Spectrum of soft quantum-chromodynamics partons in jets and the hadron plateau in e^+e^- annihilation

Ya. I. Azimov, Yu. L. Dokshitser, and V. A. Khoze
B. P. Konstantinov Leningrad Institute of Nuclear Physics

(Submitted 26 January 1982)

Pis'ma Zh. Eksp. Teor. Fiz. **35**, No. 9, 390–392 (5 May 1982)

The influence of coherence effects in the bremsstrahlung of soft partons on the observable spectra of hadrons in jets is discussed. The observation of distinctive spectra, with a dip at low rapidities, is a critical test of the hypothesis of soft bleaching in the hadronization of partons.

PACS numbers: 13.65. + i, 12.35.Eq, 12.35.Ht

Analysis of the space-time evolution of bremsstrahlung processes in perturbation theory (we will restrict this paper to e^+e^- annihilation)[1] shows that an early bleaching of dispersing jets q and $\bar{q}$ over a finite time $t_c \sim R$ is probable, while the hadronization of a parton jet is completed at parametrically large times, $t_{\rm had} \sim WR^2$. The color of each jet (the two original jets and the additional jet which forms because of the hard emission of gluons and $q\bar{q}$ pairs) is localized in a Lorentz-contracted disk with a transverse dimension $R \sim 1$ F, which is the same as the typical hadron dimension. The jet bleaching radius is determined by nonperturbative effects and is parametrically $R \approx \langle \bar{\psi}\psi \rangle^{-1/3} = (250\ \text{MeV})^{-1}$ [the bleaching results from the production of pairs of light quarks, which is in turn caused by the intense bremsstrahlung emission of gluons with $k_\perp \sim R^{-1}$, $\alpha_s(R^{-2}) \sim 1$].

The colorlessness of each jet as a whole over $\rho_\perp \gtrsim R$ cuts off the emission of partons with $k_\perp < R^{-1}$, removing the infrared catastrophe in the running constant $\alpha_s(k_\perp^2) \approx 4\pi / b \ln k_\perp^2/\Lambda^2$.

As a result, the influence of nonperturbative confinement effects is minimized; it reduces to a combining into white hadrons of partons which have been prepared previously by bremsstrahlung processes, locally in phase space. A direct consequence of the early local bleaching is a similarity between the observed hadron spectra and the parton spectra calculated from perturbation theory:

$$E_h \frac{dn^h}{dp_h} \approx E_g \frac{dn^g}{dp_g} (x, W; Q_0^2) K_g^h (Q_0^2), \tag{1}$$

where $x = 2E_h/W \approx 2E_g/W$; and $Q_0{}^2$ is the minimum virtuality of the gluon perturbation theory, whose choice sets the boundary between the perturbation theory and hadronization.

Equation (1) confirms the hypothesis of soft bleaching,[2] which is the starting point for an analysis of hadron distributions in hard processes. According to (1), the x dependence of the detected hadron and of the total energy of the process, W, is controlled by the perturbation theory, while the physics of confinement determines the specific values of the coefficients (K_g^h) for the conversion of gluons into direct hadrons of various

types (h).

The similarity relation applies to comparatively soft particles (outside the fragmentation region), $(WR)^{-1} \lesssim x \ll 1$, which determine the basic multiplicity of the jet [in the case $x \ll 1$, the spectra of the bremsstrahlung q and $\bar{q}$ are proportional to dn^g, so that we can restrict the right side of (1) to the distribution of gluon-partons]. The slowest hadrons in the event are formed over times $t \sim R$; with increasing t, hadrons with energies $E_h(t) \sim tR^{-2}$ form.

In several papers, the idea of an *independent* emission of particles by different elements of a hard parton cascade[2] has been extended without justification to the range of small x, leading to a parametric overestimate of the multiplicity[3] n^g and of the height of the plateau $dn^g/d\ln(1/x)$ (see Ref. 4, for example). Coherence effects similar to the Chudakov effect in quantum electrodynamics have a radical effect on the nature of the parton spectra at $x \ll 1$. In particular, the bremsstrahlung of the lightest gluons, with $E_g \sim k_{\perp g} \sim Q_0 \sim R^{-1}$, which are responsible for the center of the hadron plateau, is formed in a time $t \sim R$, during which the hard partons in the jet which begins to cascade at $t_{\text{ann}} \sim 1/W$ separate from the axis of the jet in the transverse direction by only $\Delta\rho_\perp \sim t\langle 0\rangle \ll R$. A gluon with $\lambda_\perp = (k_{\perp g})^{-1}$ is emitted by such a jet coherently, as a single color charge; consequently, the number of such g's and thus slow hadrons is insensitive to the cascading and should not increase with W, in sharp contrast with the expectations based on the previous picture of a classical cascade (see the review in Ref. 5, for example). As a result, partons with intermediate energies $E_g \sim \sqrt{WQ_0}$ are bred most effectively.

Ermolaev and Fadin have shown through an analysis of Feynman diagrams of quantum chromodynamics in all orders of perturbation theory[6] that a destructive interference occurs in the soft emission, as a result of which the probabilistic picture for the independent emission of partons holds in only a *bounded* kinematic region of successively contracting bremsstrahlung cones, $\theta_{i+1} \ll \theta_i$. When the angular order is taken into account, the cascading of a gluon is described by the evolution equation

$$\epsilon \frac{dn_g^g}{d\epsilon}(\epsilon, E; \theta_0) = \delta\left(\frac{\epsilon}{E} - 1\right) + \int_{\epsilon/E}^{1} d\left(\frac{\epsilon}{\omega}\right) \Phi_G^G\left(\frac{\epsilon}{\omega}\right) \int_{\theta_0^2}^{1} \frac{d\theta^2}{\theta^2} \frac{\alpha_s(\epsilon^2\theta^2)}{4\pi} \times \left[\omega \frac{dn_g^g}{d\omega}(\omega, E; \theta)\right], \tag{2}$$

where $\Phi_G^G(z)$ is the standard expression[2] for the $g \to gg$ spectrum, and $\theta_0 = \theta_{\min} \approx Q_0/\epsilon$. In the crude, doubly logarithmic approximation $[\Phi_G^G(z) \approx 4N/z, \alpha_s = \text{const}]$ we then find the rapidity spectrum $y \approx \ln\epsilon/Q_0$ $(0 \leqslant y \leqslant y_{\max} = E/Q_0)$ and a multiplicity n_g^g (in a quark jet, $n_g^g \approx 4/9 n_g^g$):

$$\frac{dn_g^g}{dy} \approx \frac{2N\alpha_s}{\pi} y \frac{I_1(\mathrm{v})}{\mathrm{v}}, \text{ where } \mathrm{v} \equiv \sqrt{\frac{2N\alpha_s}{\pi} y(y_{max} - y)}, \tag{3}$$

$$n_g^g = \mathrm{ch}\left(y_{max}\sqrt{\frac{2N\alpha_s}{\pi}}\right). \tag{4}$$

From the simple expression in (3) and also from a more refined analysis (which incorp-

orates quark loops, a running α_s, and the single-logarithmic corrections) it follows that the parton spectrum[1)] has an unusual "humped" shape with a maximum at $y \sim y_{\max}/2$.

When the running $\alpha_s(k_\perp^2)$ is taken into account, the parton multiplicity increases with the jet energy in accordance with

$$\ln n^g \propto \sqrt{\frac{8N}{b} \ln \frac{E^2}{\Lambda^2}}, \tag{5}$$

which differs by a factor of $1/\sqrt{2}$ from the standard expression.[3] This difference was first pointed out by Mueller,[7] who independently reproduced the angular conditions[6] in the three-loop approximation.

In this picture of hadronization we would expect to observe a dip at the center of the hadron plateau, as in the parton spectrum [at the previous energies, the maximum in dn^g/dy occurs at $y = (0.3\text{-}0.35)y_{\max} = 1.5\text{-}2$].

The fact that experiments to date have yielded no reliable indications of a dip can be attributed to the following factors: 1) a finite spread $\Delta y \sim 1$ in (1) due to the physics of hadronization; 2) a filling of the dip in the observed spectrum of *light particles* (π) due to a decay of resonances (ρ, ω, Δ, ...); 3) an effect of events involving the production of heavy quarks, $e^+e^- \to c\bar{c}$, where the plateau is flatter; 4) kinematic effects due to the selection of events and the form in which the experimental results are presented.[1]

We wish to emphasize that the emission of baryons (p, Λ) and of other massive hadrons, for which the decay of resonances and other factors tending to mask the dip are less important, should exhibit a humped plateau structure even today.

Significantly, if the dip at the center of the plateau does not appear with increasing W and with improvements in the experimental procedure, then the hope for a perturbation-theory description of the physics of hard processes, which generated the concept of soft bleaching, will prove groundless.

We wish to thank V. S. Fadin for a discussion and E. M. Levin and M. G. Ryskin for collaboration.

1)An accurate account of the decay kinematics by itself (without coherence effects) also leads to a maximum in dn/dy, although it occurs parametrically further to the left, at $y \sim y_{\max}^{3/4}$. This result was derived by E. M. Levin, M. G. Ryskin, and the present authors.

1. Ya. I. Azimov, Yu. L. Dokshitser, and V. A. Khoze, Fizika vysokikh énergiĭ (Materialy XVII Zimneĭ shkoly LIYaF) (High-Energy Physics, Proceedings of the Seventeenth Winter School of the Leningrad Institute of Nuclear Physics), Vol. 1, 1982, p. 200.
2. Yu. L. Dokshitzer, D. I. Dyakonov, and S. I. Troyan, Phys. Rep. **58C**, 270 (1980).
3. W. Furmanski, R. Petronzio, and S. Pokorski, Nucl. Phys. **B155**, 253 (1979).
4. E. Amati *et al.*, Nucl. Phys. **B173**, 429 (1980).
5. Ya. I. Azimov, Yu. L. Dokshitser, and V. A. Khoze, Usp. Fiz. Nauk **132**, 443 (1980) [Sov. Phys. Usp. **23**, 732 (1980).
6. B. I. Ermolaev and V. S. Fadin, Pis'ma Zh. Eksp. Teor. Fiz. **33**, 285 (1981) [JETP Lett. **33**, 269 (1981)].
7. A. H. Mueller, Phys. Lett. **104B**, 161 (1981).

Translated by Dave Parsons
Edited by S. J. Amoretty