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A POSSIBLE ORIGIN OF THE LARGE e/π RATIO AT LOW p_T IN HADRONIC COLLISIONS AT HIGH ENERGY

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It is suggested that the increase of the e/π ratio at low transverse momenta in hadronic collisions is caused by the subprocesses like $Q\overline{Q} \to e^+e^- + X$ of quarks and antiquarks created during the space-time evolution of the collision. As a model of such a process we calculate $Q\overline{Q} \to e^+e^-$ + "gluon". The p_T spectra of single leptons and mass spectra of dileptons following from this model are estimated and compared with the data.

1. Introduction

The production of prompt leptons in hadronic collisions has been extensively studied over the last few years [1, 2]. The data on single lepton production show that for $p_T \geqslant 1$ GeV/c and small c. m. s. angles the ratios e/π and μ/π are both about 10^{-4} over the Fermilab and CERN-ISR energy ranges. The situation at lower transverse momenta is much less clear. The most detailed study of the e/π ratio for $p_T < 1$ GeV/c has been performed at the CERN-ISR by the ARCHMN collaboration [3, 4]. Their data indicate that the e/π ratio increases to about $5 \cdot 10^{-4}$ for $p_T \approx 0.2-0.4$ GeV/c.

The purpose of the present note is to show that such an increase of the e/π ratio at low p_T can be expected in models [5, 6] where prompt leptons originate from annihilations of quarks (Q's) and antiquarks ($\overline{Q}$'s) created during the space-time evolution [7, 8] of a hadronic collision.

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In our previous calculations [6] we have considered only the annihilations $Q\bar{Q} \to \mu^+\mu^-$ of quarks and antiquarks created during the collision. The results were in a reasonable qualitative agreement with the Chicago–Princeton data [9] on the mass, p_T, and x_F-spectra of low mass (LM) dimuons produced in hadronic collisions. Both basic assumptions of the model ((*i*) the contribution of Q's and $\bar{Q}$'s created during the collision has to be included, and (*ii*) the constraints following from the space-time evolution of the collision have to be taken into account) have been essential. If Q's and $\bar{Q}$'s created during the collision are not considered one cannot explain the copious LM dimuon production, and if the constraints following from the space-time evolution are not respected one gets excessively large $d\sigma/dM_{\mu\mu}$ at $M_{\mu\mu} \gtrsim 2-3$ GeV/c^2.

There are, however, two properties of the data which do not seem to be well reproduced by the model of Ref. [6]. First, the dileptons with low masses are somewhat more concentrated at low x_F, and second, the data [3, 4] show that the e/π ratio increases at low p_T. In the present paper we shall show that both these features follow from a model in which, apart from the process $Q\bar{Q} \to e^+e^-$, one considers also $Q\bar{Q} \to e^+e^- + X$, where X e. g. a gluon[1]. The point is rather simple. The annihilation $Q\bar{Q} \to e^+e^- + X$ has three particles in the final state and consequently both the transverse and longitudinal momentum are shared by three particles. As a consequence, the dilepton from $Q\bar{Q} \to e^+e^- + X$ will have lower x_F than that from $Q\bar{Q} \to e^+e^-$ and similarly single leptons from $Q\bar{Q} \to e^+e^- + X$ will have lower p_T than those from $Q\bar{Q} \to e^+e^-$. In making calculations we shall take X to be a "gluon".

In the rest of the introduction we shall briefly describe the model of Ref. [6], basic ideas of which are used also here. Then in Section 2 we shall discuss in some detail the process $Q\bar{Q} \to e^+e^-$ + "gluon". Comparison with data is given in Section 3. Finally, Section 4 contains some comments and conclusions.

The model (described in more detail in Ref. [6]) is based on the Bjorken–Gribov picture [7, 8] of the space-time evolution of hadronic collisions. In this picture the hadronic

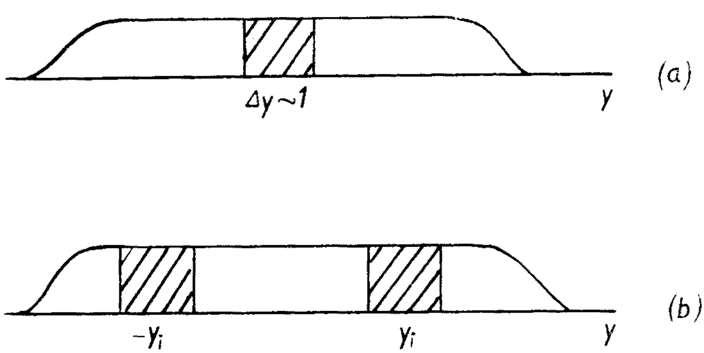

Fig. 1. A sketch of the Bjorken–Gribov picture [7, 8] of the space-time evolution of the hadronic collision. For $0 < t < \tau_0 \approx 1$ fermi/c only the wee parton region is excited, (a); at $t_i \approx \tau_0 \cosh(y_i)$ the excitation reaches rapidity regions around $\pm y_i$, (b)

[1] In what follows we shall refer to $Q\bar{Q} \to e^+e^-$ and to $Q\bar{Q} \to e^+e^- + X$ as to processes I and II, respectively.

collision is initiated by the interaction of wee partons [10]. At the very beginning of the collision only the region of about $|\Delta y| \approx 1$ around $y = 0$ (in the hadronic c. m. s.) is excited (Fig. 1a). This region then cools down within a time $\tau_0 \approx 1$ fm/c by emitting hadrons and by exciting the neighbouring rapidity regions. In this way at $t \approx \tau_0 \cosh(y)$ the regions around $\pm|y|$ are excited (Fig. 1b). The quarks and antiquarks created (e. g. by the conversion of gluons) during the excitation time of a particular rapidity region can either recombine to hadrons or annihilate (via processes I or II) to dilepton pairs.

This picture leads to the following expression for the number of dileptons produced per hadronic collision

$$\Delta n = \sum_{1,2} \iint dy_1 dy_2 d^2 p_{T1} d^2 p_{T2} \varrho_{12}(y_1, \vec{p}_{T1}, y_2, \vec{p}_{T2})$$

$$|\vec{v}_1 - \vec{v}_2| \sigma_{12}^A(y_1, \vec{p}_{T1}, y_2, \vec{p}_{T2}) V_1 t_1 w(y_1, y_2). \tag{1}$$

Here $\varrho_{12}(y_1, \vec{p}_{T1}, y_2, \vec{p}_{T2})$ is the spatial density distribution for finding a Q and an $\overline{\text{Q}}$ with rapidities and transverse momenta y_1, $\vec{p}_{T1}$, and y_2, $\vec{p}_{T2}$. This function we take (implicitly) from our study [11] of the multiparticle production in the quark-parton model. The annihilation cross section is denoted as σ_{12}^A, V_1 is the volume of the excited region around $y \approx y_1$ and t_1 is the duration of this excitation. The function $w(y_1, y_2)$ takes into account that only those Q's and $\overline{\text{Q}}$'s can annihilate which come from the (limited) rapidity region excited at a given time. We use the parametrization [6] $w(y_1, y_2) = \exp(-A(y_1 - y_2)^2)$ with $A = 0.8$.

2. *Contribution from* $Q\overline{Q} \to e^+e^- + X$

In Ref. [6] we have taken σ_{12}^A as given explicitly by $\text{Q}\overline{\text{Q}} \to \mu^+\mu^-$. Here we shall consider also the process $\text{Q}\overline{\text{Q}} \to e^+e^- + X$ and for the sake of definiteness we shall perform the calculations for the annihilation $\text{Q}\overline{\text{Q}} \to e^+e^- +$ "gluon". The cross section for this QCD process cannot at present be reliably calculated for small masses of the $\text{Q}\overline{\text{Q}}$ pair and for rather soft gluons, what is precisely the region we are interested in here. Still, as far as we are interested mainly in the effects coming from the differences caused by the kinematics of processes I and II, we can hope that the calculation corresponding to a model example of a QED process $\text{Q}\overline{\text{Q}} \to e^+e^- + \gamma$ can give qualitatively sensible results. Our approach is thus the following one: We calculate the contribution from "QED" diagrams $\text{Q}\overline{\text{Q}} \to e^+e^- + \gamma$ and multiply it by an appropriate factor (actually this change corresponds to $e^2/4\pi \to Cg^2/4\pi$, where g is the quark–gluon coupling constant and C is a numerical factor, $C \approx 1$).

The cross section for the QED process $\text{Q}\overline{\text{Q}} \to e^+e^- + \gamma$ is given by the following expression

$$\frac{d^2\sigma}{dM^2 dt} = \frac{\alpha}{3\pi} F(M^2) \frac{d\sigma(\text{Q}\overline{\text{Q}} \to \gamma\gamma^*)}{dt}, \quad F(M^2) = \frac{M^2 + 2\mu^2}{M^4} \sqrt{\frac{M^2 - 4\mu^2}{M^2}}, \tag{2}$$

$$\frac{d\sigma(Q\bar{Q}\to\gamma\gamma^*)}{dt} = 8\pi\alpha^2\left(\frac{e_Q}{e}\right)^4\frac{1}{s(s-4m^2)}A,$$

$$A \equiv \tfrac{1}{4}\left(\frac{t'}{u'}+\frac{u'}{t'}\right)+\tfrac{1}{2}\frac{M^4}{m^4}\frac{m^4}{t'u'}-\tfrac{1}{2}\frac{M^2}{m^2}\left(\frac{m^4}{t'^2}+\frac{m^4}{u'^2}\right)-\tfrac{1}{2}\frac{M^2}{m^2}\left(\frac{m^2}{t'}+\frac{m^2}{u'}\right)$$

$$-\left(\frac{m^2}{t'}+\frac{m^2}{u'}\right)^2-\left(\frac{m^2}{t'}+\frac{m^2}{u'}\right),$$

$$t' = (P-P_1)^2-m^2, \quad s = (P_1+P_2)^2, \quad s+t'+u' = M^2.$$

In the c. m. s. of the $Q\bar{Q}$ collision we obtain after some manipulations

$$\frac{d^2\sigma(Q\bar{Q}\to e^+e^-\gamma)}{dMd(\cos\theta^*)} = \tfrac{4}{3}\alpha^3\left(\frac{e_Q}{e}\right)^4\frac{(1+2\mu^2/M^2)\sqrt{1-4\mu^2/M^2}}{MW^2P^*\sqrt{s/4-m^2}\,(E_1^{*2}-P_1^{*2}\cos^2\theta^*)}$$

$$\times\left\{\frac{(M^2+2m^2)P_1^{*2}\sin^2\theta^*}{\sin^2\theta^*+(m^2/E_1^{*2})\cos^2\theta^*}+P^{*2}(E_1^{*2}+P_1^{*2}\cos^2\theta^*)\right\}, \qquad (3)$$

where θ^* is the angle between $\vec{P}_1^*$ and $\vec{P}^*$ and $|\vec{P}^*|$ is denoted simply as P^*.

The infrared divergence is manifestly given by the factor P^{*-1} in r. h. s. of Eq. (3). For $P^*\to 0$ we have $M\to\sqrt{s}$ and this means that the 4-momentum of the real photon in Fig. 2 is vanishing and the virtual quark is going on-shell. This configuration is then

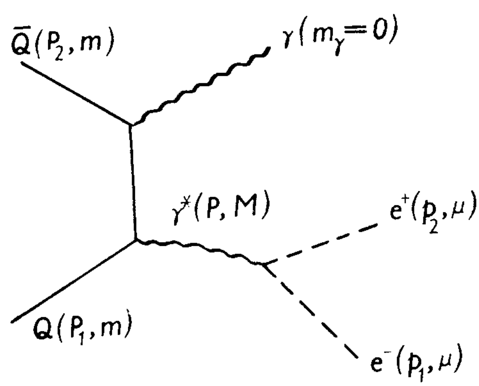

Fig. 2. Feynman diagram for the QED process $Q\bar{Q}\to e^+e^-+\gamma$

kinematically similar to the annihilation $Q\bar{Q}\to\mu^+\mu^-$ and this was already studied in Ref. [6]. We shall therefore simply cut away this region by taking into account only that part of Eq. (3) which corresponds to $2\mu < M < \beta W$, with $\beta < 1$ (in actual calculations we have taken $\beta = 0.75$).

In QCD a respectable calculation of the process $Q\bar{Q}\to e^+e^-+$"g" at low energies (and this is what we need here) is impossible. We shall therefore assume that the true cross section for the dilepton production is similar to the simple-minded perturbation theory and we shall use Eq. (3) multiplied by the factor

$$B \equiv \tfrac{4}{3}\frac{\alpha_s}{\alpha}, \qquad \alpha_s = g^2/4\pi, \tag{4}$$

where $\alpha = e^2/4\pi$ and g is the quark-gluon coupling constant. The factor 4/3 is appropriate when one takes colour into account while not assigning colour to quarks explicitly[2]. It is an analogon of the 1/3 occurring in the Drell–Yan model with coloured quarks.

3. *Comparison with the data*

The results presented below were obtained in a Monte Carlo calculation which, technically, was rather similar to the one described in Ref. [6]. We first generated the explicit configurations of Q's and $\bar{Q}$'s created during the collision. All parameters of this distribution were fixed by our studies [11] of the multiparticle production. For each configuration we calculated (again by Monte Carlo) the corresponding contribution from the annihilation $Q\bar{Q} \to e^+e^- + $"g" to single and dilepton spectra. This contribution was given by Eq. (1) with the annihilation cross section σ_{12}^A being by Eqs. (2) and (3). This contribution was then added to that corresponding to the $Q\bar{Q} \to e^+e^-$ annihilation [6].

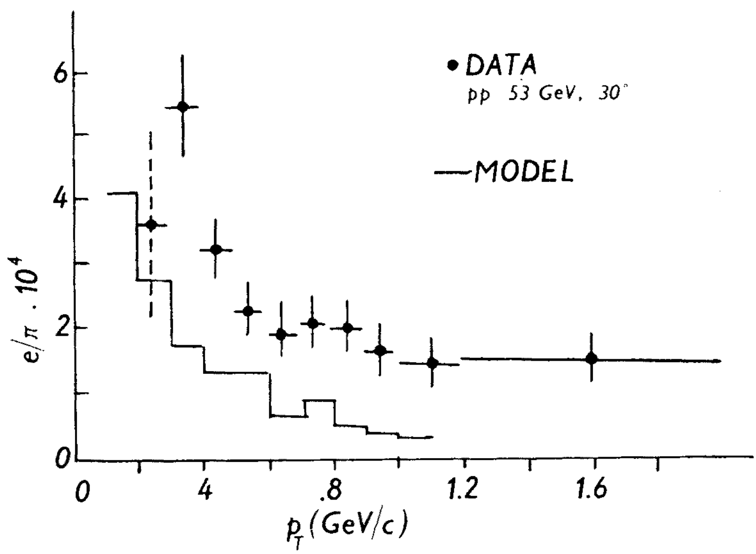

Fig. 3. e/π ratio calculated in the model (histogram) for p-p collision at $\sqrt{s} = 53$ GeV and c. m. s. production angle 30°. Data points come from Ref. [4]. In order to roughly simulate the experimental situation, the contribution to the e production from e^+e^- pairs with masses below 100 MeV was not included into the presented histogram

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[2] In more detail $B = (\sum_{ijA} (\lambda_{ij}^A/2)^2 \cdot \sum_1^3 (e_Q^2 \cdot g^2)/[9 \sum_1^3 (e_Q^4 \cdot e^2]$, where e_Q are quark charges in the units of the electron charge and $e^2 = 4\pi\alpha$.

The relative weight of the two contributions corresponds to $\alpha_s = 1.5$ (see Eqs. (3) and (4)). The other parameters are the same as in Ref. [6].

In Fig. 3 we present the p_T dependence of the e/π ratio compared with the data [4]. The e-production was calculated as described above and the π-production (to calculate the e/π ratio) was taken from the parametrization of the data [12]. We did not use our results on π-production, since they contain larger fluctuations than the data. As shown, however, in our previous work on multiparticle production [11] the p_T-dependence of the π-production is reasonably well described by our model [11].

As seen in Fig. 3 the general trend of the data on e/π is well reproduced, although the absolute values of the calculated e/π ratio are still somewhat below the data. However, this is not surprising since the contributions from leptonic decays of vector mesons and of charmed particles were not included into our calculations of the inclusive e production[3].

The value of the "coupling constant" $\alpha_s = 1.5$ used here is rather arbitrary. It was chosen in order to obtain a significant contribution to e/π ratio in the low p_T region. However, the contribution of the "process II" cannot be taken arbitrarily large, since one has to describe also the low mass dilepton continuum observed in hadronic collisions.

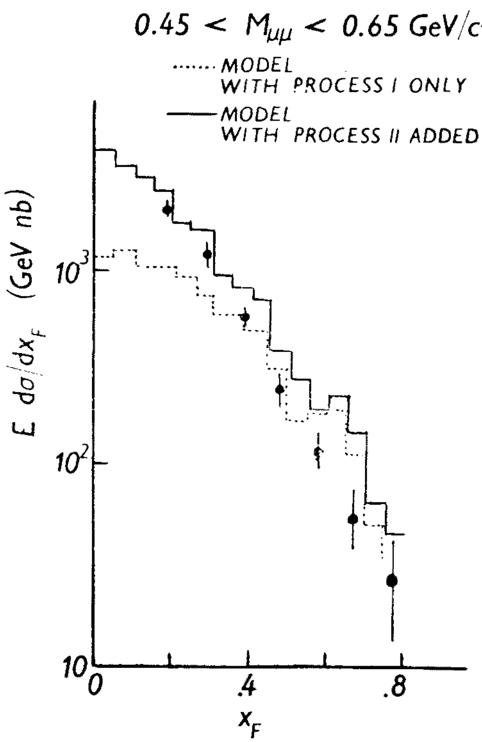

Fig. 4. The x_F dependence of low mass dimuon continuum in p-Be collisions at 150 GeV/c [9] (recalculated per nucleon) compared with the model calculation for p-p collision (histograms)

[3] For $p_T \gtrsim 0.5$ GeV/c one expects [13] that these contributions lead to $e/\pi \sim 0.5 \cdot 10^{-4}$.

It is rather encouraging, that the addition of the "process II" contribution (corresponding to the same value $\alpha_s = 1.5$) improves the description of the low mass dimuon continuum when compared to the situation with only "process I" taken into account, as is illustrated in Fig. 4. The x_F-spectrum of dimuons is much steeper in the "process II" component because of the three particle final state in the $Q\bar{Q} \to \mu^+\mu^- + $"g" annihilation and the data [9] really show an excess in the low x_F region above the "process I" contribution.

The mass spectrum of the low mass dimuon continuum as observed [9] in p–Be collisions at 150 GeV/c is also described fairly well as it is clear from Table I.

TABLE I

Low mass dimuon continuum spectrum for $\bar{p}$-Be collisions at 150 GeV/c [9] (recalculated per nucleon) compared with the model calculations. All cross sections are given in nanobarns and correspond to the region $x_F > 0.15$

Dimuon mass [GeV]	Data	Model (process I only)	Model (process II included)
0.21—0.45	460±55	250	640
0.45—0.65	180±22	104	196
0.65—0.93	87±10*	75	99
0.93—1.13	11.5±1.4*	20	23

* Continuum only.

4. *Comments and concluding remarks*

Let us mention first a basic point. In this model it is assumed that pseudoscalar and vector mesons are formed by the recombination of a Q and an $\bar{Q}$. The transverse momenta of Q's and $\bar{Q}$'s in the intermediate stages of the collision are chosen so as to lead to correct p_T-spectra of mesons produced in this way. We make no specific assumptions about the dynamics responsible for the required transverse momenta of Q's and $\bar{Q}$'s. We picture it as something rather complicated consisting of the scattering of quarks, production and absorption of gluons, etc. During such a "boiling of the quark soup" sometimes (in fact very rarely) occur processes $Q\bar{Q} \to e^+e^-$ or $Q\bar{Q} \to e^+e^- + $"g". The gluon in the latter case enters again into the complicated strong interactions, but these leptonic annihilations of Q's and $\bar{Q}$'s, being very rare, cannot modify the p_T distributions of Q's and $\bar{Q}$'s in the intermediate state. One can, of course, ask what would happen if apart from simple recombination considered here one would allow also a recombination with the emission of a gluon. This question cannot be answered within the present model. It would require a complete revision of the previous work on multiparticle production [11] and it would lead to a different distribution of Q's and $\bar{Q}$'s in the intermediate stages of the collision. To put it shortly: the results on multiparticle production [11] and those on single and dilepton production presented in Ref. [6] and here are valid only to the extent that directly produced mesons are formed by simple recombination of Q's and $\bar{Q}$'s and the low mass dileptons originate from the processes $Q\bar{Q} \to e^+e^-$ and $Q\bar{Q} \to e^+e^- +$ "g", where the dominant contribution is given by Q's and $\bar{Q}$'s created during the collision.

As shown above, such a model leads to x_F, p_T, and mass spectra of low mass dileptons which are in a qualitative agreement with the data. Moreover the model explains also the rise of e/π ratio at low p_T. The rise of e/π at low p_T is essentially due to the three-body final state in the process $Q\bar{Q} \to e^+e^- +$ "g". In our calculation this process is to be considered only as a representative of various processes with a similar final state (like "g" + Q $\to \gamma^* +$ Q with a subsequent $\gamma^* \to e^+e^-$). The value of the coupling constant $\alpha_s = 1.5$ is to be understood also in this context. In that sense our calculation of $Q\bar{Q} \to e^+e^- +$ "g" has mainly illustrative purposes. Reliable theoretical calculations of such processes would require a deeper understanding of QCD at lower energies and of the whole problem of the evolution of hadronic jets.

From a phenomenological point of view the confirmation or rejection of the picture advocated here can come from a good data on the production of low mass e^+e^- pairs in hadronic collisions at high energies.

Alternative explanations of the e/π increase at low p_T invoke the production of charmed particles [13, 14, 15]. The required cross sections for the charmed-particle production are, however, rather large, or specific decay modes of charmed particles have to be assumed [15].

Let us also note that a similar behaviour of e/π ratio at low p_T can be expected in other models [16] which include constraints following from the space-time evolution of the collision, provided that the appropriate subprocesses like $Q\bar{Q} \to e^+e^- +$ "g" are taken into account.

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