Collinear fragmentation of pseudoscalar quarkonia from NLO NRQCD

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1. The Multi-Scale Challenge in Quarkonium Production

The production of heavy quarkonia at high transverse momentum ($q_T \gg m_Q$) involves a duality between

- Short-distance production at low-to-moderate pT
- Single-parton VFNS at moderate-to-large pT

First set of collinear fragmentation functions for the pseudoscalar quarkonium: `https://github.com/FGCeliberto/Collinear_FFs`.

2. NRFF1.0: Theoretical Foundation at μ_0

The initial scale FFs are computed at $\mu_0 = 2m_Q$ using NLO Short-Distance Coefficients (SDCs).

$$D_{i\to\eta_Q}(z,\mu_0) = \frac{\alpha_s^2(\mu_0)}{m_Q^3}\langle\mathcal{O}^{\eta_Q}(^1S_0^{(1)})\rangle\mathcal{F}_i(z) \tag{1}$$

1. All parton channels are known at NLO
2. Singlet-color
3. HF-Nrevo combines elements of hadronic structure with QCD precision (collinear factorization)

2. NRFF1.0: Theoretical Foundation at μ_0

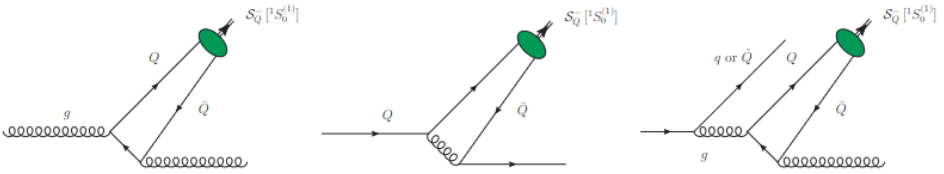

Figure: $S_Q^- \ [^1S_0^{(1)}]$

3. The HF-NRevo Scheme: Bridging the Thresholds

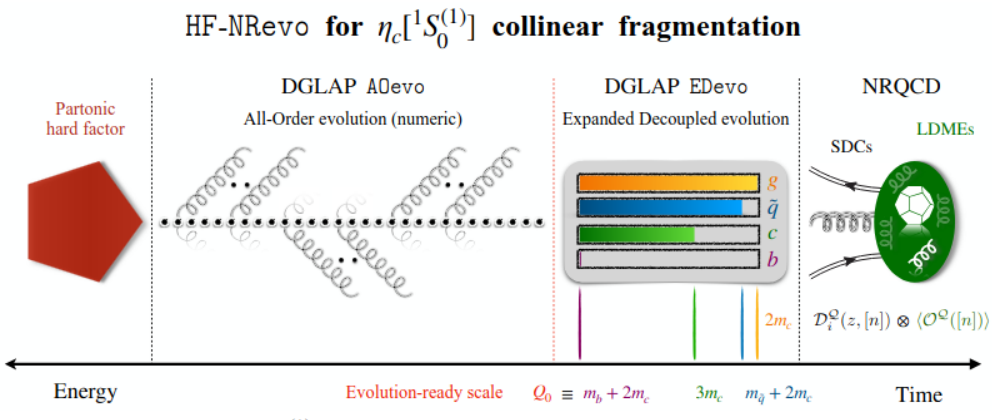

Figure: Evolution workflow within the HF-NRevo scheme

4. Justification for EDevo Matching

Why is EDevo necessary?

- For η_c and η_b, the transition between flavor schemes is implemented through standard VFNS matching across heavy-quark thresholds, consistently with the perturbative evolution of the fragmentation functions
- **EDevo**: it is crucial to preserve the thresholds, that, in heavy flavor specis, are present in light parton channels (non constituent quarks and gluon).

5. Quarkonium FFs from HF-NRevo evolution

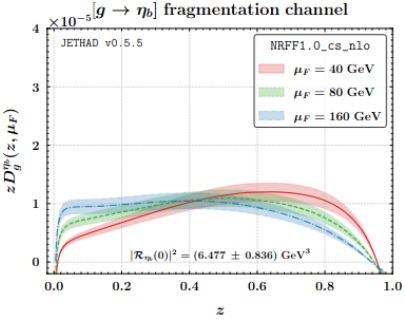

Figure: $[g \to \eta_b]$

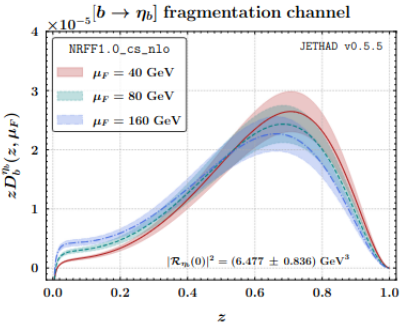

Figure: $[b \to \eta_b]$

5. Quarkonium FFs from HF-NRevo evolution

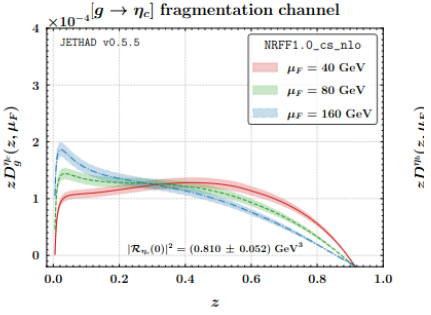

Figure: $[g \to \eta_c]$

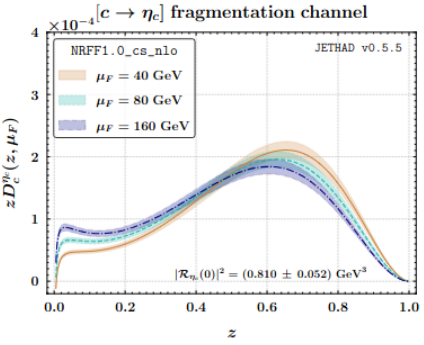

Figure: $[c \to \eta_c]$

6. High-Precision Benchmark: η Sector

- BFKL effect;
- Kinematic cuts of LHC (CMS) in function of growing rapidity
- The kinematical phase-space decreases due to the emission of gluons in function of rapidity.

7. High-Energy Resummation (HyF)

At very high energies (small x), we encounter logarithms ΔY that can destabilize NLO results

$$\sigma_{\text{Hybrid}} = \sigma_{\text{NLO}} + \sigma_{\text{NLL res}} \tag{2}$$

Hybrid factorization for the semi-inclusive hadroproduction of a η_c and η_b quarkonium accompanied by a hadron or a light jet.

F.G. Celiberto, Eur. Phys. J. C 81 (2021) 8, 691 [2008.07378 [hep-ph]]
F.G. Celiberto, Phys. Rev. D 105 (2022) 11, 114008 [2204.06497 [hep-ph]]

7. High-Energy Resummation (HyF)

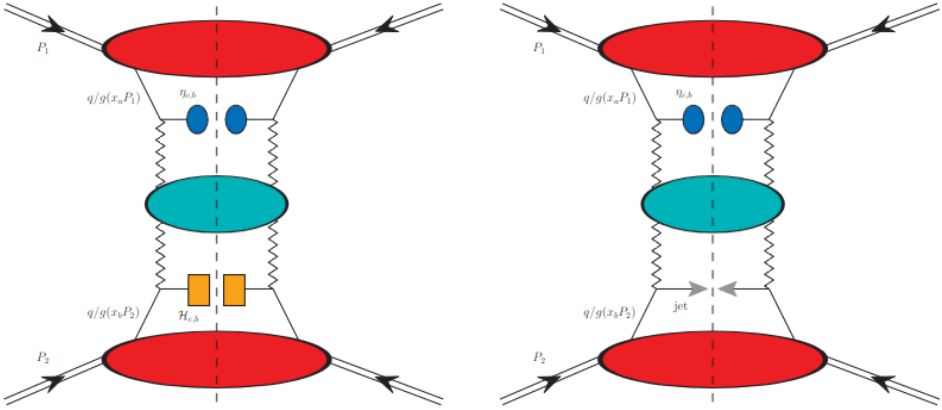

Figure: Hybrid factorization for the semi-inclusive hadroproduction

8. Predictions for η Production

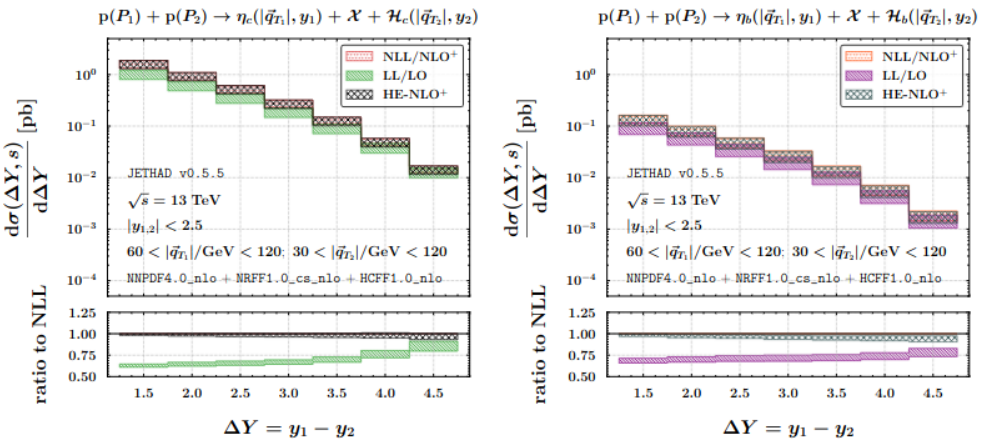

Figure: Predictions for η rapidity distributions.

8. Predictions for η Production

Observations:

- We provide the first NLO-evolved predictions for η_b at 13 TeV.
- The cross-section is sensitive to the choice of LDME $\langle \mathcal{O}^{\eta_b} \rangle$.
- Future data from ATLAS and CMS will allow us to constrain the bottom sector LDMEs using our FF sets.

9. Numerical Stability: Scale Variations

To assess theoretical reliability, we performed a 7-point variation of μ_R and μ_F.

- **Result:** The HF-NRevo scheme exhibits significantly reduced scale sensitivity compared to LO sets.
- Resumming the $\ln\left(q_T^2/m_Q^2\right)$ terms into the FF absorbs the bulk of the scale dependence that plagues fixed-order NRQCD.
- This stability is a prerequisite for extracting LDMEs from experimental data.

10. Technical Delivery: The NRFF1.0 Set

Scientific transparency and reproducibility are ensured by:

- APFEL++ Integration: The evolution kernels are implemented in a high-performance C++ framework.
- LHAPDF Availability: The evolved FFs are released in the standard LHAPDF format.
- This allows the community to use NRFF1.0 directly in Monte Carlo generators like Pythia8 or MadGraph5_aMC@NLO `https://github.com/FGCeliberto/Collinear_FFs`

11. Physics Discussion: The Gluon-Octet Interplay

A subtle point from the paper:

- While η_Q is a color-singlet state, the evolution effectively mimics color-octet contributions at high scales.
- The $g \to \eta_Q$ fragmentation, which dominates at LHC, is a "heavy-quark loop" induced process at NLO.
- Our consistent treatment deals with the suppression of color octet

12. Summary of Key Achievements

Theoretical and Phenomenological Impact

- **New Scheme:** Introduced HF-NRevo for threshold-consistent evolution.
- **First NLO Set:** Released NRFF1.0 for η_c and η_b.
- **Predictions:** We released predictions to compare future data at Hi-Lumi LHC.

13. Outlook: The Next Generation

- **Vector States:** The HF-NRevo scheme is currently being extended to J/ψ and Υ, where the color-octet contributions are more complex.
- **TMD Evolution:** Future work involves moving beyond collinear factorization to Transverse Momentum Dependent (TMD) fragmentation.
- **Exotic States:** This framework provides the consistent basis for studying the fragmentation of tetraquarks and other exotics.