Soft particle production and QCD coherence

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Abstract
We discuss the behaviour of the energy spectrum of particles in jets near the limit of small momenta of a few hundred MeV. In QCD parton cascades the soft gluons are coherently emitted from all faster partons in the jet and their production rate is predicted to scale. The observed charged and identified particle spectra follow this behaviour surprisingly well supporting of the hypothesis of the Local Parton Hadron Duality (LPHD) for this extreme limit. Further tests of this perturbative approach are discussed.

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1 Introduction

The study of multiparticle production in hard collision processes can yield valuable information about the characteristic features of the partonic branching processes in QCD and the transition from the coloured partons to the colourless hadrons. The parton branching process is driven by the gluon bremsstrahlung which becomes singular in the limit of collinear or soft emission. Analytical calculations in the Double Logarithmic Approximation (DLA) take into account the contributions from these singularities. An improved accuracy is obtained in the Modified Leading Logarithmic Approximation (MLLA) which includes corrections of relative order $\sqrt{\alpha_s}$ (for a review, see \cite{1}).

There is no commonly accepted theory of hadronization, but experimental data can be used to improve our knowledge about the partonic interactions in the limit of small momentum transfer. Here we consider the hypothesis of the LPHD which assumes that sufficiently inclusive observables at the hadronic level are directly given by the corresponding quantities computed for the parton cascade. A striking success of this approach is the prediction of the energy distribution of particles with an approximately Gaussian shape in the variable $\xi = \log E_{jet}/E$ for particles with energy $E$ in a jet of energy $E_{jet}$ (the so-called “hump-backed plateau” \cite{2,3,4}).

Here we focus on the soft end of the spectrum ($E \lesssim 1$ GeV). We recall that the gluons of long wave length are emitted coherently by the total colour current which is independent of the internal structure of the jet and is conserved.
when the partons split. The soft radiation then depends essentially on the total colour charge of the initial partons. Due to the coherence of the gluon radiation it is not the softest partons but those with intermediate energies \( E \sim E_{jet}^{0.3-0.4} \) which multiply most effectively in QCD cascades. Applying the LPHD hypothesis one expects that the hadron spectrum at low momentum \( p \) should be nearly independent of the jet energy \( E_{jet} \). Quantitatively, we consider the invariant density \( Edn/d^3p \equiv dn/dydp_T \) in the limit of vanishing rapidity \( y \) and transverse momentum \( p_T \), or, equivalently, for vanishing momentum \( p \), i.e.

\[
I_0 = \lim_{y \to 0, p_T \to 0} \frac{E}{2} \lim_{p \to 0} \frac{dn}{d^3p} = \frac{1}{2} \lim_{p \to 0} \frac{Edn}{d^3p} \quad (1)
\]

where the factor \( 1/2 \) takes into account that both hemisphere are added in the limit \( p \to 0 \). If the dual description of hadronic and partonic final states is really adequate down to very small momenta, the finite, energy independent limit of the invariant hadronic density \( I_0 \) is expected from the colour coherence argument. This expectation is supported by the experimental data for both charged and identified hadrons in the full energy range explored so far in \( e^+e^- \) annihilation. Furthermore we discuss how the QCD picture explaining this result can be further tested. For more details we refer to the paper .

2 Particle production in the soft limit

We consider first the analytical predictions for the energy spectrum of partons near the soft limit. The asymptotic behaviour of the energy spectrum is obtained from the DLA in which energy conservation is neglected and only the leading singularities in the parton splitting functions are kept. The evolution equation of the single parton inclusive energy distribution originating from a primary parton \( A \) is given by

\[
D_A^p(\xi, Y) = \delta_A^p \delta(\xi) + \int_0^\epsilon d\xi' \int_0^{Y-\xi} dy' \frac{C_A}{N_C} \gamma_0^2(y') D_g^p(\xi', y') \quad (2)
\]

Here we have used the logarithmic variables \( \xi = \log(1/x) = \log(Q/E) \) and \( Y = \log(Q/Q_0) \) with \( E \) the particle energy and \( Q \) the jet virtuality \( Q = p_\Theta \) for a jet of primary momentum \( P \) and opening angle \( \Theta \); \( C_A \) is the respective colour factor, \( N_C \) for \( A = g \) and \( C_F \) for \( A = q \); \( \gamma_0 \) denotes the anomalous dimension of multiplicity and is related to the QCD running coupling by \( \gamma_0^2 = 4N_C\alpha_s/2\pi \) or \( \gamma_0^2 = \beta^2/\log(p_{\perp}/\Lambda) \) with \( \beta^2 = 4N_C/b, \ b \equiv (11N_c - 2n_f)/3; \ \Lambda \) is the QCD-scale and \( N_C \) and \( n_f \) are the number of colours and of flavours respectively.
The shower evolution is cut off by $Q_0$, such that the transverse momentum $p_{\perp} \geq Q_0$.

In case of fixed $\alpha_s$ the exact DLA solution is known:

$$D_A^g(\xi, Y, \gamma_0) = \delta_A^g(\xi) + \frac{C_A}{N_C} \gamma_0 \sqrt{\frac{Y - \xi}{\xi}} I_1 \left( 2\gamma_0 \sqrt{\xi (Y - \xi)} \right)$$  \hspace{1cm} (3)

where $I_1$ is a modified Bessel function of first kind. This distribution in $\xi$ vanishes for $\xi \to 0$ and $\xi \to Y$ as required by eq. (2). The exact MLLA correction is obtained by multiplying the DLA result (3) with the factor $\exp(-a \gamma_0^2 (Y - \xi)/4N_C)$ where $a = \frac{11}{3} N_C + \frac{2n_f}{3N_c^2}$.

In case of running $\alpha_s$ the first terms of an iterative solution of the DLA equation (2) have been derived; the MLLA correction is again given by an exponential damping factor in analogy to the fixed $\alpha_s$ case.

While the limiting behaviour of the partonic energy spectrum in the soft region follows from the general principle of colour coherence the detailed form of the observable hadronic spectrum is predicted uniquely from the LPHD hypothesis only for $E \approx p \gg Q_0$, but not near the kinematical boundary because of the sensitivity of the spectrum to the cut-off procedure. In the usual application of the MLLA the partons are treated as massless with energy $E = p \geq p_{\perp} \geq Q_0$, so $\xi \leq Y$. Experimental hadronic spectra are usually presented as function of momenta $p$ or $\xi_p = \log(1/x_p)$ which is not limited from above. The same kinematic limit for partons and hadrons is obtained if the hadronic mass $m_h$ and the partonic $p_{\perp}$ cut-off $Q_0$ are taken the same.

For the relation between parton and hadron distributions one may require that the invariant density $\frac{dn}{d^3p}$ of hadrons approaches a constant limit for $p \to 0$ as is observed experimentally. For the spectra which vanish linearly as in (3) this is achieved by relating the hadron and parton spectra as:

$$E_h \frac{dn(\xi_E)}{dp_h} = K_h E_p \frac{dn(\xi_E)}{dp_p} \equiv K_h D_A^g(\xi_E, Y)$$  \hspace{1cm} (4)

with $E_h = \sqrt{p_{\perp}^2 + Q_0^2} = E_p \geq Q_0$, where $K_h$ is a normalization parameter referring to a single jet. Then, indeed, for hadrons the invariant density $\frac{Edn}{d^3p} = K_h D_A^g(\xi, Y)/4\pi(E_h^2 - Q_0^2)$ approaches the finite limit as in (3):  

$$I_0 = K_h \frac{C_A \beta^2}{8\pi N_C \lambda Q_0^2}.$$  \hspace{1cm} (5)
Figure 1: Invariant density $E \frac{d^3 n}{d^3 p}$ as a function of the particle energy $E$ for $Q_0 = 270$ MeV. Predictions of MLLA and DLA with fixed $\alpha_s$ (with $\gamma_0 = 0.64$) at cms energies of $\sqrt{s} = 3$ GeV (lower two curves) and 91 GeV (upper two curves) with $D_0^g$ computed using eq. (4).

In the fixed $\alpha_s$ limit $\beta^2/\lambda$ is replaced by $\gamma_0$ and $I_0 \sim 1/Q_0^3$. With prescription (4) the moments of the full energy spectrum $D(\xi, Y)$ are well described by the MLLA formulae at $Q_0 = 270$ MeV in a wide energy range.

The relation (4) is not unique, however. We found that the alternative prescription based on phase space arguments, $d n/d\xi_p = (p/E)^3 D(\xi, Y)$ (see e.g. 10):

$$E_h \frac{d n}{d^3 p_h} = K_h \left( \frac{1}{4 \pi E^2} \right) D_0^g(\xi E, Y)$$

works well for charged pions for all energies $E$ in the LEP region and for charged particles at low energies $E$ if $D_0^g$ is the MLLA “limiting spectrum” with $Q_0 = \Lambda = 138$ MeV. The low cut-off mass is plausible in this region, which is dominated by pions.

In order to illustrate the above exact analytical results we compare in Fig. 1 the computations from DLA and MLLA (in case of fixed $\alpha_s$) for low particle energies using the relation (4) between parton and hadron spectra. The single particle invariant density approaches an energy independent value in the soft limit $\xi \to Y$ ($E \to Q_0$). This originates from the soft gluon emission
Figure 2: a) Invariant density $E dn/d^3p$ of charged particles in $e^+e^-$ annihilation as a function of the particle energy $E = \sqrt{p^2 + Q_0^2}$ at $Q_0 = 270$ MeV at various cms energies with $D_g$ computed using eq. (4) ($K_h = 0.45$); b) the same as in a), but at $Q_0 = 138$ MeV with $D_g$ computed from the Limiting Spectrum using eq. (6) ($K_h = 1.125$).

contribution of order $\alpha_s$ (the term of order $\gamma_0^2$ in the expansion (3)) which is determined by the total colour charge of the primary partons due to the colour coherence. In this limit the MLLA converges towards the DLA as the energy conservation constraints are unimportant and the parton splitting functions are only probed for very small fractional momenta. The approximate results with running $\alpha_s$ show the same features.7

3 Discussion of experimental results

Fig. 2a shows the charged particle invariant density, $E dn/d^3p$, as a function of the particle energy $E$ at different cms energies ranging from 3 GeV up to LEP-1.5 cms energy (133 GeV)11 in comparison with the MLLA predictions for running $\alpha_s$ in the approximate form.8 In this figure, eq. (4) is used to relate parton and hadron spectra at the effective mass $Q_0 = 270$ MeV which was found to provide a good description of the moments of the energy spectra over a large cms energy interval. In Fig. 2b the same data are compared with the MLLA limiting spectrum ($\lambda = 0$), but using eq. (6) with the mass value $Q_0 = 138$ MeV. Whereas this mass value is plausible for small energies $E$, the fit does not work well for the full region of energies $E$ or the lower
energies. Note that, while these fits behave differently very close to the boundary $E \simeq Q_0$, they clearly demonstrate the scaling behaviour expected from colour coherence. Furthermore they reproduce the considerable energy dependence of the initial slope which can be related to the running of $\alpha_s$ in the MLLA damping factor.

It is remarkable that the data from all $ cms $ energies tend to converge in the soft limit; we find $ I_0 \simeq 6.8 \text{ GeV}^{-2} $ (using $ Q_0 = 270 \text{ MeV} $) and $ I_0 \simeq 4.6 \text{ GeV}^{-2} $ (using $ Q_0 = 138 \text{ MeV} $). Inspecting the soft limit more closely, the LEP data seem to tend to a limiting value larger by about 20% as compared to the lower energy data. This may be well due to the overall systematic effect in the relative normalization of the different experiments. Alternatively, there could be a contribution from incoherent sources, for example, from weak kaon and heavy quark decays.

The good scaling behaviour of the soft limit $ I_0 $ is also found in case of identified particles $ \pi, K, $ and $ p $. Remarkably, the scaling continues down to the lowest energy where data are available, at $ \sqrt{s} = 1.6 \text{ GeV} $.

4 Further tests of the parton hadron duality picture

It is suggestive to relate the observed limiting behaviour of particle spectra for vanishing momenta to the expected behaviour of soft gluon emission off the primary partons. The particle rate $ I_0 $ in this limit (see eq. (5)) cannot be directly predicted, as it depends on the normalization factor and the cut-off parameter $ Q_0 $. However, the remarkable scaling behaviour of $ I_0 $ in $ e^+e^- $ annihilation provides one with a standard scale for the comparison with other processes. It would be very interesting to study whether the soft particle production is universal, i.e., a purely hadronic quantity or whether the intensity $ I_0 $ indeed depends on the colour topology of the primary active partons in the collisions process. This could provide one with a direct support of the dual description of soft particle production in terms of the QCD bremsstrahlung.

In what follows we consider some possibilities to test this hypothesis further and discuss what one may expect from the comparison of the $ e^+e^- $ reaction with other collision processes.

4.1 $ gg $ Final State

A direct test of the relevance of QCD coherence for the soft production limit is the comparison of the $ q\bar{q} $ with the $ gg $ colour singlet final state. In the $ gg $ final state the same line of argument applies as above for the $ q\bar{q} $ final state, but the colour charge factor is increased by $ N_C/C_F = 9/4 $ in eq. (5) implying roughly a doubling of the soft radiation intensity $ I_0 $. An approximate realization of
the colour octet antenna is possible in $e^+e^- \rightarrow q\bar{q}g$ with the gluon recoiling against a quasi–collinear $q\bar{q}$ pair\[.\]

4.2 3-Jet Events in $e^+e^-$ Annihilation

To be more quantitative, we consider the soft radiation in 3-jet $q\bar{q}g$ events of arbitrary jet orientation into a cone perpendicular to the production plane and compare it to the radiation into the same cone in a 2-jet $q\bar{q}$ event again perpendicular to the primary $q\bar{q}$ directions. The analysis of these configurations avoids the integration over the $k_T \geq Q_0$ boundaries along the jets. We restrict ourselves to calculations of the soft gluon bremsstrahlung of order $\alpha_s$. From the experience above with the two-jet events this contribution dominates in the soft limit whereas higher order contributions take over with increasing particle energy.

Let us consider first the soft radiation into arbitrary direction $\vec{n}$ from a $q\bar{q}$ antenna pointing in directions $\vec{n}_i$ and $\vec{n}_j$:\[\]

\[
dN_{q\bar{q}} = \frac{dp}{p} d\Omega_{\vec{n}} \frac{\alpha_s}{(2\pi)^2} W^{q\bar{q}}(\vec{n}) , \quad W^{q\bar{q}}(\vec{n}) = 2C_F(ij) \tag{7}\]

with $(ij) = a_i a_j$, $a_{ij} = (1 - \vec{n}_i \cdot \vec{n}_j)$ and $a_i = (1 - \vec{n}_i \cdot \vec{n}_i)$. Such an antenna is realized, for example, in a $q\bar{q}\gamma$ event, and can be obtained by the appropriate Lorentz boost from the $q\bar{q}$ rest frame. The soft gluon radiation in a $q\bar{q}g$ event is given as in (7) but with the angular factor

\[
W^{q\bar{q}g}(\vec{n}) = N_C[(\hat{1}^+) + (\hat{1}^-) - \frac{1}{N_C}(\hat{1}^-)] \tag{8}\]

where $(+, -, 1)$ refer to $(q, \bar{q}, g)$.

For the radiation perpendicular to the primary partons $(\hat{i}j) = a_{ij} = 1 - \cos \Theta_{ij}$, with the relative angles $\Theta_{ij}$ between the primary partons $i$ and $j$. For 2-jet events of arbitrary orientation one obtains in this case

\[
W^{q\bar{q}}_{\perp}(\Theta_{+\ominus}) = 2C_F(1 - \cos \Theta_{+\ominus}) \tag{9}\]

Correspondingly the ratio $R_{\perp}$ of the soft particle yield in 3-jet events to that of 2-jet events in their own rest frame ($W^{q\bar{q}}_{\perp}(\pi) = 4C_F$) is given by

\[
R_{\perp} \equiv \frac{dN^{q\bar{q}g}_{\perp}}{dN^{q\bar{q}}_{\perp}} = \frac{N_C}{4C_F} [2 - \cos \Theta_{1+} - \cos \Theta_{1-} - \frac{1}{N_C}(1 - \cos \Theta_{+\ominus})] \tag{10}\]

This yields, in particular, the limiting cases $R_{\perp} = 1$ for soft or collinear primary gluon emission ($\Theta_{1+} = 1 - \Theta_{1-}$, $\Theta_{+\ominus} = \pi$) and the effective $gg$ limit $R_{\perp} = \ldots$
\(N_C/N_F\) for the parallel \(q\bar{q} (\Theta_{\perp} = 0)\) configuration, as expected. Eq. (10) also predicts \(R_{\perp}\) for all intermediate cases, in particular, for Mercedes-type events one finds \(R_{\perp} = 1.59\). In this case no jet identification is needed for the above measurements. We also note that the large angle gluon radiation is independent of the mass of the quark (for \(\Theta \gg m_Q/E_{\text{jet}}\)).

### 4.3 Hard Processes with Primary Hadrons and Photons

We consider here processes with dominantly 2-jet final states. These include semihard processes which are initiated by partonic 2-body scatterings. In case of quark exchange (in particular deep inelastic scattering processes \(\gamma_V p, \gamma_V\gamma\) at large \(Q^2\) in the Breit frame\(^{15,16}\), the two outgoing jets originate from the colour triplet charges and \(I_0\) should be as in \(e^+e^-\) annihilation; in the case of gluon exchange \(I_0\) should be about twice as large \((N_C/C_F)\) as expected for a \(gg\) jet system. In 2-jet events the limiting density \(I_0\) may be most conveniently determined as a limit of \(dn/dy d^2p_T\) at \(y \approx 0\) for \(p_T \to 0\). In general the deep inelastic processes may have contributions from both quark exchange and gluon exchange which are expected to dominate in different frames. Final states with several well separated jets can be treated in analogy to the \(e^+e^-\rightarrow 3\)-jet events discussed before.

The frame dependence can be studied conveniently in these exchange processes by considering \(I_0(y) = \frac{dn}{dy d^2p_T} \mid_{p_T \to 0}\) as a function of rapidity \(y\), measured, say, in the \(cmn\) frame. The Breit frame is reached by a Lorentz transformation in the direction of the incoming photon, and corresponds to a different rapidity, \(y_{\text{Breit}}\), in the \(cmn\). One would then expect for the processes with the virtual photons at large \(Q^2\) in general a “quark plateau” of \(I_0(y)\) in the current region of length \(\Delta y \approx \log(Q/m)\) near \(y_{\text{Breit}}\) and a transition to a “gluon plateau” in the complementary region of length \(\Delta y \approx \log(W^2/Qm)\) where \(m\) is a typical particle mass. The existence of a plateau corresponds to the energy independence of \(I_0\) as seen in \(e^+e^-\) annihilation. So, if gluon exchange occurs with sufficient hardness in the process, \(I_0\) should develop a step like behaviour but never become larger than twice the \(I_0\) value in \(e^+e^-\) annihilation. The height of the “plateau” is a direct indicator of the underlying exchange process (quark or gluon like).

### 4.4 Soft Collisions (Minimum Bias Events)

These processes (with initial hadrons or real photons) are not so well understood theoretically as the hard ones but it might be plausible to extrapolate the gluon exchange process towards small \(p_T\). Experimental data at ISR
energies, however, do not follow the expectation of a doubling of $I_0$ in comparison to $e^+e^-$ annihilation, rather the intensities are found to be similar.

On the other hand, as shown in Fig. 3, $I_0$ roughly doubles when going from $\sqrt{s} \sim 20$ GeV at S$p\bar{p}$/ISR to $\sqrt{s} = 900$ GeV at the S$p\bar{p}$S Collider. If additional incoherent sources like weak decays can be excluded, such behaviour could indicate the growing importance of one-gluon exchange expected from the perturbative picture. Then a saturation at $I_{hh}^0/I_{e^+e^-}^0 \sim 2$ is expected and no additional increase for a semihard $p_T$ trigger. A rise of $I_{hh}^0$ could also result from incoherent multiple collisions of partons (e.g. Ref. 22).

4.5 Production of $W$ pairs in $e^+e^-$ annihilation

If each of the W’s decays into 2 jets the limiting soft particle yield will be twice the yield in $e^+e^- \rightarrow q\bar{q}$, provided the interconnection phenomena are neglected. This tests directly the hypothesis of independent emission.

5 Conclusions

The analytical perturbative approach to multiparticle production, based on the MLLA and the LPHD, has proven to be successful in the description of various
inclusive characteristics of jets. It is of importance to investigate the limitations of this picture, in particular in the soft region where non-perturbative effects are expected to occur.

It is remarkable that the intensity of the soft hadron production follows to a good approximation a scaling law in a range of two orders of magnitude in the $c.m.s$ energy of $e^+e^-$ annihilation (1.6-140 GeV). Such a scaling law is derived analytically for the soft gluons in the jet and follows directly from the coherence of the soft gluon radiation from all emitters. It appears that the production of hadrons which is known to proceed through many resonance channels nevertheless can be simulated in the average through a parton cascade down to a small scale of a few 100 MeV as suggested by LPHD. The scaling behaviour down to the very low $c.m.s$ energy of 1.6 GeV can only be explained within a parton model description if the cut-off scale $Q_0$ is well below 1 GeV.

It will be interesting to investigate the suggested scaling property (1) and its possible violation further in the same experiment to avoid systematic effects; this seems to be feasible at LEP and HERA for the simplest processes. In particular, the effect of weak decays on scaling violations should be clarified. The sensitivity of the soft particle production to the effective colour charge of the primary emitters can be tested through the transverse production rates in multijet events. The soft radiation in $e^+e^-$ annihilation can be used as a standard scale in the comparison of various processes. In this way the soft particle production can be a sensitive probe of the underlying partonic process and the contributions from the incoherent sources.

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