Snowmass2021 LoI: **Constraining heavy flavor PDFs at hadron colliders**

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Abstract

In this letter of interest, we discuss the possibility of constraining heavy-flavor parton distribution functions (PDFs) in the proton using heavy-flavor initiated processes at hadron colliders in global QCD analyses.

Introduction. Collinear parton distribution functions (PDFs) of the proton map out the longitudinal distribution of its inner constituents quarks and gluons. They are a staple product of QCD factorization and are a crucial limiting factor in the accuracy of theoretical predictions for many important observables in hadronic collisions. Advances of QCD global analyses to determine PDFs encompass progress in higher-order QCD theory calculations as well as statistical methods to analyze high-precision data. They are critical to the high-energy physics programs at the Large Hadron Collider (LHC) to enhance its discovery potential in the next runs of activity, and for Future Colliders (HL-LHC, FCC-hh, LHeC, EIC). As of today, proton PDFs still remain the major source of uncertainty in most of the theory predictions at hadron colliders. Reducing PDF uncertainties is critical to investigate the properties of the Higgs boson and electroweak symmetry breaking (EWSB), and to look for deviations from the Standard Model (SM).

Modern global QCD analyses [1–5] determine collinear proton PDFs and their combinations using the combined HERA I+II [6] deep-inelastic scattering (DIS) measurements in addition to many high-precision Large Hadron Collider (LHC) data, e.g., single-inclusive jet production, production of Drell-Yan pairs, top-quark pairs, and high-p_T Z bosons. Despite these great efforts, heavy-flavor (HF) PDFs deserve dedicated attention as their current constraints remain weak.

In this Letter of Interest we consider to include new selected high-precision hadron collider data in future global QCD analyses to improve constrains on HF PDFs.

Constraining heavy-flavor PDFs. Constraining HF PDFs is a twofold task. First, it corresponds to the ability of a specific QCD framework (scheme) to give correct predictions for the cross section of observables involving the third generation of quarks. The heavy quark (HQ) pair is tied to the gluon, i.e., HQs are perturbatively generated. In this case, constraints reflect our ability to access gluon splitting and when one of the HQs goes along the beam-pipe with proton's remnant. Basically, it represents the ability of our scheme to capture HF perturbative dynamics. Second, it corresponds to the possibility of directly accessing HQ PDFs parametrized at the initial scale, i.e., to consider an intrinsic HQ in the proton [7, 8].

Assuming that these contributions factorize, recent PDF analyses [2, 9–11] explored the impact of a "fitted HQ" in their determinations ("fitted charm"). The fitted charm is interpreted as the intrinsic charm plus other (possibly not universal) higher $\mathcal{O}(\alpha_s)$ / higher power terms. There is no agreed definition/framework to factorize intrinsic HQ contributions at the present day. DIS HQ factorization by J. Collins [12], was proved only for radiative HQs. Intrinsic HQs are corrections that scale like $\left(\Lambda^2_{QCD}/m^2_Q\right)\ln Q^2/\mu^2$ and there is no consensus on how to factorize these contributions. Moreover, these contributions are comparable in size to NNLO and N3LO corrections, and therefore it is important to distinguish them from radiative contributions of different nature in future global QCD analyses of PDFs [13, 14]. New precision measurements at the LHC run II, EIC, and future collider programs will be determinant to have a better understanding of this effects. In fact, hadron collider-based searches can be complementary to DIS, especially direct to measurements at EIC.

Heavy-flavor schemes. Massive and massless schemes are different frameworks for the treatment of HQs in scattering reaction calculations and represent different ways of reorganizing the perturbation series [15, 16].

In a massive scheme, the mass m_Q of the HQ is approximately of the same size of the typical hard scale Q of the process under consideration, and both these quantities are much larger than the mass of the proton m_P: $Q \approx m_Q \gg m_P$. This means that HQs can only be created in pairs in high-Q interactions, and the scheme gives a correct description in the threshold region. In this case, there is no HQ PDF inside the proton. HQs are generated as massive final states and m_Q functions as an infrared cut-off.

In a massless scheme instead, the typical scale of the process is much larger than both the HQ mass and the proton mass: $Q \gg m_Q \gg m_P$. In this case, logarithmic terms of the type $\ln(Q^2/m_Q^2)$ appear in the perturbative expansion, the heavy quark is considered essentially massless and enters also the running of the strong coupling α_s. These logarithms may spoil the convergence of the fixed order expansion and need to be resummed through DGLAP renormalization group equations.

Many high-precision observables currently included in global QCD analyses at NNLO, extend over a wide kinematic region of momentum fraction x and momentum transfer Q. It is therefore natural to evaluate all fitted cross sections in a factorization scheme that incorporates features of both the massive and massless schemes. These general-mass (GM) factorization schemes [17–26] interpolate between massless (or zero mass (ZM)) and massive (fixed-flavor number (FFN)) schemes assuming that the number of quark flavors varies with energy, and at the same time including dependence on HQ masses in relevant kinematical regions. They require a subtraction mechanism to avoid double-counting in the collinear region. Higgs and vector boson production in proton-proton collisions $pp \to H, \gamma^*/Z/W^{\pm}$, and heavy-flavor production in DIS, are examples of this. In particular, a precise determination of DIS structure functions in PDF fits requires a GM scheme to accurately predict key scattering rates at the LHC. As more and more high-precision measurements in hadronic collisions become available, is desirable to have GM schemes extended to NNLO and beyond in the case of proton-proton reactions.

Accessing HF PDFs in future global QCD analyses. Associated production of a Z boson with charm or bottom quark jets in proton-proton collisions provides direct access to c and b PDFs. $Z+$ b-jets cross sections have been recently measured at CMS [27] and ATLAS [28] at 13 TeV, and at 7 and 8 TeV center of mass energies [29–31]. Cross section measurements at 7 TeV for the same process in the forward region have been performed at LHCb [32, 33]. These measurements are sensitive to HQ PDF treatments and can in principle be incorporated in new PDF analyses to validate HQ schemes, constrain HQ PDFs and probe initial-scale parametrizations for intrinsic HFs.

The theory prediction for this process has been calculated in the 4 flavor scheme (FS) and in the massive-b 5FS and has been studied for single and double bottom-quark initiated processes, which are relevant for Higgs and Z production at the LHC [34–48]. 4FS and 5FS theory predictions are expected to provide complementary information once they are consistently matched, and give compatible results. A very recent calculation for the fixed-order theory prediction for Z + b-jet at $\mathcal{O}(\alpha_s^3)$ in QCD [49], combines ZM NNLO and FFNS at NLO within the FONLL scheme [25]. It would be interesting to analyze the same calculation within a different HF scheme, e.g., S-ACOT-χ [21], at the same perturbative order. An equivalent version of S-ACOT-χ applied to hadron-hadron kinematics has been recently studied in [50].

This would prepare the ground for novel global PDF analyses including Z + c/b-jet cross section measurements where one can explore the separation between the perturbative and the nonperturbative HQ by directly probing the c/b-quark PDF [7]. This task encompasses a large number of preliminary activities which include (and are not limited to): a dedicated set up of the theory calculation (scheme selection/validation) and its numerical implementation within a specific fitting package; the production of reliable fast tables for theory predictions to allow for short CPU runtime in global PDF fits; a thorough statistical analysis to assess the compatibility of experimental measurements for these processes within the fit.

Summary. In this LoI we propose to use cross section measurements for Z boson in association with charm or bottom quark jets in proton-proton collisions in future global QCD analyses to probe HF PDFs and validate intrinsic HFs models. Precision measurements at the LHC run II already offer the possibility of probing heavy flavors using novel processes. Higher-order calculations are progressing at fast pace, and it is expected that missing pieces necessary to investigate the impact of different HQ schemes on PDFs will be available in the very near future. This will offer new opportunities to improve our current knowledge of HF PDFs and test QCD factorization in the unprecedented kinematic regime of future colliders.

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