Theory of multiparticle production in the soft region

Valery A Khoze† and Wolfgang Ochs‡

† Department of Physics and Institute for Particle Physics Phenomenology University of Durham, Durham, DH1 3LE, UK

‡ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
Föhringer Ring 6, D-80805 Munich, Germany

E-mail: V.A.Khoze@durham.ac.uk, wwo@mppmu.mpg.de

Abstract. We review theoretical and experimental advances in the application of the perturbative QCD approach to the description of particle distributions in jets in the (semi) soft region with particular emphasis on HERA physics.

1. Introduction

In the last years hadron-jet physics has been intensively studied in e^+e^-, hadron-hadron and ep scattering processes. The advantage of HERA is that here the measurements can be performed at various hardness scales, from very large Q^2 down to moderate and even small momentum transfer, thus probing the interface between the hard and soft physics. The data clearly show that the broad features of hadronic jet systems, calculated at the parton level, agree surprisingly well with the measured ones. This proves the dominant role of the perturbative phase of jet evolution and supports the hypothesis of local parton-hadron duality (LPHD) [1, 2]. Important tests of the hadroproduction dynamics come from the studies of the so-called semisoft region (small values of $x_p = p/E_{\rm jet}$, but formally $p \gg m_h$). As long as the process of colour blanching and hadronization is local in the configuration space the asymptotic shapes of the distributions are fully predicted. The sub-asymptotic corrections are expressed as power series in $\sqrt{\alpha_s}$. This is the so-called Modified Leading Logarithmic Approximation (MLLA) [1, 3] which takes into account all essential ingredients of parton multiplication in the next-to-leading order.

Colour coherence has led to a dramatic revision of expectations for particle distributions. Thus, the coherent effects in the **intrajet** cascades, resulting on the average in the angular ordering of sequential branching, gave rise to the *hump-backed* shape of particle spectra [4, 5]. It is not the softest particles, but those with the energies ($E_h \sim E^{0.3-0.4}$) which multiply most effectively. Due to the **interjet** coherence which is responsible for the string [6]/drag [7] effects in the multi-jet events, it can be verified that the dynamics of the colour governs the hadroproduction.

In this talk we focus on some selected aspects of jet physics in the (semi)soft region. The main goal is to illustrate some phenomenological advances of the perturbative approach, for a broader outline see e.g.[8, 9].

2. Inclusive spectra and jet universality

A bright perturbative prediction is the *hump-backed* shape of the partonic distribution in the variable $\xi = \log \frac{1}{x}$. As a consequence of coherence, soft parton multiplication is suppressed and the spectrum acquires a characteristic bell-like shape [4, 5]. It is amazing that the inclusive spectra of hadrons exhibit the same shape in a large kinematic region in good agreement with the MLLA-LPHD predictions. Moreover, the data on various hard processes demonstrate a remarkable universality assuming the proper choice of the cascading variables. Recall that the evolution parameter corresponding to the struck quark in DIS in the Breit frame is $\sqrt{Q^2}/2$ at four-momentum transfer Q^2. The energy scale for particle distribution in jets of energy E_{jet} within the restricted cone Θ_0 is $E_{jet}\Theta_0$ in the small angle approximation, see [8]. The ξ-distribution can also be discussed in terms of the moments or other characteristics. A summary of predictions and comparison with data can be found in [9]. Here we discuss two recent results: the ξ-distributions at HERA and the variation of the peak position ξ^* in the full energy range explored so far.

2.1. ξ distributions at HERA

A recent measurement of the ξ distribution by the ZEUS collaboration is shown in Figure 1 [10, 11]. The Gaussian shape is observed again at all jet energies $E_{jet} = Q/2$. The MLLA prediction is based on leading and next-to-leading order logarithmic approximations which become increasingly better at higher jet energies and particle momenta exceeding the cut-off Q_0 in the cascade evolution. A rather simple analytic expression is available in the limit when the cut-off and the QCD scale become equal, $Q_0 = \Lambda$ ("limiting spectrum"). Because of the cut-off Q_0 the spectrum ends at $\xi_{max} = Y = \log(E_{jet}/Q_0)$. The limiting spectrum (dotted line in Figure 1, MLLA-0) ends at a finite value above the peak and fits the data rather well, however, it predicts zero intensity beyond the limit ξ_{max}. In fact, the observed spectra in the variable $\xi_p = \log(E_{jet}/p)$ have no upper limit for $p \to 0$, therefore in the very soft region with $p \sim Q_0$ there is no agreement between theory and experiment.

This kinematical mismatch between theory and experiment can be avoided if Q_0 is interpreted as particle mass and the theoretical prediction is taken for the parton energy ($E = \sqrt{p^2 + Q_0^2}$), or, $\xi_E = \log(E_{jet}/E)$ [12, 13]. Then, both the theoretical prediction and the experimental data have the same upper boundary $\xi_{max} = Y$. Transforming back the limiting spectrum to ξ_p yields the prediction MLLA-M in Figure 1 which fits the full spectrum quite well at the highest available energies but exceeds the data at lower Q. An improved but still not fully satisfactory result is obtained by treating the

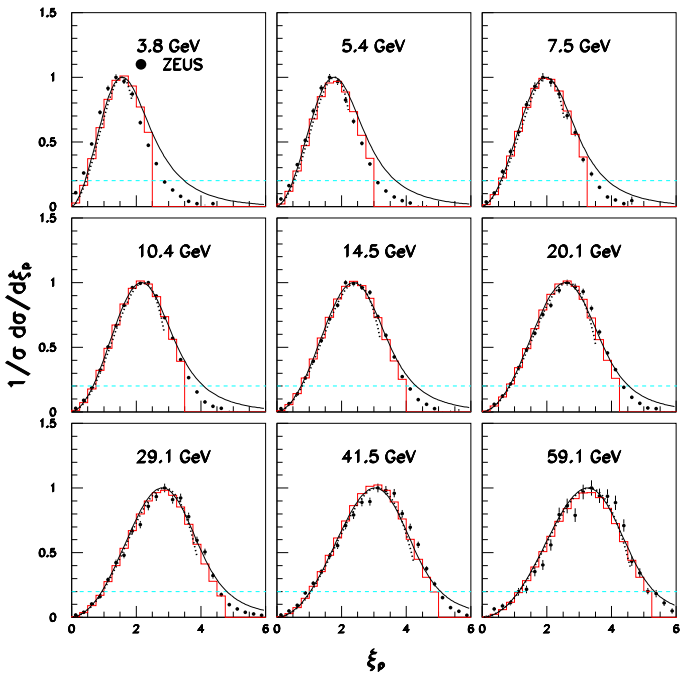

Figure 1. The charged particle ξ_p distribution in the current fragmentation region in the Breit frame for different Q bins as measured by the ZEUS Collaboration [10]. The full and dotted lines are the MLLA-M and MLLA-0 predictions with $\Lambda = 280$ MeV respectively, the histogram is the fit of the MLLA with $\Lambda = 280$ MeV and $m_{eff} = 230$ MeV. Figure from [11].

effective mass as an additional parameter (histogram in Figure 1).

The discrepency of MLLA-M at large ξ can be attributed to the approximate form of the limiting spectrum obtained in MLLA which is not appropriate for the very soft particles where the coupling $\alpha_s(k_T)$ becomes large. A better approximation for the soft particles around $\xi \sim Y$ has been proposed already some time ago [12] based on a modified perturbative expansion, and this analytic result has been shown to describe very well the ξ spectrum above the peak. These mass effects can clearly not be derived directly from pQCD but they are plausible and not in contradiction either. Fortunately, with increasing jet energy these kinematic effects become less and less important, as already visible in Figure 1.

Similar effects appear in the determination of the ξ_p moments which involve the integrals up to the upper boundary of the spectra. The results at lower energies Q depend considerably on whether the cut-off ξ_{max} is taken into account or not. This leads to large discrepancies between the experimental ξ_p moments [10, 11] and the predictions from the limiting spectrum [14] at low Q. On the other hand, the agreement is rather good if the moments are determined from the ξ_E spectrum taking the particle mass as Q_0 [12]. Again, the results from different assumptions on mass effects converge with increasing Q [11].

Note that in spite of the known similarity between the space- and time-like evolution at large x, there is an essential difference between the small-x behaviour of the DIS structure functions and the jet fragmentation. In the former case at small Bjorken-x the perturbative description at very high energies ultimately breaks down and the problem becomes essentially non-perturbative. There are two main limitations on the application of the perturbative approach: diffusion of gluons away from the hard scale into the infrared and unitarity constraints, see for example [15]. In the timelike cascades, on the contrary, due to colour coherence the density of the low Feynman-x particles is not growing, and the influence of confinement dynamics reduces merely to an overall normalization.

Better salesmen might be tempted to claim that the observation of the hump-backed plateau in jet fragmentation has already clearly revealed the drastic low x-driven violation of DGLAP, a phenomenon which in other observables many people are still so desperately targeting without any success.

2.2. Peak position ξ^* of ξ distribution

An important characteristic is the peak position ξ^*. The high-energy behaviour of this quantity is predicted [14] as

$$\xi^* \;=\; Y\left[\frac{1}{2}+\sqrt{\frac{C}{Y}}-\frac{C}{Y}\right] \tag{1}$$

with the constant term given by

$$C \;=\; \frac{a^2}{16N_C b} \;=\; 0.2915(0.3513) \qquad \text{for } n_f \;=\; 3(5),$$

with Y and Q_0 as given above. Furthermore $a = 11N_C/3 + 2n_f/3N_C^2$, $b = (11N_C - 2n_f)/3$. In the large-N_C limit parameter C becomes independent of both n_f and N_C and approaches its asymptotical value of $C = \frac{11}{3}\frac{1}{2^4} \simeq 0.23$. Therefore the energy behaviour of ξ^* is determined by such a fundamental parameter of QCD as the celebrated $\frac{11}{3}$ factor in the coefficient b.

A nice confirmation of the perturbative picture has been presented recently by the CDF collaboration [16], see Figure 2. The studies of the charged particle distributions were performed for a variety of di-jet masses ($80 < M_{jj} < 630$ GeV) and jet opening angles Θ_0. The shapes of the measured ξ-distributions at various hardness scales $E_{jet}\Theta_0$ turn out to be very close to the MLLA expectations. As the di-jet mass increases, the peak position ξ^* shifts towards larger values of ξ in perfect agreement with the theory, whereas it smoothly approaches the results from DIS and e^+e^- collisions at lower energies.

Note that by choosing a small opening angle one can study relatively low hardness scales but in a more friendly environment: because of the Lorentz boost, eventually all particles corresponding to the "hump" become relativistic. This is a serious argument against the attempts to explain the particle depopulation at large ξ by the finite mass effects.

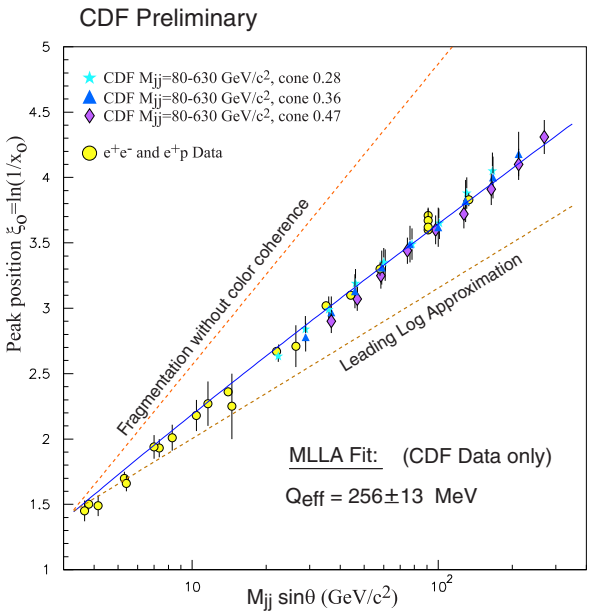

Figure 2. Peak position ξ^* of the inclusive ξ distribution plotted against di-jet mass $\times$ $\sin\Theta_0$ in comparison with the MLLA prediction (central curve); also shown are (in arbitrary normalization) the double logarithmic approximation (lower curve with asymptotic slope $\xi^* \sim Y/2$) and expectation from cascade without coherence. Result by CDF Collaboration [16].

3. Soft limit of particle spectra

The low momentum data provide further confirmation of the basic ideas of QCD coherence and LPHD. The analysis in [17] was performed in terms of the particle density $\frac{dn}{d^3p}$ for e^+e^- annihilation at low momenta in quite a wide *cms* energy region (from ADONE to LEP-2). The spectra were found to be in good agreement with analytical perturbative results applicable for low particle energies emphasized above [12, 17], see Figure 3. The H1 data [18] also show agreement with the perturbative expectations, thus confirming again the universality of soft particle production.

The prediction for very low momenta $p \lesssim$ mass is dependent to some extent on the treatment of kinematic mass effects as discussed in the previous section. However, the fact that in the soft limit $p \to 0$ the curves become flat in Figure 3, i.e. independent of jet energy, is a generic result and applies for different possible implementations of mass effects studied in [17]. It is a direct consequence of colour coherence: in the soft limit the wave length of the produced particle (gluon) is so large that it cannot resolve details of the primary parton jet but probes only the primary $q\overline{q}$ pair. The emission probability is then given by the Born term which is independent of $\sqrt{s}$.

We also emphasize the observation in [17] that the approach to energy independence for $p \to 0$ varies with particle type. It seems that the energy independence is reached for momenta $p \lesssim$ mass, namely for the heavier protons already at much larger $p \sim 0.6$ GeV and for kaons at $p \sim 0.3$ GeV.

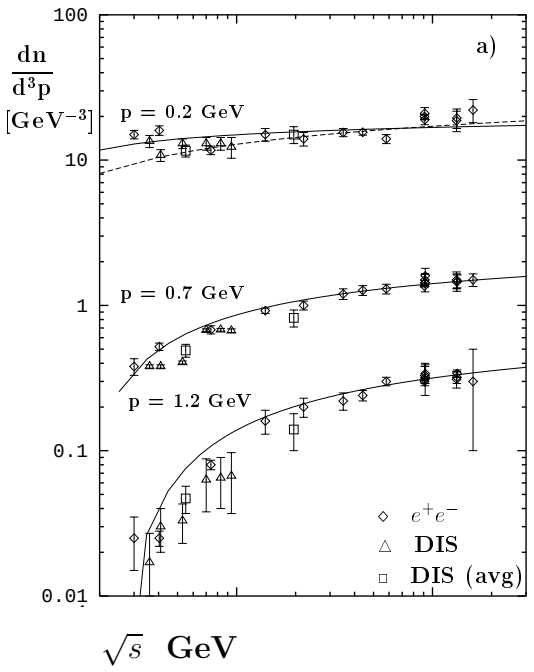

Figure 3. Particle density at fixed momentum p as function of *cms* energy $\sqrt{s}$; the dashed curve for an alternative implementation of mass effects. Taken from [17].

Without doubt, it is not a priori clear at all whether one can appeal to the perturbative expertise when exploring the low momentum domain. However, an attempt to stretch the perturbative expectations to the limit of their applicability looks quite intriguing. This could, in principle, provide a clue for understanding some conceptual problems of the LPHD. Whether or not the transition between two stages of jet development is smooth is a question for experiment. It is therefore important to test these predictions further in various ways.

Another prediction of this kind for soft particles concerns the relative production in quark and gluon jets. The same arguments – dominance of Born term – lead one to expect the ratio of densities $r(g/q) = \frac{dn}{d^3p}(g-jet)/\frac{dn}{d^3p}(q-jet)$ to approach the limit [17]

$$r(g/q) \to \frac{C_A}{C_F} = \frac{9}{4} \qquad \text{for} \quad p \to 0. \tag{2}$$

This prediction would apply directly to the comparison of soft particles in $q\overline{q}$ and gg systems. The latter system can be realized approximately in the process $e^+e^- \to q\overline{q}g$ with the $q\overline{q}$ pair recoiling against the g; in this case the ratio (2) is found around $r(g/q) \sim 1.8$ [19], in qualitative support of the prediction (2), but a bit lower than expected, and this could be due to the non-collinearity of the three jets in the actual measurement. Note that the ratio of total jet multiplicities in quark and gluon jets stays considerably below the limit (2), both in theory and experiment, see for example review [20].

Another interesting possibility to test the prediction (2) is in the final state of diffractive DIS to which we come back below.

4. String/drag phenomena

The existing data on inter-jet particle flows in $e^+e^- \to q\bar{q}g$ events are also strongly in favour of soft gluon coherence. Within pQCD such effects arise from interference between the radiation off the $q, \bar{q}$ and g. Note that colour-related effects could play a valuable role as a new tool helping to distinguish the new physics signals [8, 9].

4.1. Particle production between jets

Let us recall a few facts concerning comparison with theory for the string/drag effect in $e^+e^- \to q\bar{q}g$. DELPHI [21] performed the verification for the ratio R_γ

$$R_\gamma \;=\; \frac{N_{q\bar{q}}(q\bar{q}g)}{N_{q\bar{q}}(q\bar{q}\gamma)} \tag{3}$$

of the particle densities in the interquark valley in the $e^+e^- \to q\bar{q}g$ and $e^+e^- \to q\bar{q}\gamma$ events for the Y-shaped events using the q-jet tagging. The ratio R_γ in the $q\bar{q}$ angular interval $[35°, 115°]$ was found to be

$$R_\gamma^{\rm exp} \;=\; 0.58 \;\pm\; 0.06. \tag{4}$$

This is in perfect agreement with the theoretical expectation [7].

$$R_\gamma^{th} \;\approx\; \frac{0.65N_C^2 - 1}{N_C^2 - 1} \;\approx\; 0.61 \tag{5}$$

Another result [21] concerns the ratio $R_g = N_{qg}/N_{q\bar{q}}$ in the $q-g$ and $q-\bar{q}$ valleys in the symmetric $e^+e^- \to q\bar{q}g$ events with the q-jet tagging. Quantitatively, comparing the minima at $\pm[50°, 70°]$, this ratio is found to be

$$R_g^{\rm exp} \;=\; 2.23 \;\pm\; 0.37. \tag{6}$$

This is to be compared with the prediction [7]

$$R_g^{th} \;\approx\; 2.4. \tag{7}$$

A clear interference pattern arises in the large-E_T production of colourless objects, for instance, in $V+$ jet events in proton scattering (with $V = \gamma, W^\pm$ or Z). The hadronic antenna patterns for such processes are analogous to that in the string-drag case. Recently the first data on $W+$ jet production at the Tevatron [22] have become available. The interference effects are clearly seen, and they are in good quantitative agreement with the perturbative calculations [23].

Let us emphasize that in all drag-related measurements the inter-jet flows are dominated by the low energy hadrons (pions with typical momenta in the few 100 MeV range). It looks intriguing that such distant offsprings are controlled by the pQCD rules.

4.2. Particle production perpendicular to the event plane

An instructive test of the LPHD approach can be performed when studying the particle flow in the direction transverse to the 3-jet event plane, see [17]. Recently DELPHI [26] have presented the first results on the particle yield in the transverse direction for the Y-shaped symmetric events. Figure 4 shows the multiplicity within the cone with the fixed half opening angle of 30° perpendicular to the event plane. The plotted curve represents the lowest order formula

$$R_\perp = \frac{N_C}{4C_F}[2 - \cos\Theta_{1+} - \cos\Theta_{1-} - \frac{1}{N_C^2}(1 - \cos\Theta_{+-})] \tag{8}$$

where the angles Θ_{ij} are between $q, \overline{q}, g$ (labeled as $+, -, 1$). We observe good agreement with the angular dependence of the perturbative prediction which provides a new test involving dominantly soft particles, independent of the hadronization models.

The absolute normalization is also possible in terms of the radiation into a cone of the same size in two-jet events and this normalization is assumed in (8). It would correspond to three jets with $\Theta_1 = 0$ in Figure 4. Changing the event topology from the parallel $q - (qg)$ to anti-parallel $g - (q\overline{q})$ configurations should increase the soft perpendicular radiation by the factor 9/4 as in (2) and (8) for $\Theta_{+-} = 0$, $\Theta_{1+} = \Theta_{1-} = \pi$. In Figure 4 we are observing just the beginning of this rise as far as is possible in this class of symmetric events.

It would be interesting to measure the same radiation for other three-jet topologies closer to the $q\overline{q}-g$ configuration such as studied by OPAL [19]. This would test equation (8) closer to its maximum $R_\perp = N_C/C_F$.

Furthermore, it would be interesting to see whether the increase of radiation observed in Figure 4 persists, in the same way, down to very low particle momenta. It seems impossible to have a directional dependence of densities in the limit $p \to 0$, but it could become visible for momenta $p \sim$ mass. This is the scale where the energy (E_{jet}) independence expected from the perturbative calculation establishes for π, K and p particles [17].

4.3. Conventional QCD vs. new physics mechanisms

The antenna pattern can be used as a discriminative tool to dissect the colour structure of the large-E_T events, as a way to distinguish between conventional QCD and new physics mechanisms. This diagnostic power is illustrated in [27] where the topology of hadronic flows corresponding to Higgs production at hadron colliders is discussed. There the radiation samples were compared for the signal ($gg \to H \to b\bar{b} + g$) and background ($gg \to b\bar{b} + g$) production. It was found that the main difference between these two comes from the radiation *between* the final-state jets. In particular, there is approximately 4/3 more radiation between these jets for the Higgs production. This is due to the absence of a colour connection between the quarks in the background process.

Another topical example concerns central Higgs production in the events with double rapidity gaps, for recent discussion and references see [28].

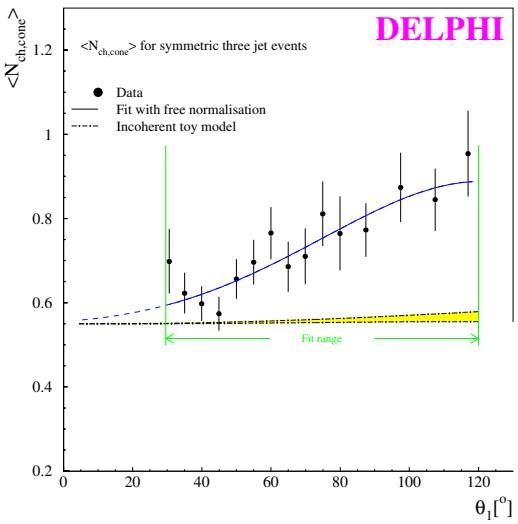

Figure 4. Multiplicity within a 30°-cone perpendicular to the event plane of symmetric three-jet events as a function of the angle Θ_1 between the low energy jets [26]. The curve represents the perturbative prediction (8).

5. Further tests with soft particles in photoproduction and DIS

Colour coherence leads to a rich diversity of effects in γp and DIS processes (as well as in high-$p_\perp$ events in hadronic collisions). Here we note a few lines of further studies.

5.1. Radiation perpendicular to event plane

The dependence of the soft perpendicular radiation on the scattering angle of the hard partons in various di-jet production processes have been worked out [13]. In particular, for small angle scattering the intensity of soft particles is larger in di-jet production with resolved photons (dominantly gluon exchange) by the factor C_A/C_F in comparison with direct photoproduction (dominant quark exchange). Monte Carlo studies have shown that the expected effects should be observable under realistic conditions [29]. The verification and detailed study of the angular and momentum dependence will provide further clues to the applicability of perturbative QCD calculations in this regime.

5.2. Soft radiation in diffractive 2-jet events

In theoretical models the diffractive cluster produced in DIS is generated through Pomeron-photon interactions leading to $q\overline{q}$ final state at low diffractive masses M_X and to $q\overline{q}g$ systems at higher masses with the gluon in the Pomeron direction and the $q\overline{q}$ pair in the photon direction. A recent jet analysis by the ZEUS Collaboration [24] indeed supports this view by showing the jet in the pomeron direction being broader than the one in the photon direction. Then the soft particles in this system are expected again to be produced by colour octet sources and therefore the soft particle density is

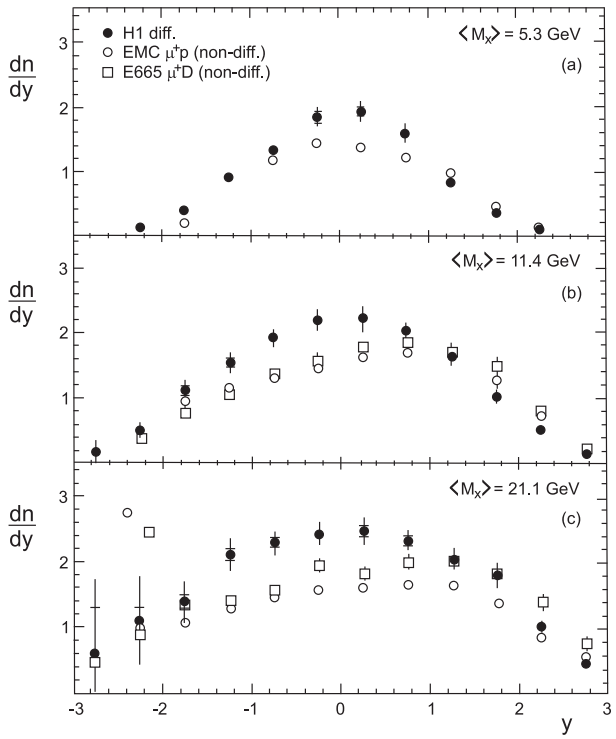

Figure 5. Rapidity distribution of charged particles in three intervals M_X of the diffractively produced system in DIS (H1 Collaboration [25]) in comparison with results from non-diffractive events at corresponding hadronic energies $W = M_X$.

higher. This phenomenon has been observed indeed by the H1 Collaboration some time ago [25] in the comparison of rapidity distributions of particles in the diffractive and the non-diffractive systems, see Figure 5. One observes the increased central production of particles in the diffractive events as expected from the gluonic emitter. It is remarkable that the difference between the primary gluon and quark jets appears already at such a low mass as $M_X \sim 5$ GeV. The difference may become clearer if one restricts further to 2-jet events and to soft particles.

5.3. Radiation in diffractive multi-jet events

The multi-jet structure in diffractive DIS events opens up new possibilities for tests of coherent soft particle production. In particular, the study of diffractive three-jet events as in [24] allows studies complementary to the e^+e^- case. For a given resolution y_{cut} and sufficiently high diffractive mass M_X the two-jet configuration should be dominated by the octet configuration like gg, whereas the 3-jet configuration contains the events with a gluon jet in Pomeron direction recoiling against $q\overline{q}$. The radiation into a cone perpendicular to the 3-jet plane is then governed again by the general formula (8) with the appropriate identification of angles. If normalized to 2-jet events one would replace in (8) the prefactor N_C/C_F by 1 corresponding to the replacement of the two-jet configuration $q\overline{q}$ by gg.

It should be noted that particle density in the sidewise cone is not entirely energy ($\sqrt{s} = M_X$) independent, this occurs only in the soft limit when the lowest order radiation diagrams dominate.

The verification of the radiation pattern (8) in diffractive events would test both, the partonic interpretation of these events and the perturbative approach to the soft radiation.

6. Summary

The existing data show that the analytical perturbative approach to multihadron production in QCD jets is in a remarkably healthy shape. This justifies the attempts to work in terms of quarks and gluons down to the low momentum scale, the region which is usually viewed as being entirely non-perturbative. Further tests, especially of the characteristic predictions from soft gluon coherence, should determine the range of applicability of the theory towards low momenta.

It is clear that the agreement between parton level predictions and the data cannot work in all aspects. Resonances exist in nature but not in the quark gluon cascade. Recent studies by ZEUS [30] show the qualitative agreement of perturbative predictions with data even for various multiparticle correlation phenomena in angular regions of variable size, but there is also a disagreement for correlations between particles at low p_T near the boundary Q_0. In this kinematic region we encountered already some problems in the inclusive studies of section 2. It is therefore important to explore further the region of validity of this phenomenological framework.

The key concept of this approach is that the conversion of partons into hadrons occurs at low virtualities, and that it is physics of QCD branchings which governs the gross features of the jet formation. The data demonstrate that the transition betwen the perturbative and non-perturbative phases is quite smooth, and that the spectacular coherence phenomena successfully survive the hadronization stage.

Concluding this talk let us emphasize that, certainly, there is no mystery within the pQCD framework. Of real importance is that the experiment proves that the transformation between the perturbative and non-perturbative phases takes place very smoothly. This may (one day) shed light on the dynamics of colour confinement.

Acknowledgments

VAK thanks Leverhulme Trust for a Fellowship and the theory group of the Max-Planck-Institute, Munich for their hospitality.

References

[1] Dokshitzer Yu L and Troyan S I 1984 *Proc. 19th Winter School of the LNPI* Vol. 1 (Leningrad) p 144
Dokshitzer Yu L and Troyan S I 1984 preprint LNPI-922

[2] Azimov Ya I *et al* 1985 *Z. Phys.* **C27** 65
Azimov Ya I *et al* 1986 *Z. Phys.* **C31** 213
[3] Mueller A H 1983 *Nucl. Phys.* **B213** 85
Erratum 1984 *Nucl. Phys.* **B241** 141
[4] Dokshitzer Yu L, Fadin V S and Khoze V A 1982 *Phys. Lett.* **B115** 242
Dokshitzer Yu L, Fadin V S and Khoze V A 1982 *Z. Phys.* **C15** 325
[5] Bassetto A *et al* 1982 *Nucl. Phys.* **B207** 189
[6] Andersson B, Gustafson G and Sjöstrand T 1980 *Phys. Lett.* **B94** 211
[7] Azimov Ya I *et al* 1985 *Phys. Lett.* **165** 147
[8] Dokshitzer Yu L *et al* 1988 *Rev. Mod. Phys.* **60** 373
[9] Khoze V A and Ochs W 1997 *Int. J. Mod. Phys.* **A12** 2949
Khoze V A, Ochs W and Wosiek J 2001 *At the frontiers of Particle Physics, Handbook of QCD*, ed. M Shifman Vol 2 (Singapore: World Scientific) p 1101
[10] ZEUS Collaboration: Breitweg J *et al* 1999 *Eur. Phys. J.* **C11** 251
[11] Brook N H, Skillicorn I O 2001 *Phys. Lett.* **B497** 55
Brook N H *these Proceedings*
[12] Lupia S and Ochs W 1996 *Phys. Lett.* **B365** 339; 1998 *Eur. Phys. J.* **C2** 307
[13] Khoze V A, Lupia S and Ochs W 1996 *Phys. Lett.* **B386** 451
[14] Dokshitzer Yu L, Khoze V A and Troyan S I 1992 *Int. J. Mod. Phys.* **A7** 1875
[15] Mueller A H 1997 *Phys. Lett.* **B 396** 251
[16] Safonov A N (for CDF Coll.) 2000 *Nucl. Phys.* **B** (*Proc. Suppl.*) **86** 55
CDF Collaboration: Affolder T *et al* submitted to *Phys. Rev. Lett.*
[17] Khoze V A, Lupia S, and Ochs W 1997 *Phys. Lett.* **B394** 179; *Eur. Phys. J.* **C5** 77
[18] Adloff C *et al* 1997 *Nucl. Phys.* **B504** 3
[19] OPAL Collaboration: G Abbiendi *et al* 2000 *Eur. Phys. J.* **C17** 373
[20] Dremin I M and Gary J W 2001 *Phys. Rep.* **349** 301
[21] DELPHI Collaboration: Abreu P *et al* 1996 *Z. Phys.* **C70** 179
[22] D0 Collaboration: Abbott B *et al* 1999 *Phys. Lett.* **B464** 145
[23] Khoze V A and Stirling W J 1997 *Z. Phys.* **C76** 59
[24] ZEUS Collaboration: S Chekanov *et al* 2001 *Phys. Lett.* **B516** 273
De Wolf E A *these proceedings*
[25] H1 Collaboration: Adloff C *et al* 1998 *Eur. Phys. J.* **C5** 439
[26] Hamacher K *et al* 1999 preprint DELPHI 99-115 CONF 302
[27] Heyssler M , Khoze V A and Stirling W J 1999 *Eur. Phys. J.* **C7** 475
[28] Khoze V A 2001 Preprint hep-ph/0105224
[29] Butterworth J M, Khoze V A and Ochs W 1999 *J. Phys.* **G25** 1457
[30] ZEUS Collaboration: Chekanov S *et al* 2001 *Phys. Lett.* **B510** 36