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Quarkonium fragmentation in a variable-flavor number scheme: Towards NRFF1.0

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We report progress on the determination and study of quarkonium production within the fragmentation approximation. Our analyses address the moderate and large transverse-momentum regime, where the collinear fragmentation of a single parton is expected to dominate over the short-distance production, directly from the hard scattering, of the constituent $(Q\bar{Q})$ system. Parton fragmentation channels to pseudoscalar and vector quarkonia are built on the basis of non-Relativistic QCD next-to-leading computations, which we use to model initial-scale fragmentation inputs. Thus, a preliminary family of Variable-Flavor Number-Scheme (VFNS) fragmentation functions, named `NRFF1.0`, are constructed through standard DGLAP evolution. Statistical uncertainties are obtained from a Monte Carlo, replica-like approach embodying missing higher-order uncertainties.

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1. Opening remarks

In the domain of fundamental interactions, hadrons containing either open or hidden heavy flavors play a crucial role. Heavy quarks, in particular, are key indicators in the search for signs of New Physics, due to their predicted interactions with beyond-Standard-Model particles. Moreover, their masses, which lie above the perturbative QCD threshold, make them ideal candidates for rigorous tests of the strong interaction. The study of formation mechanisms of quarkonia, the so-called "hydrogen atoms" of QCD [1], stands as a valuable tool to unveil core aspects of the strong force. Quarkonium physics bridges precision studies of perturbative QCD and explorations of the proton structure. Hadronic decays of S-wave bottomonia allow for precise determinations of α_s [2, 3]. Forward emissions of quarkonia test the positivity of gluon parton densities (PDFs) at small-x and -Q^2 [4–7]. Quarkonia provide valuable insights for 3D tomographic imaging of the proton at small [8–14] and moderate x [15–21]. Unresolved photoproductions of J/ψ plus a charm-jet at the EIC will "measure" the intrinsic-charm valence PDF in the proton [22–25]. The theoretical description of quarkonium hadronization is challenging. Numerous models have been proposed, but none fully account for all experimental observations. To unravel the quarkonium puzzle, an effective theory, known as Non-Relativistic QCD (NRQCD), was built [26, 27]. NRQCD prescribes that all possible Fock levels participate to the physical-quarkonium state. They are organized into a double series of powers of α_s and v, the latter being the $(Q\bar{Q})$ relative velocity. NRQCD cross sections are cast as a sum of perturbative Short-Distance Coefficients (SDCs), each of them being multiplied by a nonperturbative Long-Distance Matrix Element (LDME). For analogies with FFs for open heavy-flavored particles, see [28–30]. NRQCD allows for rigorous testing of quarkonium production mechanisms, especially the *short-distance* creation of a $(Q\bar{Q})$ pair in hard scatterings, which prevails at low $|\vec{p}_T|$. As $|\vec{p}_T|$ increases, another mechanism competes: the *fragmentation* of a single parton followed by its inclusive decay into the observed quarkonium [31]. We describe collinear fragmentation to pseudoscalar and vector quarkonia in color singlet, via a preliminary version of our `NRFF1.0` FF sets. They builds on a new scheme, the Heavy-Flavor Non-Relativistic evolution (`HF-NRevo`) [32], which makes use of NLO NRQCD initial-scale inputs and embodies a consistent DGLAP evolution and a MHOU-driven uncertainty analysis from a MC, replica-like treatment [33].

2. Quarkonium fragmentation from `HF-NRevo`

Being masses of constituent heavy quarks well above $\Lambda_{\rm QCD}$, initial-scale inputs of quarkonium FFs are thought to contains perturbative inputs. Therefore, a consistent use of collinear factorization is needed here. To this extend, we propose a novel methodology, named `HF-NRevo` [32]. It bases upon three core aspects: interpretation, evolution, and uncertainties. The interpretation allows one to decipher the short-distance formation at low transverse momentum ($|\vec{p}_T|$) as a two-parton fragmentation in a Fixed-Flavor Number Scheme (FFNS), and enabling subsequent FFNS-to-VFNS matching [34]. This is supported by the observation that, when accounting for transverse-momentum dependence is considered, distinct singularity patterns are found in the matching tails of low-$|\vec{p}_T|$ shape functions [35] and moderate-$|\vec{p}_T|$ FFs [36]. According to `HF-NRevo` [32], the DGLAP evolution of quarkonium FFs happens in two steps. First, an *expanded* and *decoupled* evolution

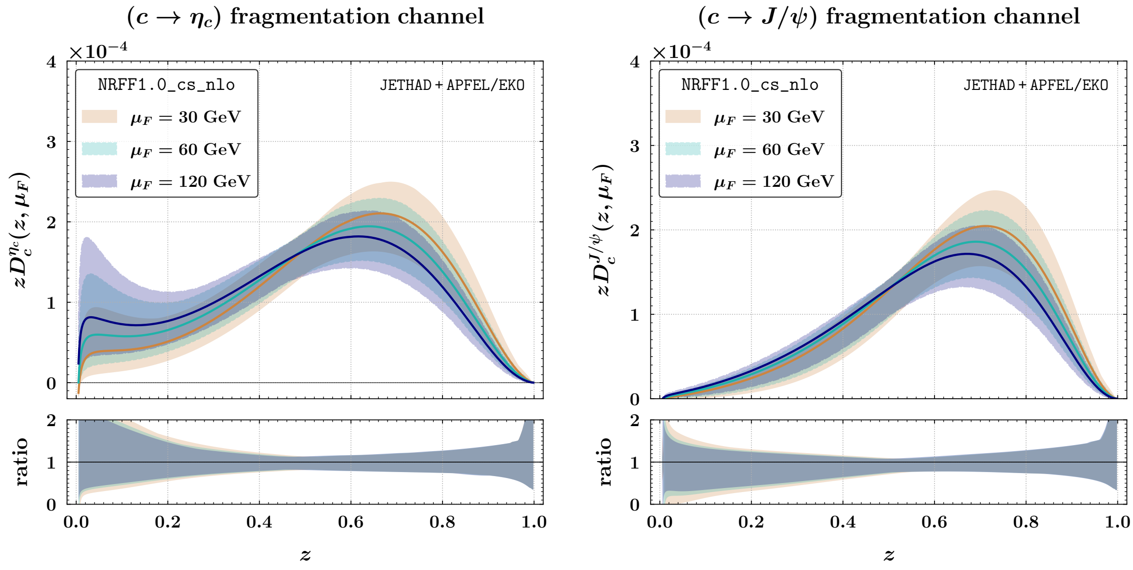

Figure 1: NLO charm to color-singlet η_c and J/ψ FFs. Preliminary results of `NRFF1.0` sets.

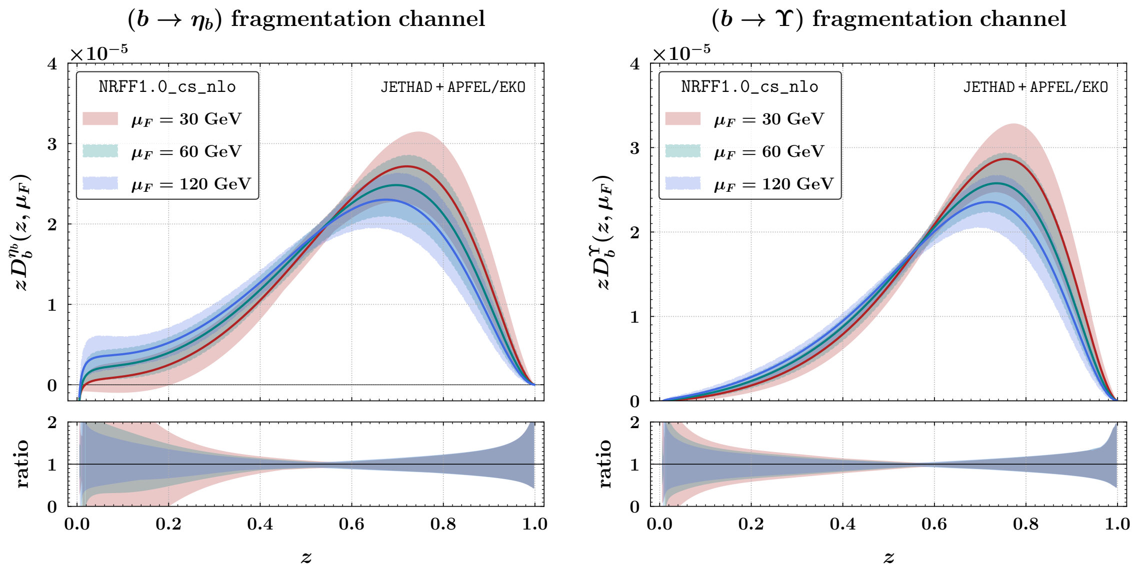

Figure 2: NLO bottom to color-singlet η_b and Υ FFs. Preliminary results of `NRFF1.0` sets.

(`EDevo`, done symbolically via `JETHAD` [37–45]), accounts for thresholds of all parton species. Then, the standard *all-order* evolution (`AOevo`, done numerically via `APFEL++` [46]; connecting `EKO` [47] with `JETHAD` is underway) activates. Finally, the size of MHOUs due to variations of DGLAP-evolution thresholds is gauged. In particular, we make a simultaneous scan of factorization and renormalization scales entering the initial inputs of our FFs, by varying them of a factor 1/2 to two. This strategy is in line with analyses on PDFs that use theory-covariance-matrix approaches [48, 49] or the `MCscales` method [50]. For simplicity, here we show four fragmentation channels, namely charm to charmonium and bottom to bottomonium FFs [51–53]. Left and right plots of Fig. 1 are for ($c \to \eta_c$) and ($c \to J/\psi$) `NRFF1.0` FFs, with μ_F ranging from 30 to 120 GeV. Analogously, left and right plots of Fig. 2 are for $(b \to \eta_b)$ and $(b \to \Upsilon)$ `NRFF1.0` FFs, with μ_F in the same range as before.

3. Towards `NRFF1.0`

By means of the novel `HF-NRevo` methodology, we built a preliminary version of `NRFF1.0` quarkonium collinear FF sets. These functions feature color-singlet initial-scale inputs from all parton channels, calculated within NRQCD at NLO. We defined a consistent DGLAP scheme to set evolution thresholds and used a Monte Carlo replica-like treatment to address uncertainties arising from missing higher-order corrections. The `NRFF1.0` FFs are set to replace the `ZCW19`$^+$ and `ZCFW22` determinations currently used in the study of vector quarkonia [54, 55] and B_c mesons [56, 57]. They will provide essential guidance for quarkonium physics at the HL-LHC [58, 59], the EIC [60–62], and future lepton machines [63]. Moreover, they will serve as a benchmark for AI-based extractions [64–68]. Future endeavors will include: exploring color-octet contributions [69, 70], implementing a general-mass VFNS [71–73], and extending our studies to exotic hadrons [74–76]. As a long-term goal, by suitably adapting the `HF-NRevo` framework, we also plan to address quarkonium-in-jet collinear fragmentation. This will provide us with a valuable tool to map the substructure of heavy-flavored jets, with potential applications to the study of quarkonium-modulated jet angularities.

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