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HIGHER TWIST, HEAVY QUARK, AND COHERENT PHENOMENA IN QCD*

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Scaling violations in QCD arise in two basic ways: (1) logarithmic corrections, associated with the variation of the running coupling constant and the radiative corrections which produce structure- and fragmentation-function evolution; and (2) power-law corrections, due to finite mass effects, multiparticle scattering processes, coherent wavefunction effects, and other non-perturbative phenomena. A complete quantitative confrontation of experiment and theory must take into account both types of corrections.[1]

A large class of power-law suppressed contributions in QCD are related to multiparticle subprocesses where more than the minimum number of quarks or gluons are scattered from the initial to final directions. These include the entire class of high momentum transfer form factor and exclusive hadron scattering processes, and the "direct" semi-inclusive reactions in which all of the valence quarks of a meson or baryon enter directly into a short-distance subprocess: $gq \to Mq$, $qq \to B\bar{q}$, $Mq \to \gamma^* q$, *etc.*[2,3] The amplitude for such wave function sensitive reactions can be systematically computed in perturbation theory from the convolution of the corresponding quark and gluon irreducible amplitude T_H (computed as if the hadrons were replaced by collinear quarks) with the distribution amplitudes $\phi_H(x_i, Q)$ defined in Ref. 4. The nominal power-law dependence is obtained from dimensional counting:[5] $T_H \sim Q^{4-n} F(\theta_{\rm c.m.})$ where n is the total number of incident and outgoing particles. The normalization scale and multiparticle correlations are determined by ϕ_H.

One of the clearest ways to separate logarithmic and power-law corrections to scaling is in the Drell-Yan process $\pi N \to \ell\bar{\ell} X$ at large longitudinal momentum. For $x_1 \to 1$, the antiquark in the meson wavefunction becomes far-off shell $k_1^2 - m^2 \sim -k_\perp^2/(1-x_1) \to -\infty$, so that the dominant subprocesses can be identified as $(q\bar{q})q \to \gamma^* q$. A simple perturbative gluon-exchange calculation[2] generates the form ($x_1 \sim 1$)

$$\frac{d\sigma}{d\cos\theta\, dx_1} \propto (1-x_1)^2(1+\cos^2\theta) + \frac{C}{Q^2}\sin^2\theta$$

where θ is the μ^+ center-of-mass angle. The constant C can be computed from a moment of the pion form factor and is normalized to $\langle k_\perp^2 \rangle$. Evidence for this dependence in $\pi N \to \mu^+\mu^- X$ at large x_F (dominance of the higher twist longitudinal component of the meson structure function) was found by the Chicago-Princeton experiment E-444 at FNAL and has been recently confirmed by experiments E-615 (test run) and NA-10 at the SPS.[6] The normalization of the longitudinal term appears larger than the leading order prediction of Ref. 3, but this could be to neglect of higher-order gluonic radiative corrections. Further checks of the predicted aximuthal and Q^2 dependence are necessary.

Related higher order QCD direct higher twist subprocesses are predicted to dominate $e^+e^- \to \pi X$ and $\ell N \to \ell' \pi X$ at $z \to 1$ (corresponding to fragmentation functions $\sim (1-z)^2 + C/Q^2$). Berger and I have predicted the existence of processes of the type $\pi N \to$ Jet + Jet $+X$, where the beam meson interacts *directly* in p_T^{-6} subprocesses ($\pi g \to q\bar{q}$, $\pi q \to gq$) leaving *no* forward spectator jet.[7] In inclusive high p_T hadron production, direct p_T^{-6} processes like $gq \to \pi q$ produce mesons at large p_T at $z \to 1$ with an enhanced normalization due to "trigger bias". (In this type of process, soft radiative corrections from the $(q\bar{q})$ can produce accompanying same-side particles, simulating a standard quark or gluon jet.) If such higher twist contributions are dominant for pion production, then one predicts γ/π ratios growing as p_T^2 at fixed θ_{cm} and x_T. This scaling behavior is consistent with ISR and fixed target data, rather than the $(1-x_T)^{-2}$ dependence predicted by leading twist subprocesses. Further, ISR and FNAL data[8] for the p/π ratio in pN collisions scales as p_T^{-3} or p_T^{-4} at fixed x_T and $\theta_{\rm c.m.}$ again ruling out leading twist subprocesses, and indicating the dominance of higher twist subprocesses. This, however, does not necessarily imply a quark-diquark scattering subprocess[8] (with scale $M_d^2 \sim 20\ GeV^2$) since there are many candidate higher twist subprocesses.

Although there are many qualitative phenomenological successes of the leading order $2 \to 2$ subprocess description of large p_T hadron production, a quantitative confrontation with the extensive body of data from FNAL, the ISR and the SPS will require a thorough analysis of leading and non-leading subprocesses. One must use fragmentation and structure functions with longitudinal higher-twist contributions, as well as solve the problem of setting separate scales $\hat{Q}^2$ for the subprocesses and each distribution function's evolution. The calculation of K-factors from higher order corrections has not been completed. Furthermore, even in deep inelastic-lepton scattering the role of (possibly A-dependent) higher twist contributions is not well understood: for example, Blankenbecler *et al.*,[9] have predicted huge contributions $800\,\mu^2/Q^2(1-x)^2$ to the nucleon structure function ($\mu^2 \gtrsim 0.01\ GeV^2$) and $\sigma_L/\sigma_T \sim 2 \times 10^5 \mu^2/Q^2$, simply by computing the minimal two-gluon exchange amplitudes.

One of the essential complications of the QCD analysis of hadron production at high transverse momentum is the necessity to include transverse momentum smearing intrinsic to the hadronic wavefunctions as well as from radiation from the active quarks and gluons. The use of *off-shell* kinematics is necessary to avoid a singular integration region from massless gluon exchange (the same coherence scale sets the lower cutoff for structure function evolution). Furthermore, it is likely that the intrinsic transverse momentum distribution is x-dependent, increasing as $x \to 1$: recent SFM[8] data for spectator transverse momentum is consistent with the postulate that the valence-quark light-cone Fock state wavefunction in the nucleon has higher $\langle k_\perp^2 \rangle$ than that of higher Fock states. This, in turn, provides a natural explanation for the magnitude of the nucleon form factor and other exclusive processes at large Q^2.[4]

In the case of massive lepton-pair production, there are now convincing arguments that the leading-twist cross section obeys Drell-Yan factorization.[10,11] However, even in Abelian theories, factorization is destroyed by finite-velocity corrections and by finite-target-length effects, due to elastic and inelastic

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initial state interactions in the target.[12] At quark energies large compared to a scale proportional to the target length, interactions in the target *vanish* (Landau-Pomeranchuk effect), but at finite Q^2 (~ 10 GeV^2 for heavy nuclei) a number of new A-dependent phenomena are predicted,[12] including growth of the lepton-pair transverse momentum with $A^{1/3}$. This effect, due to multiple elastic quark-nucleon scattering, has not been confirmed by experiment. We note that the size of the $\langle k_\perp^2 \rangle$ growth could be compensated somewhat if the intrinsic transverse momentum of quarks in nuclei is reduced,[12] just as $\langle x \rangle$ is observed to decrease with increasing A (EMC effect).

The underlying QCD mechanisms for heavy quark production in hadronic collisions are poorly understood in QCD.[13] The $gg \to Q\overline{Q}$ fusion mechanism in leading order does not account for the magnitude, leading x_F dependence, A-dependence, diffractive contributions, or the striking flavor dependence of charm production. [See, *e.g.*, the SPS data[14] showing an anomalously large cross section times branching ratio for $A^+(csu)$ production by 135 GeV/c Σ^-).] The data could be indicating important contributions due to finite quark velocity effects and/or higher twist "intrinsic" heavy quark contributions in the hadron wavefunction. EMC data[15] for the charm structure function indicates that the charm quark distribution in the nucleon is considerably harder than usual sea-quark distributions. This in agreement with expectations for intrinsic heavy quark contributions in the nucleon wavefunction[16] corresponding to terms connecting up to six gluon fields in the effective Lagrangian[17] $\sim (D_\alpha F_{\mu\nu})^2/M_Q^2$. The anamolously large cross section, leading x_F, and diffractive properties of the charm cross section could also signal other intrinsic contributions, or possibly low relative velocity enhancements of the fusion mechanism, analogous to Coulomb corrections of relative order $\pi\alpha/v$ in QED.[18] Understanding these mechanisms is crucial for the extrapolation to heavier particle production including $b\bar{b}$, $t\bar{t}$, and supersymmetric particles.

The higher-twist, finite-velocity effects discussed here are examples of just some of the coherent phenomena expected in QCD. For example, coherent effects must be taken into account in order to understand interference effects between quark and gluon jets, as well as interference between the forward-spectator jet system and the high p_T jets which occur in hadronic collisions. A simple model for QCD (based on corresponding effects in atomic collisions), which can account for such interference effects, is discussed in Ref. 19.

REFERENCES

1. For general approaches to higher-twist/power law-suppressed QCD contributions see H. D. Politzer, Nucl. Phys. B172, 349 (1980); R. K. Ellis, W. Furmanski, R. Petronzio, Nucl. Phys. B207, 1 (1982); and W. E. Caswell, R. R. Horgan, S. J. Brodsky, Phys. Rev. D18, 2415 (1978). Disconnected processes are discussed in H. D. Politzer *(op. cit.)* and N. Paver and D. Trelani, Trieste preprint SISSA-60/83/E (1983).

2. E. L. Berger and S. J. Brodsky, Phys. Rev. Lett. 42, 940 (1979); G. R. Farrar and D. R. Jackson, Phys. Rev. Lett. 35, 1416 (1975); E. L. Berger, Z. Phys. C4, 289 (1980).

3. S. J. Brodsky, E. L. Berger, G. P. Lepage, SLAC-PUB-3027, published in the *Proceedings of the Workshop on Drell-Yan Processes, Batavia, Illinois (1982)*; E. L. Berger and S. J. Brodsky, Phys. Rev. D24, 2428 (1981).

4. G. P. Lepage and S. J. Brodsky, Phys. Rev. D22, 2157 (1980); S. J. Brodsky, T. Huang, and G. P. Lepage, SLAC-PUB-2540 (1980).

5. S. J. Brodsky and G. R. Farrar, Phys. Rev. Lett. 31, 1153 (1973); Phys. Rev. D11, 1309 (1979).

6. For references, see M. Jacob, this conference.

7. Experimental tests for direct pion-induced dijet reactions are discussed by T. Fields, this conference.

8. See H. G. Fischer, this conference.

9. J. F. Gunion, P. Nason, R. Blankenbecler, Phys. Lett. 117B, 333 (1982); Phys. Rev. D29, 2491 (1984).

10. J. C. Collins, D. E. Soper, G. Sterman, Phys. Lett. 134B, 263 (1984).

11. G. T. Bodwin, to be published.

12. G. T. Bodwin, S J. Brodsky, G. P. Lepage, SLAC-PUB-2927 (1982) and SLAC-PUB-3136 (1983), *Proceedings of the Workshop on Non-Perturbative QCD, Stillwater, Oklahoma (1983)*, and to be published.

13. See A. Kernan and G. Van Dalen, Phys. Report 106, 6 (1984).

14. S. F. Giagi *et al.*, Phys. Lett. 122B, 455 (1983).

15. J. J. Aubert *et al.*, Phys. Lett. 110B, 73 (1982); and C. Gossling, Ph.D. Thesis (1984) and private communication.

16. S. J. Brodsky, P. Hoyer, C. Peterson, N. Sakai, Phys. Lett. 93B, 451 (1980).

17. S. J. Brodsky, J. C. Collins, S. D. Ellis, J. F. Gunion, and A. H. Mueller, contributed to the Snowmass Future Facilities DPF Conference (1984). In this paper it is shown that twist-six terms give a M_Q^{-4} scaling contribution to the heavy quark production cross section.

18. S. J. Brodsky and J. F. Gunion, to be published.

19. S. J. Brodsky, contribution to the Snowmass Future Facilities DPF Conference (1984).