Vol. B9 (1978) ACTA PHYSICA POLONICA No 3

RELATIONSHIP BETWEEN LOW MASS DIMUON AND MESON PRODUCTIONS IN HADRON-NUCLEUS COLLISIONS

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(*Received October 13, 1977*)

It is pointed out that the following two assumptions: (a) low mass dimuons produced in hadronic collisions are originated by annihilations of quarks and antiquarks created during the collision and (b) mesons produced in these collisions come from recombinations of quarks and antiquarks, imply a close similarity between the shapes of inclusive spectra of low mass dimuons and directly produced mesons. Some data corroborating such a similarity are briefly reviewed and crucial tests concerning the A-dependence of low mass dimuon production in various rapidity regions are proposed.

1. *Introduction*

Recent studies of dimuon production in collisions of pions, protons and neutrons with nuclei [1–5] indicate (but not prove) an interesting similarity between shapes of inclusive spectra of mesons (in particular ϱ, ω and ϕ) and low mass dimuons.

In this paper we shall first show (Section 2) that such a similarity naturally follows from quark-parton models in which

i) dimuons with low masses, $M_{\mu\mu} < 1\text{–}2$ GeV/c^2, are originated by annihilations of quarks (Q's) and antiquarks ($\overline{\text{Q}}$'s) created during the collision [6–8],

ii) limitations imposed by the space-time evolution [9, 10] are properly taken into account, and

iii) mesons in multiparticle final states arise from recombinations of Q's and $\overline{\text{Q}}$'s separated by small rapidity gaps [11–13].

We shall then (Section 3) briefly list the experimental evidence supporting the similarity between meson and low mass (LM) dimuon inclusive spectra and finally (Section 4) we shall point out that crucial tests of this similarity and of the model [7, 8] which predicts it can be performed by comparing the A-dependence of inclusive spectra of LM dimuons and mesons in hadron-nucleus interactions.

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2. *Mechanism of low mass dimuon and meson production in a quark-parton model*

According to the quark-parton model [14] a hadronic collision starts with the interaction of wee partons in a region with $\Delta y \sim 1$ around $y \approx 0$ (in the c. m. system). This region gets excited and cools down by emitting hadrons and by exciting neighbouring regions in rapidity where the process is repeated [9]. The excitation spreads in this way

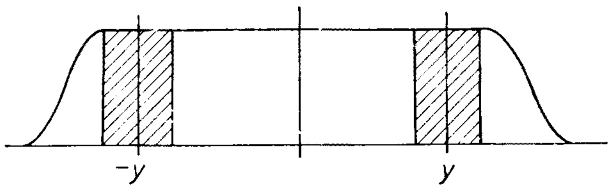


Fig. 1. Space-time evolution of a hadronic collision [9]. Rapidity regions around $\pm y$ are excited at the time $t \sim t_0 \cosh(y)$

further, reaching rapidity y at time $t \sim t_0 \cosh(y)$, where $t_0 \sim 1$ fermi/c (see Fig. 1) and $\cosh(y)$ is the Lorentz γ-factor.

In this picture [9] mesons are supposed [11–13] to arise from recombinations of Q's and $\overline{\mathrm{Q}}$'s which are excited at the same time (and, as a consequence, are separated by small rapidity gaps). Such models [11–13] predict a copious production of meson resonances and a considerable part of pions in the final state comes from vector meson decays.

Two years ago Bjorken and Weisberg [6] suggested that dimuons produced in hadronic collisions are due to annihilations of quarks and antiquarks created during the collision. In Refs [7, 8] we have constructed a model which combines this idea with the restrictions imposed by the space-time evolution of the collision. In this model dimuons are supposed to be produced by two dynamically different mechanisms. The former is the standard Drell-Yan (DY) process which is a hard (long range in rapidity) annihilation of a Q from one of the colliding hadrons with an $\overline{\mathrm{Q}}$ from the other one. This process is in action only at the very beginning of the collision, e. g. before the spacetime evolution started by the interaction of wee partons develops (note that in DY calculations one uses parton distribution functions corresponding to *free*, *noninteracting* nucleons). The DY process describes well [5, 7, 8] the production of dimuons with large masses.

The other mechanism is the annihilation of Q's and $\overline{\mathrm{Q}}$'s created (e. g. by conversion of gluons to $\mathrm{Q}\overline{\mathrm{Q}}$ pairs) during the space-time evolution of the collision. However, as seen in Fig. 1, at any time t during the evolution of the collision, the length (in rapidity) of the excited region is only about $\Delta y \sim 1$. The mass of the system consisting of a Q with rapidity y_1 and effective mass m_{Q} and an $\overline{\mathrm{Q}}$ with y_2 and m_{Q} is $2m_{\mathrm{Q}}^2(1+\cosh(y_1-y_2))$ (transverse momenta neglected for simplicity) and as a consequence the mass of the dimuon obtained by the annihilation of this $\mathrm{Q}\overline{\mathrm{Q}}$ pair is small if $|y_1-y_2| \leqslant 1$.

The annihilation of Q's and $\overline{\mathrm{Q}}$'s created during the evolution of the collision yields in this way only dimuons with low masses (the LM component). The LM component dominates at low $M_{\mu\mu}$, below 1–2 GeV/c^2, whereas the DY mechanism takes over at $M_{\mu\mu} > 2$–3 GeV/c^2.

For the present discussion we need only one qualitative feature of the model. If a Q and an $\overline{Q}$ are both present for a time Δt in the same excited region they can either recombine to a meson or, during the short time of their existence, they can annihilate to a lepton pair. The ratio of these two possibilities is given by the internal dynamics of the excited region and because of that it is independent of the total momentum (or y and p_T) of the excited region. In this way we arive at the conclusion.

> Inclusive spectra of low mass dimuons and of directly produced neutral mesons are, up to a constant multiplicative factor, identical. (1)

The rule applies only to mesons which are produced directly i.e. by recombination of $Q\overline{Q}$ pairs (as opposed to those which appear as products of resonance decays).

The statement (1) is, in fact, a bit too strong since the assumption *i*), *ii*) and *iii*) (see Section 1) are probably violated in regions of phase space dominated by the diffractive dissociation (the assumption *iii*) is doubtful there). Because of that and of possible presence of other mechanisms not covered by *i*) — *iii*) it is more appropriate to speak about similarity rather than identity. The similarity should hold true also for large p_T phenomena where both mesons and low mass dileptons arise from $Q\overline{Q}$ pairs created during the evolution of a jet.

Furthermore, there are good reasons to believe that the quark-parton model is relevant ([15, 16] and references quoted therein) also for hadron-nucleus collision and because of that we can extend the statement (1) as follows

> The A-dependence of inclusive spectra of low mass dimuons and of directly produced mesons are similar. (2)

This statement is based on the natural expectation that basic subprocesses responsible for meson and LM dimuon production are the same in hadron-hadron and hadron-nucleus collisions and that the assumptions *i*) — *iii*) (see Section 1) are valid in both cases. It is this statement which in fact leads to strong tests of *i*) — *iii*).

In the next section we shall briefly list the evidence corroborating the statement (1) and in Section 4 we shall present some consequences of statement (2). The experimental study of these consequences would be a crucial test of the assumptions *i*) — *iii*).

3. *Evidence about similarities between low mass dimuon and meson productions in hadronic collisions*

At present the most relevant information concerning similarities between the LM dimuon and the direct meson productions is contained in the pBe $\to \mu\mu X$ and π^+Be $\to \mu\mu X$ Chicago-Princeton data [1] at 150 GeV. The experiment has had a very good resolution in the dimuon mass and the group has presented detailed information about the p_T- and x_F-dependences of dimuon spectra for $0 < p_T < 2$ GeV/c, $0.15 < x_F < 1.0$ and $0.21 < M_{\mu\mu} < 3.5$ GeV/c^2. The inclusive cross-sections are plotted separately for different dimuon mass bins. The two lowest bins $0.21 < M_{\mu\mu} < 0.45$ and $0.45 < M_{\mu\mu} < 0.65$ GeV/c^2 correspond to LM dimuons and the third one with $0.65 < M_{\mu\mu} < 0.93$ GeV/c^2 is dominated by dimuons from ϱ^0 and ω decays (this contribution is 2–3 times higher than that from the background continuum below the ϱ, ω peaks). We shall therefore take the mass bin $0.65 < M_{\mu\mu} < 0.93$ GeV/c^2 as representing the properties of ϱ^0 and ω production. A look at the data (see Figs 2 and 3 in [1]) shows that

— the x_F-dependence of LM dimuon and ϱ^0 inclusive cross sections are rather similar,

— the same holds true for the p_T-dependence of corresponding cross sections,

— the difference between π^+Be and pBe interaction is similar for production of LM dimuons and of the ϱ^0-meson.

These analogies noticed by the Chicago-Princeton group [1, 2] provide so far the most convicing hints about the similarity between the LM dimuon and ϱ^0 production.

4. Prediction for the A-dependence of the low mass dimuon production in hadron-nucleus collisions

Information about the A-dependence of the LM dimuon production is rather meagre. The Fermilab–Columbia–Hawaii–Illinois group [3] have studied dimuon production by the neutron beam (obtained from the primary 400 GeV/c proton beam) incident on Be, Al, Cu and Pb targets. Dimuon yields were studied separately for four mass bins (0.6, 0.9 GeV/c^2), (1.10, 1.40), (1.40, 2.60) and (2.6, 3.6). Dimuon yields were parametrized as A^γ, with γ depending on the mass $M_{\mu\mu}$, longitudinal p_L, and transverse p_T momentum of the dimuon. These results, strictly speaking, contain no information about the low mass dimuon production since the mass bin $0.6 < M_{\mu\mu} < 0.9$ GeV/c^2 is dominated by ϱ and ω and there are no data for $M_{\mu\mu} < 0.6$ GeV/c^2.

Still, these data are important in another respect. The dependences $\gamma(M_{\mu\mu})$, $\gamma(p_T)$ and $\gamma(p_L)$ indicate that dimuons with large masses (above 2 GeV/c^2) are produced by a mechanism which is different from the one responsible for the production of dimuons with lower masses. In this way the data corroborate our assumption about two mechanisms of dimuon production (Drell–Yan for large masses and annihilations of $Q\bar{Q}$ pairs created during the evolution of the collision for low masses). In what concerns the production of dimuons with larger masses the data agree with the qualitative expectations of the quark--parton model [17].

We shall now list the predictions, following from the statement (2) on the A-dependence of dimuon production on nuclei.

In order to make detailed comparisons one would need to have the data on "directly produced" mesons in hadron-nucleus interactions. Such data are at present rather rare even for hadron-hadron collisions [18] and for hadron-nucleus collisions they are simply not available at all. We shall therefore assume that the ratio between "directly produced" and "all" particles is roughly indepedent of A and we shall base our predictions on the similarity between the production of LM dimuons and "all" (direct plus decay products) mesons produced non-diffractively in hadron-nucleus collisions.

In this way our predictions for the dimuon production in hadron-nucleus collisions are based on the statement

The A-dependence of the dimuon production roughly follows the general trend of the nondiffractive part of multiparticle production in hadron nucleus collisions. (3)

The data [19] show that the number of charged particles produced in hadron-nucleus collisions is approximately $\langle n\rangle \sim 0.5\,(1+\bar{\nu})$ where $\bar{\nu} = A\,\sigma_{hp}/\sigma_{hA}$. Here σ_{hp} and σ_{hA} are the inelastic cross sections for hadron-proton and hadron-nucleus interactions and $\bar{\nu}$ is the average thickness of the nucleus in units of the mean free path. Since $\sigma_{hA}\,\langle n\rangle$ is the integrated inclusive cross section we have for the dimuon production

$$\int \frac{d\sigma}{dy}(hA \to \mu^+\mu^- X)dy \sim \sigma_{hA}\langle n\rangle \sim A, \tag{4}$$

where one integrates over the whole rapidity range.

There is also an information about the rapidity (or pseudorapidity) distribution of particles in hadron-nucleus collisions [19]. In the fragmentation region the rapidity density of produced particles is roughly independent of A, while in the nucleus fragmentation region it is proportional to $A^{1/3}$ (see [19,20] and in particular [21]). To get the inclusive

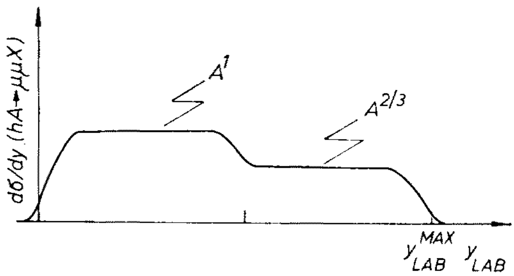


Fig. 2. Qualitative predictions for $d\sigma/dy(hA \to \mu\mu X)$ for low mass lepton pairs

cross section we have to multiply this by $\sigma_{abs} \approx A^{2/3}$. According to the statement (3) we have to expect the same qualitative features in the production of low mass dimuons in hadron-nucleus collisions. A rough sketch of the expected behaviour is shown in Fig. 2.

Detailed data on the energy and A-dependence of the particle production in hadron--nucleus collisions are available over the Fermilab energy range [22]. The data give directly the pseudorapidity density dN/dy of charged particles per inelastic hadron-nucleus collision. As $dN/dy = (1/\sigma_{hA})(d\sigma_{hA}/dy)$ we have

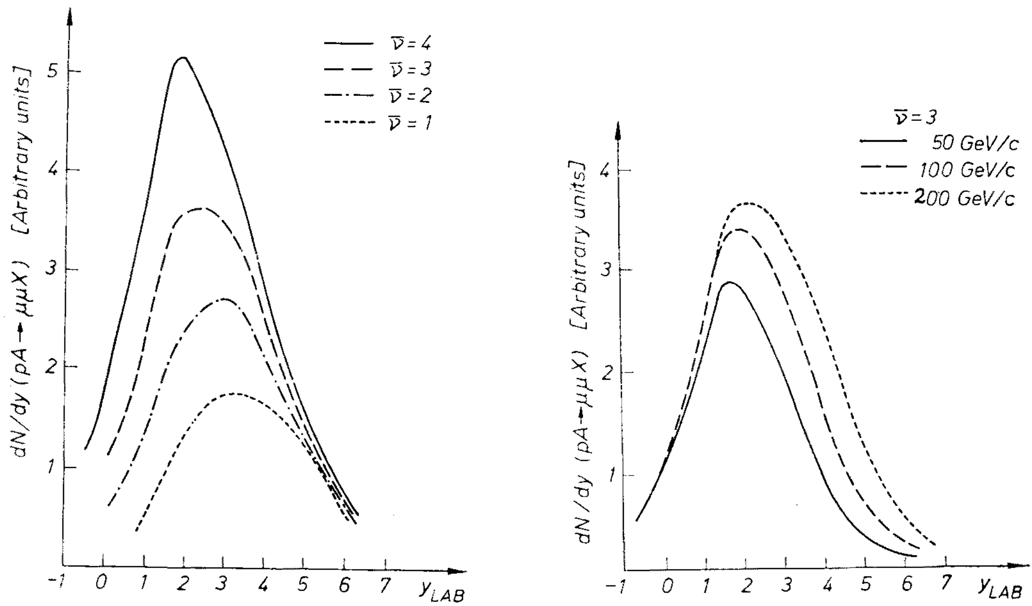
$$\frac{dN}{dy}(hA \to \text{meson}+X) \sim A^{-2/3}\frac{d\sigma}{dy}(hA \to \text{meson}+X) \sim A^{-2/3}\frac{d\sigma}{dy}(hA \to \mu\mu X). \tag{5}$$

Here we have first used the fact that $\sigma_{hA} \sim A^{2/3}$ and then in passing from meson to LM dimuon production we have applied the conjectured statement (3).

The predictions based on the data on $dN/dy(hA \to \text{meson} + X)$ taken from [22] are shown in Figs 3a and 3b.

As seen in Fig. 3a the production cross section $d\sigma/dy(\mathrm{p}A \to \mu+\mu+X)$ is proportional to $A^{2/3}$ for large laboratory rapidities and roughly proportional to A for nucleus fragmentation region. Both these features appear on a qualitative sketch in Fig. 2. Fig. 3b indicates that the shape of the nucleus fragmentation region remains unchanged with the increasing energy of the collision (at fixed A).

Another interesting feature of the multiparticle production in hA collisions is the linear dependence [19] of the average number of fast (shower) particles on the number of nuclear



a b

Fig. 3a. The rapidity density $dN/dy(\mathrm{p}A \to \mu\mu\, X)$ of low mass muon pairs should be proportional to the rapidity density of multiparticle production. The curves are hand drawn through experimental histograms [22] for charged particle production in proton-nucleus collisions at 200 GeV/c. Note that $\bar{\nu} \sim A^{1/3}$
Fig. 3b. The expected energy dependence of $dN/dy(\mathrm{p}A \to \mu^+\mu^- X)$ for fixed A. The curves are hand drawn through the experimental histograms [22] for dN/dy (charged particle production in pA collisions at 50, 100 and 200 GeV/c)

fragments. This, according to (3), should be also reflected in the LM dimuon production where the number of LM dimuons, proportional to $A^{-2/3} \int \frac{d\sigma}{dy} (\mathrm{p}A \to \mu\mu X)$, should rise linearly with the number of nuclear fragments.

5. *Comments and conclusions*

The arguments given above were based on the assumed analogy between the dynamics of the low mass dimuon and meson productions. This analogy follows rather naturally from the quark-parton model picture of the space-time evolution of hadronic collisions.

Verification of the suggested analogy between LM dimuon and meson productions would test the dynamical similarities between both production mechanisms and, on a deeper level, the general features of the Bjorken–Gribov picture of the space-time evolution of hadron collisions.

At present the data on the LM dimuon production are available only in the projectile fragmentation region, where $d\sigma/dy(hA \to \mu\mu X)$ seems to be consistent with the $A^{2/3}$ behaviour.

As discussed above the crucial test of the present picture of the collision would be provided by the data on the A-dependence of the low mass dimuon production in the nucleus fragmentation region. Even qualitative features of such data would represent a crucial test of quark-parton model ideas about mechanisms of the meson and the low mass dimuon productions.

The present note grew out of conversations with Vlado Černý and Peter Lichard. The author is indebted to them for valuable discussions and numerous comments.

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