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QCD PHYSICS OF JETS
IN THE TEV RANGE

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ABSTRACT

The main aim of this talk is to demonstrate the present status of the analytical perturbative QCD approach to jet physics in hard processes. We concentrate on the colour coherence phenomena in the jet-like final states and the possibility to use them as valuable additional tool, helping to extract and to study manifestations of new physics.

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1. INTRODUCTION

This talk summarizes some recent advances in applications of the perturbative approach (PA) to the description of jetty final states in hard processes (HP). It is complementary to the talk given by G. Marchesini [1] and presents the quantitative predictions for jet characteristics in hadronic collisions in terms of analytical calculations (see Refs. [2-4]). The main idea is to reorganize the perturbative expansion in such a way that its zero-order approximation is systematic and involves an arbitrary number of produced particles. This can be achieved through the iteration of basic $A \rightarrow B+C$ branchings. This approximation is the Modified Leading Logarithmic Approximation (MLLA), which takes care of both double logarithmic and single logarithmic effects in a systematic way [5,6].

The interest in the detailed studies of jets in HP is twofold: On the one hand, they are important for testing both perturbative and nonperturbative QCD, for design of experiments and the analysis of their data. On the other hand, the characteristic features of jet-like states could provide a valuable additional tool, helping to extract and to study manifestations of new physics.

In the last decade hadron jet physics has been intensively studied at both $e+e-$ and hadronic accelerators (see Refs. [7-9]). It will be one of the central problems of investigation for the $pp(\bar{p}) e+e-$, and ep colliders of the future.

The existing data show that hadronic event characteristics calculated at the MLLA parton level agree very well with the measured ones. This supports the hypothesis of the Local Parton-Hadron Duality (LPHD) [6,10] (see also Refs. [11]) and provide great encouragement for future experiments aimed at the multijet production at very high energies.

According to the LPHD concept, the conversion of partons into hadrons occurs at a low virtuality scale, independent of the scale of the primary HP, and involves only low momentum transfers, leading to a close similarity between parton and hadron distributions.

The PA (MLLA + LPHD) attempts to describe the global features of the hadronic systems, such as the mean multiplicities and multiplicity distributions, angular pattern of energy and multiplicity flow, inclusive energy spectra and correlations of particles, etc., without making any reference at all to a fragmentation scheme. The nonperturbative effects are reduced to normalizing constants relating hadronic characteristics to partonic ones (see Ref. [12]).

The perturbative predictions for these characteristics of the HP are in good agreement with the results of Monte Carlo Simulation programs (see Ref. [1] and references therein) based on coherent QCD parton shower picture.

We shall focus below on the manifestations of the colour coherence phenomena. The rediscovery of coherence in the context of QCD [13] has led to a dramatic revision (see, e.g., Ref [12]) of theoretical expectations for soft particle distributions.

Thus, the coherent effects in the intrajet partonic cascades, (see Fig. 1a), resulting, on average, in the angular ordering (AO) of sequential branching, gave rise to the hump-backed shape of particle spectra-one of the most striking PA predictions [14] Not the

softest particles but those with the intermediate energies ($E_h \sim E^{0.35}$) proliferate most abundantly in the QCD cascades.

Due to the interjet coherence (see Fig. 1b), which is responsible for the drag effects in the multijet events (see Refs. [12,15-18]), a very important physical phenomenon can be experimentally verified, namely, the fact that the particle production is accordance with the QCD radiophysics of hadron flows.

It is entirely unremarkable that the quantum mechanical interference effects should be observed in QCD. However, it is of importance that the experiment demonstrates that such interference effects survive the hadronization phase.

The MLLA formulae for partonic distributions essentially simplify in the limiting case, when the formal boundary Q_0 between the perturbative and nonperturbative phases of jet evolution is chosen equal to Λ (the so-called limiting distributions, see Refs. [6,12]). In some sense such a choice is a specific attempt to model confinement.

Whether or not the jet energies are sufficiently large for PA to be applied is, of course, a question to experiment. So far the experimental data in e^+e^- collisions (see Refs. [7,9,19]) have demonstrated that the PA works unexpectedly well. At least, starting from the Z^0 energy, the finite energy corrections do not change sizeably the perturbative scenario.

For hadronic collisions the underlying HP physics is more complicated, and the energy range for applicability of the PA is now less clear (see Refs. [1]).

However, the nature of jets, based on the dominant role of the QCD bremsstrahlung processes, is the same for both reactions. Therefore, at least, at the energies of the future hadronic supercolliders the main physical phenomena in jet physics and characteristics of final states should also be under control of the PA. Presumably at the LHC-SSC energies the colour coherence effects should be well distinguishable from the minimum bias background.

Finally, let us enumerate the virtues of high $P_\perp$ hadronic reactions for studies of QCD jet dynamics.

1. A diversity of hard interactions at small distances; by varying the experimental conditions (triggers) one may extract the dominant subprocess and turn from one subprocess to another.

2. Dependence of length and height of the hadron spectra on the different parameters: the length is determined by the total energy of the collision, and the height and the plateau structure - by the process hardness (trigger $E_\perp$). Thus, information becomes available that is inaccessible in e^+e^- annihilation.

3. There is the purely practical argument that just in high $p_\perp$ hadronic collisions the largest possible energies (hardness) will be reached. These reactions are also the best source of high energy gluon jets. Detailed studies of such processes are necessary for designing the future experiments and the analysis of their data, for finding new heavy objects. In particular, interjet coherence effects could provide a valuable additional tool, helping to extract and to study new phenomena.

The variety and complexity of colour antennae typical for high $p_{\perp}$ processes, complicate the picture of final hadronic distributions. However, at very high energies, when particle multiplicities become large enough, the possibility arises of using a detailed analysis of hadron flows on an event by event basis to extract information about colour transfer at small distances.

2. QCD PROPERTIES OF AN "INDIVIDUAL JET"

In spite of the importance of interjet coherence phenomena the notion of an individual partonic jet makes sense if one does not deal with the azimuthal effects, but considers only multiplicities, energy spectra and correlations, etc. In this case, all the influence of the jet ensemble on a given jet may be encoded in a single parameter θ_0 , the jet "opening angle." This, in essence being the angle between the considered jet and the nearest other one.

Jet characteristics prove to depend not on the jet energy E but on the hardness Q of the process producing the jet, $Q=E\theta_0$ at $\theta_0 \ll 1$.

One can study the properties of an individual quark jet when measuring the different inclusive distributions in the process $e^+e^- \rightarrow \text{hadrons}$. For example, the inclusive particle spectrum for e^+e^- annihilation is the sum of two q-jet distributions

$$\frac{1}{\sigma} \frac{d\sigma}{d(\ln \frac{1}{x})} = 2\bar{D}_q^h(l, Y) \quad (1)$$

where

$$l = \ln \frac{1}{x}, \quad Y = \ln \frac{E}{\Lambda},$$

$$x = \frac{E_h}{E}, \quad 2E = W \text{ is the total c.m.s. energy}$$

Formally, the decay into two gluons of the C - even ultra-heavy quarkonium states, $\chi_Q = Q\bar{Q}$, might define the individual gluon jets.

Let us discuss the collimation of a QCD jet around the parent parton j momentum ($j = q, g$) [12]. This phenomenon is of special interest when considering the space-energy portrait of events as a natural partonometer for registering HP dynamics.

The angular cone $\Theta_{\epsilon j}$, in which an energy fraction ϵj is deposited, is given by:

$$\frac{\Theta_{\epsilon j}}{\Theta_0} = \left(\frac{E\Theta_0}{\Lambda} \right)^{-\gamma_j(\epsilon j)} \quad (2)$$

where, for example, (see Fig. 2)

$$\begin{aligned} \gamma_q(0.9) &\approx 0.55, \quad \gamma_q(0.5) \approx 0.83; \\ \gamma_g(0.9) &\approx 0.30, \quad \gamma_g(0.5) \approx 0.54; \end{aligned} \quad (3)$$

It follows from Eqs. (2), (3) and Fig. 2 that the energy collimation in a quark jet is stronger than in gluon one, and the collimation grows as energy increases.

The collimation of multiplicity N inside a jet behaves as

(4)

$$\frac{\theta_{\delta j}}{\theta_o} \propto [N(E\theta_o, \Lambda)]^{-b/8N \ln 1/\delta j}$$

$$b = \frac{11}{3} \cdot N_c - \frac{2nf}{3},$$

where $\Theta_{\delta j}$ is the cone, where the jet multiplicity fraction δj is concentrated. Thus, the angle, say, $\theta_{1/2}$ decreases with the increase of the energy scale

$Q = E\theta_o \sim E$ approximately as $N^{-1/4}(Q, \Lambda)$, *i.e.* parametrically much slower than in the case of the energy collimation of Eq.(2).

Note, that an attempt to fix a jet axis with the accuracy better than the natural angular width of the corresponding energy flux seems to be physically unreasonable.

The average multiplicity of partons (gluons) in a gluon jet is given by the asymptotic limiting formula [5,6,20].

(5)

$$\ln(N^g) \equiv \sqrt{\frac{32N_c\pi}{\alpha_s(Y)}} \frac{1}{b} + \left(\frac{B}{2} - \frac{1}{4}\right) \ln \alpha_s(Y) +$$

$$+ O(1); B = \frac{a}{b}, a = \frac{11}{3}N_c + \frac{2nf}{3N_c^2}$$

(More elaborated analytical formulae may be found in Refs. [6,10].)

Note that change of scale parameter Λ by a factor of $O(1)$ would correspond to a correction of $O(\sqrt{\alpha_s})$ in multiplicity N . Such corrections are subleading to the MLLA and therefore this parameter cannot be compared directly with the values obtained from other experiments.

The first term in Eq. (5) is reduced by a factor $\frac{1}{\sqrt{2}}$, relative to the incoherent case. This reduction is a direct result of the destructive interference of soft gluon emission.

In the framework of the LPHD scenario the MLLA analytical expressions describe the hadron inclusive distributions with the values of parameter Λ and the normalization factors K determined phenomenologically from comparison with the data at the present energies.

When analyzing the distribution of charged particles one should take into account that it is, in fact, a mixture of different particles, spectra of which prove to be not exactly

(6)

$$\bar{D}^{ch} = \bar{D}^{\pi^\pm} + \bar{D}^{K^\pm} + \bar{D}^{p(\bar{p})} + \dots$$

similar. This can, in principle, cause some $K^{ch}(Y)$ dependence at fixed values of $K^{\pi^\pm}, K^{K^\pm}, K^{p(\bar{p})}$ (see Ref. [21]).

First comparison with the experimental data showed [10] that the relative yields of hadrons of various species can be reasonably simulated in PA by the conjecture $(Q_0)_{eff} = m_h$ (keeping the same value of Λ_{eff}). Such fits gave the following values of the conversion factors K^h and Λ_{eff} [10,21]:

$$K^{\pi^\pm} \cong 1, \quad \frac{K^{K^\pm}}{K^{\pi^\pm}} = 0.22; \quad \frac{K^{p(\bar{p})}}{K^{\pi^\pm}} = 0.11;$$

$$\Lambda_{eff} = 0.155 \text{ GEV.}$$

Fig. 3 displays the energy dependence of charged particle multiplicity in $e+e-$ collisions together with the prediction of Eq. (5) (neglecting the possible weak energy dependence of the conversion factor). The PA result is seen [22] to agree well with the $e+e-$ data and the HERWIG [23] Monte Carlo points, as shown in Fig. 3. Taking this agreement as a testing ground, one can predict the dynamics of the multiplicity increase, shown in Fig. 4. [24]

Assuming five flavours the ratio of particle multiplicities in a gluon jet and a quark jet with the accuracy to $O(\alpha_s)$ terms is given by [25].

$$N_g/N_q = \frac{9}{4}(1 - 0.27\sqrt{\alpha_s} - 0.07\alpha_s \dots) \quad (7)$$

The MLLA expression for the limiting spectrum of relativistic particles in the region $\ln 1/x \gg 1$ can be presented in a form [6] (see also Ref. [12]):

$$\bar{D}^{lim} \equiv [\bar{D}_g^g(1, Y)]_{MLLA} = \frac{4N_c}{b} \Gamma(B) \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\tau e^{-B\alpha} \left[\frac{ch\alpha + (1 - 2\zeta)sh\alpha}{\frac{4N_Y}{b} \frac{\alpha}{sh\alpha}} \right]^{\frac{B}{2}} \quad (8)$$

$$I_B \left(\sqrt{\frac{16N_Y}{b} \frac{\alpha}{sh\alpha} [ch\alpha + (1 - 2\zeta)sh\alpha]} \right)$$

which is especially convenient for numerical integration.

Here

$$\alpha = \alpha_0 + i\tau, \quad \tanh \alpha_0 = 2\zeta - 1, \quad \zeta = 1 - \frac{1}{Y},$$

I_B is the modified Bessel function of order B .

This spectrum exhibits the above mentioned "hump-backed" structure with a maximum at particle energies $E_0 = x_0 E$ approaching asymptotically

(9)

$$\ln\left(\frac{1}{x_0}\right) = \frac{1}{2}Y(1+B\sqrt{\frac{b}{4N_cY}}) + O(1)$$

In Ref. [26] a transparent expression for the $\bar{D}(1,y)$ has been obtained in a form of a distorted Gaussian.

Note that in the framework of the MLLA the l-distributions of q and g-jets differ only by the normalization factor $\frac{C_F}{N_c} = \frac{4}{9}$. Account for the Next - to - MLLA effects, namely, $\sim O(\sqrt{\alpha_s})$ terms [21], shows that the distribution in a q-jet is pretty close to the limiting spectrum. The asymptotic position of the maximum is slightly shifted to higher $\delta_q(\ln(\frac{1}{x_0})) \approx -0.01$. Spectrum in a g-jet is shifted to lower x as compared to the limiting case: $\delta_g(\ln(\frac{1}{x_0})) \approx 0.04$, see Refs. [21,26].

A strong support to the PA ideas came recently from the OPAL data [19] on the inclusive momentum distribution of charged particles at the Z^0 . To observe the expected energy evolution these data were combined with the TASSO results [27].

Fig. 5 shows that the MLLA limiting formula (8) provides an excellent description of both the space and the energy evolution of the spectrum. Especially spectacular is the confirmation of the energy evolution of the peak position (see Eq.(9)), which is independent of the normalization factors.

These results wonderfully confirm the QCD cascading picture of the multiple hadroproduction. One may expect even higher credibility of the MLLA expressions at larger jet energies where the subasymptotic corrections are less important.

Fig. 6 illustrates the dependence of the limiting distribution in a g-jet on its hardness $Q=E\Theta_0$ [24]. In this figure one can clearly see the rise of the maximum $E_0 = x_0E$ with the jet energy and an increase of the hump height, reflecting the rise of multiplicity.

Account for the specific QCD features of jets could be of importance for design of future experiments and the analysis of their data.

It is noteworthy that according to Eq. (9) E_0 in particle spectra grows rather slowly with the jet energy E; even at $E \approx 1.5$ TEV, its value reaches only $E_0 \approx 3$ GEV.

To explore the coherent origin of the hump-backed particle spectrum and in an attempt to study the depletion in its soft part for jets produced in hadronic collisions, it proves to be important to look at particles restricted to lie within a particular opening angle with respect to the jet [28]. For example, one might consider the energy distribution of particles accompanying the production of an energetic particle and lying within an opening angle Θ_0 about the direction of the trigger particle momentum.

Parton cascades in these situations will populate mainly the region

$$\frac{m_h}{\sin \frac{\theta_o}{2}} \langle E_h \rangle E$$

with E_h and m_h being the energy and the mass of the observed particle, respectively ($m_h \geq \Lambda$). The maximum of the distribution, in E_h , is now forced to larger energies

$$\ln \frac{E_o}{m_h} = \frac{1}{2} \ln \frac{E}{m_h (\sin \frac{\theta_o}{2})}$$

$$-B \left(\sqrt{\frac{b}{16N_c} \ln \frac{E(\sin \frac{\theta_o}{2})}{\Lambda}} - \sqrt{\frac{b}{16N_c} \ln \frac{m_h}{\Lambda}} \right)$$

If one chooses Θ_o moderately small and varies E , coherence will give a moving peak in accordance with the relation:

$$\frac{E}{E_o} \frac{dE_o}{dE} = \frac{1}{2} - B \sqrt{\frac{b}{64N_c Y(\theta_o)}}$$

with

$$Y(\theta_o) = \ln \frac{E(\sin \frac{\theta_o}{2})}{\Lambda}$$

The angular cut Θ_o is especially useful for jets produced in hadronic collisions, since one is able to eliminate much of the soft background.

Fig. 7 illustrates the energy distribution of charged hadrons in different cones Θ around the jet axis at $\frac{E\theta_o}{\Lambda} = 10^4$ [12].

Finally, let us make some comments on the multiplicity distribution in QCD jets. As was shown in Ref. [29], the predicted multiplicity moments, including the next-to-leading corrections, are very close to those of a negative binomial distribution

$$\frac{\sigma(n)}{\sigma_{tot}} = k(k+1)\dots(k+n-1) \frac{1}{n!} \left(\frac{\langle n \rangle}{k} \right)^n \left(1 + \frac{\langle n \rangle}{k} \right)^{-n-k},$$

with

$$\frac{1}{k} \cong 0.4 - 0.9 \sqrt{\alpha_s} + O(\alpha_s)$$

It is not excluded that $O(\alpha_s)$ terms are rather important at nonasymptotic energies.

3. RADIOPHYSICS OF LARGE $P_\perp$ HADRONIC JETS

In the framework of PA, the source of multihadron production in QCD jets is gluon bremsstrahlung, so one should expect that the produced hadrons are a consequence of the colour dynamics at small distances. Therefore, the detailed features of the parton-shower system, such as the flow of colour quantum numbers, influence significantly the distribution of colour-singlet hadrons in the final state.

The drag [15] (or string [30]) effect in the $q\bar{q}g$ events of $e+e-$ annihilation is one of the best example of the interjet collective phenomena revealing the wave nature of hadroproduction in HP.

It is instructive to note, that originally this effect was predicted as the result of a Lorentz boost exerted by a gluon on the nonperturbative string stretched between quarks [30]. But in the PA picture it is a result of interference among the gluon waves radiated from the $q\bar{q}g$ composite emitter [15].

The $e+e-$ data (see Refs. [7,31] and references therein) have strongly supported the predicted drag of the interjet particles in the direction of the gluon jet (net destructive interference in the $q\bar{q}$ valley). They demonstrated that the wide angle particles really do not belong to any particular jet, but their emission properties depend on the overall jet ensemble.

Let us emphasize that the observation of the colour interference between soft hadrons from, say, $q-$ and g -jets reveals the QCD wave properties of hadronic flows. Thus, it can be considered as an experimental proof of the common bremsstrahlung nature of the hadroproduction mechanisms for both jets. The properties of drag interference phenomena are deeply rooted in the basic structure of non-Abelian gauge theory.

Future detailed tests of QCD coherence dynamics require comprehensive studies of the total three dimensional pattern of particle flows in the multi-jet events. Of special interest here are the angular structure and the energy dependence of multiplicity flow.

The studies of the interjet collective phenomena in hadronic collisions look very promising (see Refs. [1,4,12,16,32]). Here the soft radiation pattern can be represented as an incoherent sum of contributions, subject to an angular ordering constraint.

Unfortunately so far the experimental study of the particle flow radiophysics at the hadronic colliders is still in its infancy. With the new experiments at the (super)colliders it is to be hoped that the interjet dynamics will reveal its strength both as a probe of perturbative and nonperturbative QCD and as a valuable tool, helping to study manifestations of new physical phenomena.

To illustrate, how the interjet coherence connects the structure of hadronic accompaniment in HP with the t -channel colour transfer, let us consider high $p_\perp$ scattering of partons $A+B \rightarrow A'B'$ ($E_A \sim E_B \sim \sqrt{s}$) at relatively small angles $\theta_s \approx \frac{p_\perp}{E} \ll 1$. The hardness of the process is determined by the momentum transfer $p_\perp \approx \sqrt{-t}$, which naturally restricts the transverse momenta of the accompanying gluon bremsstrahlung $l_\perp < p_\perp$ and, so the development of partonic cascades.

In the structure of the final hadronic system three regions may be separated. Two of them adjoin the fragmentation regions of the colliding hadrons and occupy the intervals (14)

$$\Delta\eta = \ln p_{\perp} / \Lambda ,$$

where η is the pseudorapidity

$$\eta = \frac{1}{2} \ln \frac{1 + \cos \theta}{1 - \cos \theta}$$

The hadronic spectrum in each of these intervals is saturated with the particles from the bremsstrahlung cones of the incoming and the scattered partons, and so results from an incoherent sum to two jets with angular opening $\theta = \theta_s$. The height of the distribution is determined, roughly speaking, by the sum of parton' colour charges' $C_A + C_{A'}$ and $C_B + C_{B'}$ respectively,

In the central region

$$|\eta| < \eta(\theta_s) \equiv \ln \frac{\sqrt{s}}{p_{\perp}} \approx \ln \frac{E}{p_{\perp}} \quad (15)$$

(final particle angles larger than the scattering angle θ_s) the incoming and the scattered partons radiate coherently, and, as a result, the hadron density is determined by the colour charge C_t of the t-channel exchange. Since in the given kinematics ($\hat{t} \ll \hat{s}$) gluon exchange dominates, we conclude that in the central region hadronic spectrum is determined by the 'colour strength' of the gluon current C_g , and what is of importance, it becomes universal, independent of the nature of scattered partons ($A, B = q \text{ or } g$).

As was shown in Ref. [12], the resulting spectrum, accounting for the parton branching effects, is independent of the energy (pseudorapidity) of the particle registered at angle $\theta > \theta_s$ at fixed transverse momentum $k_{\perp}$:

$$\frac{d\sigma}{\sigma d\eta dk_{\perp}} \equiv 4N_c \int_{k_{\perp}}^{p_{\perp}} \frac{dl_{\perp}}{l_{\perp}^2} \frac{\alpha_s(l_{\perp}^2)}{2\pi} \bar{D}_g\left(\frac{k_{\perp}}{l_{\perp}}, \ln \frac{l_{\perp}}{\Lambda}\right) \quad (16)$$

In this expression $x \cdot \bar{D}_g$ is the standard distribution of particles in a gluon jet, for which the product of energy and opening angle equals Q .

Integrating over $k_{\perp}$ of hadrons at fixed η , one obtains

(17)

$$f(\eta, \ln \frac{p_\perp}{\Lambda}) = \frac{d\sigma}{\sigma d\eta} = \int^{p_\perp} \frac{dl_\perp}{l_\perp} 4N_c \frac{\alpha_s(l_\perp^2)}{2\pi} \int_0^1 dx \bar{D}_g(x, \ln \frac{l_\perp}{\Lambda})$$

Thus, the hadron yield in the interval $|\eta(\theta)| < \eta(\theta_s) \equiv \ln \frac{E}{p_\perp}$ does not depend on the rapidity, so a flat distribution emerges, whose height is determined by the hardness of the scattering process.

The rich diversity of the collective drag phenomena has been studied for high $p_\perp$ hadronic collisions [2,16,24,32].

One of the simplest examples is the prompt production of the colourless object (γ , W , Z ...) at large $p_\perp$, as shown in Figs. 8. Here the drag phenomena are very similar to 3-jet events of e^+e^- annihilation. The radiation pattern in Fig. 8a) was calculated [12,28] for final pions projected onto the scattering plane. The particle production proves to be largest between the directions for the incoming gluon and the outgoing quark, but approximately 2.8 times smaller between the directions of the incoming quark and the outgoing quark.

The drag effect here leads to an azimuthal asymmetry of particles, which can be seen by looking end on at the struck q -jet (see for details Ref. [12]). The study of such an asymmetry may indicate which of the incoming particles has shaken off the hard gluon.

Fig. 8b, shows the QCD antenna pattern function P which is defined as the ratio of the two-to-three and two-to-two cross sections in the soft limit at 90° in the parton centre of mass [32] (see also Refs. [12,26]).

One can easily see from Fig. 8b, the essential qualitative difference between the two mechanisms of the production of W -bosons at the hadronic colliders.

(18)

$$(i) \quad q(p_1) + \bar{q}(p_2) \rightarrow W(p_3) + g(p_4),$$

$$(ii) \quad q(p_1) + g(p_2) \rightarrow W(p_3) + q(p_4),$$

Therefore it may be possible to distinguish whether a W is produced by process (i) or (ii) on an event by event basis (see Refs. [12,32] for details).

Figs. 9a,b, show the QCD antenna patterns for 90° scattering in the centre of mass for two of the principal two-to-two scattering processes responsible for jet production in $p\bar{p}$ collisions, see Refs. [12,16,28,32].

(19)

$$q(p_1) + \bar{q}(p_2) \rightarrow q(p_3) + \bar{q}(p_4)$$

$$g(p_1) + q(p_2) \rightarrow g(p_3) + q(p_4)$$

It can be seen from Fig. 9b, that there is an asymmetry of about factor four between the first and the third quadrant.

If detectable, this asymmetry would allow the separation of g and q-jets on an event by event basis. By moving to large rapidity one can select events in which the fraction of the longitudinal momentum carried by one of the partons is very large and the other is very small, leading to an enriched contribution from the qg-scattering, see Refs.[32].

One of the interesting tasks for the future experiments seems to be the study of colour coherent phenomena in the structure of the final states in deep inelastic scattering (see Refs. [1,12,33]). Of special interest here is the evolution of the distributions with q^2 and x_B .

Colour interference between jets seems to become a phenomenon of large potential value as a new additional tool for discriminating between HPs. For example, reconstruction of antenna pattern by the effects of particle drag may help to study the production of new colourless heavy objects - the Higgs boson H, new quarks and leptons, supersymmetric particles, and so on. Most of these objects produce hadronic jets, and the configurations of interjet particles should differ from familiar QCD processes like parton scattering.

An interesting example came from the study of the accompanying particle distribution in the heavy Higgs production [12]. Here the radiation pattern should be quite different depending on the production mechanism of a Higgs boson, see Figs 10,11. If H boson is produced via the g-g fusion of Fig. 10b), then the standard hadronic distribution $f(\eta, \ln \frac{MH}{\Lambda})$

Λ arises in hadronic spectrum. However in the case of the W-W mechanism of Fig. 10a, the central region (15) should be empty, and the process looks as the quasi-diffractive one (the gluon emission by initial and final partons at large angles cancel each other coherently because in t-channel colour is not transferred).

Monte Carlo simulation using PYTHIA programm for 500 GEV Higgs production at the LHC energy confirms this qualitative statement, [34].

Another example is the comparison of the production of a colourless object via gg or $q\bar{q}$ collisions. Here, if the hard kinematics is the same, the heights of the accompanying plateau should differ approximately by a factor of two ($N_c/C_F = 9/4$).

4. PA AND SHOWER MONTE CARLO ALGORITHMIC SCHEMES

The well-elaborated shower Monte Carlo simulation programs for jet physics has been presented on the market (for reviews see, e.g., Refs. [1,35,36]).

All of them are of a probabilistic and iterative nature. The models evolve steadily in time, in particular, by building in realistic fragmentation and proper QCD cascades. The QCD-inspired models describe very successfully the existing data, based on the concept of the well-developed parton shower, and prove to be very useful tools for experimentalists.

The model-builders aim to formulate the Monte Carlo algorithms to be as faithful as possible representatives of the QCD dynamics of jets. Over the last few years, one could observe an obvious convergence between the different classes of models and a growing tendency to reproduce the important ingredients of PA

Note that the Monte Carlo simulation technique permits one to reproduce the flow of colour in the parton cascade, at least to leading order in N_c , since to this order the colours of all external lines may be traced continuously through the corresponding tree diagram. In a Monte Carlo simulation it is straightforward to intertwine the QCD parton shower with a nonperturbative fragmentation model for the conversion of parton configurations into hadrons at any desired scale of virtuality Q_0 .

One of the aims for model improvement is the most adequate incorporation of the colour coherence, reflecting the quantum mechanics of QCD.

It is important to notice, however, that the description of multipartonic system development in terms of classical Markov chains is of limited value in principle. Of special interest here are $1/N_c^2$ suppressed soft contributions [6,12].

Another example is connected with the interjet collective phenomena in the multijet ensembles. These effects could be reproduced in a classical probabilistic language only in the large N_c limit (see Ref. [12]). The problem is that nowadays we simply do not know how to handle $1/N_c^2$ terms in Monte Carlo simulations. Normally, the neglect is not serious ($\leq 10\%$), but under special conditions these terms may even become dominant.

The azimuthal asymmetry of QCD jets is one of the simplest examples when the colour-suppressed terms are essential, see Ref. [12] for details. Here the qualitative difference between the predictions of QCD and its large N_c -limit proves to be the most spectacular in the case of high $p_\perp$ $p\bar{p}$ scattering with the identification of the scattered q-jet.

Concluding this section, let us emphasize that the relative smallness of the nonclassical effects does not diminish their fundamental importance. These consequences of QCD radiophysics are a serious warning against the traditional ideas on independently evolving partonic subsystems.

5. CONCLUSION

I would like to deliver this talk as my entrance fee to the 200 TEV Club. The main aim of the talk was twofold: On the one hand, I tried to demonstrate the present level of reliability and maturity of the QCD PA to the description of the jetty final states in HP. On the other hand, the idea was to show that the QCD studies within the PA are far from being exhausted. For example, it looks very promising to use the spectacular collective QCD effects as a valuable tool for studying the manifestations of new physical phenomena. Therefore, the future experiments of hadronic supercolliders definitely need PA-like activity (hopefully by the QCD chapter of the 200 TEV Club).

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REFERENCES

1. G. Marchesini, invited talk at this workshop.
2. For reviews see, A. Bassetto, M. Ciafaloni, and G. Marchesini, *Phys. Rep.* **C100** (1983) 201; Yu. L. Dokshitzer, V. A. Khoze, A.H. Mueller, and S.I. Troyan, *Rev. Mod. Phys.* **60** (1988) 373; Yu. L. Dokshitzer, V.A. Khoze, and S.I. Troyan, in *Perturbative QCD*, ed. A. H. Mueller (World Scientific, Singapore, 1989), p.241.
3. Yu. L. Dokshitzer, Talks given at the International Schools of Subnuclear Physics, Erice, 1989, 1990.
4. V.A. Khoze, proc. of the Int. Symp. on Lepton and Photon Interactions at High Energies, Stanford, Aug. 1989 (World Scientific) p. 387.
5. A. H. Mueller, *Nucl. Phys. B* 213 (1983) 85 and erratum quoted in *Nucl. Phys.* **B241** (1984) 141.
6. Yu. L. Dokshitzer and S. I. Troyan, *Proc. XIX Winter School of the LNPI*, V.I. 144 (1984); preprint LNPI-922(1984).
7. W. Hofmann, *Ann. Rev. Nucl. Part. Sci.* **38** (1988) 27; P. Mättig, *Phys. Rep.* **C177**(1989) 141; K. Sugano, *Int. Journ. Mod. Phys. A3* (1988) 2249.
8. R. Cashmore, lecture given at the Cargese Summer Institute, Aug., 1990.
9. M. Jacob, Talk at the 25th Int. Conf. on High Energy Physics, Singapore, Aug. 1990.
10. Ya. I. Azimov *et al.*, *Z. Phys.* **C27** (1985) 65; *Z. Phys.* **C31** (1986) 213.
11. D. Amati and G. Veneziano, *Phys. Lett.* **83B** (1979) 87; G. Marchesini, L. Trentadue, and G. Veneziano, *Nucl. Phys.* **B181** (1981) 335.
12. Yu. L. Dokshitzer, V. A. Khoze and S.I. Troyan in Ref. 2.
13. B.I. Ermolayev and V.S. Fadin, *JETP Lett.* **33** (1981) 285; A. H. Mueller, *Phys. Lett.* **B104** (1981) 161.
14. Yu.L. Dokshitzer, V.S. Fadin and V. A. Khoze, *Phys. Lett* **B115** (1982) 242; A. Bassetto *et. al.*, *Nucl. Phys.* **B207** (1982) 189.
15. Ya I. Azimov *et. al.*, *Phys. Lett* **B165** (1985) 147, *Yad. Fiz* **43** (1986) 149.
16. R.K. Ellis, G. Marchesini and B. R. Webber, *Nucl. Phys.* **B286** (1987) 643.
17. Yu. L. Dokshitzer *et.al.*, *Phys. Lett* **B245** (1990) 243.
18. Yu. L. Dokshitzer *et.al.*, *CERN TH* 5738/90.
19. OPAL Collaboration, M.Z.Akrawy *et.al.*, CERN EP/90-94.
20. B.R. Webber, *Phys. Lett.* **B143** (1984) 501.

21. Yu. L. Dokshitzer, V.A. Khoze and S.I. Troyan LU TP 90-12 (1990)
22. B.R. Webber, talk given at the 25th Rencontre de Moriond, March 1990.
23. G. Marchesini and B.R. Webber, *Nucl. Phys.* **B310** (1988) 461.
24. Yu. L. Dokshitzer, V.A. Khoze and S.I. Troyan Preprint LNPI-1230 (1986).
25. J.B. Gaffney and A.H. Mueller, *Nucl. Phys.* **B250** (1985) 109.
26. C.P. Fong and B.R. Webber, *Phys. Lett* **B229** (1989) 289.
27. TASSO Collaboration., W. Braunschweig *et.al.*, DESY 90-013.
28. Yu. L. Dokshitzer, V.A. Khoze, A.H. Mueller and S.I. Troyan in Ref.[2].
29. E.D. Malaza and B.R. Webber, *Nucl. Phys.* **B267** (1986) 702.
30. B. Andersson, G. Gustafson, and T. Sjöstrand, *Phys Lett.* **94B** (1980) 211.
B. Andersson, B. Gustafson, G. Ingelman, and T. Sjöstrand, *Phys. Rep.* **97** (1983) 31.
31. DELPHI Collaboration, Contribution to the 25th Int. Conf. on High Energy Physics, Singapore, Aug. 1990.
32. R.K. Ellis, FERMILAB-Conf.-87/108-T (1987)
33. M. Ciafaloni, *Nucl. Phys.* **B296** (1987) 249. L.V. Gribov *et. al.*, *Phys. Lett.* **202B** (1988) 276; *JETP* **34** (1988) 12.
34. T. Sjöstrand, private communication.
35. B. Andersson, LU TP 88-2 (1988).
36. T. Sjöstrand, lecture given at the Cargese summer Institute, Aug. 1990.

FIGURE CAPTIONS

Fig. 1. Two types of coherence effects: a) intrajet coherence; b) interjet coherence.

Fig. 2 Energy and multiplicity collimation in the QCD jets [12]. The lower scale corresponds to the case $\Lambda=0.155$ GEV . ϵ means energy fraction, δ -multiplicity fraction.

Fig. 3 The energy rise of charged particle multiplicity in $e+e^-$ collisions. The dashed line corresponds to the double logarithmic case.

Fig. 4 LPHD expectations for the average particle multiplicities in the QCD jets [24]. The lower scale corresponds to the total jet opening angle and $\Lambda=0.155$ GEV .

Fig. 5 Energy evolution of the $\ln(p)$ distribution of charged particles in the $e+e^-$ collisions [19] together with the predictions of the limiting MLLA formula (8), assuming $\bar{D}_q = \frac{4}{9}\bar{D}^{\text{lim}}$

Fig. 6 Limiting energy spectrum of partons in a gluon jet with an opening angle θ_0 and energy E . The values in the brackets correspond to the total jet opening angle and $\Lambda=0.155$ GEV . The lower scale shows the energies of particles corresponding to such a case.

Fig. 7 Dependence of the energy spectrum of partons in a gluon jet with an opening angle $\frac{E\theta_0}{\Lambda} = 10^4$ on the aperture of the registered particle flow [12]. The narrower is the registration cone, the harder are the particles within this cone. The value of energy, given in brackets, corresponds to the total jet opening angle and $\Lambda=0.155$ GEV .

Fig. 8a): The energy rise of $\pi^\pm$ multiplicities in the 30° sectors in large $p_\perp$ prompt $\diamond(W)$ production: $\frac{E_\perp}{\Lambda} = 2 \cdot 10^2$, 10^3 and 10^4 [12]. The values of energy at $\Lambda=0.155$ GEV are given for 90° in the parton-parton centre of mass.

Fig. 8b): Polar plot showing QCD antenna pattern P for the large $P_\perp$ production of W -bosons of 90° scattering in the centre of mass [32]. The value of P is given by the radial distance of the curves from the origin. The plots have been cut off at $P=4$, so the singularities in the collinear regional are not displayed.

Fig. 9a): Polar plot showing QCD antenna pattern P for the identical quark process $q\bar{q} \rightarrow q\bar{q}$ [32].

Fig. 9b): Polar plot showing QCD antenna pattern P for the process $gq \rightarrow gq$ [32].

Fig. 10: Hadronic Higgs production via a) W - W fusion and b) g - g fusion.

Fig. 11: Qualitative picture illustrating the difference in accompanying particle distributional for the Higgs production mechanism of Figs. 10a), b).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Energy evolution of the $\ln(p)$ -spectrum

p [GeV/c]

Fig. 5

Fig. 6

Fig. 7

a)

$$pp(\bar{p}) \rightarrow \gamma(W) + \dots$$

b)

Fig. 8

b)

Fig. 9

Fig. 10

Fig. 11