CERN-TH.5197/88

ON THE ORIGIN OF ANOMALOUS SOFT PHOTONS
IN MUON-PROTON INTERACTIONS AT HIGH ENERGY

P. Lichard

Department of Theoretical Physics
Comenius University, 84215 Bratislava, Czechoslovakia

N. Pišútová

Department of Nuclear Physics
Comenius University, 84215 Bratislava, Czechoslovakia

and

J. Pišút*

CERN - Geneva

ABSTRACT

We present arguments supporting the conjecture that anomalous prompt photons observed recently in muon-proton interactions by the European Muon Collaboration (EMC) at CERN are of the same dynamical origin as low mass lepton pairs produced in hadronic collisions. The EMC data are found to be in a qualitative agreement with the soft annihilation model. The conjecture implies that the rate of anomalous photon production depends quadratically on the rapidity density of secondary hadrons in the rapidity region of the photon. A study of this dependence is suggested as a crucial test of the conjecture.

*Permanent address: Dept. Theor. Physics, Comenius University, Bratislava

1.Introduction

The European Muon Collaboration (EMC) have recently observed [1] the production of anomalous prompt photons in 200GeV deep inelastic muon-proton interactions. Anomalous prompt photons are those photons which remain after subtraction of contributions from electromagnetic decays of hadrons and of the muon bremsstrahlung. Deep inelastic events retained in the analysis are characterized by $3 \leq Q^2 \leq 100 \text{GeV}^2$, $100 \leq W^2 \leq 300 \text{GeV}^2$ and $x_{B,J} \geq 0.02$. Mean values within these bands were: $\langle Q^2 \rangle = 19 \text{GeV}^2$, $\langle W^2 \rangle = 195 \text{GeV}^2$ and $\langle \nu \rangle = 113 \text{GeV}$. We are using here the standard notation in which Q^2 denotes the absolute value of the square of the virtual photon four-momentum, W is the total c.m.s. energy of the hadronic system formed in the interaction and ν is the laboratory energy lost by the interacting muon.

Prompt photons in the final state appear with the rate of 0.13 ± 0.05 per interaction. The average transverse momentum $\langle p_T^2 \rangle^{1/2}$ of these photons with respect to the virtual photon direction is 0.245GeV . The $\langle p_T^2 \rangle^{1/2}$ with respect to the scattered muon is about twice as large. As pointed out by EMC[1] this indicates that anomalous prompt photons are originated at the hadronic vertex.

In the variable $z = E_\gamma/\nu$ where E_γ is the prompt photon lab.energy, prompt photons populate predominantly the region extending from $z = 0.05$ to $z = 0.3 - 0.4$. The EMC have kept in the analysis only prompt photons with $E_\gamma > 5 \text{GeV}$.

Anomalous soft photons have been observed earlier by Goshaw et al.[2] and by Chliapnikov et al.[3]. The phenomenon observed by the EMC is, most likely, not quite the same as the one found in Refs.[2, 3]. Goshaw et al.[2] found a clear signal of prompt photons with $p_T < 20 \text{MeV}/c$ and $p_L^* \leq 22 \text{MeV}/c$, consistent with bremsstrahlung by final state hadrons. Chliapnikov et al.[3] have observed prompt photons with $\langle p_T^2 \rangle^{1/2}$ of about 35MeV (estimated from Fig.68 in Hedberg's Thesis [4]) concentrated at very low c.m.s. momenta: $-0.001 \leq x \leq 0.008$, consistent in shape with the contribution from the hadronic bremsstrahlung, but larger in size by a factor of about four. The EMC anomalous photons have $\langle p_T^2 \rangle^{1/2}$ about 7 times larger than those of Refs.[2, 3] and, as will be discussed below, their distribution in $x = x_{cm,s}$ is most likely also broader.

The anomalous low mass e^+e^- pairs have been observed earlier in hadronic interactions [4, 5, 6, 7, 8] (and references quoted therein). The most characteristic feature of these low mass e^+e^- pairs is the observation made by the AFS Collaboration [4, 5, 6] of the quadratic dependence of low mass e^+e^- production rate on the rapidity density of final state pions in the rapidity region of the lepton pair.

The mechanism responsible for the production of low mass lepton pairs and low p_T single leptons in hadronic collisions is not quite clear, but the quadratic dependence indicates that lepton pairs are produced at the intermediate stage of the collision ("parton soup" or "miniplasma") by interactions of partons which later on form the final state hadrons [9 - 14].

The purpose of the present paper is to put forward arguments supporting the conjecture that the anomalous prompt photons observed by the EMC are of the same dynamical origin as low mass lepton pairs produced in hadronic collisions. The paper is organized as follows: In Sect.2 we show that the EMC data are in a qualitative agreement with the soft annihilation model [10, 11, 15, 16] which gives also a reasonable de-

scription of low mass lepton pair production in hadronic collisions. The model treats low mass lepton pairs and EMC anomalous photons as being originated by the same dynamical mechanism. In Sect.3 we analyze the available experimental information on both types of processes. Sect.4 contains a general discussion of the status of the soft annihilation model, its possible developments and its relationship to the quark-gluon plasma and Lund[17] models of low mass lepton pair and soft photon production. We point out here also that the production of soft photons and low mass lepton pairs is, according to the soft annihilation model, a general feature of e^+e^- annihilation to hadrons, deep inelastic lepton-nucleon scattering and hadronic interactions. Conclusions are presented in Sect.5.

2. Photon production in the soft annihilation model and the EMC anomalous photons

We shall show in this Section that the soft annihilation model[10, 11, 15, 16] gives a qualitative description of the EMC data on the production of anomalous photons in muon-proton interactions. The model contains a few parameters whose approximate values are determined by plausible physical arguments, but the exact values remain free. We have not tried to fit the EMC data by varying these parameters but rather kept them fixed at values which give a reasonable agreement with the data on low p_T single positron and low mass dilepton production.

We do not intend to infer from the comparison anything about the model itself. It is admittedly crude and needs some amendments. It treats, however, on the same basis the production of low mass lepton pairs and of real photons and the relationship between these two types of processes will remain practically unchanged even if the model is made more sophisticated. A qualitative agreement of the model with the EMC data thus provides a strong argument in favour of a common dynamical origin of EMC real photons and of low mass e^+e^- pairs as observed in Refs.[4 – 8].

We shall not describe here details of the soft annihilation model[10, 11, 15, 16], we shall just briefly mention its essential features.

The model is based on the idea[9, 15] that during the evolution of a hadronic or deep inelastic collision there is an intermediate stage in which partons can interact as independent particles. The space-time evolution of the collision is assumed to proceed according to a standard Lorentz covariant Bjorken-Gribov picture of the inside-outside cascade. Any rapidity region of the hadronic system is excited only within the interval $\tau_1 < \tau < \tau_2$ where τ is the proper time of the region, τ_1 is the proper time at which the coherence of partons is lost and τ_2 is the proper time of the formation of final state hadrons. This space-time evolution excludes interactions of intermediate stage partons separated by large rapidity gaps and leads to an increase of only low mass and low p_T lepton pairs and low p_T photons. The constraint is built into the soft annihilation model [15] by allowing only interactions of partons separated by a small rapidity gap ($\Delta y \approx 1$).

In the version of the model used so far we have taken into account only interactions of quarks and antiquarks. Their rapidity distributions have been generated in such a way [18] that distributions of final state hadrons obtained by recombinations of these quarks

and antiquarks agree with data on multiparticle production. In generating distributions of quarks and antiquarks [18] valence quarks play a special role having a tendency to keep larger momentum fractions of incident hadrons. In describing the hadronic system formed in deep-inelastic collisions, valence quarks are specified in the following way: in the direction of the incident virtual photon there is a single valence quark -the one which has absorbed the virtual photon, and in the opposite direction there are two remaining valence quarks of the incoming proton. Apart from this difference the space-time evolution of the hadronic system formed in a $\mu - p$ collision is the same as in a hadronic collision. We should note that in what concerns the central region of the collision, technicalities in the treatment of valence quarks are not very important.

In the soft annihilation model we have assumed that low mass lepton pairs are originated by annihilations of quarks and antiquarks during the intermediate stage according to diagrams shown in Figs. 1a and 1b. The latter of the two diagrams is phenomenologically required [16] by the increase of single lepton production at low p_T and of dilepton production at low m_{ee} [4, 5, 6, 19, 20]. The calculation of the cross-section for anomalous photon production within the soft annihilation model is based on the diagram in Fig. 1c which is simply related to that in Fig. 1b.

Results of our calculations of anomalous photon production are compared with the EMC data [1] in Figs. 2 and 3. Calculations have been performed for hadronic systems formed in deep inelastic μp scattering with $Q^2 = 19 \text{ GeV}^2/c^2$ and $\nu = 113 \text{ GeV}$, whereas the data correspond to events with different values of Q^2 and ν and only the averages take on the quoted values.

Note that our results are normalized by the model itself (no arbitrary multiplicative constant). This shows that the rate of anomalous photons is well reproduced by the model.

The agreement with z distributions in Fig. 2 is satisfactory at least for $0.05 < z < 0.2$ where errors of data are rather small. At larger values of z around $0.6 - 0.7$ calculations are somewhat below the data but a more detailed discussion of this point should probably await until systematic errors dominating in this region [1] are decreased.

As seen in Fig. 3 our p_T^2 distributions are more flat than the EMC data. This probably indicates that apart from the diagram in Fig. 1c one should also consider bremsstrahlung of photons in parton-parton scattering in the intermediate stage of the collision. In order to have a consistent scheme such diagrams should be also included in the analysis of low mass lepton pair production. In Figs. 4a and 4b we give an example of such a diagram for both γ and low mass e^+e^- production.

Although the agreement between the model and the EMC data is not perfect we interpret the results of the comparison as an evidence in favour of a common dynamical origin of low mass e^+e^- pairs as observed in hadronic collisions and of the anomalous EMC photons.

3. Relationships between basic features of low mass dilepton and direct soft photon production

Results of the soft annihilation model presented above give a strong indication of a common dynamical origin of low mass lepton pairs and anomalous EMC photons. These

results are, to some extent, model dependent. In order to see the connection in a model independent way one has to study relationships between essential features of both processes in a more direct phenomenological way. An attempt at such an analysis is presented in this Section, with emphasis being put on missing links and gaps.

We start with comparing basic features of anomalous photon [1] and lepton pair [4–8] production.

The rate of anomalous prompt photons observed by the EMC is 0.13 ± 0.05 per interaction. About the same rate is expected if we assume that the EMC photons are of the same origin as low mass lepton pairs produced in hadronic interactions. The AFS Collaboration data [4] show that at $M=100\text{MeV}$ and $y \approx 0$

$$\frac{d\sigma_{ee}}{dM dy} \approx 2 \cdot 10^{-3} \frac{d\sigma(\pi^0)}{dy} \text{GeV}^{-1} \quad (1)$$

Note that both cross-sections in Eq.(1) refer to standard averaged values and not to cross-sections corresponding to a specified value of pion multiplicity (where the quadratic dependence appears). The data as given in Ref.[4] are also not yet corrected for acceptance and their normalization might somewhat change.

The relationship between low mass e^+e^- and real photon production is given by a general expression [7, 21, 22]

$$\frac{d\sigma_{ee}}{dM dy} = \frac{2\alpha}{3\pi} \frac{1}{M} \sqrt{1 - \frac{4m^2}{M^2}} \left(1 + \frac{2m^2}{M^2}\right) F(\hat{s}, M^2, y) \frac{d\sigma(\gamma)}{dy} \quad (2)$$

where m is the electron mass, M the dilepton mass and the ratio of virtual to real photon production

$$F(\hat{s}, M^2, y) = \frac{d\sigma(\gamma^*(M))/dy}{d\sigma(\gamma)/dy}$$

takes into account differences between phase space and form factors for virtual and real photon production. Symbol $\hat{s}$ denotes the square of the c.m.s. energy of the subprocess in which the photon is produced. For instance in a case of a decay of a resonance with mass m_R , $\hat{s} = m_R^2$. Eq.(2) is easy to derive by separating out photon propagator and vertex by the technique of invariant integration [22] in diagrams like those in Figs.1b and 4a and comparing results with those calculated from Figs.1c and 4b.

Assuming that for $M \leq 100\text{MeV}$, $F(\hat{s}, M^2, y) \approx 1$ and neglecting m/M we find from Eq.(2)

$$\frac{d\sigma_{ee}}{dy dM} \approx \frac{2\alpha}{3\pi} \frac{1}{M} \frac{d\sigma(\gamma)}{dy} \quad (3)$$

Combining Eqs.(1) and (3) and passing from cross-sections to rates per event we get for the AFS data[4] at $y \approx 0$

$$\frac{dN(\gamma)}{dy} \approx 0.12 \frac{dN(\pi^0)}{dy} \quad (4)$$

In order to get an estimate of the expected direct photon production in the EMC experiment we shall assume that Eq.(4) is valid also for muon-proton scattering at any rapidity and not only for $y \approx 0$.

Multiparticle production in deep inelastic μp interactions is similar to that in hadronic collisions at the same c.m.energy. The average c.m.energy in the EMC data is $s^{1/2} = W \approx 14 \text{ GeV}$. In $\pi - p$ or $p - p$ collisions the same c.m.energy is reached at $E_{Lab} \approx 100 \text{ GeV}$. At this energy the averaged charged multiplicities in $\pi^+ - p$ and $p - p$ interactions [23, 24] are $\langle n_c(\pi p) \rangle = 6.63 \pm 0.15$ and $\langle n_c(pp) \rangle = 6.37 \pm 0.06$. One can thus expect $N(\pi^0) \approx 2$ for a μp EMC interaction. Inserting that into Eq.(4) integrated over rapidity we obtain an estimate for the EMC experiment

$$N(\gamma) \approx 0.12 N(\pi^0) \approx 0.24 \quad (5)$$

per μp interaction. The estimate is, not surprisingly, by a factor of about 2 larger than the experimental result [1] $N(\gamma)_{exp} \approx 0.13 \pm 0.05$. In fact, when deriving Eq.(5) we have neglected the experimental cut $E_\gamma > 5 \text{ GeV}$ which strongly influences the rate (compare the crosses and the histogram in Fig.3). Furthermore the assumptions leading to Eq.(5) (in particular Eq.(3)) imply that $d\sigma_{ee}/dM$ behaves as $1/M$ for $M_{ee} < 100 \text{ MeV}$. Although this behaviour is most likely at low M_{ee} , the AFS data [4] at $M_{ee} > 100 \text{ MeV}$ are rather consistent with $1/M_{ee}^2$ behaviour (see Fig.61 in Ref.[4]). Corrections on both these effects bring the estimate in Eq.(5) closer to the EMC result.

The average transverse momentum $\langle p_T^2 \rangle^{1/2}$ of the EMC anomalous prompt photons (with respect to the virtual photon momentum) is $0.25 \pm 0.016 \text{ GeV}/c$, the estimate being obtained from the parametrization

$$\frac{dN}{dp_T^2} = \text{const.} \exp[-(16 \pm 2)p_T^2]$$

quoted in Ref.[1].

The transverse momentum dependence of low mass lepton pairs has been studied in Refs.[7, 8]. The authors have found a rather strong dependence of $\langle p_T^2 \rangle^{1/2}$ on Feynman x . In Ref.[7] $\langle p_T^2 \rangle^{1/2} = 0.37 \pm 0.04 \text{ GeV}/c$ for $0.1 < x < 0.2$ and $\langle p_T^2 \rangle^{1/2} = 0.45 \pm 0.07 \text{ GeV}/c$ for $0.2 < x < 0.45$. The general tendency is a decrease of $\langle p_T^2 \rangle^{1/2}$ with decreasing x . Unfortunately there are no detailed data available on the dilepton mass dependence of $\langle p_T^2 \rangle^{1/2}$ in the region of low dilepton masses. The AFS data indicate [4, 5, 6] that the e/π ratio increases at low values of p_T and that the anomaly in lepton pair production is connected with low dilepton masses and low transverse momenta. It is therefore possible that in the $M_{ee} \rightarrow 0$ limit the p_T -dependence of e^+e^- pairs and of real EMC photons become consistent. Note in this connection that soft annihilation model results in Fig.3 are also broader in p_T^2 than the EMC data.

Longitudinal momentum dependence of low mass e^+e^- pairs have been studied in $\pi^- p$ collisions at $16 \text{ GeV}/c$ [7] and at $17 \text{ GeV}/c$ [8]. In the former case the authors find for the mass bin $0.2 < M_{ee} < 0.7 \text{ GeV}/c^2$ the x -distribution $d\sigma/dx \approx A(1-x)^\beta$ with $\beta = 9.78 \pm 2.64$. In the latter experiment [8] $d\sigma/dx \approx \text{const.} \exp[-(5.5 \pm 0.7)x]$ for $0.2 < M_{ee} < 0.6 \text{ GeV}/c^2$. As discussed in Refs.[4, 8] these results are consistent mutually and with data on low mass dimuon production at comparable energies if the difference between the electron and muon mass is taken into account (the difference is seen in lepton mass dependent terms in Eq.(2)).

Low mass dimuon production in hadronic collisions at higher laboratory energies [25] (see also Fig.19 in Ref.[7]) have a somewhat steeper x -dependence and the question of the scaling in x is not yet clear. For comparison with the EMC results on soft photons one would also like to have data on the x -dependence of dilepton production at low dilepton masses, say below $200 \text{ MeV}/c^2$ or at least below $400 \text{ MeV}/c^2$. In general the dilepton data are concentrated at low values of x .

A direct comparison of the x -dependence of low mass dilepton and EMC anomalous photon data is not possible since the EMC data are plotted as function of $z = E_\gamma/\nu$. Even from data presented in this way one can see that the anomalous photons are concentrated in the small $x = x_{\text{c.m.s}}$ region. To see that one can argue in the following way.

Any model with the standard space-time evolution will represent the final z -distribution of anomalous photons as an integral over contributions from excited regions located at different values of rapidity. Each of the sources will probably not differ very much from a thermal source with the temperature of about 200 MeV . A thermal source at rest leads to the following photon distribution [13, 26, 27, 28]

$$E \frac{dN}{d^3p} = \frac{dN}{dy dp_T} \approx A \exp(-E/T) = A \exp(-\frac{p_T ch y}{T}) \quad (6)$$

where (E, p) is the four-momentum of the photon and y is its rapidity defined in a standard way. For a thermal source moving with rapidity y_o we have

$$dN = A \exp(-\frac{p_T ch(y - y_o)}{T}) \frac{d^3p}{E} \quad (7)$$

Making use of $E = p_T ch y$, $p_z = p_T sh y$ we obtain for the E -distribution of photons in the lab. system

$$\frac{dN}{dE} = A \int_0^E \frac{p_T dp_T}{\sqrt{E^2 - p_T^2}} \exp(-\frac{1}{T}(E ch y_o - (E^2 - p_T^2)^{1/2} sh y_o)) \quad (8)$$

Separating strongly E -dependent terms by using $\sqrt{E^2 - p_T^2} \approx E - p_T^2/2E$ and passing to the variable $z = E/\nu$ we find that

$$\frac{dN}{dz} \sim \frac{1}{z} \exp[-\frac{z}{z_o(T, y_o)}] \quad (9)$$

where

$$z_o(T, y_o) = \frac{T}{\nu} \exp(y_o) \quad (10)$$

In Fig.5 we show some z -distributions of photons from thermal sources with $T=0.2 \text{ GeV}$ and $T=0.25 \text{ GeV}$ and for different rapidities y_o .

The rapidity of a thermal source at rest in the c.m.s. of the hadronic system produced in the $\mu - p$ collision is given as

$$y_o = \frac{1}{2} \ln \frac{1 + \beta}{1 - \beta} = \ln \frac{\nu + M + \sqrt{\nu^2 + Q^2}}{\sqrt{2M\nu + M^2 - Q^2}} \approx 2.75$$

where β is the velocity of the c.m. of the hadronic system with respect to the lab.frame: $\beta = (\nu^2 + Q^2)^{1/2}/(M + \nu)$.

In Figs.5a and 5b one can see that the shape of the the z-distribution of anomalous photons roughly corresponds to thermal sources moving with rapidities $y_o \approx 2.5 - 3.5$ what means small x in the c.m. of the hadronic system.

This little exercise in kinematics is of course inconclusive, sources are not exactly thermal, and true temperatures are unknown.

The positive information following from this exercise is that steeply falling z-distributions of anomalous photons might still be consistent with distributions concentrated at small values of x in the c.m. of the hadronic system.

In order to perform a model independent comparison of the longitudinal momentum distribution of anomalous EMC photons with that of low mass dileptons, it is necessary to have the photon spectrum plotted in x .

4. Discussion

The main point made in the present paper is the prediction of the quadratic dependence of the anomalous photon rate on the rapidity density dN/dy of final state hadrons in the rapidity region of the photon. The physics behind the quadratic dependence as observed by the AFS Collaboration for low mass lepton pairs [4, 6] and predicted for anomalous soft photons is not completely clear, since there are at least two possible explanations: soft annihilation model and the longitudinal hydrodynamic expansion (QGP types of models) of the matter produced in pp[4, 6] and μp collisions. We shall now briefly sketch both scenarios.

The soft annihilation model. In general the yield of low mass dileptons or soft photons is proportional to the expression

$$N_\gamma \approx N_{ee} \approx \rho_1 \cdot \rho_2 \cdot V \cdot t \cdot v_{rel} \cdot \sigma \quad (11)$$

where ρ_1, ρ_2 are densities of interacting partons (quarks and antiquarks), v_{rel} and σ are their relative velocity and the production cross-section and $V \cdot t$ is the volume of the interaction region multiplied by the time over which the excited matter is present.

In the soft annihilation model one assumes that the volume and time during which the excited matter ("quark-gluon soup" or "miniplasma") exists are independent of the density of matter and given essentially by the proton radius and the transverse velocity of the shrinking of the system. On the other hand ρ_1 and ρ_2 are both proportional to dN/dy since final state hadrons are formed by recombinations of quarks and antiquarks. Because of that $N_\gamma \approx N_{ee} \approx \rho_1 \cdot \rho_2 \sim [dN/dy]^2$.

The QGP-like models assume that even in pp and μp collisions the QGP or a mixed phase or the hadronic gas in thermal equilibrium are formed. The transverse shrinking is sometimes neglected and longitudinal hydrodynamical expansion dominates the space-time evolution of the system. These models also lead to the quadratic dependence of the low mass dilepton production on the rapidity density of final state hadrons. Experimental signature for the latter type of models is the change of the proportionality constant when a phase transition occurs [14]. Theoretically the motivation for both approaches can be probably studied by simulations of the evolution of the excited matter [29].

Observation of the soft direct photon production by the EMC [1] is, as we believe, closely connected with other "anomalous" electromagnetic processes, accompanying the multiparticle production. Other items in the list of such processes are the following ones

- soft dilepton production in hadronic collisions [4,5,6,30,31]. The soft annihilation model [10,15,16] has been shown to be in a qualitative agreement with the existing data, except, perhaps, for the Bevalac data at very low energy.

- soft dimuon production in deep inelastic scattering with both neutrinos [32] and muons [33] as projectiles. Soft dimuons manifested themselves in these experiments by trimuons in the final state, each trimuon consisting of a leading muon and of an unlike muon pair with a low invariant mass. Such trimuons were expected [34,35] on the basis of similarities between multiparticle production in hadronic collisions and in deep inelastic scattering, which led to the conjecture that the soft annihilation mechanism operates also in lepton-hadron interactions and in general in any process in which hadronic jets are formed.

- the production of soft (low transverse momentum) photons in hadronic collisions. The situation here is, however, rather controversial since soft photons observed [3] in K^+p interactions at 70 GeV/c and quite recently in p-Be and p-Al interactions by the Helios collaboration [36] seem to have considerably lower $\langle p_T \rangle$ than expected on the basis of the soft annihilation model [37] with the simplest annihilation diagram (Fig.1c).

As pointed out in a recent interesting paper by Andersson, Dahlquist and Gustafson [17] understanding the very low p_T production in hadronic collisions [3,36] is a rather difficult problem. The inclusive photon spectra are reminiscent of the bremsstrahlung, but they are almost by an order of magnitude larger. The Low's theorem [38] says that at the limit of vanishing photon momentum the bremsstrahlung off initial and final state hadrons dominates and the problem is to find a radiation mechanism which satisfies this constraint and gives a dominant contribution already at 10-20 MeV/c.

A possible solution to the conundrum may be provided by a modification of the standard QCD shower model proposed recently by Van Hove [39] in connection with an attempt to understand various anomalous soft enhancements: i) the anomalous low- p_T enhancements in inclusive single particle distributions in hadronic, hadron-nucleus and nucleus-nucleus collisions, ii) low- p_T anomalous photon and low-mass dilepton production [3,36] and iii) short range (in rapidity) fluctuations of multiparticle production (intermittency [40]). The model is motivated also by results of studies [41,42] of the connection between the QCD shower evolution and multiparticle production.

In Van Hove's model [39] it is conjectured that as a result of shower evolution a metastable state of supercooled quark-gluon plasma (ScQGP) may be formed in any type of collision leading to multiparticle production. The essential point is that this ScQGP would extend over rather large spatial volume with, perhaps, $R_T \approx 4 - 6 fm$ and form an intermediate parton system (IPS) of a rather low density. As we shall discuss in a more detail elsewhere, bremsstrahlung emitted in collisions of partons in such an IPS can dominate over the one from the initial and final state hadrons for photon momenta larger than $1/l$ where l is the mean free path of partons in the IPS. For mean free path approaching the dimension of the IPS the bremsstrahlung from parton-parton collisions can come down to photon momenta registered in Refs. [3,36].

Another possible approach to understanding low- p_T photon production consists in

studying the enhancement of the bremsstrahlung due to the Bose-Einstein correlations of pions in the final state[43]. As far as we know this has not yet been analyzed in more detail.

In what concerns possible improvements of the soft annihilation model we should probably make the composition of the IPS more closely connected with the composition of partons during the QCD shower evolution, include bremsstrahlung in the IPS and during the shower evolution, consider the possibility of large spatial dimensions of the IPS and analyze in detail limitations imposed by Low's theorem.

5. Conclusions

The comparison of the EMC data [1] with the soft annihilation model gives indications that the EMC anomalous photons are of the same dynamical origin as the low mass lepton pairs observed in hadronic interactions. An unclear point is a broader shape of p_T^2 -distributions in the model. This argument is somewhat model dependent, but since the parameters were adjusted to the low mass pair data, the dependence on the model is presumably rather small.

Analyzing both types of data feature by feature (Sect.3) we have found that:

- the rate of anomalous photons is consistent with the assumption of a common dynamical origin of low mass lepton pairs and of EMC anomalous photons

- distributions of low mass lepton pairs in p_T^2 seem somewhat broader than for anomalous photons. The question could be clarified by data on p_T^2 distributions for very low mass lepton pairs,

- it is quite possible that longitudinal momentum distributions of both processes are consistent but the question can be answered only when the EMC data are plotted vs. $x = x_{cms}$.

A crucial and most interesting test of the common dynamical origin of both processes would be provided by the quadratic dependence of anomalous photon rate on dN_π/dy in the rapidity region of the photon. The width of this rapidity region can be roughly estimated in the following way: suppose that the photon is produced by a thermal source located at rapidity y_o . The temperature of the source is T . Approximating $ch(y - y_o)$ in Eq.(7) by $(y - y_o)^2/2$ we get

$$dN(\gamma) \approx \exp\left[-\frac{(y - y_o)^2}{2T/p_T}\right]$$

That means that the distance of the photon from y_o is about $\sqrt{T/p_T} \approx 1$ for $p_T \approx 0.2 \text{ GeV}$. The rapidity distance of pions produced by the same source from y_o is about 1 so the soft photon production should be proportional to $(dN_\pi/dy)^2$ for the rapidity difference between the pion and the photon of about 2.

We recommend an experimental study of the dependence of the anomalous photon rate on dN_π/dy .

Acknowledgements

We are indebted to Professor L. Van Hove for reading the manuscript and for numerous useful comments. We would like to thank Julia Thompson, C. Fabjan, T. Blažek, V. Černý,

C.Fabjan, J.Fláčnik, U.Goerlach and W.Willis for numerous useful and stimulating discussions, comments and explanations of various theoretical and experimental aspects of the problem. Comments by V.Hedberg helped to clarify the text in various places.

References

- [1] J.J.Aubert et al.(EMC):Evidence for anomalous prompt photons in deep inelastic muon scattering at 200GeV,preprint CERN-EP/88-33, subm.to Phys.Lett.B.
- [2] A.T.Goshaw et al.:Phys.Rev.Lett.43 (1979)1065
- [3] P.V.Chliapnikov et al.,Phys.Lett.B141 (1984)276
- [4] V.Hedberg:Production of positrons with low transverse momentum and low mass electron-positron pairs in proton-proton collisions at a centre-of-mass energy of 63 GeV.Thesis,University of Lund, preprint LUNFD6/(NFFL-7037)/1987,March 1987
- [5] T.Åkesson et al.(AFS Collaboration):Phys.Lett.B152 (1985) 411
- [6] T.Åkesson et al.(AFS Collaboration):Phys.Lett.B192(1987)463
- [7] D.Blockus et al.:Nucl.Phys.B201(1982)205
- [8] M.R.Adams et al.:Phys.Rev.D27(1983)1977
- [9] J.D.Bjorken and H.Weisberg:Phys.Rev.D13(1976)1405
- [10] V.Černý,P.Lichard and J.Pišút:Phys.Rev.D24(1981)652
- [11] V.Černý,P.Lichard and J.Pišút:Zeit.f.Physik-Particles and Fields C31 (1986)163
- [12] E.V.Shuryak:Phys.Reports 61(1980)71
- [13] R.C.Hwa and K.Kajantie:Phys.Rev.D32(1985)1109
- [14] M.I.Gorenstein and O.P.Pavlenko:Zeit.f.Phys.-Particles and Fields C37 (1988)611
- [15] V.Černý,P.Lichard and J.Pišút:Acta Phys.Pol.B9(1978) 901
- [16] V.Černý,P.Lichard,Š.Olejnik and J.Pišút:Acta.Phys. Pol.B10(1979)537
- [17] B.Andersson,P.Dahlquist and G.Gustafson:Soft photons in the Lund model,Lund University preprint,LUTP 88-1 (1988)
- [18] V.Černý,P.Lichard and J.Pišút:Phys.Rev.D16(1977) 2822 ;D18(1978)2409 ;D18(1978)4052
- [19] L.Baum et al.:Phys.Lett.60B(1976)485
- [20] M.Barone et al.:Nucl.Phys.B132(1978)29
- [21] K.Kajantie:Sources of direct leptons,in Proc.of the 1977 Eur.Conf.on Particle Physics, Budapest ,Hungary,4.-9.July, 1977,Eds.L.Jenik and I.Montvay,Central Res.Inst.of Physics , Budapest,p.467
- [22] V.N.Baier,V.M.Katkov and V.S.Fadin:Izluchenie relativistskikh elektronov, Moscow,Atomizdat,1973,pp.113-118
- [23] W.M.Morse et al.:Phys.Rev.D15(1977)66
- [24] J.Whitmore:Phys.Reports 10C(1974)273
- [25] K.J.Anderson et al.:Phys.Rev.Lett.37(1976)799
- [26] M.Neubert:Direct photon production in ultrarelativistic heavy-ion collisions at 200GeV per nucleon,Heidelberg preprint 1988 and Diplomarbeit,Universität Heidelberg, unpublished.
- [27] E.V.Shuryak:Phys.Lett.78B(1978)150
- [28] E.V.Shuryak:Sov.J.Nucl.Phys.28(1978)408 (Yadernaya Fizika 28(1978)796
- [29] G.Bertsch,M.Long,L.McLerran,V.Ruuskanen and E.Sarkkinen: Phys.Rev.D37(1988)1202
- G.Bertsch,M.Gong and M.Tokiyama:Phys.Rev.C37(1988) 1896
- [30] K.J.Anderson et al.:Phys.Rev.Lett.36(1976)237,

- ibid. 37(1976)799, ibid. 37(1976)803;
 M.J.Corden et al.: Phys.Lett. 68B(1976)96;
 K.Bunnel et al.: Phys.Rev.Lett. 40(1978)136;
 M.Facssler et al.: Phys.Rev.D 17(1978)689;
 W.M.Morse et al.: Phys.Rev.D 18(1978)3145;
 D.M.Grannan et al.: Phys.Rev.D 18(1978)3150;
 J.Alspector et al.: Phys.Lett. B 81(1979)397;
 B.Haber et al.: Phys.Rev.D 22(1980)2107;
 R.J.Dzhelyadin et al.: Nucl.Phys. B 179 (1981)189;
 J.Ballam et al.: Phys.Rev.Lett. 41(1978)1207;
 R.Stroynowski et al.: Phys.Lett. 97B(1980)315;
 S.Mikamo et al.: Phys.Lett. 106B(1981)428;
 J.Stekas et al.: Phys.Rev.Lett. 47(1981)1686;
 [31] G.Roche et al.: Phys.Rev.Lett. 61(1988)1069
 [32] T.Hansl et al.: Nucl.Phys. B 142(1978)381
 [33] C.Chang, K.W.Chen and A.Van Ginneken: Phys.Rev.Lett. 39(1977)519
 [34] V.Černý, P.Lichard and J.Pišút: Acta.Phys.Pol. B 9(1978)269
 [35] V.Černý et al.: Czech.J.Phys. B 29(1979) 1394
 [36] U.Goerlach et al.: (NA-34 Collaboration), Talk at the XXIV.Int.Conf. on High Energy Physics, Munich, August 4-10, 1988
 [37] P.Lichard: unpublished
 [38] F.E.Low: Phys.Rev. 110(1958)974
 [39] L.Van Hove, Is Supercooled Quark-Gluon Plasma created in Multihadron Production Processes?, CERN-TH preprint in preparation
 [40] A.Bialas and R.Peschanski: Nucl.Phys. B 273(1986)703
 W.Kittel: Talk at the XXIV.Int.Conf. on High Energy Physics, Munich, August 4-10, 1988
 B.Buschbeck, P.Lipa and R.Peschanski: Signal for Intermittency in e^+e^- reactions obtained from Negative Binomial Fits, preprint, Vienna, HEPHY-PUB 513/88, July 1988
 [41] L.Van Hove and A.Giovannini: Acta Phys.Pol. B 19 (1988) No.10, November 1988 and preprint CERN-TH.4885/87, Oct.1987
 [42] L.Van Hove and A.Giovannini: Acta Phys.Pol. B 19 (1988), No.10 and preprint CERN-TH.4957/88, Jan.1988
 [43] W.Willis: private communication

Figure captions

Figure:1a Annihilation of a quark and an antiquark to a lepton pair.

Figure:1b Annihilation with the gluon emission.

Figure:1c Annihilation giving a soft photon.

Figure:2 Comparison of the EMC data [1] on anomalous photon distribution in $z = E_\gamma/\nu$ with results of the soft annihilation model (histogram).

Figure:3 Comparison of the EMC data [1] on p_T^2 distribution of anomalous photons with the soft annihilation model. The histogram corresponds to a situation when the experimental cut $E_\gamma > 5\text{GeV}$ is taken into account, the crosses to all photons with $E_\gamma > 0$.

Figure:4a Low mass dilepton production from virtual bremsstrahlung in the quark-quark scattering.

Figure:4b Real photon production by bremsstrahlung in the quark-quark scattering.

Figure:5 Comparison of the z -distribution of anomalous prompt EMC photons [1] with z -distributions produced by thermal sources moving with rapidities y_o and having temperatures :a) $T=0.2\text{ GeV}$,b) $T=0.25\text{ GeV}$.The value of the rapidity y_o is indicated near each of distributions. All curves are normalized to 0.33 photons with $z \geq 0$ per interaction.

FIG. 1a

FIG. 1b

FIG. 1c

FIG. 2

FIG. 3

FIG. 4a

FIG. 4b

FIG. 5a

FIG. 5b