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QCD resummation in hadron production

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Summary. — We present calculations of next-to-leading order and resummed QCD corrections for semi-inclusive deep-inelastic scattering and single-inclusive e^+e^- annihilation. The resummation is performed to next-to-leading logarithmic accuracy. Knowing these QCD corrections is important in order to extract parton distribution functions and fragmentation functions from present and future data for these reactions. We present phenomenological results relevant for the COMPASS, HERMES, and BELLE experiments.

PACS 13.85.Ni – Inclusive production with identified hadrons.

PACS 12.38.Bx – Perturbative calculations.

1. – Introduction

Processes with identified final-state hadrons play important roles in QCD. In the present work, we address higher-order perturbative corrections to two of the key hadron production processes, single-inclusive annihilation (SIA) $e^+e^- \rightarrow hX$ and semi-inclusive deep-inelastic scattering (SIDIS), $lp \rightarrow lhX$, where h denotes a final-state hadron. Modern analyses [1-3] of fragmentation functions variously use data for these two processes. Our study is very much motivated by the recent advent of data for these reactions with unprecedented high precision. The BELLE collaboration at KEK has presented data [4] for pion and kaon multiplicities in SIA with a very fine binning and extremely high precision at the sub-1% level. New preliminary high-statistics SIDIS data have been shown by the HERMES [5] and COMPASS [6] lepton scattering experiments over the past year or so.

In the kinematic regimes accessed by these experiments, perturbative-QCD corrections are expected to be fairly significant. The infrared cancellations between virtual and real-emission diagrams in higher orders leave behind logarithmic contributions. These “threshold logarithms” become large when the phase space for real-gluon radiation is shrinking and therefore have to be taken into account to all orders in perturbation theory. In this work, we will examine this resummation of the large corrections. We will restrict ourselves to resummation at next-to-leading logarithmic (NLL) accuracy, which should capture the main effects. A more detailed description of the analysis presented in this paper was published in ref. [7].

2. – Resummation for SIDIS multiplicities

We consider semi-inclusive deep-inelastic scattering $\ell p \rightarrow \ell h X$. Using the usual kinematic variables, the SIDIS cross section may be written as [8]

$$(1) \quad \frac{d^3\sigma^h}{dx dy dz} = \frac{4\pi\alpha^2}{Q^2} \left[\frac{1 + (1-y)^2}{2y} \mathcal{F}_T^h(x, z, Q^2) + \frac{1-y}{y} \mathcal{F}_L^h(x, z, Q^2) \right],$$

where α is the fine structure constant and $\mathcal{F}_{T,L}^h$ are the transverse and the longitudinal structure functions. SIDIS hadron multiplicities are defined by

$$(2) \quad R_{\text{SIDIS}}^h \equiv \frac{d^3\sigma^h/dx dy dz}{d^2\sigma/dx dy},$$

where $d^2\sigma/dx dy$ is the cross section for inclusive DIS, $\ell p \rightarrow \ell X$. In order to investigate higher-order effects on SIDIS multiplicities, we have to consider QCD corrections to both the SIDIS and the inclusive DIS cross section.

Using factorization, the transverse and longitudinal structure functions in eq. (1) are given by ($i = T, L$)

$$(3) \quad \mathcal{F}_i^h(x, z, Q^2) = \sum_{f, f'} \int_x^1 \frac{d\hat{x}}{\hat{x}} \int_z^1 \frac{d\hat{z}}{\hat{z}} f\left(\frac{x}{\hat{x}}, \mu^2\right) D_{f'}^h\left(\frac{z}{\hat{z}}, \mu^2\right) \mathcal{C}_{f'f}^i\left(\hat{x}, \hat{z}, \frac{Q^2}{\mu^2}, \alpha_s(\mu^2)\right),$$

where $f(\xi, \mu^2)$ denotes the distribution of parton $f = q, \bar{q}, g$ in the nucleon at momentum fraction ξ and scale μ , while $D_{f'}^h(\zeta, \mu^2)$ is the corresponding fragmentation function for parton f' going to the observed hadron h . The hard-scattering coefficient functions $\mathcal{C}_{f'f}^i$ can be computed in perturbation theory.

Since threshold resummation can be derived in Mellin-moment space [9, 10], it is useful to take Mellin moments of the structure functions \mathcal{F}_T^h and \mathcal{F}_L^h . Since x and z are independent variables, we take moments separately in both. We find from eq. (3)

$$(4) \quad \tilde{\mathcal{F}}_i^h(N, M, Q^2) = \sum_{f, f'} \tilde{f}^N(\mu^2) \tilde{D}_{f'}^{h, M}(\mu^2) \tilde{\mathcal{C}}_{f'f}^i\left(N, M, \frac{Q^2}{\mu^2}, \alpha_s(\mu^2)\right).$$

Thus, the Mellin moments of the structure functions are obtained from ordinary products of the moments of the parton distribution functions and fragmentation functions, and double-Mellin moments of the partonic hard-scattering functions. To NLO, the latter may be found in [11]. Using the techniques developed in ref. [12], we find that the final NLL resummed coefficient function becomes in the $\overline{\text{MS}}$ scheme (see also [13])

$$(5) \quad \mathcal{C}_{qq}^{T, \text{res}}(N, M, \alpha_s(Q^2)) = e_q^2 H_{qq} \left(\alpha_s(Q^2), \frac{Q^2}{\mu^2} \right) \exp \left[2 \int_0^{Q^2} \frac{dk_{\perp}^2}{k_{\perp}^2} A_q(\alpha_s(k_{\perp}^2)) \right] \\ \times \left\{ K_0 \left(\sqrt{NM} \frac{2k_{\perp}}{Q} \right) + \ln \left(\frac{k_{\perp}}{Q} \sqrt{NM} \right) \right\}.$$

Here A_q and H_{qq} are perturbative functions. For resummation at NLL, one needs to know H_{qq} to first order in the strong coupling collecting the hard virtual corrections.

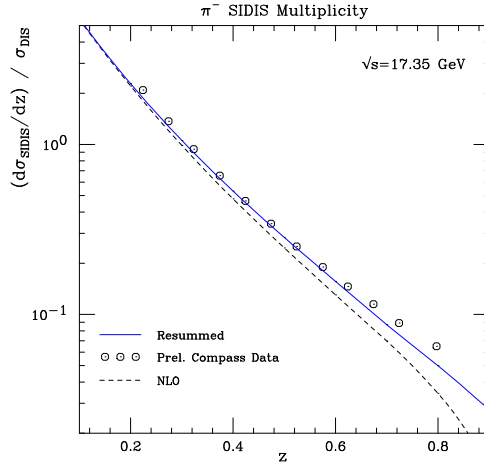


Fig. 1. – NLO and NLL resummed SIDIS multiplicities for π^- compared to the preliminary COMPASS data [6].

As the exponentiation of soft-gluon corrections is achieved in Mellin moment space, the hadronic structure function is obtained by taking the inverse Mellin transforms of eq. (4), which are given by contour integrals in the complex plane.

The NLL resummed results for DIS and SIA can be found in ref. [7] and refs. therein.

3. – Phenomenological results

We now investigate the numerical size of the threshold resummation effects for SIDIS and SIA multiplicities. For the parton distribution functions we use the NLO MSTW 2008 set of [14], whereas we choose the NLO DSS [1] pion fragmentation functions.

Starting with SIDIS, fig. 1 (fig. 2) shows our results for the NLO and the resummed multiplicities with COMPASS (HERMES) kinematics. The center-of-mass energy of COMPASS is $\sqrt{s} \approx 17.4$ GeV. The kinematic cuts employed are $0.041 < x < 0.7$,

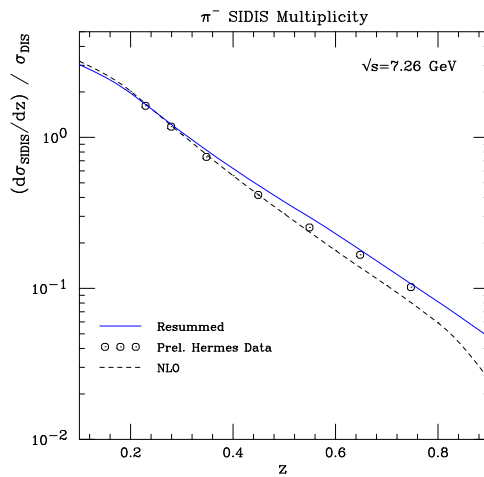


Fig. 2. – Same as fig. 1, but for HERMES kinematics. The preliminary data are from [5].

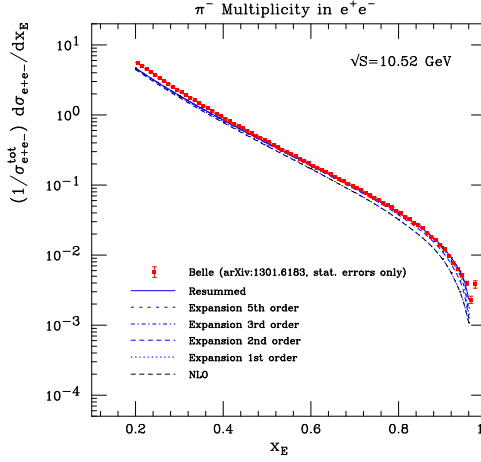


Fig. 3. – π^- multiplicity in electron-positron annihilation at $\sqrt{s} = 10.52$ GeV. The data are from [4].

$0.1 < y < 0.9$, $Q^2 > 1 \text{ GeV}^2$ and $W^2 = Q^2(1-x)/x + m_p^2 > 49 \text{ GeV}^2$, where m_p is the proton mass. For HERMES the center-of-mass energy is $\sqrt{s} \approx 7.26$ GeV. The kinematic cuts are $0.023 < x < 0.6$, $0.1 < y < 0.85$, $Q^2 > 1 \text{ GeV}^2$ and $W^2 > 10 \text{ GeV}^2$. We choose the renormalization and factorization scales as Q and consider the SIDIS multiplicity for π^- as a function of z , but integrating numerator and denominator of eq. (2) over x and y . It turns out that resummation leads to a moderate, but significant, enhancement of the multiplicities.

In fig. 3, we present our results for the SIA π^- multiplicity at $\sqrt{s} = 10.52$ GeV and for $-1 < \cos \theta < 1$. The results can also be studied as ratios $(\text{Th}' - \text{NLO})/\text{NLO}$, where Th' denotes any of the higher-order SIDIS multiplicities generated by resummation. These ratios are shown in fig. 4, making the large resummation effects even more apparent at high x_E .

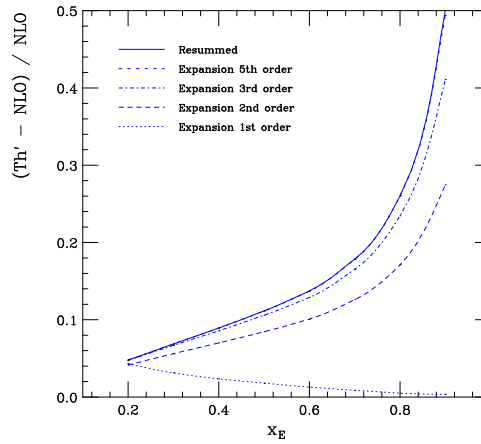


Fig. 4. – Ratios $(\text{Th}' - \text{NLO})/\text{NLO}$, where Th' corresponds to the multiplicity at higher orders as generated by resummation.

4. – Conclusions

We have derived threshold-resummed expressions for the coefficient functions for the SIDIS and SIA processes. We have presented phenomenological results for pion multiplicities for these processes in the kinematic regimes presently accessed by the COMPASS, HERMES and BELLE experiments. We found that resummation leads to modest but significant enhancements of the multiplicities. Our main point is that, given the good accuracy of the new preliminary data sets, it will be crucial to include resummation effects for both processes in the next generation of analyses of fragmentation functions.

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