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INTERFERENCE BETWEEN SCALING AND CLUSTER DECAY PHENOMENA
IN INCLUSIVE e^+e^- ANNIHILATION

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A B S T R A C T

A recent model discussion for inclusive e^+e^- annihilation which stresses Bjorken scaling near $x = 1$ genuinely extends to incorporate hadronic cluster decay phenomena near $x = 0$. A synthesis of seemingly different models is achieved.

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In deep inelastic lepton scattering experiments, scaling is the most prominent feature down to very low energies - even if there are some subtle and not very well understood deviations. Scaling has found its interpretation in terms of quasi-free quark partons. The structure of the hadronic final states may be complicated but plays only a minor rôle on that stage.

Nothing like that can be said about the inclusive production $e^+e^- \rightarrow h + X$.¹⁾ It much resembles pure hadronic inclusive processes, there are large deviations from scaling especially for small $x = 2p_0/\sqrt{s}$, and the final state configuration is apparently very important even for a rough understanding.

Nevertheless there should be traces of electromagnetic scaling. Indeed experiments show scaling near $x=1$. This is in qualitative agreement with naive continuation from the scattering region $w = -(2pq/q^2) \geq 1$. The approach to scaling slows down for decreasing x and for x near 0, scaling is badly violated. The absolute value of the scaling function near $x=1$ is not in agreement with simple continuation ideas - it is too big - by more than one order of magnitude for inclusive π production. In Ref. 2), we have unravelled that anomalous thresholds which appear in continuing from the scattering region $w \geq 1$ to the annihilation region $0 \leq x \leq 1$ are extremely important and that they lead out of the dilemma mentioned before. They can be easily understood as the effect of on-shell resonances producing the inclusive particle in their decay. We have worked out a picture²⁾ where the production via the first few resonances [ρ, f and $SU(3)$ partners] is taken into account. The scaling of the resonance irreducible "direct" resonance structure function (i.e., without further production via higher on-shell resonances) induces scaling of the observed particle cross-section with a pre-asymptotic scale given by the resonance mass which enters the decay kinematic. This model works well for present energies though it needs to be improved in the small x region. We could explain the threshold behaviour for $x \approx 1$, pre-asymptotic scaling deviations, in particular deviations from the Callan-Gross relation, the π/K ratio, and even the rough absolute magnitude of the cross-section. The last prediction is not very accurate due to unavoidable assumptions about the unknown resonance structure functions and the resonance spectrum itself. In the very small x region the contributions considered in Ref. 2) die out too fast. Also, the threshold effects due to new quantum numbers - not discussed in Ref. 2) - have to be added³⁾.

There is quite another approach to inclusive e^+e^- annihilation which emphasizes the behaviour near $x=0$. Here the e^+e^- cross-section is compared with pure hadronic cross-sections ($pp \rightarrow \pi X$) at fixed angle (90°). One finds (at fixed s) a similar dependence on the observed momentum p at small $p \lesssim 1$ GeV, i.e., a dependence of type e^{-Rp} . A model explaining this similarity and the form of the p dependence is the thermodynamic cluster decay model of Ref. 4). In both cases the observed hadron is considered as a decay product somewhere on a long thermodynamic cascade of cluster decays. "Thermodynamic" means weighting of graphs only by the density of contributing states. Apparently in this model the only difference between e^+e^- and pure hadronic production lies in the production of the first hadronic cluster. Besides the momentum distribution the model describes well particle ratios near $x=0$. It has, however, also some disadvantages: the s dependence (normalization) is open and there is no natural way to introduce scaling phenomena. Near $x=1$ the thermodynamical distribution falls below the data which show a power behaviour in $(1-x)$. The multiplicity as well as $(d^3\sigma/d^3p)/\sigma_{\text{tot}}$ at a fixed p are predicted to grow linearly in $\sqrt{s}$. Both does not seem to be fulfilled by experiment. If one restricts the phase space to an arbitrarily oriented tube with again a thermodynamic distribution inside this tube one arrives at the uncorrelated jet model ⁵⁾. This interesting model has logarithmically growing multiplicities and power behaviour in a region near $x=1$ with the power related to the coefficient of the multiplicity. It even exhibits scaling in that region. However, the connection between this type of scaling and the Björken scaling of "direct" structure functions with Drell-Yan threshold behaviour in our model is not clear. Of course, a jet structure is highly suggestive in view of recent data ⁶⁾ but the ad hoc assumption of a universal cut-off in transverse momentum remains to be further justified. Such a universal cut-off is an important ingredient of the bag model of Ref. 7), though this model is by no means in agreement with uncorrelated longitudinal phase space near $x=1$.

Recently a two-component picture has been proposed ⁸⁾: the inclusive cross-section is the sum of a scaling (parton) component and of a (central) cluster component with thermodynamical decay distribution

$$2E \frac{d^3\sigma}{d^3p} / \sigma_{\text{tot}} = C e^{-2Rp} \quad (1)$$

with a mass of 1.8 GeV. Such an independent cluster component is supposed to be present exactly once in each single event and is claimed to be identical with the central cluster observed in pp ISR experiments. It contains only part of the produced particles and its multiplicity

$$\langle n \rangle = M_{\text{cluster}} / \langle E \rangle \quad (\langle E \rangle = \int d^3p \, e^{-2Rp} / \int \frac{d^3p}{E} e^{-2Rp})$$

is constant. The "parton" component obtained by subtraction of the cluster component (1) from the observed cross-section shows indeed less deviations from scaling. (Due to error bars it is only well determined in the region where it contributes considerably to the cross-section.) The contribution of the cluster component to σ_{tot} , calculated via the energy sum rule

$$\sqrt{s} \, \sigma_{\text{tot}} = \sum_h \int d^3p \, E \frac{d^3\sigma_h}{d^3p} \quad (2)$$

behaves as $M_{\text{cluster}} / \sqrt{s} \, \sigma_{\text{tot}}$, i.e., dies out asymptotically compared to the "parton" component. The latter component is described by an (effective) scaling structure function. Pre-asymptotic scaling deviations are introduced in a very rough way by an effective mass parameter $\bar{m} = 1.44$ GeV. The approach to a constant $R = \sigma_{\text{tot}}^{\text{hadr}} / \sigma_{e^+e^-}$ from below is supposed to arise with the scaling function introduced on the right-hand side of (2). There is no general philosophy about the origin of the cluster component and about the connection between the two components.

We would like to propose here a unified description of both components : each inclusively observed particle in e^+e^- scattering goes back to the decay of a direct inclusive resonance production which cannot be further reduced. Depending on whether this basic resonance cluster is produced with high momentum or not we have a contribution to the scaling component or to the central cluster component. The scaling component has been described in much detail by the authors in Ref. 2) and essential features have been already mentioned above. Having only a finite set of directly produced resonances below a certain mass (1.5 GeV) these resonances are chiefly fast enough in the energy range of present experiments to reproduce scaling for the observed particle if they are produced in a scaling way.

Of course, there are scaling deviations specific for the decay kinematics, i.e., dependent on the resonance mass and the exclusive decay channel. This description is much more detailed than the procedure of Ref. 8). What has to be added is the production of heavy resonances. In the context of the model of Ref. 2) we would have to ask for their structure functions which are not well known. In the electroproduction region one would suppose that they are shifted to large x since the number of contributing quarks increases. With a Gribov-Lipatov type reciprocity relation this would lead to a peaking around very small $x = (2p_0/\sqrt{s})$ in e^+e^- . These features were confirmed in a model calculation⁹⁾ by one of the authors. In view of this shift to small x and because of their large mass these resonances are produced slowly. One can doubt then that they are produced along with scaling but in the sense of Bloom-Gilman duality the last result, based on scaling structure functions, should survive. For resonances with large mass the analysis of exclusive decay channels is too complicated. The thermodynamical cluster decay offers a simple dependence for the inclusive decay distribution (c.m.s.) $\Gamma(p)/\Gamma_{\text{tot}}$ of the form (1) with C proportional to the resonance mass as well as to the multiplicity of produced particles. The decay distribution works well, e.g., for inclusive ψ decays⁸⁾. With its assumption we arrive at the cross-section (see the Figure),

$$2E \frac{d^3\sigma}{d^3p} = \sum_R \int \frac{d^3\sigma^R}{d^3p'/2E'} \frac{\Gamma^R(p',p)}{\Gamma_{\text{tot}}^R(p')} \frac{d^3p'}{2E'} \quad (3)$$

where the ratio $\Gamma^R(p',p)/\Gamma_{\text{tot}}^R(p')$ is the boosted exponential decay distribution

$$\left(p \rightarrow \left(\left(\frac{p \cdot p'}{m_R} \right)^2 - m^2 \right)^{1/2} \right).$$

Expression (3) is a highly complicated sum over irreducible resonance productions, but for slow resonances the decay distribution factors out and the remaining sum gives just a normalization. This then leads to the central cluster component. The resonance motion gives rise to a broadening of the distribution - well observed in experiments. For very high q^2 even heavy resonances are produced fast, so the p' distribution of the resonance dominates the exponential decay distribution and we have a scaling contribution. In this point we differ from Ref. 8) : the two components are not strictly

separated. For high enough energies a contribution which was completely counted as part of the central cluster at some energy can add to the parton component, whereas in Ref. 8) the parton component is fixed from the beginning and the cluster component dies away. In practice there might be no big difference since due to the peaking of high mass structure functions at small x the contribution to the (effective) scaling function would be small except for small x which - corresponding to small p - are suppressed at present energies in the parton component ansatz of Ref. 8). Actually the fast convergence of the sum of contributions to the scaling part is necessary for a fast convergence to an asymptotic value of $R = (\sigma_{\text{tot}}^{\text{hadr}} / \sigma_{\mu^+\mu^-})$. Note that the effective scaling function $F(x)$ of Ref. 8) behaves like x^{-3} for small x , corresponding to logarithmically increasing multiplicities; we have the same behaviour for the diffractive part of the irreducible structure functions in Ref. 2).

In the picture outlined above the parton component and the central cluster component cannot be separated. It is simply a question whether the produced (direct) resonance cluster is fast enough to introduce a direction or if the exponential decay distribution is dominating. Even with a restricted set of direct resonances as in Ref. 2) there is a contribution of slow production which might also be summarized in the cluster component, substituting the sum over exclusive channels by the exponential inclusive distribution.

In Ref. 8), the central cluster is assumed to appear once in each event. The fact that experiment fits with a constant cluster mass (1.8 GeV) and multiplicity works so well over a large energy regime might indicate that the resonance spectrum is effectively cut off in multiplicity and mass. It is surprising that the complicated sum (3) can be approximated in such a simple way.

Assuming a resonance decay distribution which decreases exponentially for high momenta in the rest frame one could speculate that the parton jet picture with a hadron distribution cut off transversally may be realized by direct resonances produced in the parton jet direction with a distribution $1 + \cos^2\theta$. Actually the Callan-Gross relation and pre-asymptotic deviations from it were introduced in Ref. 2) in this manner. Of course, in order to understand better a jet-like structure, we have to extend our model at least to describe two-particle correlations.

We conclude with the remark that a similar picture - importance of resonance production, interplay between scaling direct production and resonance decay - might be applicable to strong inclusive scattering - if one believes in large angle scaling phenomena.

Proceeding with this paper, we received a preprint by A. Wright (SLAC-PUB 1721). His paper is based on the anomalous threshold effects dwelled on in Ref. 2) and contains a formula similar to our Eq. (3) though the interpretation - exclusive resonance production - is completely different. The scaling of the resonance production should be only true if one can factor out the decay distribution and sum over resonances afterwards. This is fulfilled if the recoiling "anything" is always a big resonance cluster almost at rest. We also just received a preprint by M.I. Gorenstein et al. (Kiev ITP-76-32E) where this configuration is considered in detail. In particular they discuss the boost of the exponential distribution.

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FIGURE CAPTION

Inclusive "direct" cluster production followed by inclusive
cluster decay.