNLLpart+ $y_b y_t$ matching

Bonvini, Papanastasiou, Tackmann
[1508.03288, 1605.01733]

cross-section grids available

current bbH reference prediction of the



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The fully-exclusive schemes we studied

5FS+isolated power corrections

based on Gauld [2107.01226]

$$d\sigma^{GMVFNS} := \text{diagram} + d\sigma^{p.c.}$$

The diagram shows a quark-antiquark annihilation process into a Higgs boson, with a gluon jet. The quarks are labeled b and $\bar{b}$. The gluon jet is represented by a wavy line. The Higgs boson is represented by a dashed line labeled H . The power corrections $d\sigma^{p.c.}$ are highlighted in an orange box.

Focus of the talk!

CB, Gauld, Sankar, Wiesemann, Zanderighi [in preparation]

Simplified ACOT scheme

based on Aivazis, Collins, Olness, Tung [9312319]

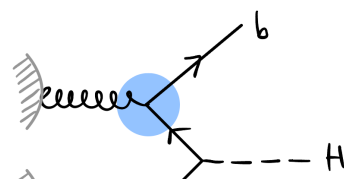
$$\text{diagram} + \text{diagram} - \text{diagram}$$

The diagram shows a quark-antiquark annihilation process into a Higgs boson, with a gluon jet. The quarks are labeled b and $\bar{b}$. The gluon jet is represented by a wavy line. The Higgs boson is represented by a dashed line labeled H . The first orders of b PDF are highlighted in a red box.

first orders of b PDF

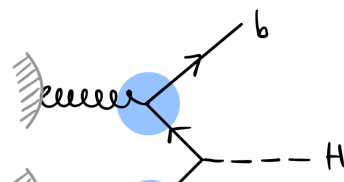
CB, Gauld, Guzzi, Nadolsky, Sankar, Wiesemann, Xie, Zanderighi [in progress]

Numerical isolation of PCs



$$\sim \log m_b + \text{const.} + \mathcal{O}(m_b)$$

Analytically known from threshold matching equations (OMEs)

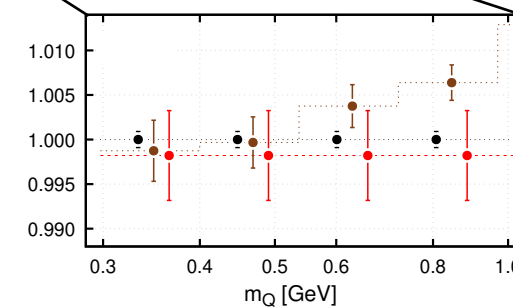
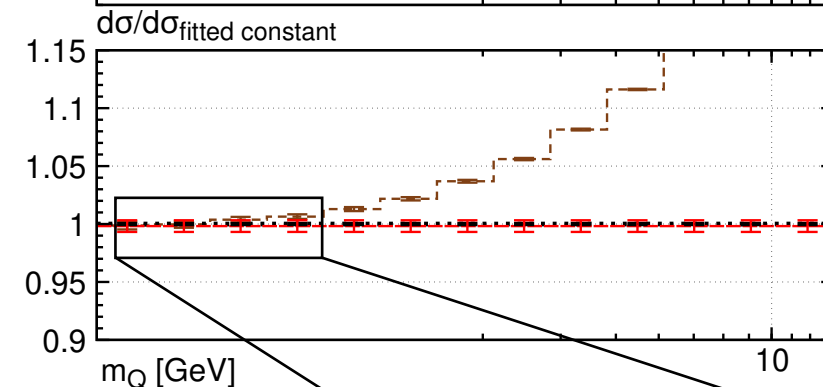
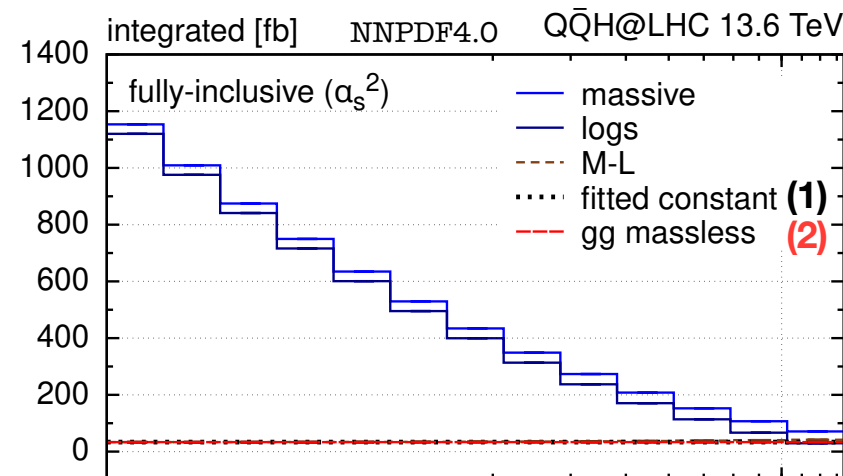


$$-d\sigma^{\log m_b} - d\sigma^{m=0, \text{fin.}} = \mathcal{O}(m_b)$$

How to compute the massless constant?

(1) $\lim_{m_b \rightarrow 0} \left\{ \begin{array}{c} \text{Feynman diagram 1} \\ \text{Feynman diagram 2} \end{array} - d\sigma^{\log m_b} \right\} = \text{const.}$

(2) $\int d\Phi_{b, \bar{b}} \left\{ \begin{array}{c} \text{Feynman diagram 1} \\ \text{Feynman diagram 2} \end{array} \right\} \text{ with } m_b = 0$
 using a NNLO subtraction/slising technology



MiNNLOPS meets qT-slicing

We present a **fixed-order MiNNLO-inspired qT-slicing** that we have studied and coded for $b\bar{b} \rightarrow H$

We construct a fixed-order qT-slicing directly from the MiNNLOPS formula

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

$$\frac{d\sigma^{res}}{dp_T d\Phi_X} = \frac{d}{dp_T} \left\{ e^{-\tilde{S}(p_T)} \mathcal{L}(\Phi_X, p_T) \right\} = e^{-\tilde{S}(p_T)} D(p_T)$$

Sudakov form factor
Luminosity

$$\frac{d\sigma_X}{d\Phi_X} = \int_0^{p_T^{max}} dp_T \frac{d\sigma^{res}}{dp_T d\Phi_X} - \int_0^{p_T^{max}} dp_T \left[\frac{d\sigma^{res}}{dp_T d\Phi_X} \right]_{\mathcal{O}(\alpha_s^2), \mu=\mu_{FO}} + \int d\Phi_{rad} \frac{d\sigma_{XJ}^{NLO}}{d\Phi_{rad} d\Phi_X}$$

Inclusive hard contribution
XJ easy part

$$\left[e^{-\tilde{S}} \mathcal{L} \right]_0^{p_T^{max}} = \mathcal{L}(\mu = M, p_T^{max}) = \frac{d|M_X|^2}{d\Phi_X} \mathcal{H}$$

$$[e^{-\tilde{S}} D]_{NNLO} = D^{(1)}(\mu_{FO}, p_T) (1 - \tilde{S}^{(1)}(\mu_{FO}, p_T)) + D^{(2)}(\mu_{FO}, p_T)$$

$$D^{(2)}(\mu_{FO}, p_T) = D^{(2)}(\mu = p_T, p_T) + \left([P_0 \otimes D^{(1)}]_{symb} - \beta_0 D^{(1)} \right) \ln \frac{p_T^2}{M^2}$$

FOatQ

Gavardi, Oleari, Re [2204.12602]
CB, Sankar, Wieseemann, Zanderighi [2402.04025]

MiNNLO~~S~~ meets qT-slicing

Modified logarithms

$$\tilde{L}(p_T) = \frac{1}{p} \ln \left[\left(\frac{M}{p_T} \right)^p + 1 \right]$$

The integral of the truncated expansion with a small cut is

$$\int_{Mr_{cut}}^M dp_T [D]_{\mathcal{O}(\alpha_s^2)} = D \Big|_{\text{Jac} \cdot \tilde{L}^n(p_T)/p_T \rightarrow \tilde{L}^{n+1}(Mr_{cut})/(n+1)}$$

The **MiNNLO-inspired qT-slicing** reads

$$d\sigma_X^{NNLO}(r_{cut}) = \underbrace{\mathcal{L}(\mu = M, M) - \left[D^{(1)}(1 - \tilde{S}^{(1)}) + D_{(FO)}^{(2)} \right]_{\tilde{L}^n(p_T)/p_T \rightarrow \tilde{L}^{n+1}(Mr_{cut})/(n+1)}}_{\text{below cut}} + \underbrace{\int_{r > r_{cut}} dr \frac{d\sigma_{XJ}^{NLO}}{dr}}_{\text{above cut}}$$

MiNNLO~~S~~ meets qT-slicing

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The choice of the functional form of $\tilde{L}$ is only a power correction in r_{cut}

One can show the correspondence with the direct-space Σ coefficients of Catani-Grazzini formulation

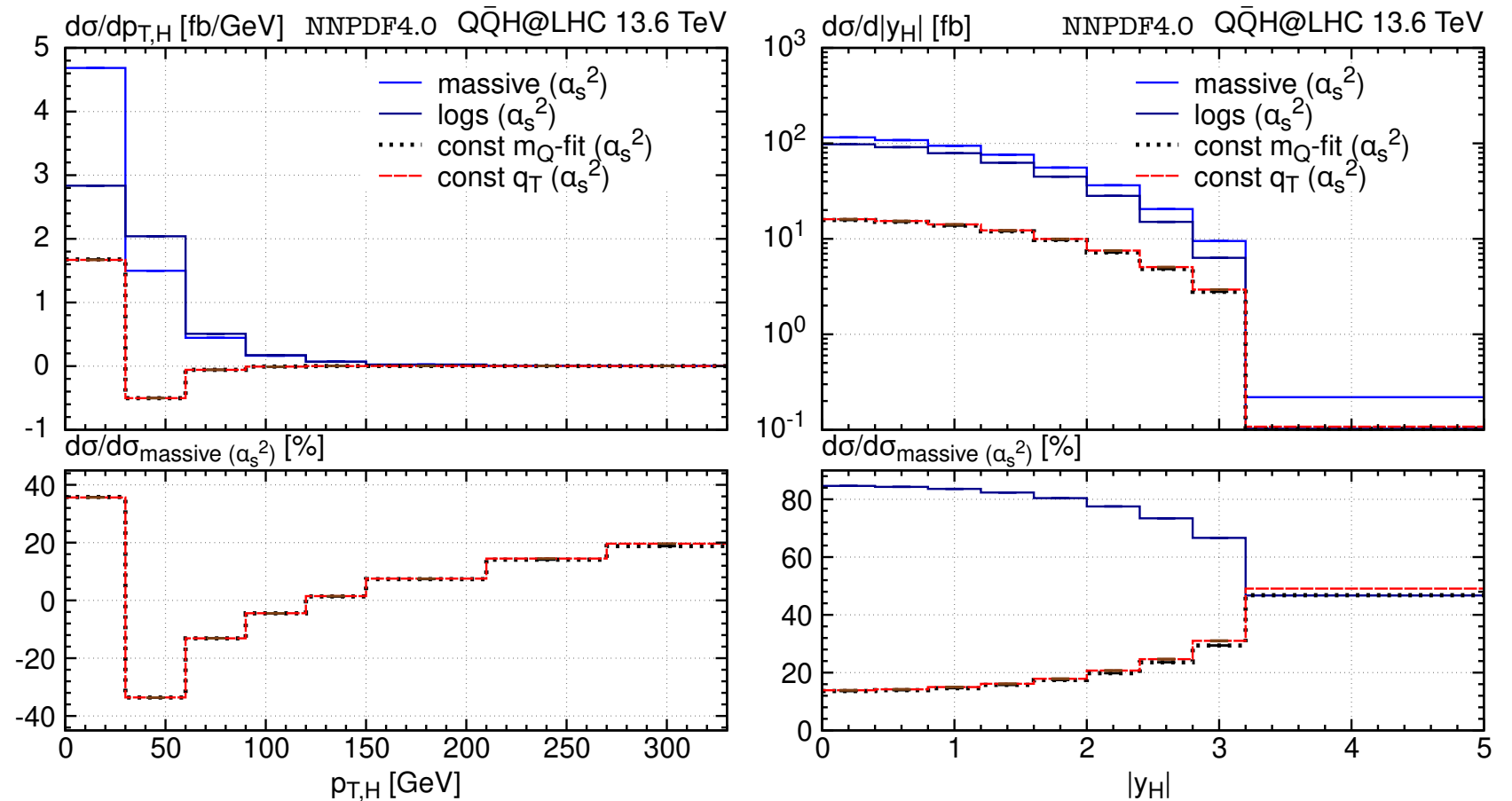
Catani, Grazzini [hep-ph/0703012]

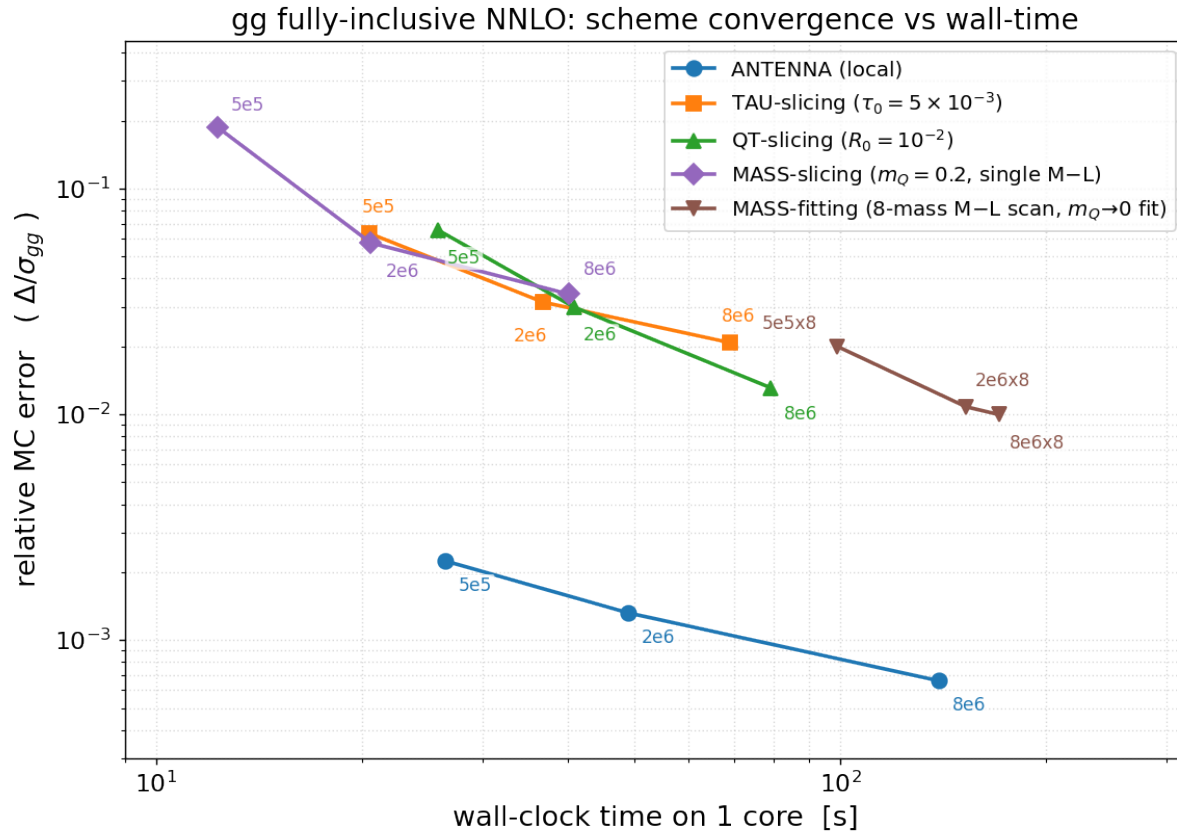
The numerical results of MiNNLO-inspired qT-slicing for $b\bar{b} \rightarrow H$:

- Have the expected $\mathcal{O}(r_{cut}^2)$ behavior
- Agree with the analytic fully-integrated coefficients for all the NNLO channels Harlander, Kilgore [hep-ph/0304035]
- Agree against our τ_0 -slicing implementation at differential level τ_0 -slicing implementation based on [1505.04794]

The extraction of the massless constant can be performed in a **differential way**, and at $\mathcal{O}(\alpha_s^2)$ validated against the MiNNLO-inspired qT-slicing.

The differential validation





ETHZ node "yueh": AMD Ryzen 9 7950X3D, 16C/32T, 5.76 GHz max — single core pinned

NNPDF4.0
 $\mu = m_h/2$

Performances

Slicing vs local subtraction
 for the gg constant $\mathcal{O}(\alpha_s^2)$

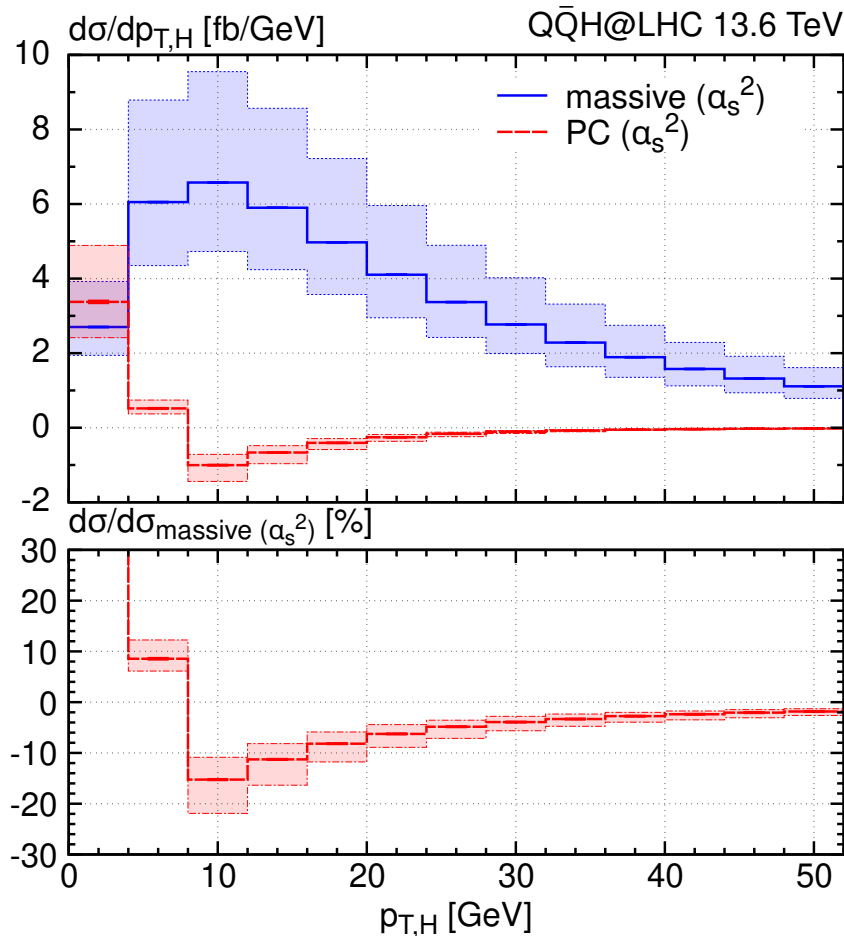
All the different methods are
 implemented in our C++ code

ANTENNA: C++ bbH implementation based on antenna subtraction Gerhmann-De Ridder, Gerhmann, Glover [hep-ph/0505111]
 with ingredients validated against DY implementation in Fortran NNLOJET Huss et al. [2503.22804]

bbH PC at differential level

NNPDF4.0, $m_b = 4.92$ GeV
 $\mu_{0,R} = \mu_{0,F} = \mu_{0,Y} = m_H/2 + 7\text{pt sv}$

We study the impact of power corrections at the **bottom-quark mass** differentially at $\mathcal{O}(\alpha_s^2)$



As expected, power corrections vanish at large transverse momenta, while they are singular at low $p_{T,H}$

$$d\sigma \sim dz dk_T^2 \frac{\mathcal{P}_0(z) k_T^2 + T_R m_Q^2}{(k_T^2 + m_Q^2)^2}$$

$m_Q \rightarrow 0 \rightarrow \frac{\mathcal{P}_0(z)}{k_T^2}$ *momton collinear pole*

$$\int_0^{p_{T,H}} d\sigma \sim \ln \frac{p_{T,H}^2 + m_Q^2}{m_Q^2} + \dots$$

$$= \ln \frac{p_{T,H}^2}{m_Q^2} + \frac{m_Q^2}{p_{T,H}^2} + \dots$$

singular power corrections at small $p_{T,H}$

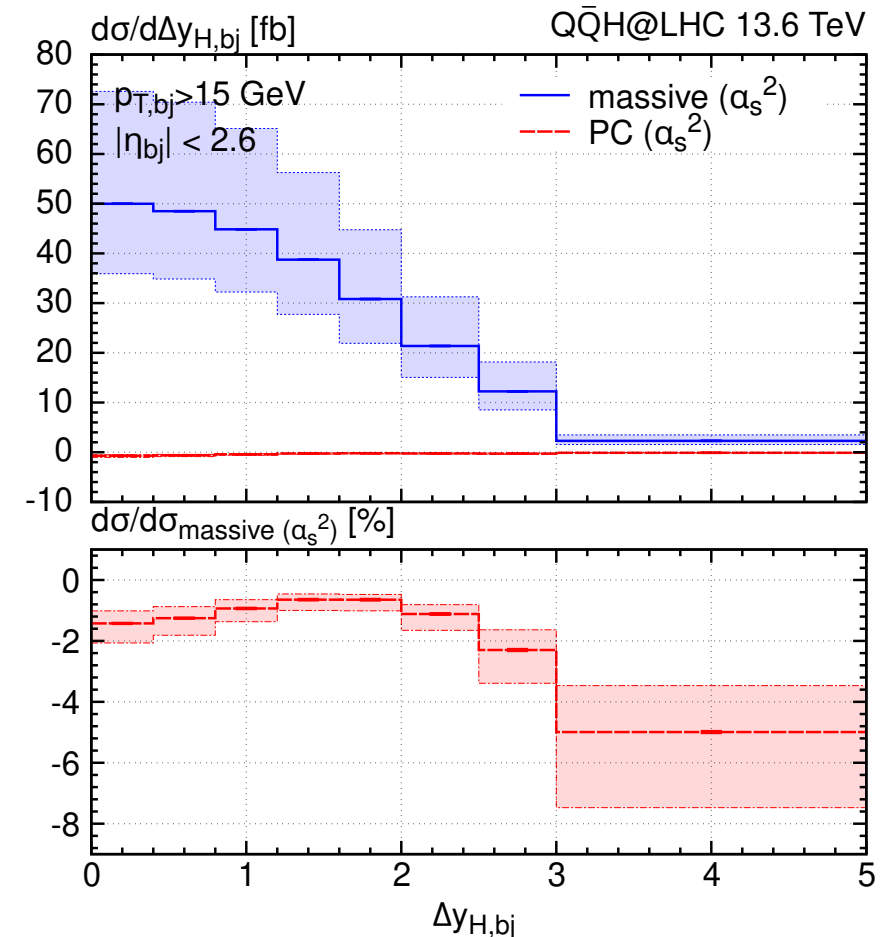
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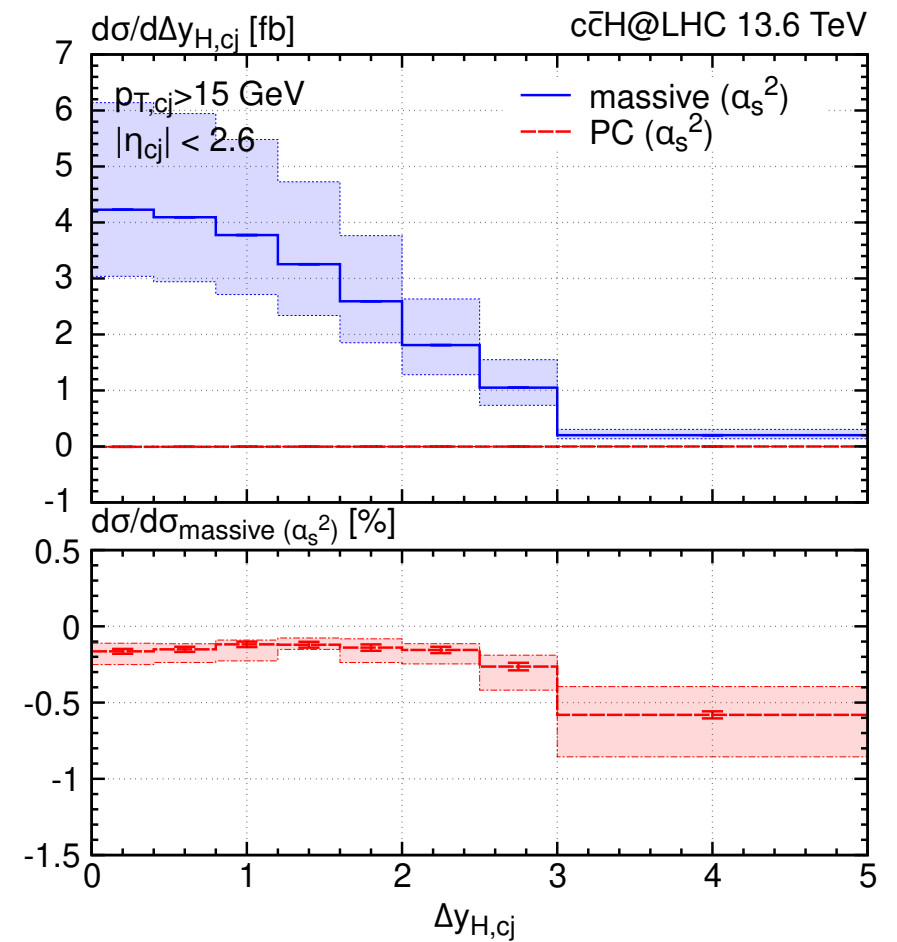
Fiducial regions with b-tagging can also be studied, notably the single-b-tag region, where one collinear enhancement survives

Very small power corrections, below 1% of the massive prediction, **except for the rapidity difference** $\Delta y_{H,bj}$ with a peculiar shape



ccH phenomenology

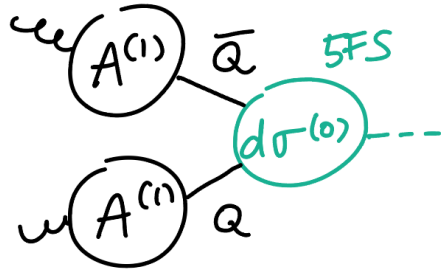
Same study at the charm mass with
even smaller power corrections



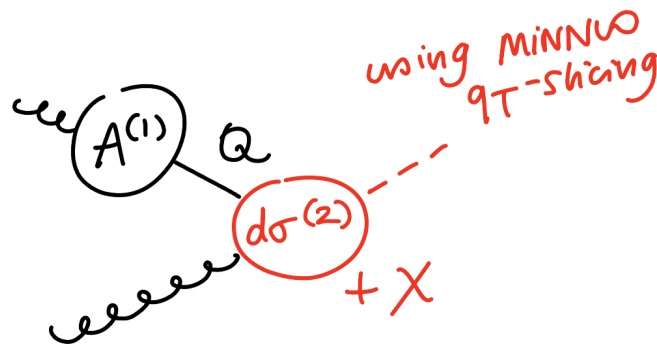
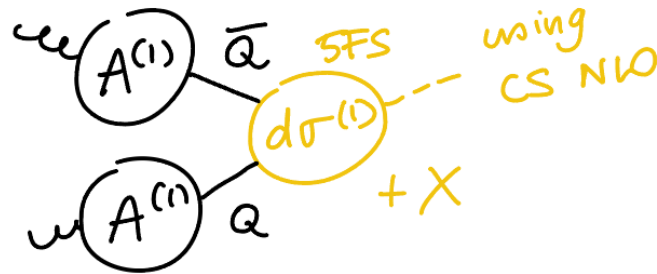
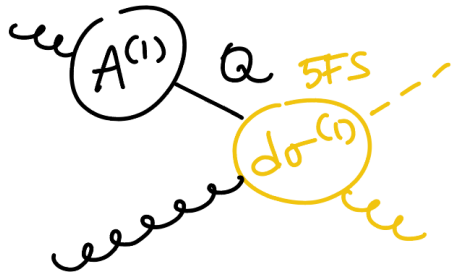
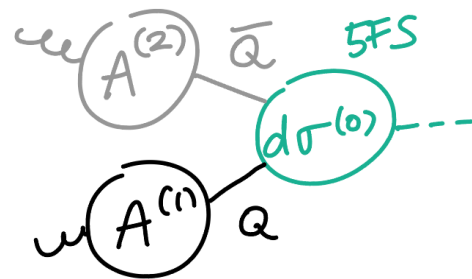
The logarithmic prediction: OMEs $\otimes$ 5FS

Next order please

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

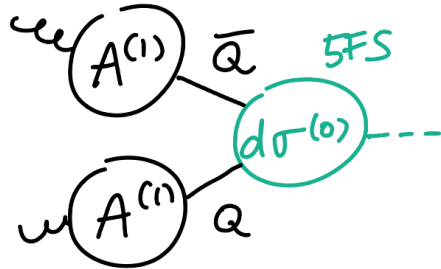


$$\mathcal{O}(\alpha_s^3)$$

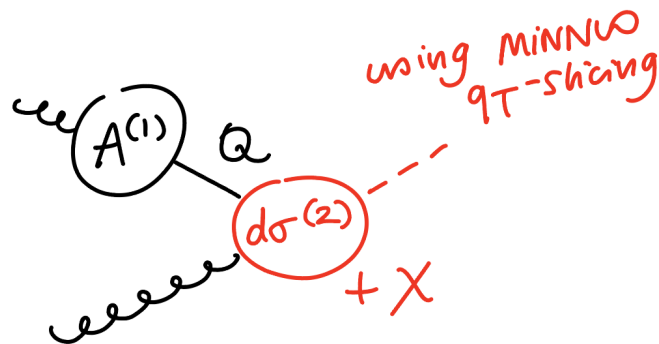
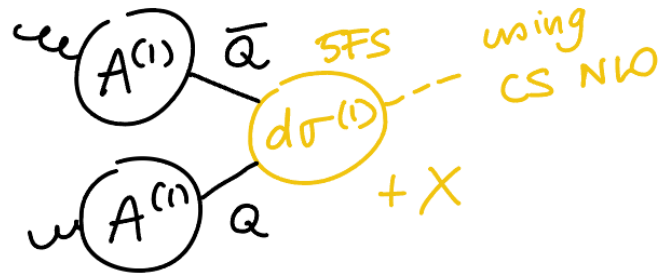
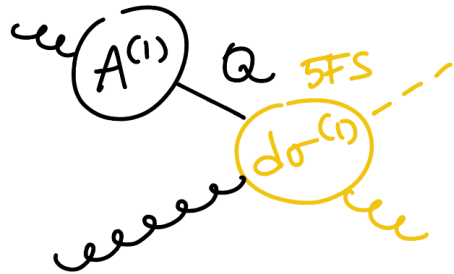
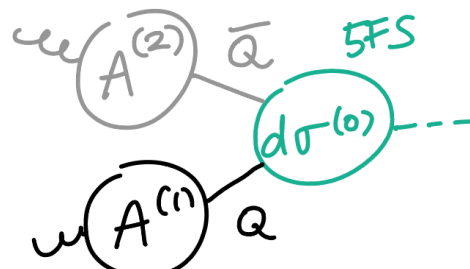


The logarithmic prediction: OMEs $\otimes$ 5FS

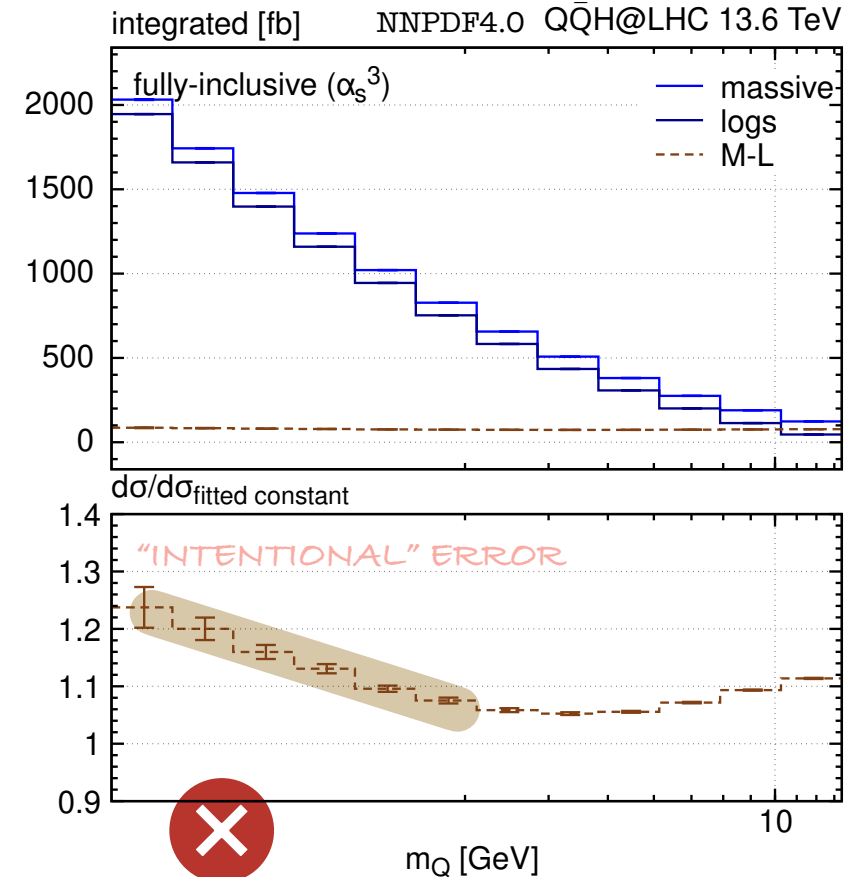
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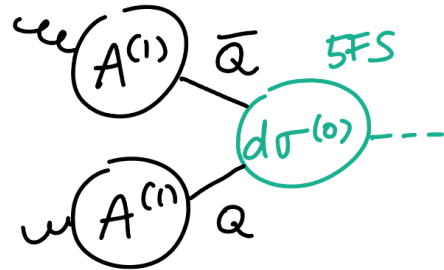
Next order please



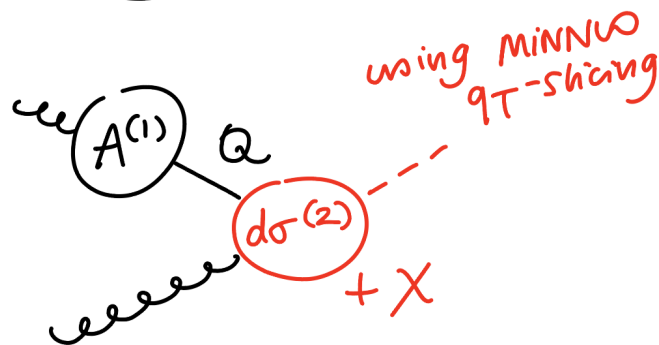
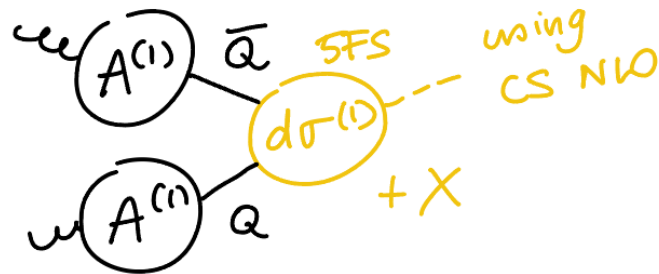
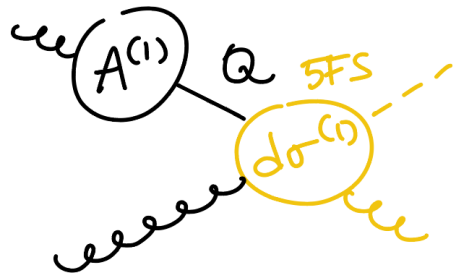
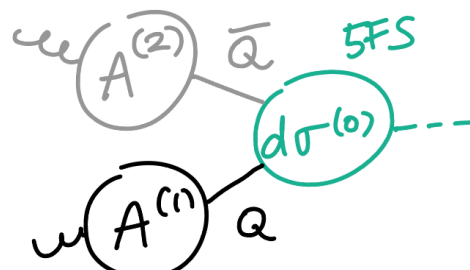
A small $\mathcal{O}(0.5\%)$ error in the massive or logarithmic input spoils the possibility to extract the N3LO constant!

The logarithmic prediction: OMEs $\otimes$ 5FS

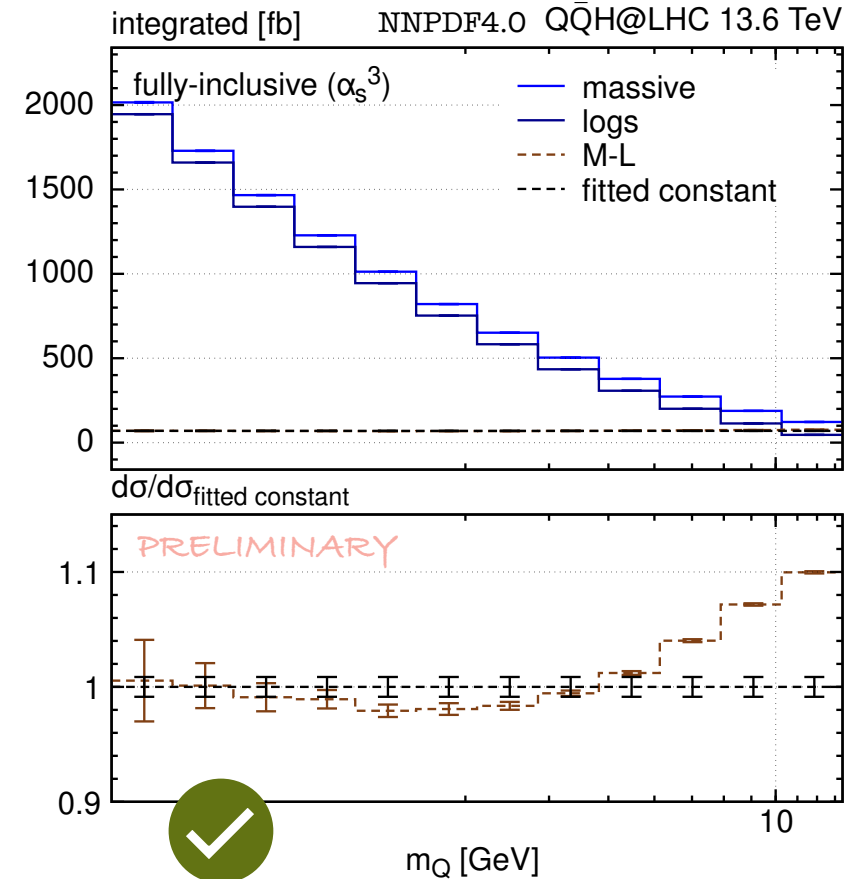
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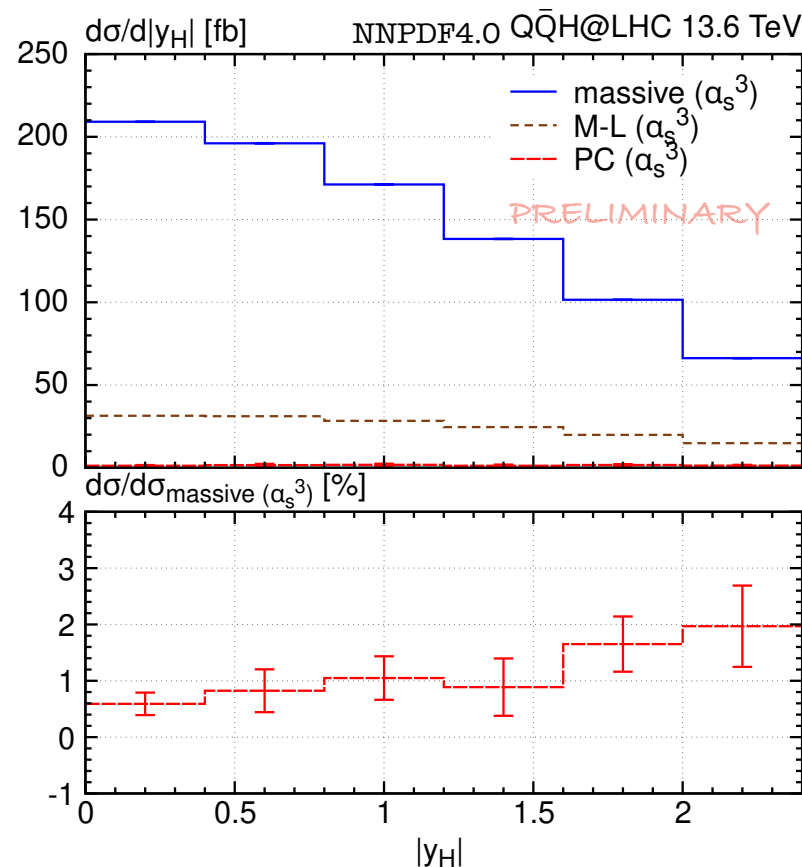
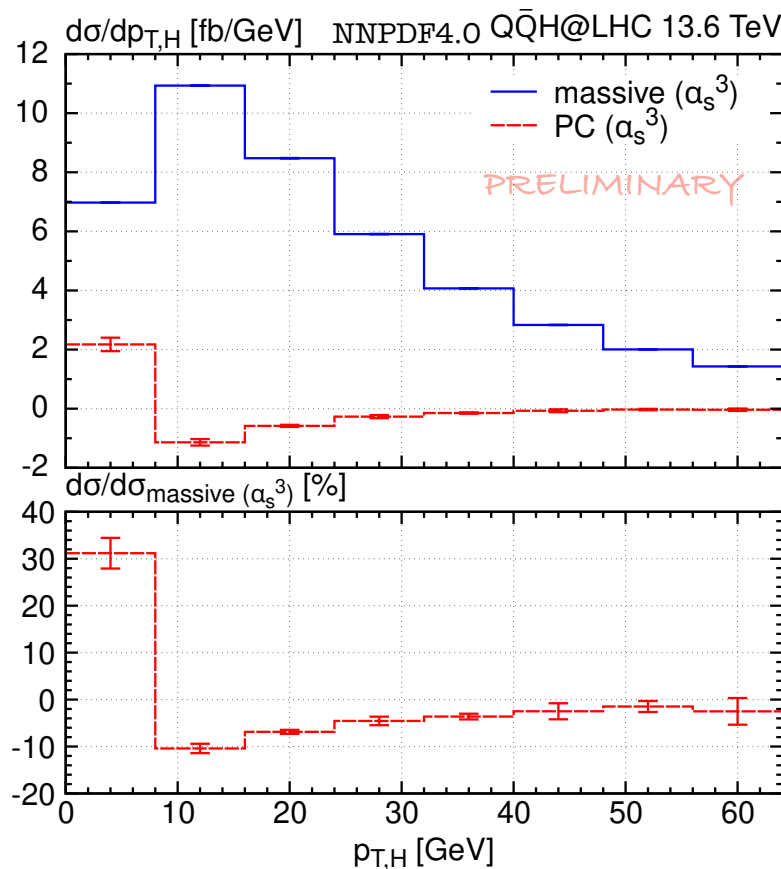
Next order please



Fundamental validation of the correct implementation of the logs!

Extracting NLO PCs bin by bin

MiNNLO qT-slicing with OMEs + small-mass fit allows us to extract the N3LO constant differentially (M-L) from NLO 4FS distributions and isolate the NLO power correction at the physical bottom mass (PC)



Computational resources: MPCDF Garching and ETH Lugano

Conclusions

We have presented a **gauge-invariant fully-exclusive isolation of power corrections** in QQH production.

- Power corrections are obtained by subtracting **logarithms plus a fitted constant** from the massive calculation
- This validates the logarithms predicted by convoluting massless channels with OMEs
- The power corrections can be added to any massless NNLO/N3LO prediction without double counting issues, giving a GM-VFNS prediction for bbH at inclusive and differential level

For the bottom quark, the **power corrections are small, around $\lesssim 1\%$** . They matter only at low Higgs transverse momentum and at large rapidity separations between the Higgs boson and the quarks.

Outlooks: application to other QQ+ processes and bbH comparison with other GM-VFNS

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Thank you for your attention!

Backup slides

Fully-integrated combinations

- **Santander matching**

Harlander, Kramer, Schumacher [1112.3478]

- ad-hoc combination as weighted average
- no longer in use by LHCHWG

$$\frac{1}{1+w} \left\{ \begin{array}{c} \text{Diagram 1} \\ \text{Diagram 2} \end{array} \right\} + w \left\{ \begin{array}{c} \text{Diagram 3} \\ \text{Diagram 4} \end{array} \right\}$$

$$w = \ln \frac{m_H}{m_b} - 2$$

Fully-integrated combinations

- **Santander matching**

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- ad-hoc combination as weighted average
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- **FONLL matching**

Forte, Napoletano, Ubiali
[1508.01529, 1607.00389]

- alternative implementation used to cross-checks
- now applied @ $N^3\text{LO}^{5FS} + \text{NLO}^{4FS}$

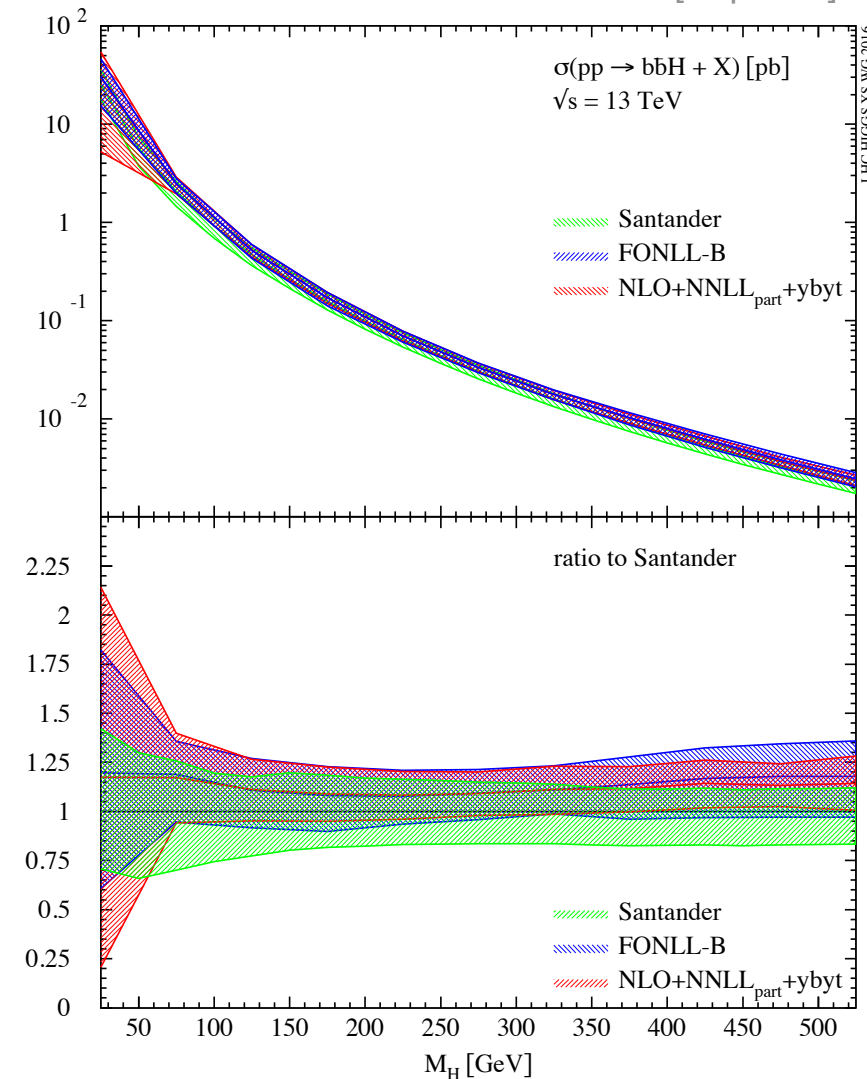
Duhr, Dulat, Hirschi, Mistlberger [2004.04752]

- **$\text{NLO}+\text{NNLL}_{\text{part}}+y_b y_t$ matching**

Bonvini, Papanastasiou, Tackmann
[1508.03288, 1605.01733]

- cross-section grids available
- current bbH reference prediction of the LHCHWG

LHCHWG [Report 4]

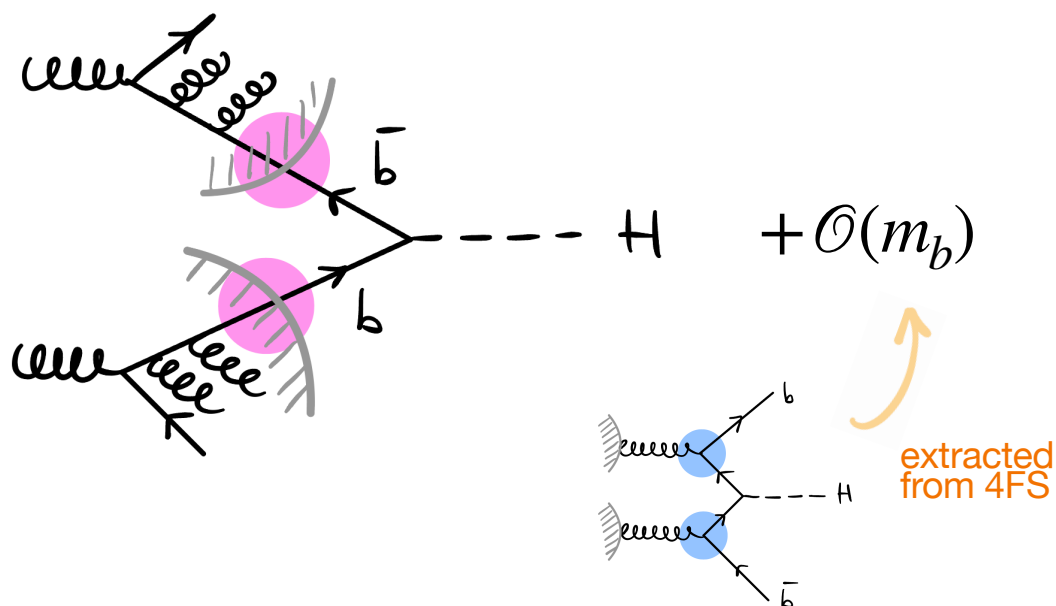


Matching at differential level

The matching of the 5FS and 4FS has been performed only at a fully inclusive level for bbH .
We want to **develop a fully differential matching** of the flavour schemes: we are investigating **two schemes**!

Power-Correction Isolation scheme

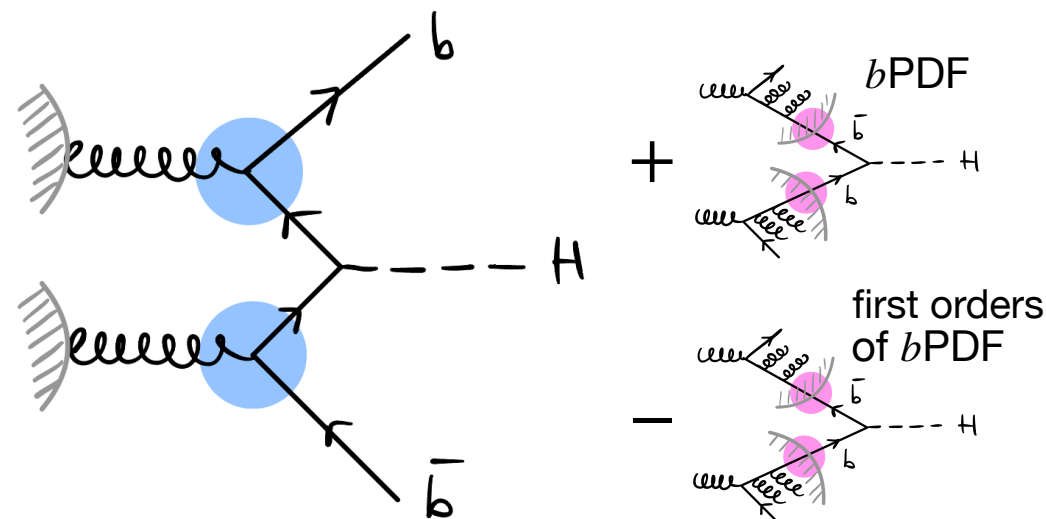
based on Gauld [2107.01226]



CB, Gauld, Sankar, Wiesemann,
Zanderighi [in progress]

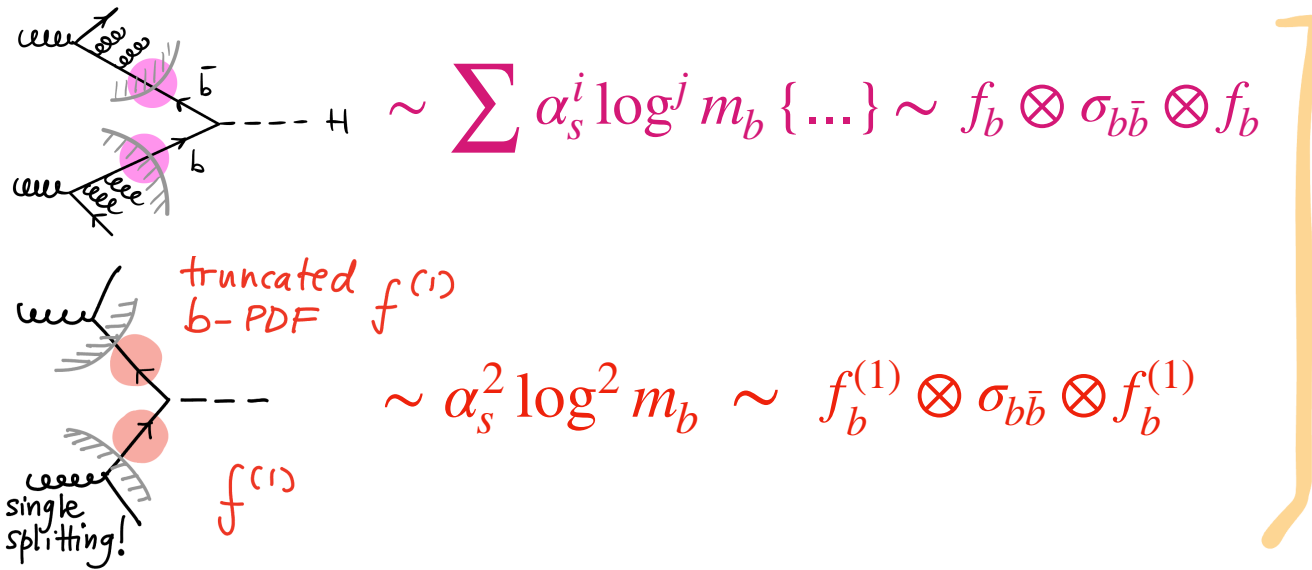
sACOT scheme

based on Aivazis, Collins, Olness, Tung (ACOT) [9312319]



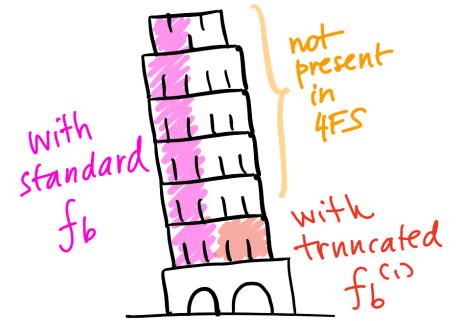
CB, Gauld, Guzzi, Nadolsky, Sankar,
Wiesemann, Xie, Zanderighi [in progress]

sACOT scheme

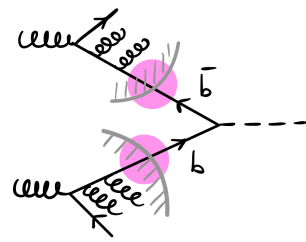


$\sim \sum \alpha_s^i \log^j m_b \{...\} \sim f_b \otimes \sigma_{b\bar{b}} \otimes f_b$
 truncated b -PDF $f_b^{(1)}$
 $\sim \alpha_s^2 \log^2 m_b \sim f_b^{(1)} \otimes \sigma_{b\bar{b}} \otimes f_b^{(1)}$
 single splitting! $f_b^{(1)}$

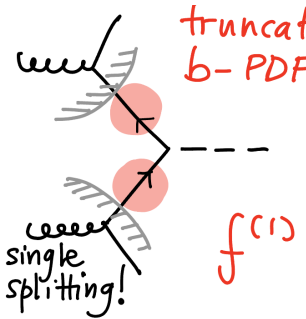
The difference gives exactly the missing tower of logs in 4FS!



sACOT scheme



$$\sim \sum \alpha_s^i \log^j m_b \{ \dots \} \sim f_b \otimes \sigma_{b\bar{b}} \otimes f_b$$

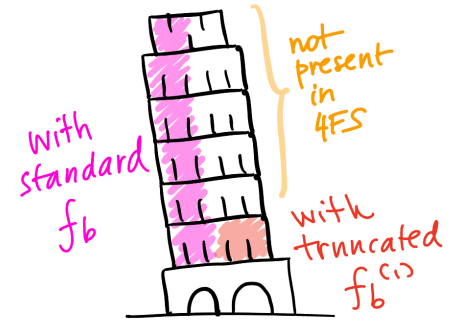


truncated b -PDF $f_b^{(1)}$

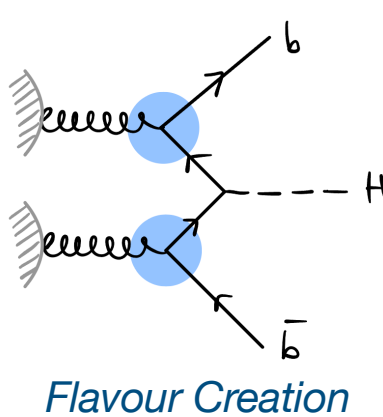
single splitting!

$$\sim \alpha_s^2 \log^2 m_b \sim f_b^{(1)} \otimes \sigma_{b\bar{b}} \otimes f_b^{(1)}$$

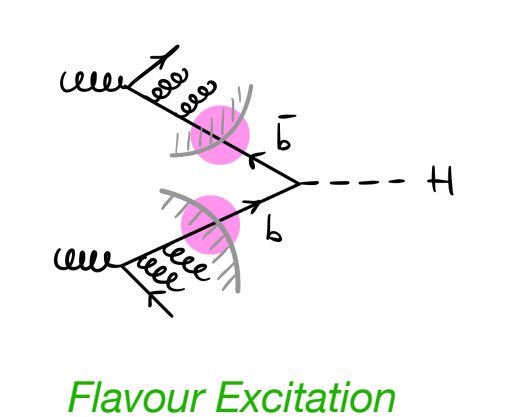
The difference gives exactly the missing tower of logs in 4FS!



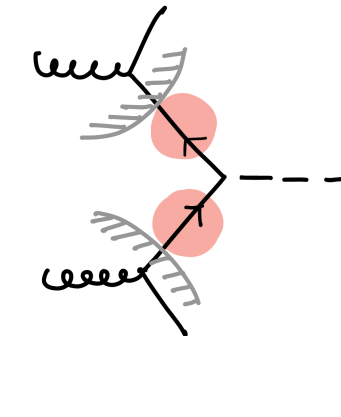
$$d\sigma^{sACOT} :=$$

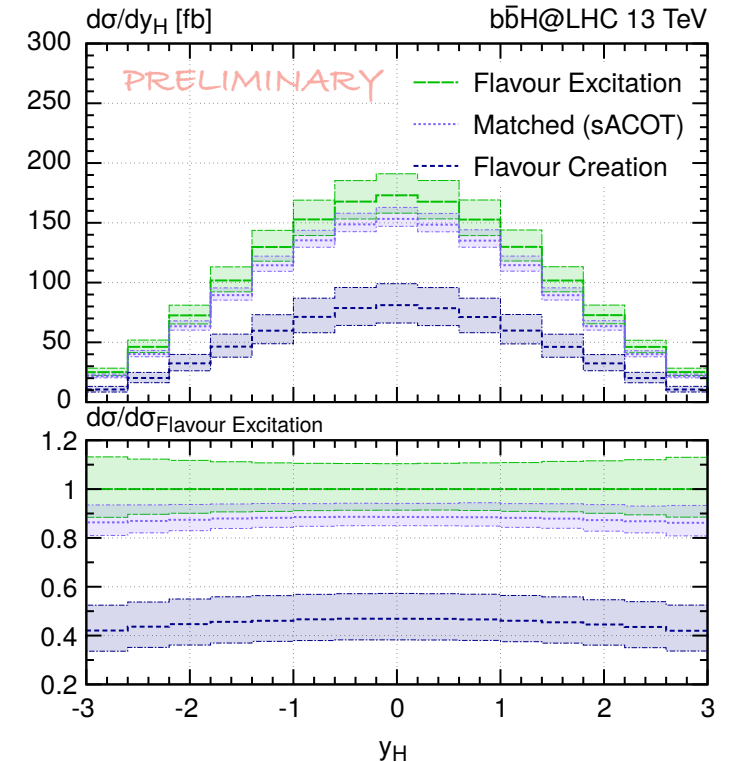


Flavour Creation



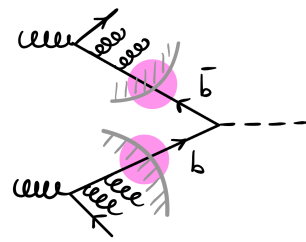
Flavour Excitation



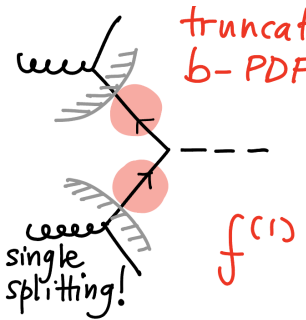


CB, Gauld, Guzzi, Nadolsky, Sankar, Wiesemann, Xie, Zanderighi [in progress]

sACOT scheme



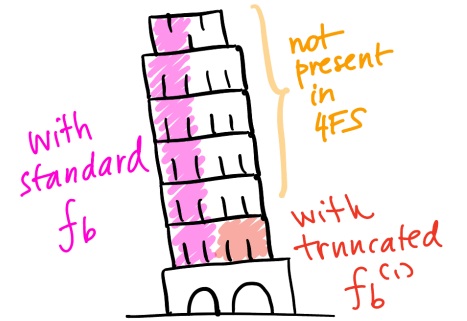
$$\sim \sum \alpha_s^i \log^j m_b \{ \dots \} \sim f_b \otimes \sigma_{b\bar{b}} \otimes f_b$$



truncated b -PDF $f^{(1)}$

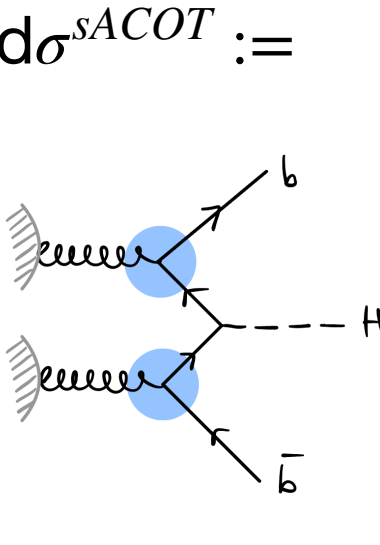
$$\sim \alpha_s^2 \log^2 m_b \sim f_b^{(1)} \otimes \sigma_{b\bar{b}} \otimes f_b^{(1)}$$

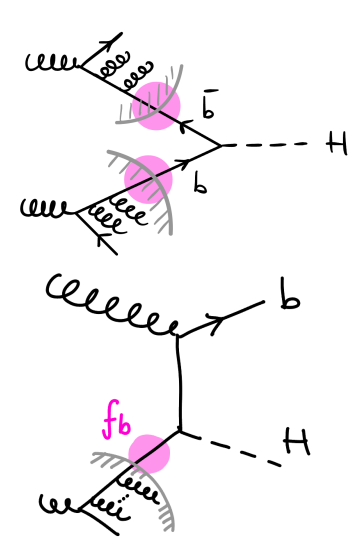
The difference gives exactly the missing tower of logs in 4FS!

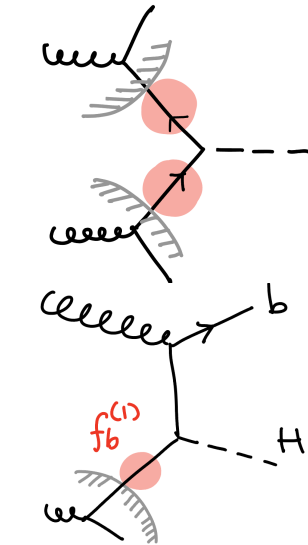


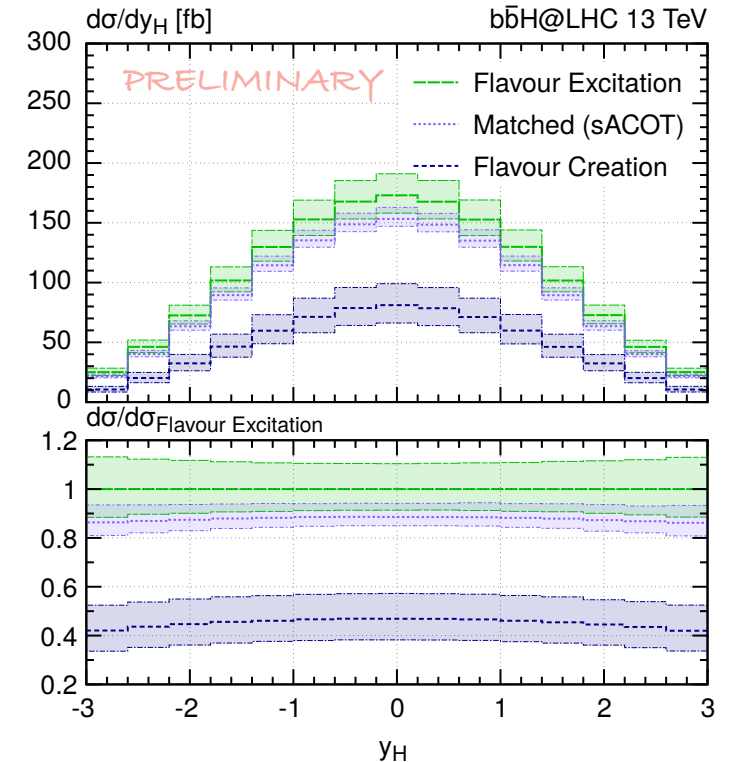
You need to **unpack the perturbative structure** of the massless scheme: non-trivial beyond this LO!

$$d\sigma^{sACOT} :=$$



$$+$$


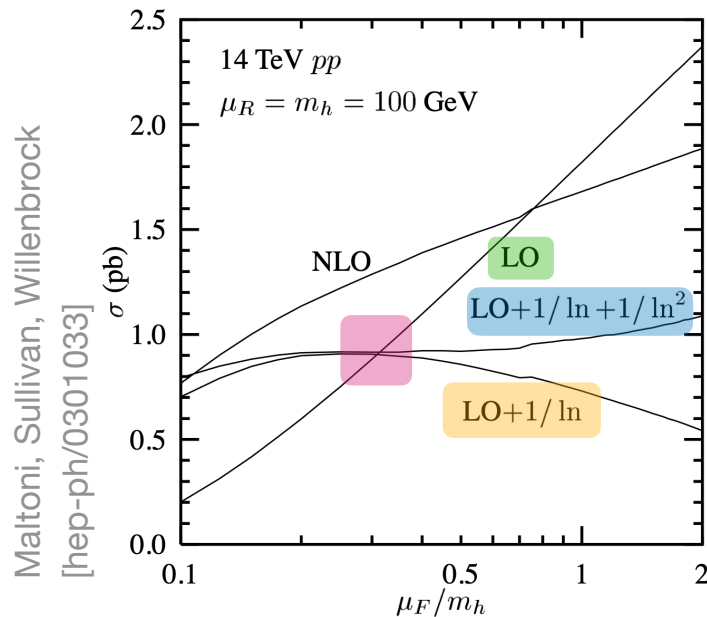
$$-$$




CB, Gauld, Guzzi, Nadolsky, Sankar, Wiesemann, Xie, Zanderighi [in progress]

Historical LO comparisons: addendum

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



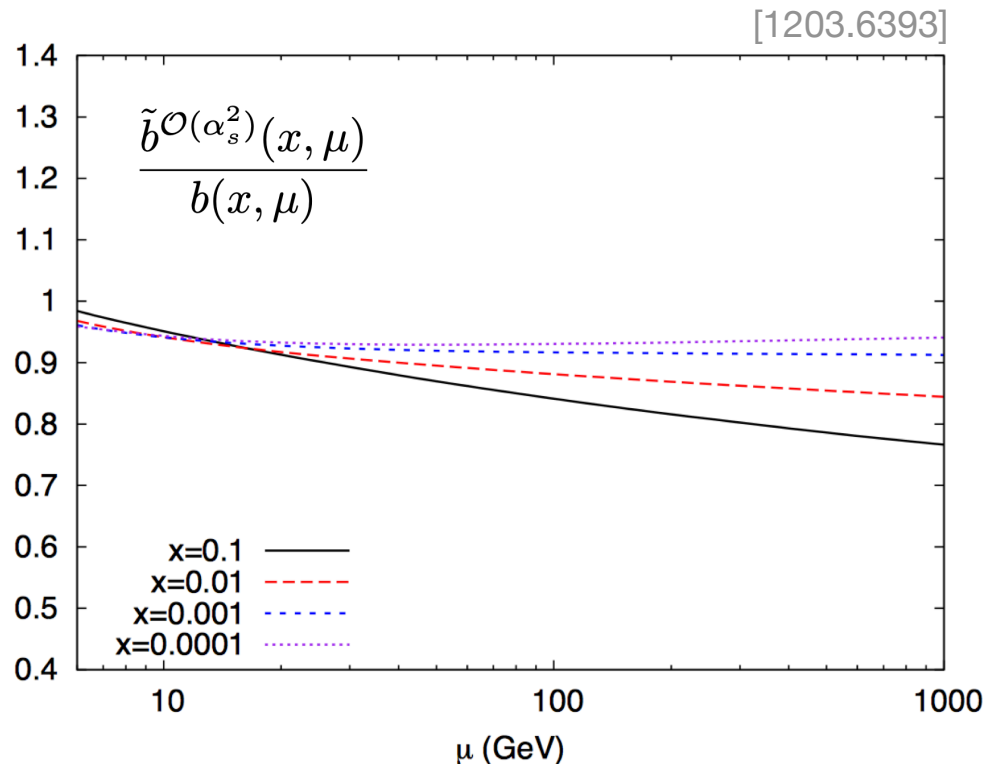
For $\mu_F = m_H/4$, FO computations in the different schemes become compatible. It turned out that the collinear logs have a small effect at this scale.

Focusing on the 5FS predictions, if we add the logarithmic corrections from $bg \rightarrow bh$ to $b\bar{b} \rightarrow h$ and also the log-enhanced terms from $gg \rightarrow b\bar{b}H$, the effect is small for $\mu_F = m_H/4$.

The improvement of the compatibility opens the **possibility of matching** together the predictions at least at the inclusive level (Santander matching, FONLL, NLO+NNLLpart+ybyt)

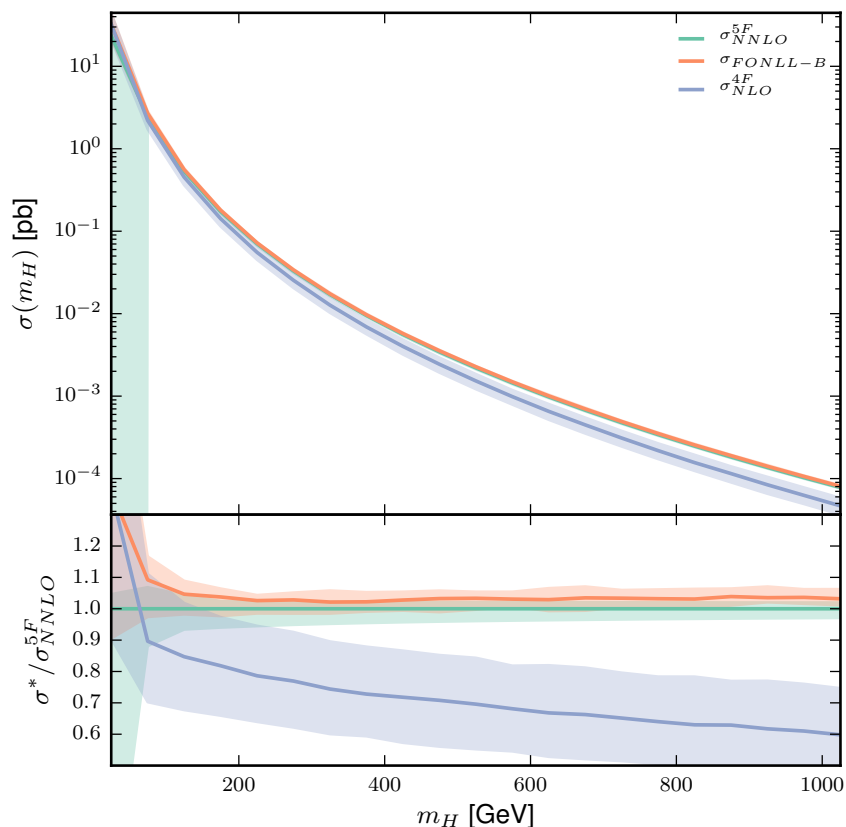
Differences between schemes

A lot of progress in understanding the origin of the differences has been made in the past years. The predictions can be merged into a consistent picture by considering two main results.



1. At NLO, the resummation effects of collinear logs are important only at high Bjorken- x
2. The possibly large ratios m_H^2/m_b^2 are always accompanied by universal phase space factors f

$$\ln^2 \frac{m_H^2 f}{m_b^2} = \ln^2 \frac{\tilde{\mu}^2}{m_b^2}, \quad \tilde{\mu} < m_H$$



Forte, Napoletano, Ubiali [1607.00389]

The basic FONLL idea is to **expand the 5FS computation** (where the logs are resummed with $N^k LL$ accuracy) and **replace** them with their **massive-scheme counterparts** (up to the $N^n LO$ level).

$$\text{FONLL-A} = NNLL + LO_{4FS}$$

$$\text{FONLL-B} = NNLL + NLO_{4FS}$$

After expressing both the 5FS and 4FS calculations in terms of the **same 5FS PDFs and strong couplings**, we can consistently remove the **overlap**,

$$\sigma^{FONLL} = \sigma^{5FS} + \sigma^{4FS} - \sigma_{m_b \rightarrow 0}^{4FS}$$

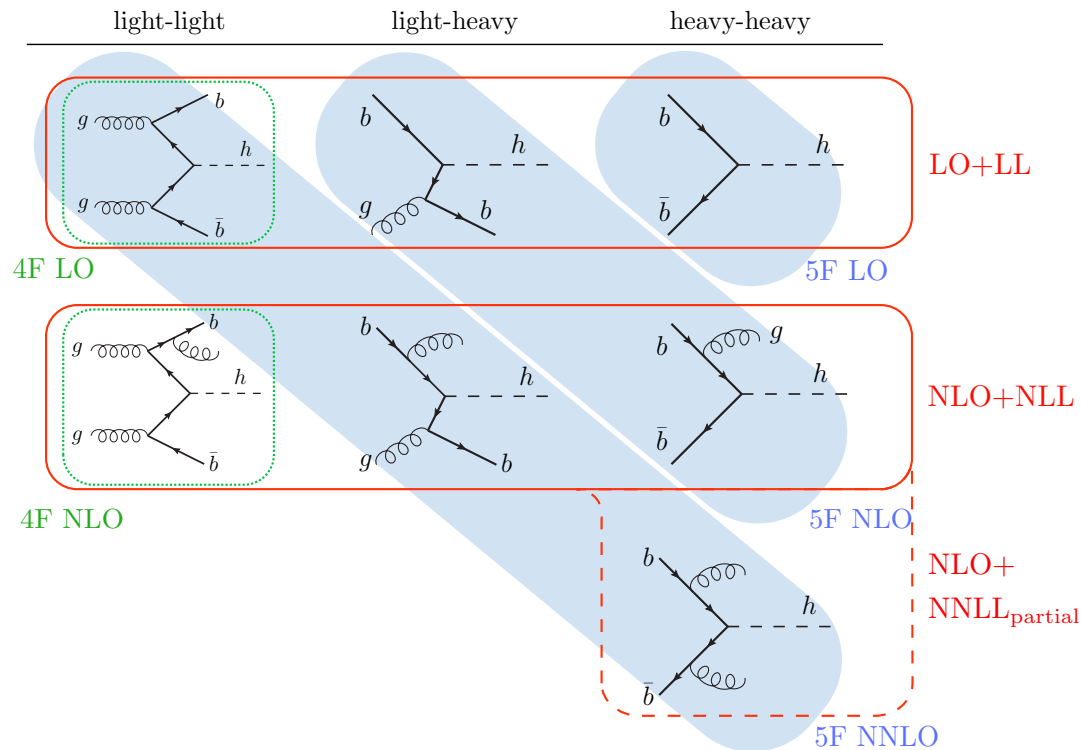
As a validation, for high values of the Higgs mass $\sigma_{FONLL} \rightarrow \sigma_{5FS}$, while σ_{FONLL} is close to the 4FS prediction for soft Higgs.

FONLL has been applied at the **differential level** for Z production in association with a bottom-flavour jet

$$d\sigma^{FONLL} = d\sigma^{5FS} + \left(d\sigma_{m_b}^{4FS} - d\sigma_{m_b \rightarrow 0}^{4FS} \right)$$

[Gauld, Gehrmann-De Ridder, Glover, Huss, Majer, 2005.03016]

NLO+NNLLpart+ybyt



NLO+NNLLpart with $\mu_b = m_b \leftrightarrow \text{FONLL-B}$

Matching of fixed-order calculation (4FS prediction) and the resum result based on the $m_b \ll m_h$ limit with 5-flavour PDFs with a resummation scale μ_b ,

$$\sigma^{FO+res} = \sigma^{res} + \left(\sigma^{FO} - \sigma^{res} \Big|_{\mu_b=\mu_F} \right)$$

for the y_b^2 contributions.

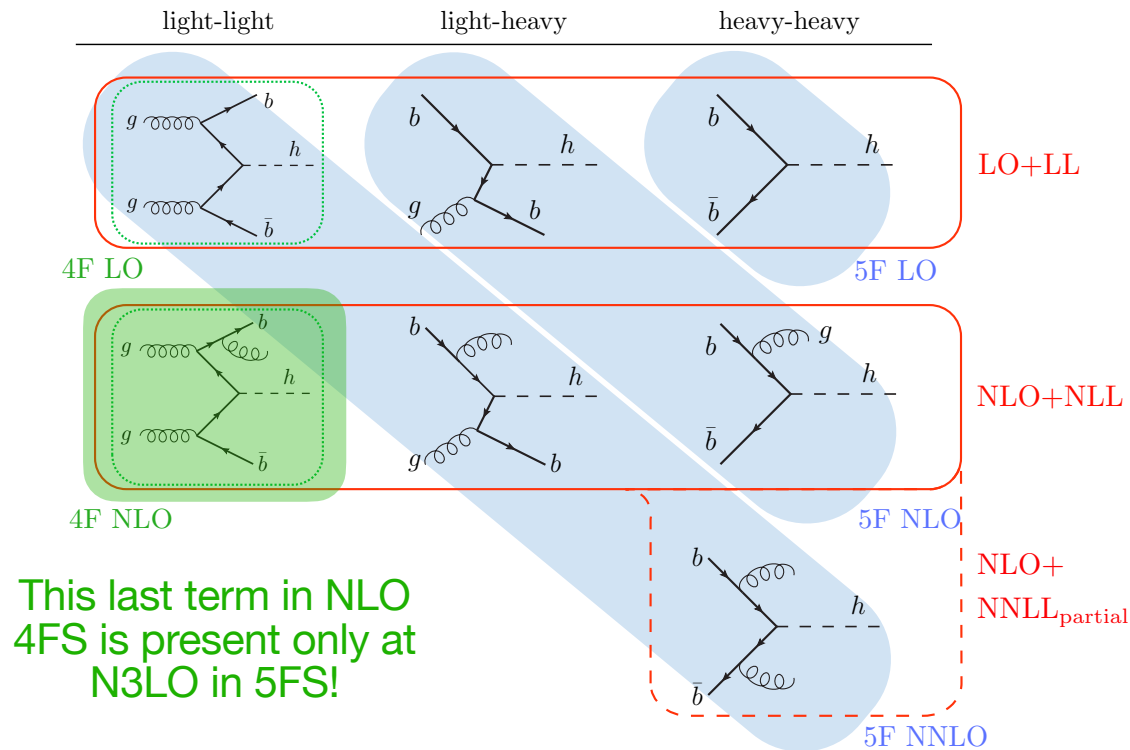
One can easily add the $y_b y_t$ contribution as a fixed-order nonsingular term. These interference effects vanish to all orders in the $m_b \rightarrow 0$ limit.

Advantages.

Using the fact that b -PDF counts as a $\mathcal{O}(\alpha_s)$ term, it contains the complete fixed-order results at each perturbative order.

The explicit dependence on μ_b enables the incorporation of a resummation uncertainty estimation from the 5FS prediction.

NLO+NNLLpart+ybyt



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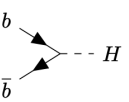
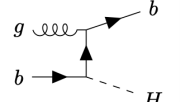
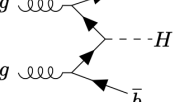
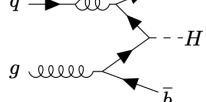
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FONLL-C: a new accuracy with the matching

The N3LO contributions in the massless scheme are recently computed.

Duhr, Dulat, Mistlberger [1904.09990]

This allows for an improvement in the matching, where all the NLO terms in the 4FS have a massless counterpart.

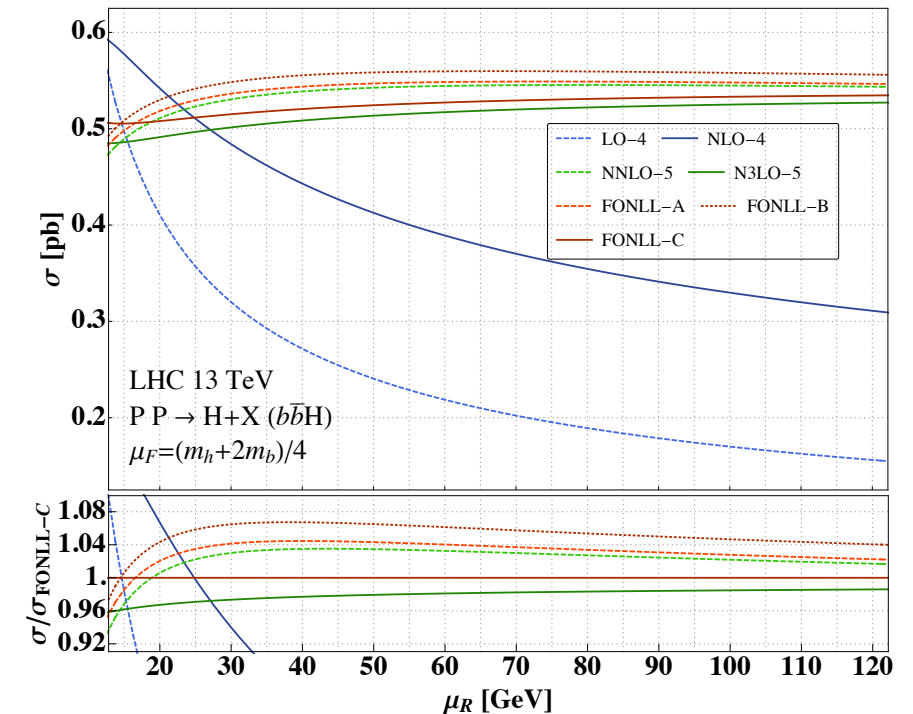
				
4FS	–	–	LO	NLO
5FS	LO	NLO	NNLO	N ³ LO

$$\sigma^{FONLL-B} = \sigma^{5FS}(NNLO) + \sigma^{4FS}(NLO) - \sigma_{m_b \rightarrow 0}^{4FS}(NLO)$$

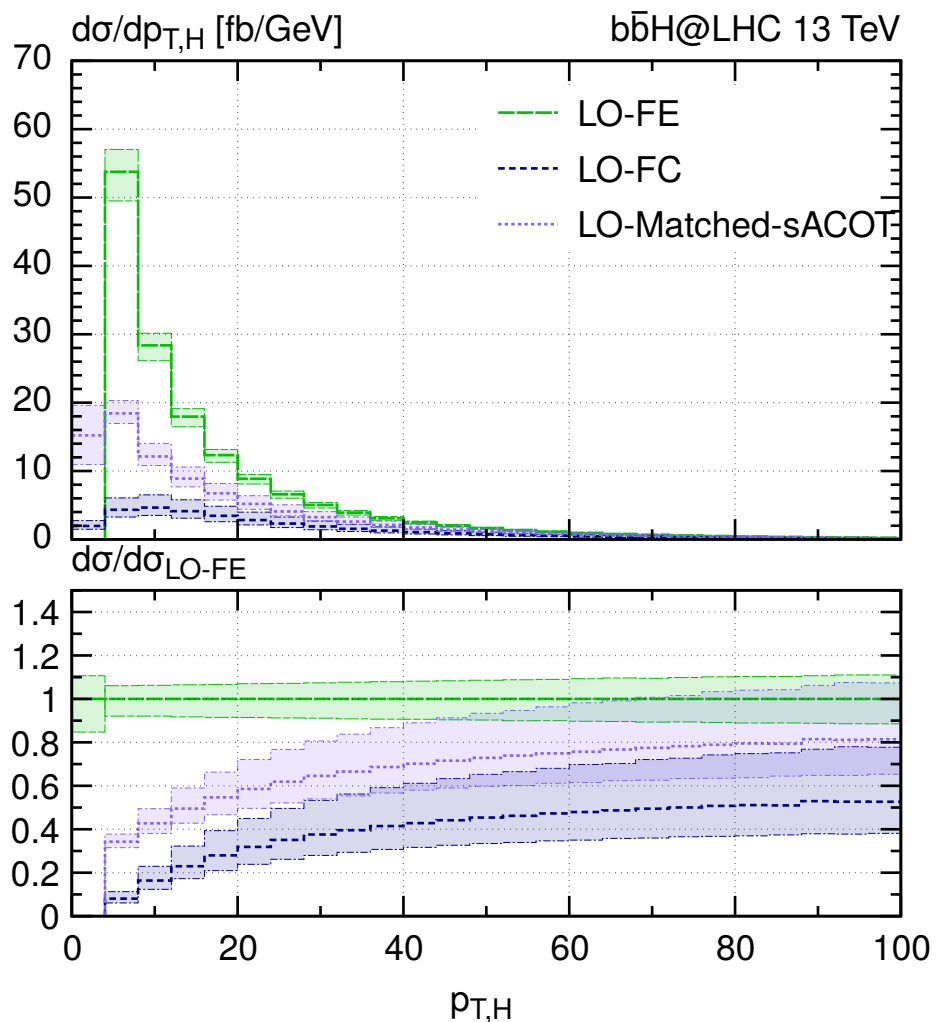
$$\sigma^{FONLL-C} = \sigma^{5FS}(N^3LO) + \sigma^{4FS}(NLO) - \sigma_{m_b \rightarrow 0}^{4FS}(NLO)$$

FONLL-C matching provides the first consistent matching at $\mathcal{O}(\alpha_s^3)$. The difference between FONLL-B and FONLL-C is not negligible and acts as a negative effect, which reflects the behaviour of the N3LO bottom-initiated corrections in 5FS.

Duhr, Dulat, Hirschi, Mistlberger [2004.04752]



bbH at the first order



We first performed the **sACOT matching** at the first order by combining:

- **Flavour Creation** (obtained using a LO_{PS} 4FS generator)
- **Flavour Excitation** and corresponding subtraction (obtained by modifying an NLO_{PS} 5FS generator with standard and subtracted PDFs)

