Z boson production in association with bottom quarks at NNLO+PS

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in collaboration with Vasily Sotnikov and Marius Wiesemann

[based on 2404.08598]

PSI

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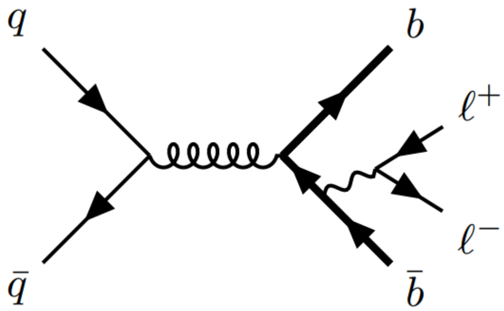
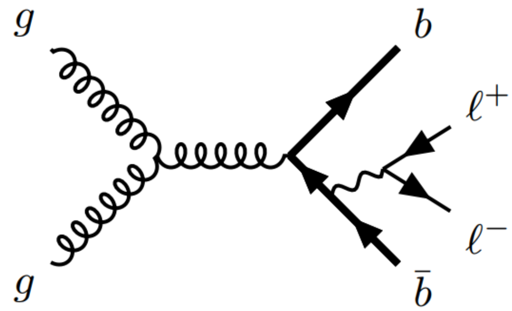
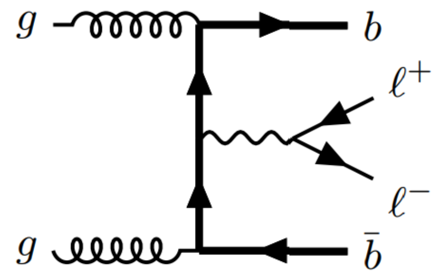
Motivation

Major background to ZH measurements	Background to various BSM searches	Heavy-quark effects to Drell-Yan





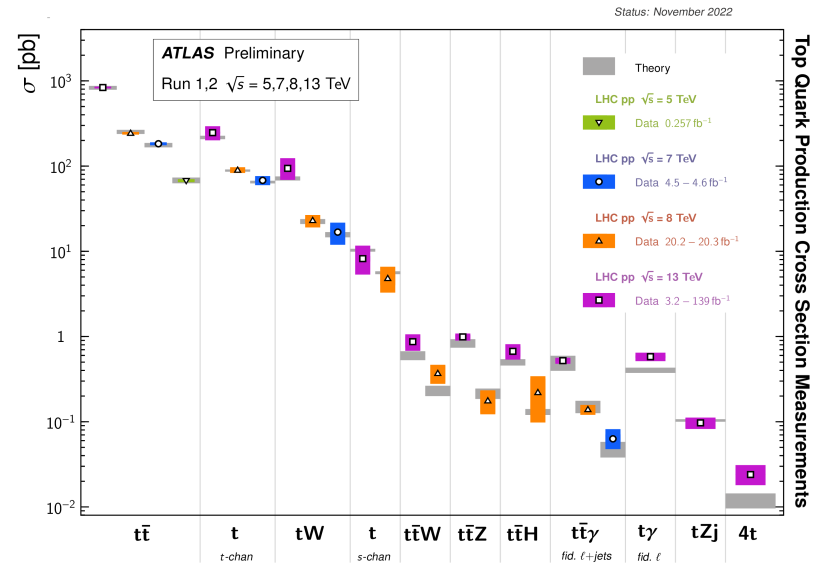


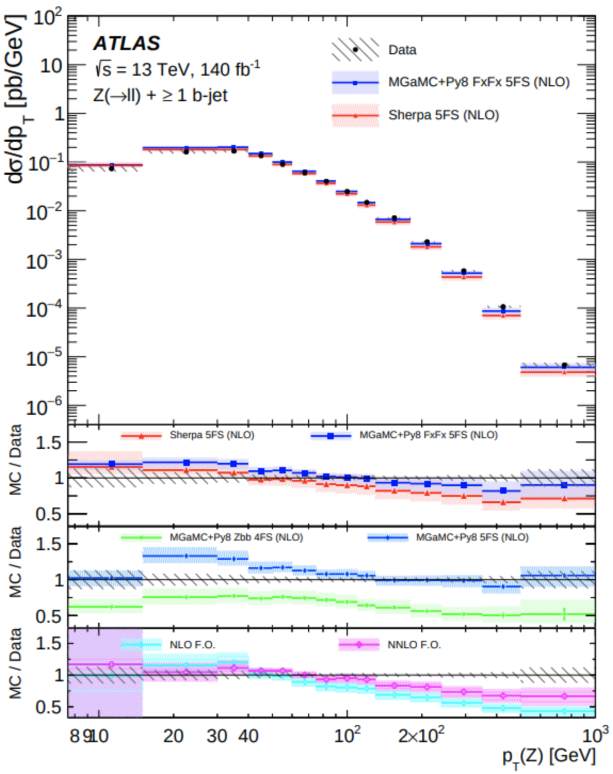
- m_b~5GeV, not too big, not too small… both 4FS and 5FS are sensible choices
- When only large scales involved 5FS expected to perform better, while finite mass effects from 4FS are relevant at scales of $O(m_b)$
- Bottom-flavoured jets straightforwardly defined in 4FS [see talk by G. Stagnitto on flavour-sensitive jet algorithms]
- Both 4FS and 5FS known up to NLO+PS in QCD, also their combination in a variable flavour number scheme
- Significant differences between 4FS and 5FS at NLO, and tension between 4FS and data
- 4FS NLO predictions affected by large perturbative uncertainties

We aim to solve the tension by improving the 4FS predictions with the NNLO corrections, plus their matching to parton showers

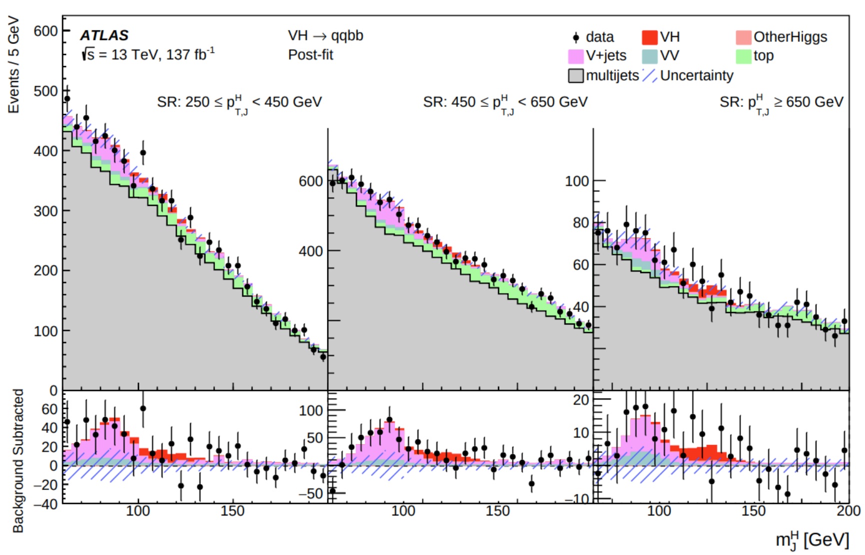
Motivation

- It is also a very interesting project from a technical point of view:
  - Phenomenological application of one of the most complex two-loop amplitudes that can be obtained with current technology
  - First NNLO+PS generator for a genuine $2 \rightarrow 3$ QCD process
  - More importantly, it represents the first NNLO+PS for a process of the type heavy-quark+colourless





Paves the way to many interesting pheno studies



Accurate simulations for processes with heavy quarks are crucial to fully exploit the physics potential of the LHC!

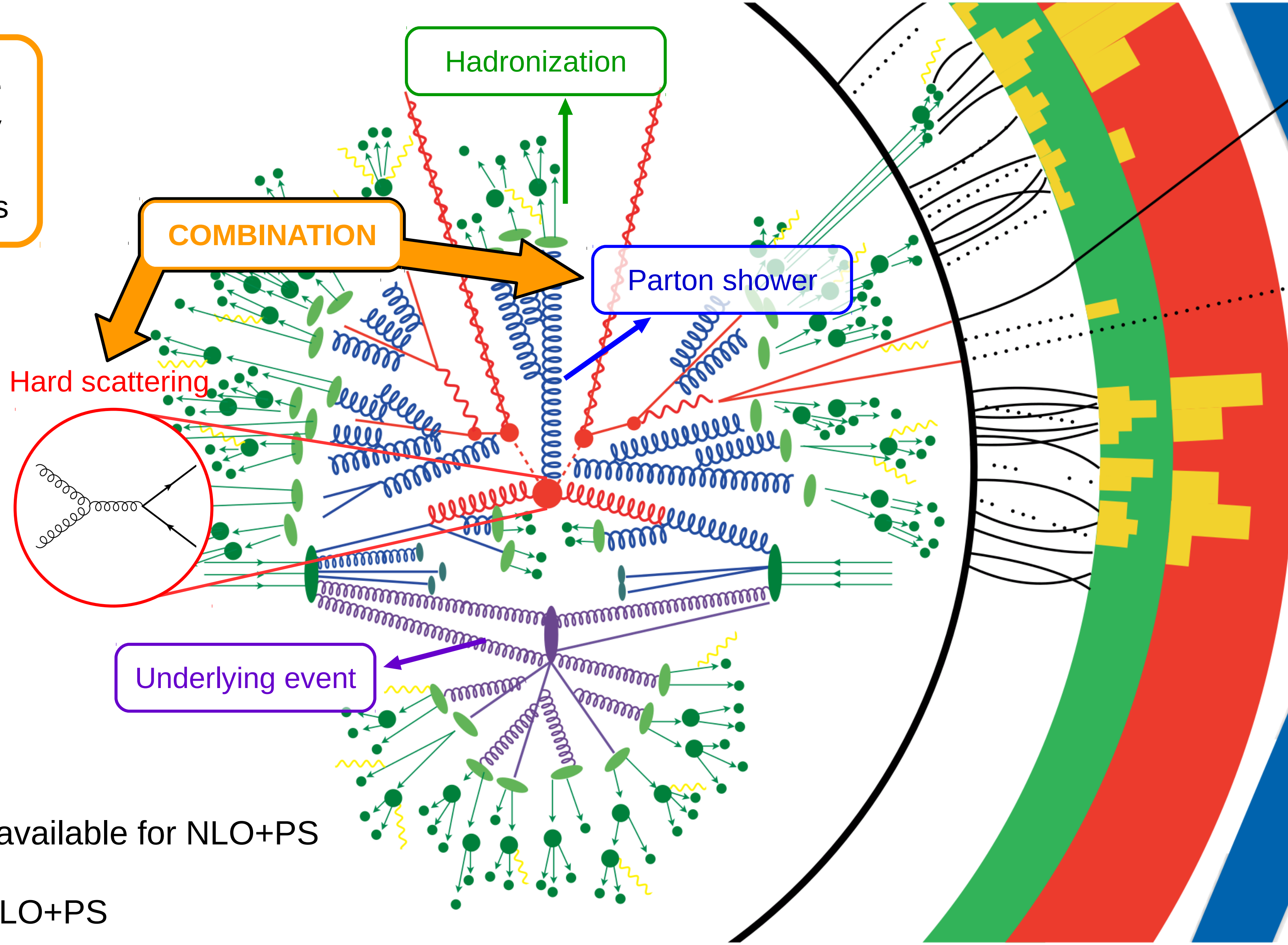
Outline

- NNLO+PS and heavy-quark production
- Extension to heavy-quark + colour singlet
- Z+bottom-pair production at NNLO+PS
- Summary and Outlook

Event generators

combining the high-energy scattering with PS and hadronization models are the cornerstone of experimental analyses

We want to keep the fixed-order accuracy when computing inclusive observables



- General approaches available for NLO+PS
- Current frontier is NNLO+PS

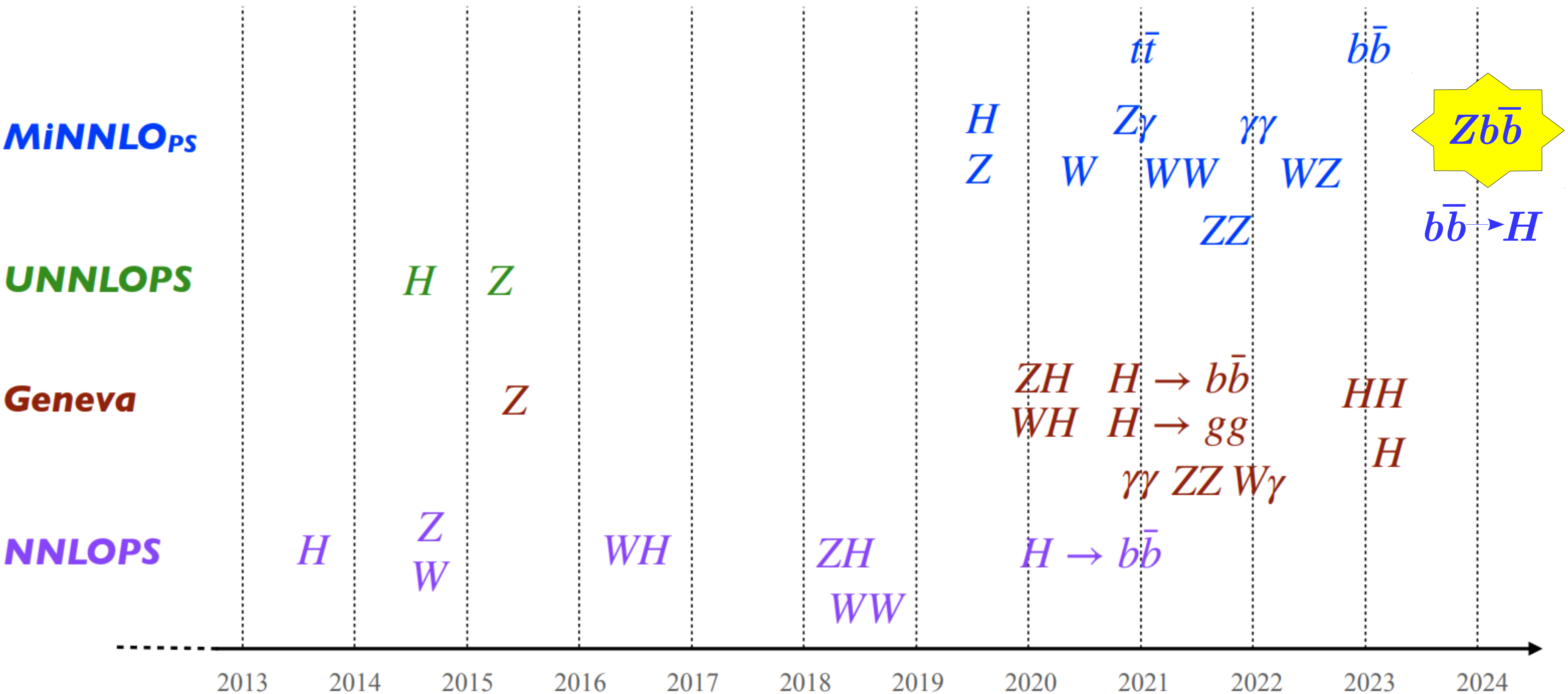
	F	$F+j$	$F+2j$
F@NNLO$_{\mathrm{PS}}$	NNLO	NLO	LO

Non trivial task!
Double counting between ME and shower, inclusion of virtual corrections, …

NNLO+PS timeline

- NNLO+PS generators for colour-singlet production available for about 10 years
- Few years ago we extended the MiNNLO method to heavy-quark production
- First NNLO+PS generator for heavy-quark+colourless obtained earlier this year

$Zb\bar{b}$, topic of this talk!



[timeline from M. Wiesemann, SM@LHC 23]

MiNNLO$_{\mathrm{PS}}$ for colour-singlet production

[Monni, Nason, Re, Wiesemann, Zanderighi]

- Derivation based on the connection between **MiNLO'** and **q_T-resummation**
- Starting point: low p_T factorization formula

$$d\sigma^{(\mathrm{sing})} \sim d\sigma^{(0)}_{c\bar{c}} \times \exp\left[-S_c(b)\right] \times \left[HC_1C_2\right]_{c\bar{c};a_1a_2} \times f_{a_1} f_{a_2}$$

- Final goal: NNLO-accurate expression for p_T distribution

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}} = \exp[-\tilde{S}(p_{\mathrm{T}})]\left\{\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}\left[\frac{\mathrm{d}\sigma_{\mathrm{FJ}}}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}}\right]^{(1)}\left(1+\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}[\tilde{S}(p_{\mathrm{T}})]^{(1)}\right) + \left(\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}\right)^2\left[\frac{\mathrm{d}\sigma_{\mathrm{FJ}}}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}}\right]^{(2)} + \left(\frac{\alpha_s(p_{\mathrm{T}})}{2\pi}\right)^3[D(p_{\mathrm{T}})]^{(3)} + \text{regular terms}\right\}$$

Already in MiNLO

Beyond accuracy

Extra term to achieve NNLO accuracy, depending on NNLL resummation coeffs

- This expression is embedded in the POWHEG $\bar{B}$ function

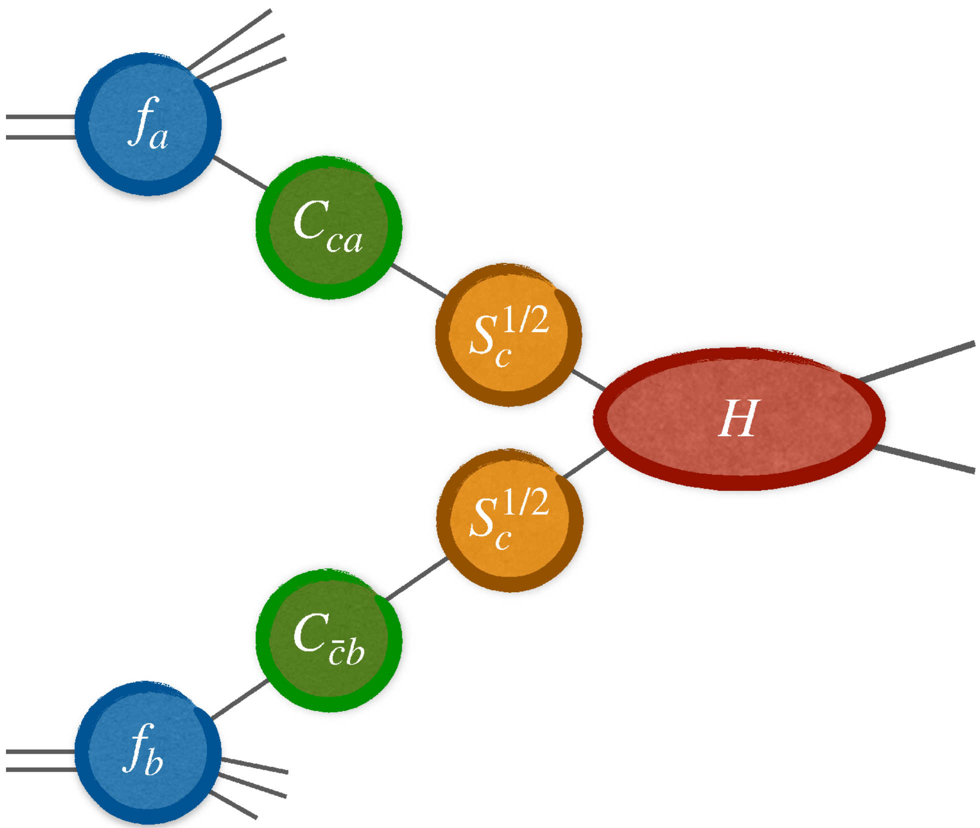
	F	$F+j$	$F+2j$
MiNLO'	NLO	NLO	LO
MiNNLO$_{\mathrm{PS}}$	NNLO	NLO	LO

- Numerically efficient, no reweighting involved (in variance to first MiNLO-based approaches)
- Applicable beyond 2 to 1 and, as we will see, even beyond colour singlet production

For details on the MiNNLO$_{\mathrm{PS}}$ colour-singlet derivation see the talk by S. Zanoli

q_T resummation: color singlet

$$d\sigma^{(\text{sing})} \sim d\sigma^{(0)}_{c\bar{c}} \times \exp(-S_c) \times [HC_1C_2]_{c\bar{c};a_1a_2} \times f_{a_1} f_{a_2}$$



Parton distribution functions

Collinear functions → hard-collinear emissions

Sudakov exponent → soft and flavor diagonal emissions

Universal

Hard function → hard process-dependent radiation

Resummed cross section physical (finite) when $p_T \to 0$

Can be computed at different logarithmic accuracies depending on which logs are included:

$$\text{LL: } \alpha_s^n L^{n+1}$$
$$\text{NLL: } \alpha_s^n L^n$$
$$\text{NNLL: } \alpha_s^n L^{n-1}$$

Can also be 'matched' to the fixed order upon expansion in α_s:

NLL+NLO, NNLL+NLO, NNLL+NNLO

q_T resummation: heavy quark pairs

Bold: operator in color space

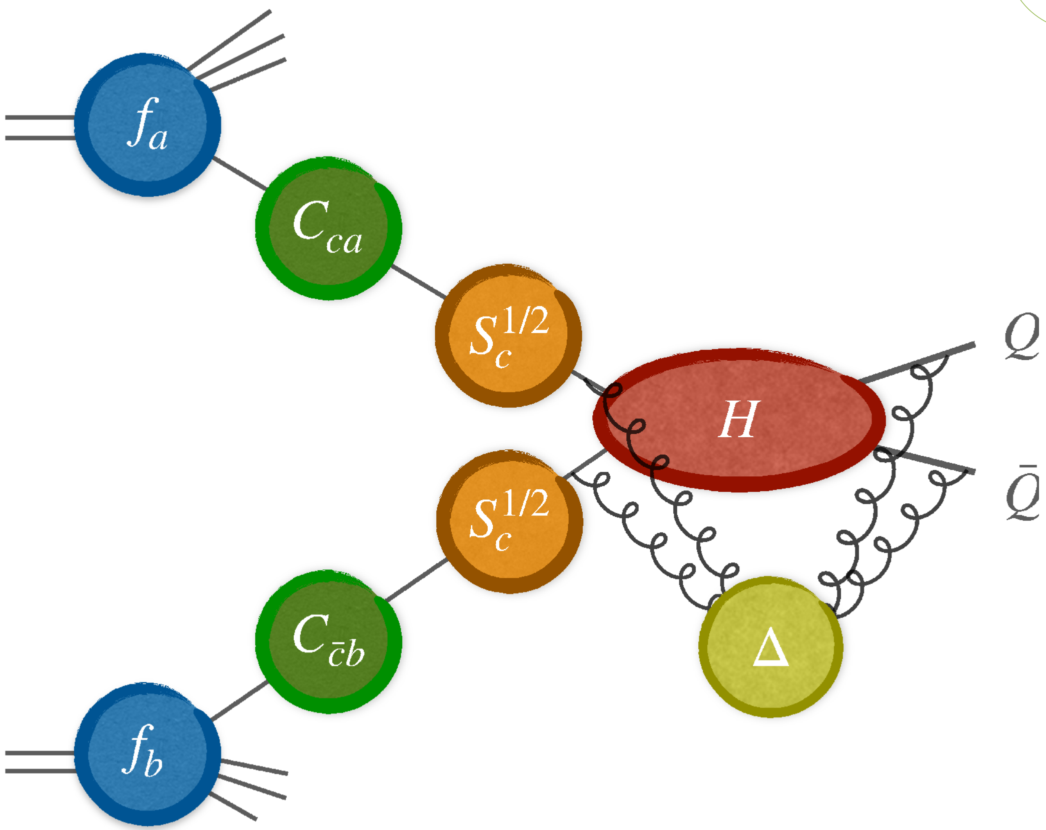
|M⟩: vector in color space

[1208.5774, 1307.2464, 1408.4564, 1806.01601]

$$d\sigma^{(\mathrm{sing})} \sim d\sigma^{(0)}_{c\bar{c}} \times \exp\left(-S_c\right) \times \left[H C_1 C_2\right]_{c\bar{c};a_1 a_2} \times f_{a_1} f_{a_2}$$

$$d\sigma^{(\mathrm{sing})} \sim d\sigma^{(0)}_{c\bar{c}} \times \exp\left(-S_c\right) \times \left[\mathrm{Tr}(\mathbf{H}\boldsymbol{\Delta}) C_1 C_2\right]_{c\bar{c};a_1 a_2} \times f_{a_1} f_{a_2}$$

Effects coming from soft emissions from the FS contained in operator **Δ**



In the colour singlet case, H is given by the (IR-subtracted) all-orders matrix element for $c\bar{c} \to F$

$$H = \mathrm{Tr}(\mathbf{H}) \sim \langle \mathcal{M} | \mathcal{M} \rangle$$

In the $t\bar{t}$ case, the presence of the operator **Δ** leads to non-trivial color correlations

$$\mathrm{Tr}(\mathbf{H}\boldsymbol{\Delta}) \sim \langle \mathcal{M} | \boldsymbol{\Delta} | \mathcal{M} \rangle$$

$$d\sigma^{(\mathrm{sing})} \sim d\sigma^{(0)}_{c\bar{c}} \times \exp\left[-S_c(b)\right] \times \left[\mathrm{Tr}(\mathbf{H}\boldsymbol{\Delta})C_1 C_2\right]_{c\bar{c};a_1 a_2} \times f_{a_1} f_{a_2}$$

$$\mathrm{Tr}(\mathbf{H}\boldsymbol{\Delta}) \sim \langle \mathcal{M} | \boldsymbol{\Delta} | \mathcal{M} \rangle$$

IR regulated virtual corrections

$$\boldsymbol{\Delta} \sim \exp\left\{-\int_{b_0^2/b^2}^{M} \frac{dq^2}{q^2}\,\boldsymbol{\Gamma}(\alpha_s(q))\right\}^{\dagger} \mathbf{D}(\alpha_s(b_0/b),\phi) \exp\left\{-\int_{b_0^2/b^2}^{M} \frac{dq^2}{q^2}\,\boldsymbol{\Gamma}(\alpha_s(q))\right\}$$

Exponential of soft anomalous dimension matrix

Operator leading to azimuthal correlations

- Soft anomalous dimension encodes logarithmic behavior of soft wide-angle emissions
- **D** encodes the azimuthal dependence of the constant terms, with $\langle \mathbf{D} \rangle_{\Phi,\mathrm{av}} = 1$
- Even for q_T azimuthally-averaged cross sections, **D** contributes in the gluon channel due to the interference with the collinear coefficient functions (starting at NNLO)
- All the ingredients for NNLL+NNLO resummation known except for $\mathbf{D}^{(2)}$
- $\mathbf{D}^{(2)}$ contributes with a constant term at $O(\alpha_s^4)$ that vanishes upon azimuthal average
- Translation between virtual corrections and IR-regulated *M* highly non trivial! The correct finite part of subtraction operator needs to be explicitly computed

$$|\mathcal{M}\rangle = \left(1 - \tilde{\mathbf{I}}\right) |\mathcal{M}\rangle_{\mathrm{unreg}}$$

Extending MiNNLO: from colour singlet to $Q\bar{Q}$

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

- MiNNLO method for colour singlet has the q_T resummation formula as starting point:

$$d\sigma^{(\mathrm{sing})} \sim d\sigma^{(0)}_{c\bar{c}} \times \exp\left(-S_c\right) \times \left[H C_1 C_2\right]_{c\bar{c};a_1 a_2} \times f_{a_1} f_{a_2}$$

- But now we have to deal with the more complicated $Q\bar{Q}$ structure:

$$d\sigma^{(\mathrm{sing})} \sim d\sigma^{(0)}_{c\bar{c}} \times \exp\left(-S_c\right) \times \left[\mathrm{Tr}(\mathbf{H}\boldsymbol{\Delta}) C_1 C_2\right]_{c\bar{c};a_1 a_2} \times f_{a_1} f_{a_2}$$

We can modify the $Q\bar{Q}$ factorization formula as long as we keep NNLO accuracy (and LL in view of the matching with the shower)

⬇

We can take it into a shape that resembles the colorless final state case

⬇

Connection to MiNNLO derivation becomes simpler

$$\mathrm{Tr}(\mathbf{H}\boldsymbol{\Delta}) \sim \langle \mathcal{M} | \boldsymbol{\Delta} | \mathcal{M} \rangle \longrightarrow \text{“Sudakov”} \times \langle \mathcal{M} | \mathcal{M} \rangle + \mathrm{h.o.}$$

MiNNLO for $Q\overline{Q}$ in three steps

(1) Simplify the exponential of the soft anomalous dimension

$$\boldsymbol{\Delta}_{\rm NLL} \equiv \boldsymbol{\Delta}(\boldsymbol{\Gamma}^{(2)} \to 0)$$

$$\langle \mathcal{M}|\boldsymbol{\Delta}|\mathcal{M}\rangle \sim \langle \mathcal{M}|\boldsymbol{\Delta}_{\rm NLL}|\mathcal{M}\rangle - \int \frac{dq^2}{q^2}\frac{\alpha_s^2(q)}{(2\pi)^2}\langle \mathcal{M}^{(0)}|\boldsymbol{\Gamma}^{(2)} + \boldsymbol{\Gamma}^{(2)\dagger}|\mathcal{M}^{(0)}\rangle$$

Same kind of term generated by $B^{(2)}$

Can be absorbed in a modified $B^{(2)}$ coefficient!

(2) Write the remaining factor in a ‘factorized’ form

$$\langle \mathcal{M}|\boldsymbol{\Delta}_{\rm NLL}|\mathcal{M}\rangle \to \frac{\langle \mathcal{M}^{(0)}|\boldsymbol{\Delta}_{\rm NLL}|\mathcal{M}^{(0)}\rangle}{|\mathcal{M}^{(0)}|^2} \times \langle \mathcal{M}|\mathcal{M}\rangle$$

Factorized form, but not NNLO accurate

Instead of

$$\langle \mathcal{M}^{(1)}|\boldsymbol{\Gamma}^{(1)} + \boldsymbol{\Gamma}^{(1)\dagger}|\mathcal{M}^{(0)}\rangle + {\rm c.c.}$$

We have

$$\frac{\langle \mathcal{M}^{(0)}|\boldsymbol{\Gamma}^{(1)} + \boldsymbol{\Gamma}^{(1)\dagger}|\mathcal{M}^{(0)}\rangle}{|\mathcal{M}^{(0)}|^2} \times \left(\langle \mathcal{M}^{(1)}|\mathcal{M}^{(0)}\rangle + {\rm c.c.}\right)$$

This mismatch can also be absorbed (up to NNLO) in an additional redefinition of $B^{(2)}$

(3) Compute the remaining exponential in a basis in which $\boldsymbol{\Gamma}^{(1)}$ is diagonal

Sum of complex exponentials

Absorbe in a redefinition of $B^{(1)}$, which is now complex (done for each term in the sum)

- We therefore arrived to the $\text{"Sudakov"} \times \langle \mathcal{M} | \mathcal{M} \rangle + \text{h.o.}$ shape we were after, keeping NNLO accuracy

Sudakov with modified $B^{(2)}$ absorbing effects from $\Gamma^{(2)}$ and from $M^{(1)}$-$\Gamma^{(1)}$ interference

Computed by diagonalizing $\boldsymbol{\Gamma}^{(1)}$ → Sum of complex exponentials

$$d\sigma^{(\mathrm{sing})} \sim d\sigma^{(0)}_{c\bar{c}} \, \exp\left[-S_c''(b)\right] \langle \mathcal{M}^{(0)} | \exp\left[\int \frac{dq^2}{q^2} \frac{\alpha_s(q)}{2\pi} (\boldsymbol{\Gamma}^{(1)} + \boldsymbol{\Gamma}^{(1)\dagger})\right] | \mathcal{M}^{(0)} \rangle \, [\mathrm{Tr}(\mathbf{H}\,\mathbf{D}) C_1 C_2]^{\phi}_{c\bar{c};a_1 a_2} \, f_{a_1} f_{a_2}$$

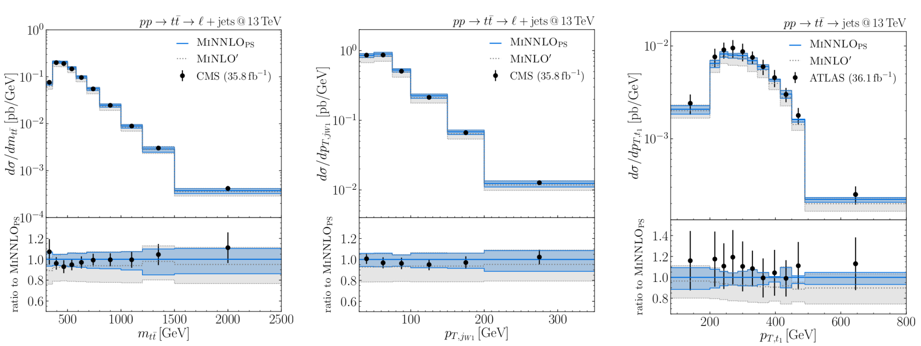
Of the form $\sum_i \exp\left[-S(B \to B_i)\right]$

More precisely, each term is an 'usual' Sudakov form factor with an effective (complex) value of $B^{(1)}$ and $B^{(2)}$

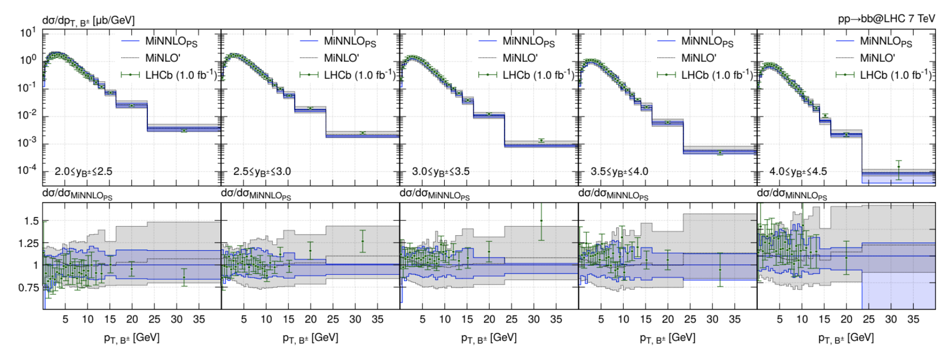
Factorization formula was the starting point for color-singlet MiNNLO

Now we have a sum of colorless-final-state-like factorization formulas

Follow MiNNLO color-singlet derivation for each of them and arrive to MiNNLO for $Q\bar{Q}$



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



[JM, Ratti, Wiesemann, Zanderighi]

Extending MiNNLO: from $Q\bar{Q}$ to $Q\bar{Q}F$

Analytic expression for $\mathbf{H}^{(0)}$ matrix → General implementation based on OpenLoops tree_colbasis

General implementation for <$D^{(1)*}G^{(1)}$> contribution (also numerical)

....

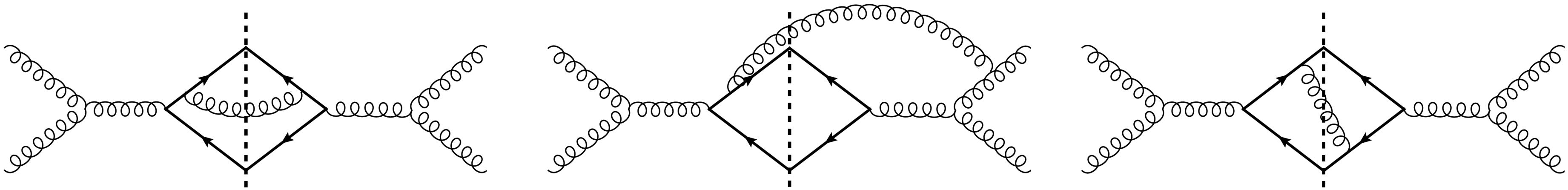
Extension of the calculation of soft contributions at low p_T to general kinematics

These contributions determine the exact subtraction operator in $|\mathcal{M}\rangle = \left(1 - \tilde{\mathbf{I}}\right) |\mathcal{M}\rangle_{\text{unreg}}$

- **I** operator can be extracted from computation of $d\sigma/d^2q_T$
- Only new soft singularities wrt color singlet → integrate the (subtracted) **soft current**

E.g. at NLO:

$$-\mathbf{J}(k)^2\big|_{\text{sub}} = \sum_{J=3,4}\left[\frac{p_J^2}{(p_J\cdot k)^2}\mathbf{T}_J^2 + \sum_{i=1,2}\left(\frac{p_i\cdot p_J}{p_J\cdot k} - \frac{p_1\cdot p_2}{(p_1+p_2)\cdot k}\right)\frac{2\,\mathbf{T}_i\cdot\mathbf{T}_J}{p_i\cdot k}\right] + \frac{2p_3\cdot p_4}{(p_3\cdot k)(p_4\cdot k)}\mathbf{T}_3\cdot\mathbf{T}_4$$



Soft function for $Q\overline{Q}$ production

From [Catani, Devoto, Grazzini, JM, 2301.11786], see also [Angeles-Martinez, Czakon, Sapeta 1809.01459]

Analytic results

Numerical results

$$\mathbf{h}(\alpha_S) = 1 + \frac{\alpha_S}{2\pi}\left(h_{34}^{(1)}\,\mathbf{T}_3\cdot\mathbf{T}_4 + h_{33}^{(1)}\,C_F\right)$$
$$+\left(\frac{\alpha_S}{2\pi}\right)^2\left(h_{34}^{(2)}\,\mathbf{T}_3\cdot\mathbf{T}_4 + h_{13}^{(2)}\,\mathbf{T}_1\cdot\mathbf{T}_3 + h_{14}^{(2)}\,\mathbf{T}_1\cdot\mathbf{T}_4 + h_{23}^{(2)}\,\mathbf{T}_2\cdot\mathbf{T}_3 + h_{24}^{(2)}\,\mathbf{T}_2\cdot\mathbf{T}_4\right.$$
$$\left.+\, h_{3434}^{(2)}\,\mathbf{T}_3\cdot\mathbf{T}_4\,\mathbf{T}_3\cdot\mathbf{T}_4 + h_{3433}^{(2)}\,\mathbf{T}_3\cdot\mathbf{T}_4\,C_F + h_{3333}^{(2)}\,C_F^2\right) + \mathcal{O}(\alpha_S^3)$$

Contributions connecting two different massive legs

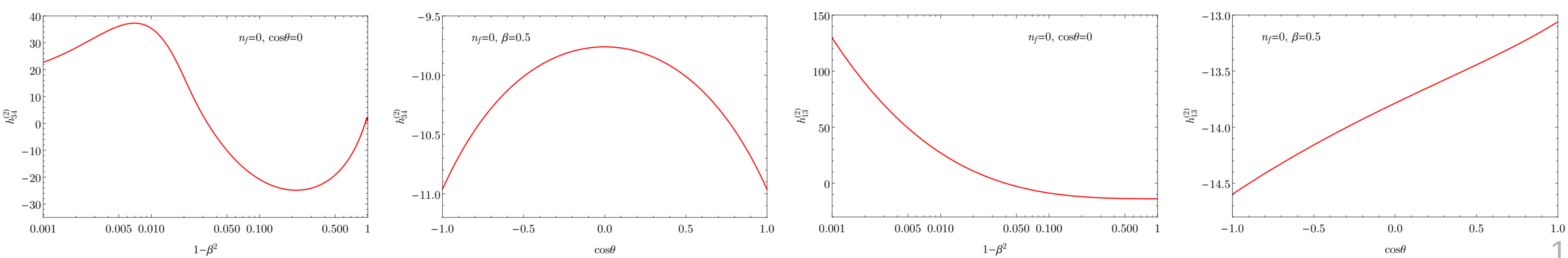
Contributions coming from the square of the NLO result, afterwards azimuthally averaged

- Numerical results pre-computed and implemented in 2-dimensional grid:

$$\left\{\beta = \sqrt{1-\frac{4m^2}{s}}\ ,\quad \cos\theta\right\} \Longrightarrow$$ 5000 points optimized for $t\bar{t}$ production

- Grids afterwards fitted using a spline approximation, negligible uncertainties

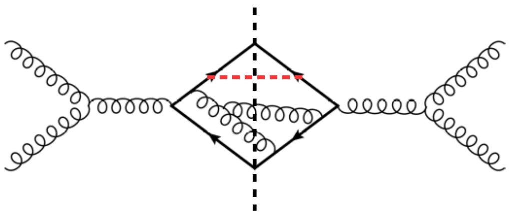
- Note: many pieces of h_{34} we know analytically, but the evaluation of MPLs was slow, so those bits are also directly included in the numerical grids



Soft function for $Q\bar{Q}$+colourless

Soft function for **H**eavy quark production in **AR**bitrary **K**inematics

[Devoto, JM, in prep]



Extension to **heavy-quark + colorless** of equivalent $Q\bar{Q}$ calculations

[Catani, Devoto, Grazzini, JM, 2301.11786],
see also [Angeles-Martinez, Czakon, Sapeta 1809.01459]

Implies removing back-to-back constraint for heavy quarks

New approach (on-the-fly) vs old results (grid+interpolation)

- C++ library for on-the-fly evaluation of soft function
- Most complicated pieces involve four-fold integrals integrated with VEGAS
- Validated against independent MATHEMATICA implementation
- About 1 second per phase space point typically enough for needed accuracy

Not a big problem for applications, but needs to be included in last stage via reweighting technique

This new development allowed not only for NNLO+PS for $Q\bar{Q}F$, but also to extend the q_T-subtraction method for this class of processes!

$t\bar{t}H$ [Catani, JM et al. 2210.07846]

$t\bar{t}W$ [Buonocore, JM et al. 2306.16311]

$b\bar{b}W$ [Buonocore, JM et al. 2212.04954]

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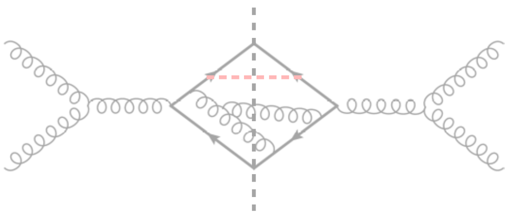

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Implies removing back-to-back constraint for heavy quarks

New approach (on-the-fly) vs old results (grid+interpolation)

- C++ library for on-the-fly evaluation of soft function

Thanks to these developments the MiNNLO$_{PS}$ formalism for processes of the type $Q\bar{Q}F$ is ready to be used with full generality, ‘only’ needed ingredient are the process-dependent two loop corrections

Not a big problem for applications, but needs to be included in last stage via reweighting technique

This new development allowed not only for NNLO+PS for $Q\bar{Q}F$, but also to extend the q_T-subtraction method for this class of processes!

$t\bar{t}H$	$t\bar{t}W$	$b\bar{b}W$
[Catani, JM et al. 2210.07846]	[Buonocore, JM et al. 2306.16311]	[Buonocore, JM et al. 2212.04954]

$Zb\bar{b}$ production

- NLO 5FS [Campbell, Ellis, Keith, Maltoni, Willenbrock ’03]
- NLO 4FS [Febres Cordero, Reina, Wackeroth ’08,’09] (see also [Campbell, Ellis, Keith ’00])
- NLO+PS in MadGraph5 aMC@NLO [Frederix,Frixione, Hirschi, Maltoni, Pittau, Torrielli ’11] (+ multi-jet merging in 5FS)
- NLO+PS in Sherpa [Krauss, Napoletano, Schumann ’16] (+ multi-jet merging in 5FS)
- NLO+PS combination 4FS + 5FS [Höche, Krause, Siegert ’19] (see also [Forte, Napoletano, Ubiali ’18])
- NNLO in 5FS one b-jet [Gauld, Gehrmann-De Ridder, Glover, Huss, Majer ’20]

NEW: First NNLO and NNLO+PS computation in 4FS
[JM, Sotnikov, Wiesemann]

Two-loop corrections

- Full corrections (five-point two-loop amplitudes with massive b's) out of reach
- We rely on massless amplitudes and apply a 'massification' procedure

Recently applied as well to Wbb production [Buonocore, JM et al. '23]

2-loop finite reminder

Poles in 5FS ⟷ Logs of m_b in 4FS

$$\mathrm{Re}\left\langle \mathcal{R}_0^{(0)} \middle| \mathcal{R}^{(2)}_{m_b \ll \mu_h} \right\rangle = \bar{\mathcal{F}}^{(2)} \left| \mathcal{R}_0^{(0)} \right|^2 + \bar{\mathcal{F}}^{(1)}\, \mathrm{Re}\left\langle \mathcal{R}_0^{(0)} \middle| \mathcal{R}_0^{(1)} \right\rangle + \mathrm{Re}\left\langle \mathcal{R}_0^{(0)} \middle| \bar{\mathbf{S}}^{(2)} \middle| \mathcal{R}_0^{(0)} \right\rangle + \mathrm{Re}\left\langle \mathcal{R}_0^{(0)} \middle| \mathcal{R}_0^{(2)} \right\rangle$$

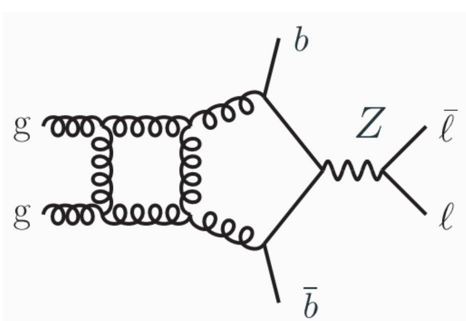
Massification coefficients [Mitov, Moch '06]

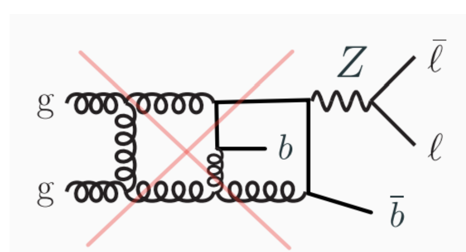
Additional contribution to account for closed b loops [Wang, Xia, Yang, Ye '23]

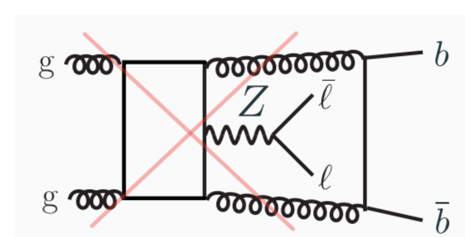
- Log-enhanced terms (blue) obtained without approximations
- Massless two-loop reminder (red) computed from analytic results

[Abreu, Febres Cordero, Ita, Klinkert, Page, Sotnikov '21], [Chicherin, Sotnikov, Zoia '21]

  - Obtained in the leading colour approximation ($1/N_c^2$ corrections)
  - No contributions with Z coupling to closed quark loop (negligible at NLO)







Setup of the calculation

- 13TeV collisions, $bb\ell\ell$ final state with ℓ=e,μ, m_b=4.92GeV, NNPDF31
- MiNNLO central scale setting: $\mu_R=\mu_F=m_{bb\ell\ell}\, e^{-L}$, $Q=m_{bb\ell\ell}/2$
  Born coupling central scale: $\mu_R^{(0)} = m_{bb\ell\ell}$
- Modified log $L = \log(Q/p_T)$ for $p_T<Q/2$, $L = 0$ for $p_T>Q$, interpolation in between
- Showering with Pythia8, using Monash tune
  Hadronization, multi-parton interactions and QED shower included
- OpenLoops for tree and one-loop amplitudes, including color- and spin-correlated
- Two-loop amplitudes from analytic results
  - Large expressions O(1Gb) ➡ elaborate numerical stability checks and rescue system through higher precision
  - Evaluation of special functions through PentagonFunctions++
    [Chicherin, Sotnikov, Zoia '21]

Total cross section

- We compute the total cross section only with a cut 66GeV < $m_{\ell\ell}$ < 116GeV
- We implemented an NLO+PS generator in the 4FS for comparison
- We compare as well with MiNLO' results (MiNNLO without $D^{(\geq 3)}$ terms)
- Only for these numbers: hadronization, MPI and QED shower are turned off

	σ_{total} [pb]	ratio to NLO
NLO+PS ($m_{b\bar{b}\ell\ell}$)	$31.86(1)^{+16.3\%}_{-13.3\%}$	1.000
MiNLO′ ($m_{b\bar{b}\ell\ell}$)	$22.33(1)^{+28.2\%}_{-17.9\%}$	0.701
MiNNLO$_{\text{PS}}$ ($m_{b\bar{b}\ell\ell}$)	$50.58(4)^{+16.8\%}_{-12.2\%}$	1.588
NLO+PS ($H_T/2$)	$41.42(1)^{+19.2\%}_{-15.4\%}$	1.000
MiNNLO$_{\text{PS}}$ ($H_T/2$)	$57.68(5)^{+18.3\%}_{-12.9\%}$	1.393

- Very large NNLO corrections of O(50%) for both scale choices
- No reduction of scale uncertainties and no overlap with NLO band

} NLO prediction and uncertainty estimation are not reliable!

- MiNLO' unphysical do to uncompensated log(m_b) fixed by two-loop virtuals
- Massless finite reminder contributes at few percent level (LCA uncertainties negligible)

Comparison to LHC measurements

[JM, Sotnikov, Wiesemann]

- We compare to a recent measurement of Z+b-jets by CMS [CMS, 2112.09659]

Object	Selection
Dressed leptons	p_T(leading) $> 35\,\text{GeV}$, p_T(subleading) $> 25\,\text{GeV}$, $\lvert\eta\rvert < 2.4$
Z boson	$71 < m_{\ell\ell} < 111\,\text{GeV}$
Generator-level b jet	b hadron jet, $p_T > 30\,\text{GeV}$, $\lvert\eta\rvert < 2.4$

- We compute fiducial cross sections at NLO+PS and NNLO+PS in the 4FS, and compare to CMS measurement and to NLO+PS in the 5FS

Obtained with MadGraph5, taken from CMS paper

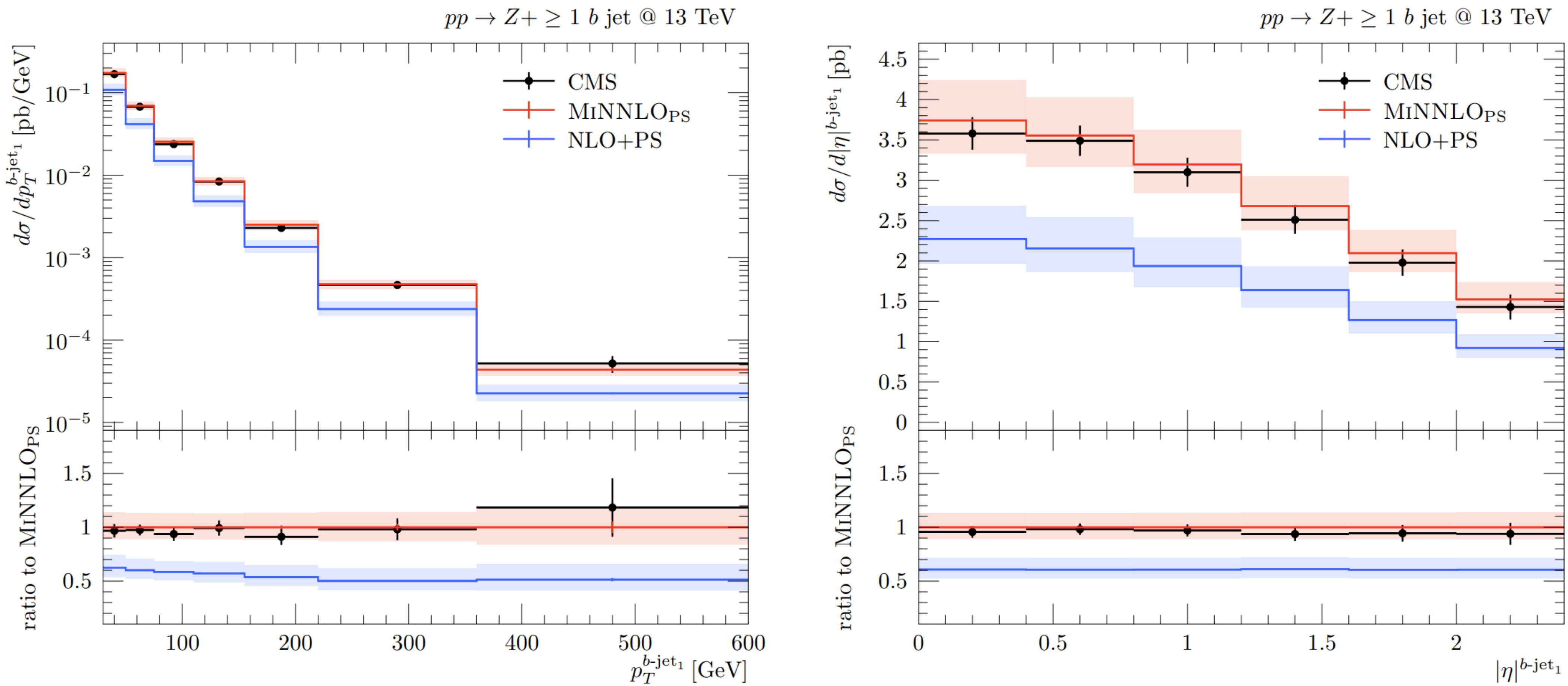
σ_{fiducial} [pb]	$Z+\geq 1$ b-jet	$Z+\geq 2$ b-jets
NLO+PS (5FS)	7.03 ± 0.47	0.77 ± 0.07
NLO+PS (4FS)	4.08 ± 0.66	0.44 ± 0.08
MiNNLO$_{\text{PS}}$ (4FS)	6.72 ± 0.91	0.79 ± 0.10
CMS	6.52 ± 0.43	0.65 ± 0.08

- Tension with data at NLO+PS in the 4FS, lifted with inclusion of NNLO corrections

- Excellent agreement between NNLO+PS (4FS) and NLO+PS (5FS) predictions

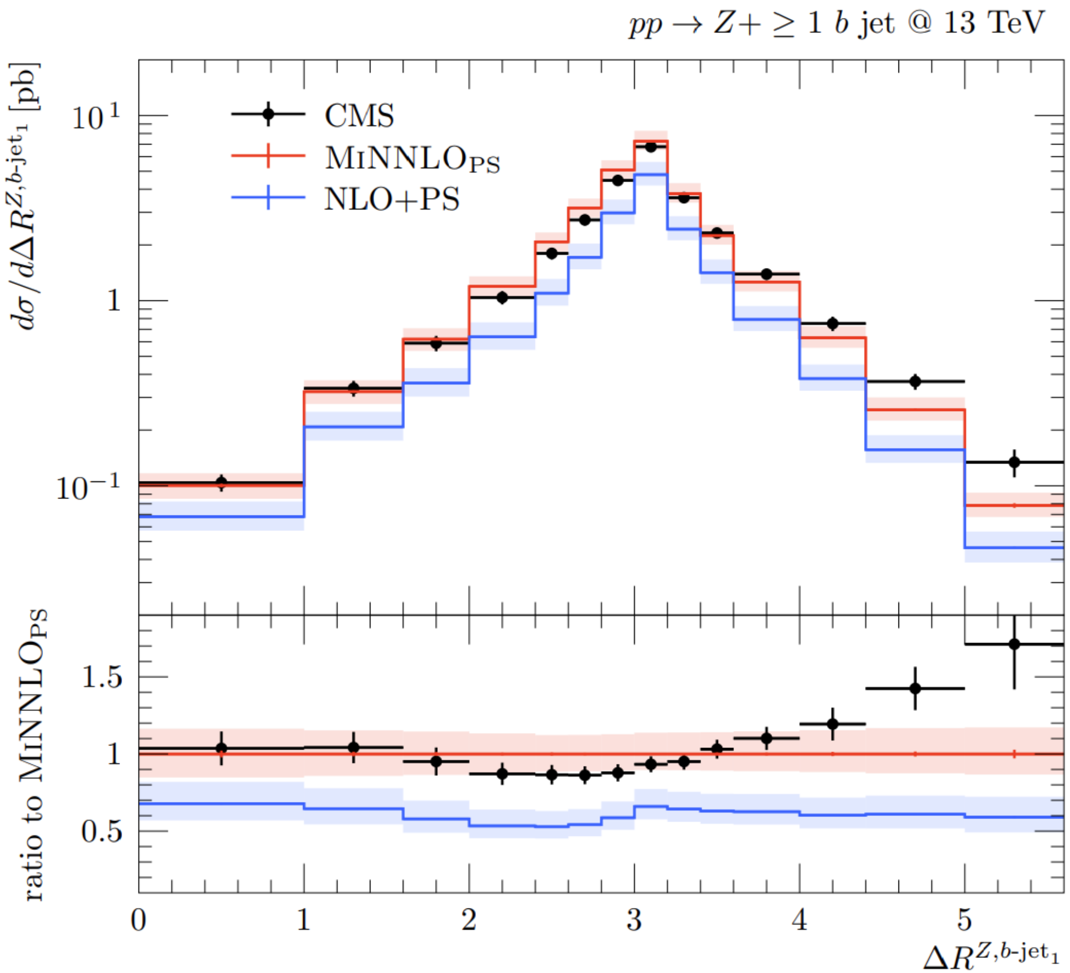
Differential distributions: Z+1b-jet

[JM, Sotnikov, Wiesemann]



- NLO+PS normalization is completely off, p_T shape not well described either
- NNLO+PS is in remarkable agreement with data, both normalization and shape
- Theory uncertainties are still larger than experimental ones in most bins

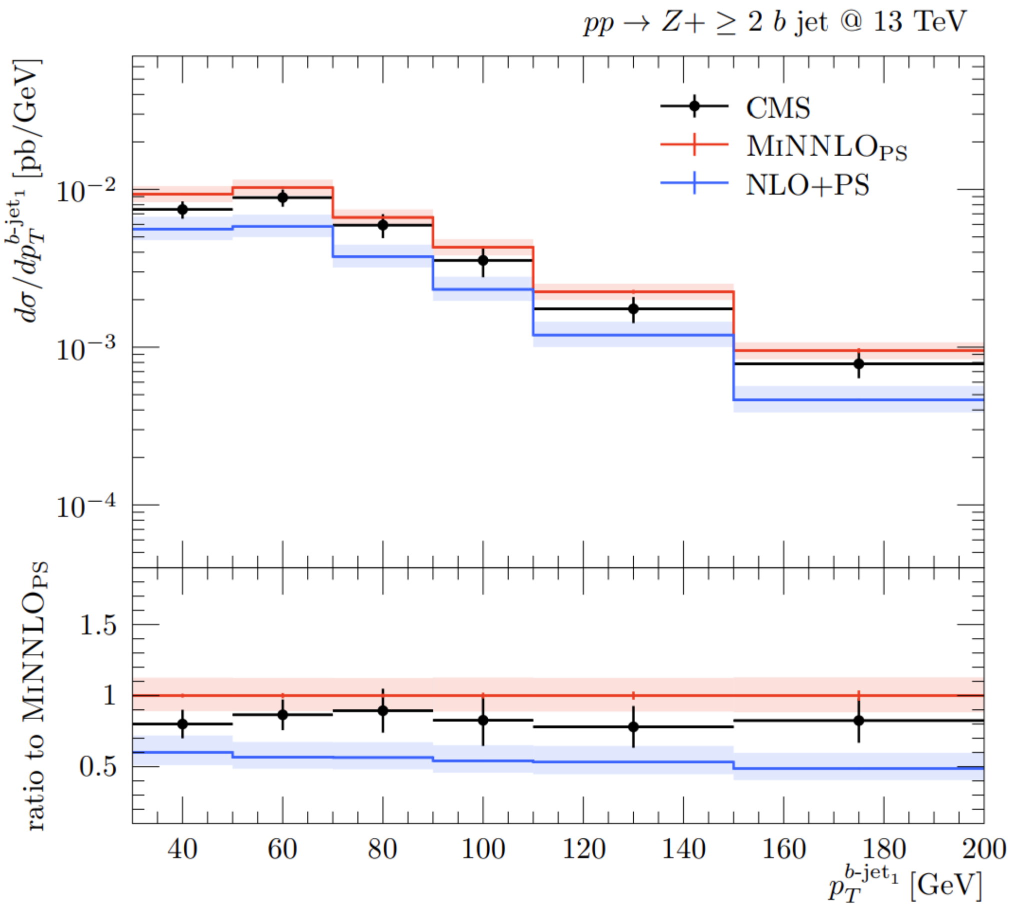
Differential distributions: Z+1b-jet

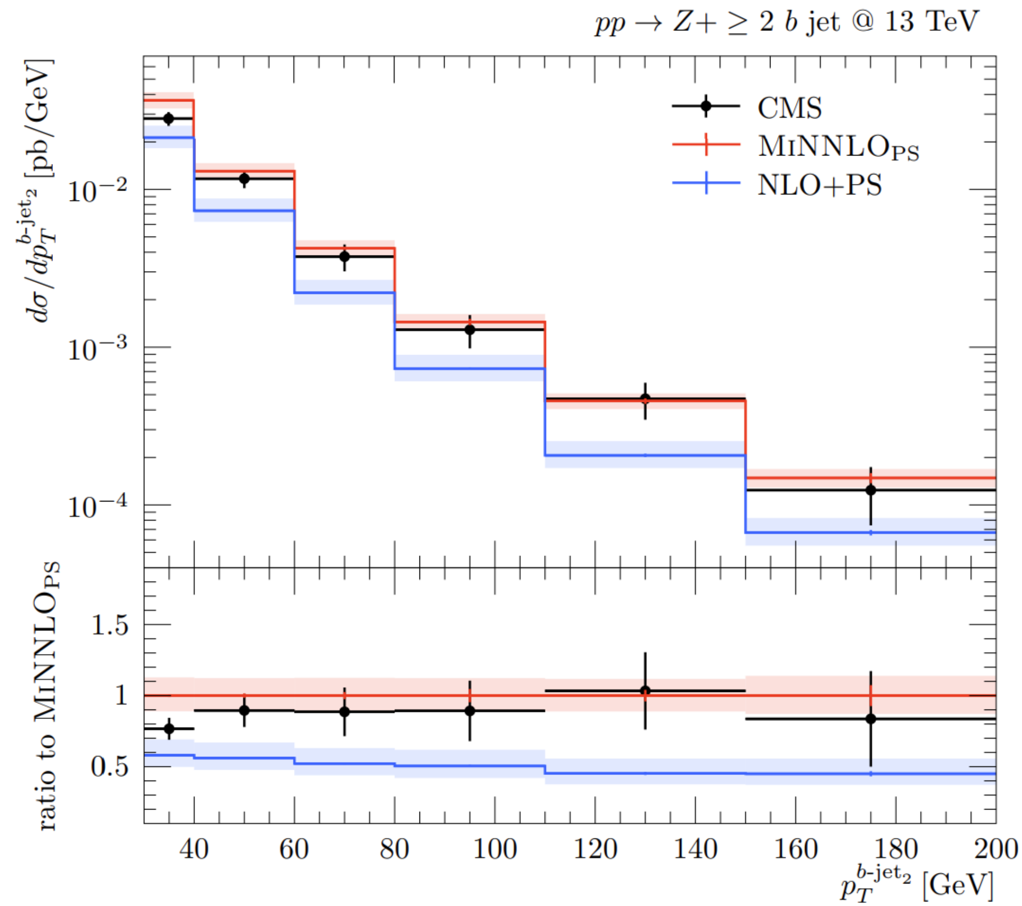


- Region of large separation between Z and leading b-jet in η-ϕ plane not well described
- Originates from region with large rapidity separation, also not well described
- Similar trend found in 5FS, though less pronounced
- Could be connected to large log(m_b) contributions

Differential distributions: Z+2b-jet

[JM, Sotnikov, Wiesemann]





- Normalization of NNLO+PS slightly overshoots data, as seen at fiducial level for ≥2b jet
- Still in good agreement within the uncertainties
- Experimental uncertainties are considerably larger due to lower statistics

Summary

- We have further extended the MiNNLO$_{PS}$ method
- Our formalism is now ready to provide NNLO+PS for processes of the type $Q\bar{Q}$+F
- Only process-dependent ingredient: two-loop amplitudes
- We finished the first application: $Zb\bar{b}$ at NNLO+PS
- Double-virtuals obtained through ‘massification’ procedure
- Most complicated final state simulated at NNLO+PS to date
- Huge improvement w.r.t. NLO+PS, good agreement with 5FS predictions and data

Outlook

- Further studies on $Zb\bar{b}$:
  - More detailed analysis of 4FS vs 5FS
  - Comparison to NNLO fixed-order
  - Dependence on shower settings
- Public release of the event generator
- Development of NNLO+PS generators for $Q\bar{Q}$F: $t\bar{t}H$, $t\bar{t}W$, $b\bar{b}H$, $b\bar{b}W$, …

Thanks!