A general-mass variable-flavor-number scheme for the $Z + b$ production at hadron colliders

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- Home
- Downloads
- Manual
- Contact

S-ACOT-MPS:
The Simplified ACOT scheme with Massive Phase Space

A single inclusive heavy-quark production

Main Goals

- Deal with the heavy-flavor in the General-Mass Variable-Flavor-Number Scheme
- Moving towards to the (N)NLO QCD calculations
- Simplify the implementation with the PDF subtraction formalism

$Z + Q(Q = c, b)$ production at the LHC to probe the heavy-flavor (c, b) PDFs

- Heavy-flavor in global QCD/PDF analyses
- QCD dynamics at small and large x
- Non-perturbative (intrinsic) charm/bottom component of the proton

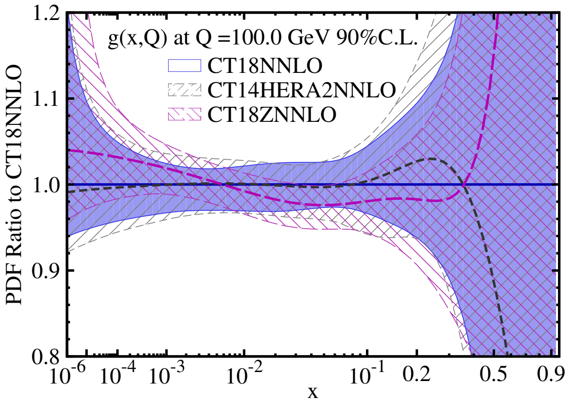
Already been done for the inclusive charm [2108.03741,2109.10905,2203.05090] and bottom [2203.06207,Thesis] production.

$Z + Q$ production

- The $Z + Q$ production probes both small and large x

$$x_{1,2} = \frac{1}{\sqrt{s}}\left(\sqrt{p_{T,Z}^2 + M_Z^2}\exp(\pm y_Z) + p_{T,Q}\exp(\pm y_Q)\right)$$

- The small and large x PDFs are poorly constrained by other experiments in global QCD analyses of PDFs.
- LHCb configuration $3 < y_Z < 4$
  - Small $p_T(\lesssim m_Q) \implies x \sim 10^{-4}$.
  - Large $p_T(> 40\ \mathrm{GeV}) \implies x > 0.3$.



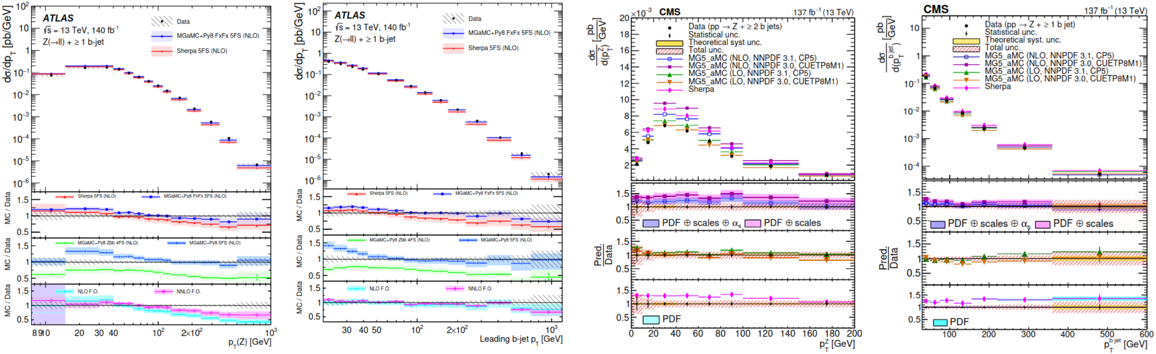
The small- and large-x uncertainty gets wide.
The CT18 gluon PDF [1912.10053]
Also see the PDF4LHC21 combination [2203.05506]

The importance of the $Z + Q$ production

- Modern PDF analyses extend on wide range of collision energies. Sensitive to mass effects, e.g., phase space suppression, large radiative corrections to collinear $Q\bar{Q}$ production. Magnitude comparable to NNLO and N3LO corrections.
- Natural to evaluate all fitted cross sections in a GMVFN scheme, which assumes that the number of (nearly) massless quark flavors varies with energy, and at the same time includes dependence on heavy-quark masses in relevant kinematical regions.
- $Z + b(\bar{b})$ are dominant backgrounds for
  - SM $Z + (H \to b\bar{b})$
  - SUSY Higgs + b-quark
  - New generation $Q \to Z + b$
- Probing this regime (and beyond, at future facilities) helps us shed light on the (intrinsic) heavy-flavor content of the proton, and on small-x dynamics.

LHC measurements: $Z + b$

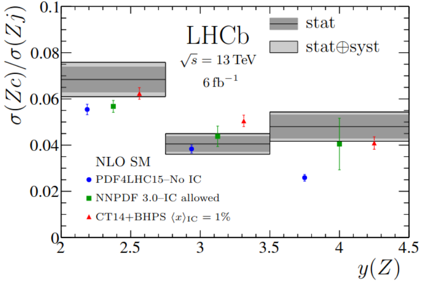
Precise measurements $Z + b/c$-jets available from the ATLAS, CMS and LHCb collaborations



[ATLAS 13 TeV, 2403.15093]

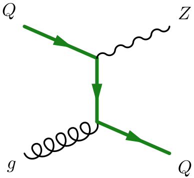
[CMS 13 TeV, 2112.09659]

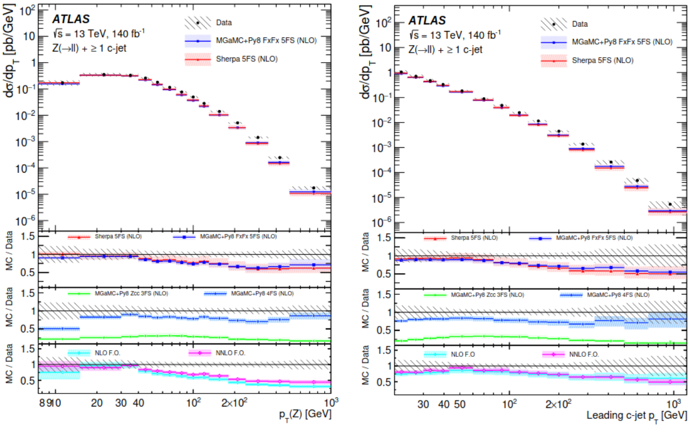
$Z + c$ to probe the HF content of the proton



[LHCb 13 TeV, 2109.08084]

- NNPDF [Nature 2022 2208.08372, 2311.00743]
- CT18FC [2211.01387]





[ATLAS 13 TeV, 2403.15093]

GMVFN schemes in a nutshell

Heavy-flavor production dynamics is nontrivial due to the interplay of massless and massive schemes which are different ways of organizing the perturbation series

- Massive Scheme (Fixed-Flavor-Number Scheme): final-state HQ with $p_T \lesssim m_Q$
  - No heavy-quark PDF in the proton. Heavy flavors generated as massive final states.
  - m_Q is an infrared cut-off.
  - Power terms p_T^2/m_Q^2 are correctly accounted for in the perturbative series
- Massless Scheme (Zero-mass): $p_T \gg m_Q \gtrsim m_p$
  - Log terms $\alpha_s \log^n(p_T^2/m_Q^2)$ that spoil the convergence of the fixed-order expansion.
  - Heavy quark is considered essentially massless and enters also the running of α_s.
  - Need to resum these logs with DGLAP: initial-state logs resummed into a heavy-quark PDF, final-state logs resumed into a fragmentation function (FF).
- Composite Scheme (General-Mass Variable-Flavor-Number Scheme): the key mass dependence and efficiently resum collinear logs, so that they combine the FFN and ZM schemes together
  - a correct treatment of heavy flavors in DIS and pp
  - accurate predictions of key scattering rates at the LHC,
  - global analyses to determine proton PDFs

Main idea for S-ACOT-MPS (massive phase space)

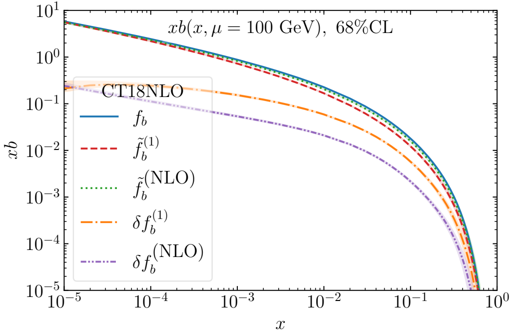
$$\mathrm{ACOT} = \mathrm{FC} + \mathrm{FE} - \mathrm{Sub}$$

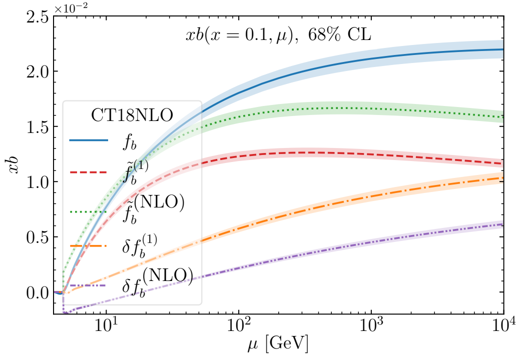
- Flavor Creation: full mass dependence
- Flavor Excitation: approximate mass dependence
- Subtraction: well defined at the quark mass threshold, to avoid the double counting

FE and Subtraction can be facilitated by introducing residual PDFs:

$$\tilde{f}_Q = \sum_n a_s^n \sum_{j=q,g} A_{Qj}^{(n)} \otimes f_j, \quad \delta f_Q = f_Q - \tilde{f}_Q.$$

Available on HEPForge





Theoretical framework for $Z + Q$

The differential cross section for partonic scattering $i + j \to Z + Q + X$ can be written as

$$\mathrm{d}\sigma = G_{ij}\left(x_A, x_B, Q^2; \frac{\mu^2}{Q^2}, \frac{m_Q^2}{\mu^2}, \alpha_s, N_f\right)$$

where the factorization gives

$$G_{ij} = \sum_{k,m}^{N_f} \int_{x_A}^{1} \mathrm{d}\xi_A \int_{x_B}^{1} \mathrm{d}\xi_B f_{k/i}(\xi_A, Q^2) H_{km}\left(\frac{x_A}{\xi_A}, \frac{x_B}{\xi_B}\right) f_{m/j}(\xi_B, Q^2)$$

And the perturbative expansion leads to

$$G_{ij}(x_A, x_B) = \sum_{k=0} G_{ij}^{(k)}(x_A, x_B)$$

$$H_{km}(\widehat{x}_A, \widehat{x}_B) = \sum_{k=0} H_{km}^{(k)}(\widehat{x}_A, \widehat{x}_B)$$

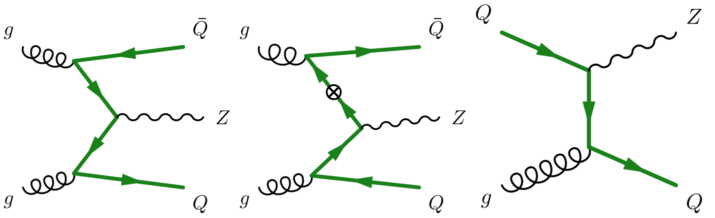
$$f_{i/j}(\xi) = \delta_{ij}\delta(1-\xi) + \sum_{k=1} A_{ij}^{(k)}(\xi)$$

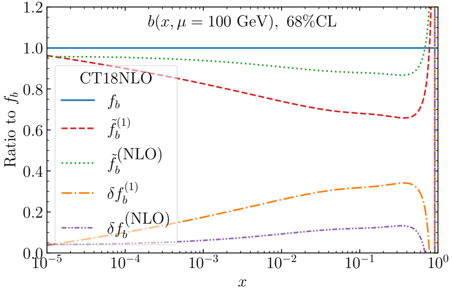
$$\widehat{x} = x/\xi$$

$A_{ab}^{(k)}(k = 1, 2\cdots)$: Operator Matrix Elements

$A_{hg}^{(1)}(\xi) = 2P_{Qg}^{(1)}(\xi)\ln\left(\mu^2/m_Q^2\right)$ for $g \to Q\bar{Q}$

Cancellation pattern at the lowest mandatory order





$$H_{gg}^{(2)}(x_A, x_B) = G_{gg}^{(2)} - A_{Qg}^{(1)} \otimes H_{Qg}^{(1)}(\widehat{x_A}, x_B) - H_{gQ}^{(1)} \otimes A_{Qg}(x_A, \widehat{x_B}$$

$$\sigma_{\mathrm{Sub}}^{(2)}(x_A, x_B) = g(x_A)\tilde{f}_Q(x_B)\sigma_{gQ\to ZQX}(x_A, x_B) + (A \leftrightarrow B)$$

We can define the subtracted and residual PDFs as

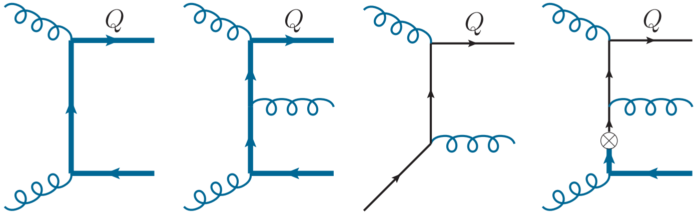
$$\tilde{f}_Q = \sum_n a_s^n \sum_{j=q,g} A_{Qj}^{(n)} \otimes f_j, \ \delta f_Q = f_Q - \tilde{f}_Q.$$

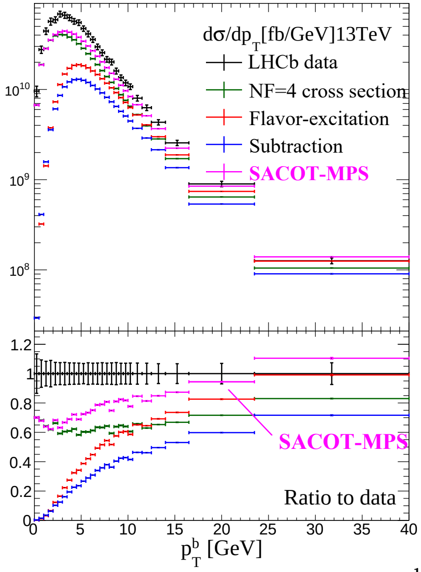
$$\tilde{f}_Q^{(1)} = \frac{\alpha_s}{2\pi} \log\frac{\mu^2}{m_Q^2}\left[P_{Qg}^{(1)} \otimes g\right](x, \mu^2)$$

Subtracted and Residual PDFs are provided in the form of LHAPDF grids [HEPForge]
Applicable for HQ related phenomenology.

The inclusive-b production

Matrix Elements taken from `MCFM` [1909.09117]



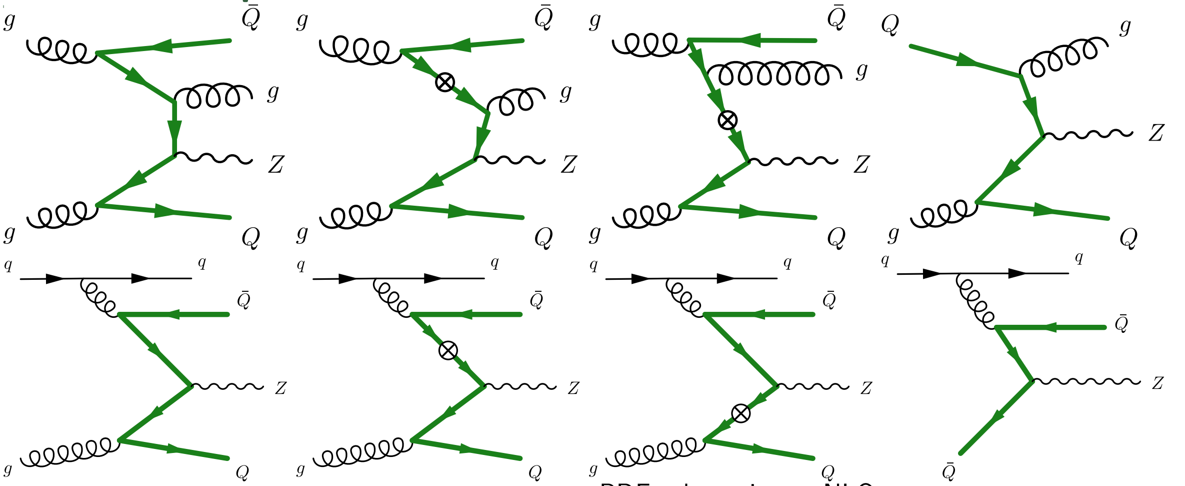


- At low p_T, Sub≃FE, FC dominates
- At high p_T, Sub≃FC, FE dominates
- A smooth transition from the FC to FE (GM-VFNS)

Thesis

Cancellation pattern at NLO

Matrix Elements taken from NLOX [1805.01353]



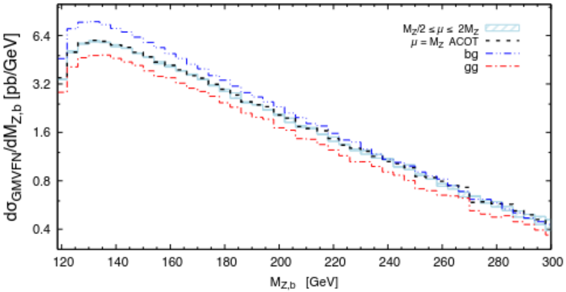
Cancellation becomes more involved

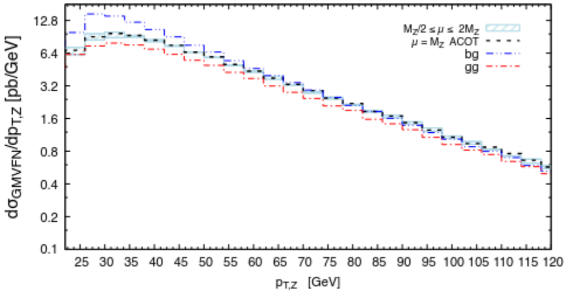
$$H_{ij}^{(3)} = G_{ij}^{(3)} - A_{Qi}^{(1)} \otimes H_{Qj}^{(2)} - A_{Qi}^{(2)} \otimes H_{Qj}^{(1)} + (i \leftrightarrow j)$$

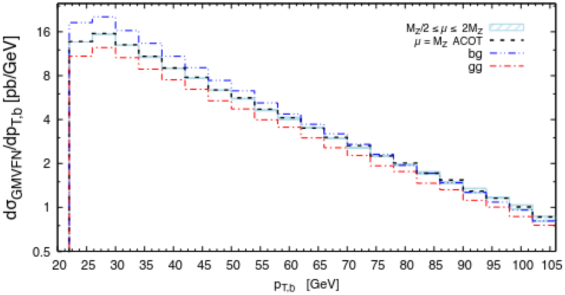
PDF subtraction at NLO

$$\tilde{f}_Q^{(2)} = \left(\frac{\alpha_s}{2\pi}\right)^2 \sum_{j=g,q} A_{Qj}^{(2)} \otimes f_j$$

Application to the $Z + b$ production

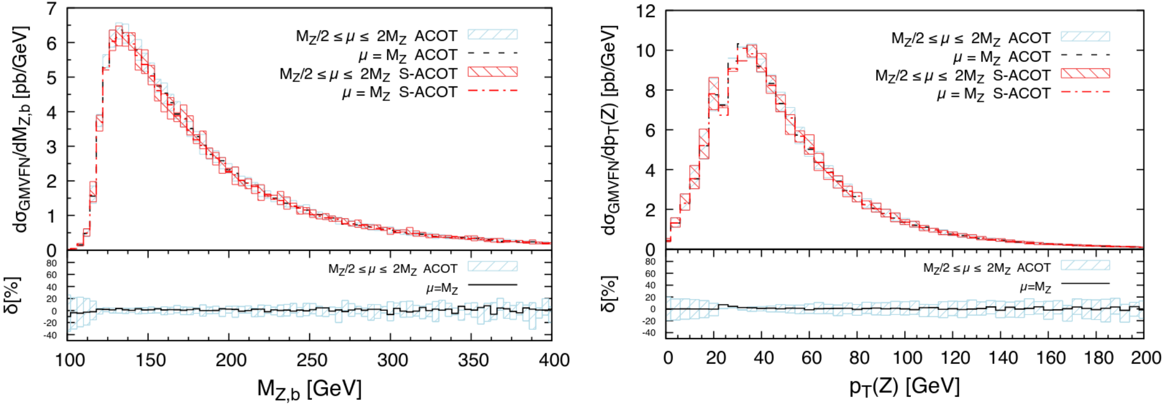






- At high $M_{Zb}, p_{T,Z}, p_{T,b}$, ACOT→FE (bg)
- At low $M_{Zb}, p_{T,Z}, p_{T,b}$, ACOT→FC (gg) trend
- The low energy cancellation is not perfect, due to the high scale nature $\mu \sim M_Z$
- It will be more pronounced in the $p_T^{Zb} \to 0$ limit

The HQ mass m_b dependence is small



- Simplified ACOT (with initial b-quark as massless)
- ACOT complete mass dependent

$$p_b = \frac{\sqrt{s}}{2}\left(x_{1,2} + \frac{m_b^2}{x_{1,2}s}, 0, 0, \pm x_{1,2} \mp \frac{m_b^2}{x_{1,2}s}\right), \; \frac{m_b}{\sqrt{s}} \le x_{1,2} \le \frac{1}{2}\left(1 + \sqrt{1 - \frac{4m_b^2}{s}}\right).$$

Concluding remarks

- We applied the S-ACOT-MPS at NLO to $Z+Q$ production at the LHC
- S-ACOT-MPS developed at NLO: used to describe $Z+Q$ production differentially
- Technically accessible towards NNLO
- Direct access to c/b-PDF: constraining the heavy-flavor PDFs.
- Residual/Subtraction PDFs are provided in the form of LHAPDF grids [HEPForge] to allow users for multiple heavy-flavor phenomenology
- The GMVFN schemes in (N)NLO QCD calculations is simplified with the PDF subtraction formalism

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- Authors: Keping Xie (PITT PACC), John Campbell (Fermilab), Pavel Nadolsky (SMU/MSU)

The (S-)ACOT scheme for the Z+b production at hadron colliders

- Authors: Marco Guzzi (KSU), Pavel Nadolsky (SMU/MSU), Laura Reina (FSU), Doreen Wackeroth (Baffalo), Keping Xie (MSU)

The $p_{T,b}, \eta_b$ distributions