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LOW MASS DILEPTON PRODUCTION IN HEAVY ION COLLISIONS

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We demonstrate that the total transverse energy dependence of the low mass dilepton (and single low p_T photon) production is a signature of the onset the evidence of plasma formation in heavy ion collisions. We present cross-sections for low mass dilepton production in proton-nucleus and heavy ion collisions, which represent lower bounds for the "collectivization" and the thermalization of matter produced in the collision. Higher cross-sections are a signature of the onset of the formation of thermalized matter.

I. INTRODUCTION

It is generally believed that in heavy ion collisions a new form of matter — the quark gluon plasma may be formed. Numerous ways have been proposed how to ascertain that quark-gluon plasma has really been formed. Neither of them is generally accepted as a completely reliable signature of plasma formation. In the present paper we shall discuss the possibility of using the production of low mass lepton pairs as a signature of the onset of plasma formation. This process is particularly interesting since already the production of low mass electron-positron pairs in high energy proton-proton collisions shows some peculiar characteristics.

It has been pointed out in Ref. [1] that a quadratic dependence of low mass dilepton production in hadronic collisions on the total transverse energy in the same rapidity bin implies that dileptons originate from the interactions of constituents present at the intermediate stage of the evolution of the collisions. Recent results of the AFS collaboration at the CERN ISR [2, 3] show a clear quadratic dependence for low p_T single leptons and for dileptons in the mass bin of 50 MeV $< m_{e^+e^-} <$ 100 MeV. The situation is less clear for the mass bin of

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$100\,\text{MeV} < m_{e^+e^-} < 600\,\text{MeV}$ but the quadratic dependence is also here possible. The total transverse energy in these collisions is built up by soft pions with an average transverse energy ε_T per particle of about 0.4 GeV, the total transverse energy in $\Delta y \sim 1$ being proportional to the multiplicity of pions N_π in the same rapidity bin. Thus we have

$$\left.\frac{dn^{e^+e^-}}{dm\,dy}\right|_{y=0} = \alpha N_\pi^2 = \beta E_T^2 \qquad (1)$$

where α is a constant of the order $10^{-4}\,\langle N_\pi^2\rangle^{-1}\,[\text{GeV}/c^2]^{-1}$ and $\beta = \alpha\varepsilon_T^{-2}$.

A special case of a mechanism leading to the quadratic dependence in Eq. (1) is provided by the soft annihilation model [4], where it is assumed that low mass dileptons are obtained by annihilations of quarks and antiquarks present at the intermediate stage of the collision [4, 5].

A simple interpretation of data consists in assuming that the quark-antiquark "soup" exists in a volume of about 1 fm^3 during a time interval of about 1 fm/c (in its rest frame[1]).

The purpose of the present note is to estimate the transverse energy dependence of low mass dilepton production in proton-nucleus and nucleus-nucleus collisions under the assumption that the density of constituents in the intermediate stage of these collisions is given as an appropriate sum of densities produced in individual nucleon-nucleon collisions and taking into account the longitudinal Lorentz contraction of nuclei and the geometry of the collision.

The transverse energy dependence of low mass dilepton production in proton-nucleus and nucleus-nucleus collisions is discussed in Sect. II. The third Section contains comments and conclusions.

II. TRANSVERSE ENERGY DEPENDENCE OF LOW MASS DILEPTON PRODUCTION IN PROTON-NUCLEUS AND NUCLEUS-NUCLEUS COLLISIONS

We start with a discussion about the proton-nucleus collision at high energy studied in the nucleon-nucleon centre of the mass frame. Each of the nucleons has still the shape of a sphere with the same radius as in the nucleon rest frame

[1]) Possible contributions to low mass dilepton production due to pion-pion interactions in the expanding pion gas were completely neglected in [4]. It is possible that such contributions are present and give a similar shape of the low mass dilepton distribution. These contributions would also lead to the quadratic dependence in Eq. (1). In future, high statistic studies of low mass dilepton production in special experiments [6] can perhaps distinquish both possible components but at present one cannot say anything definite about the nature of the intermediate stage formed in proton-proton collisions. Arguments presented below are independent of the nature of the "soup" formed in the intermediate stage of the collision.

(the reason for that is explained in Bjorken's papers [7] on the space-time evolution of hadron collisions), but the longitudinal distances between nucleons in the nucleus are Lorentz contracted. The collision is shown in Fig. 1. On its way through the nucleus the nucleon collides with N nucleons. Due to the Lorentz contraction the energy from all these collisions is released in the same space-time region and the density of the constituents in this space-time volume is a sum of all the densities produced in N subsequent collisions. That means that *the quadratic law given in Eq. (1) should be valid with the same constant* α *also for the proton-nucleus collisions.*

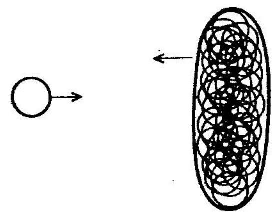

Fig. 1. A collision of a proton with a Lorentz contracted nucleus in the nucleon-nucleon c.m.s.

The test of this prediction is rather important. If low mass dilepton production turns lower than given by Eq. (1), it would mean that the energy produced in different nucleon-nucleon collisions is not released in the same space-time region[2] and this might lead to difficulties for the plasma formation in heavy ion collisions. If the dilepton production increases with E_T faster than given by Eq. (1), it would presumably mean that the volume or the time interval over which the "soup" exists increases with E_T.

Let us turn now to the case of the heavy ion collision. For simplicity we shall imagine both nuclei A and B in their rest frames as spheres with constant densities ϱ_A, ϱ_B and with radii $R_A = 1.2\,\text{fm}\cdot A^{1/3}$, $R_B = 1.2\,\text{fm}\cdot B^{1/3}$. The impact parameter of the collision (the transverse distance from the centres) is denoted as $\boldsymbol{b}$ and the transverse distance of a nucleon in B from the centre of B is denoted as $\boldsymbol{s}$. The transverse distance of the same nucleon with respect to the centre of A is $\boldsymbol{b} + \boldsymbol{s}$ (Fig. 2).

The overlapping region of the two nuclei can be divided into "tubes", each of them with the size of the inelastic nucleon-nucleon cross-section σ. All nucleons in the tube in A interact with all nucleons in the corresponding tube in B (Fig. 3).

[2]) The case of the dilepton production in proton-nucleus collisions has been studied in detail in a recent paper by Lichard [8]. He gives results corresponding as well to only a partial overlap of space-time regions in which the energy is released in two successive collisions.

Because of the Lorentz contraction both nuclei appear as pancakes in the nucleon-nucleon c.m.s. If there are m nucleons in the tube in B and n nucleons in the corresponding tube in A, there will be $m \cdot n$ nucleon-nucleon collisions in the collision of these two tubes.

Suppose now that each of these $m \cdot n$ nucleon-nucleon collisions produces μ pions in the rapidity interval of $\Delta y = 1$ near $y^* = 0$. The number of low mass dileptons produced within this interval in the collision of the two tubes will be $\alpha(\mu m \cdot n)^2$, where α is the same as in Eq. (1).

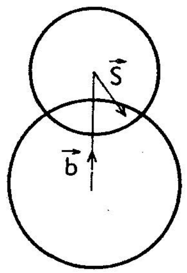

Fig. 2. Geometry of the BA collision viewed from the beam axis.

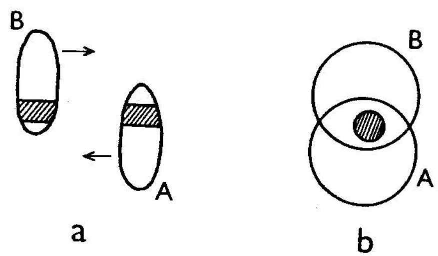

Fig. 3. Interacting tubes in nuclei A and B: a) side view b) view along the beam axis.

The total number of dileptons produced in the AB collision at a given b is then given as a sum over such contributions from the colliding tubes:

$$\frac{\mathrm{d}n^{e^+e^-}}{\mathrm{d}m\,\mathrm{d}y} = \alpha \sum_{\text{tubes}} (\mu m_i n_i)^2 = \alpha \sum_{\text{tubes}} (N_\pi^i)^2, \tag{2}$$

where $N_\pi^i = \mu m_i n_i$ is the number of pions within $\Delta y = 1$ produced in a given tube-tube collision.
The corresponding transverse energy is roughly given as

$$E_T = \sum_{\text{tubes}} (0.4\,\mathrm{GeV})\,\mu m_i n_i = \sum_{\text{tubes}} E_T^i \tag{3}$$

where E_T^i is the transverse energy released in all the nucleon-nucleon collisions within the i-th tube.

Now comes the main point. Eq. (2) corresponds to a situation in which the excited region corresponding to the i-th tube evolves independently of the excited regions formed by collisions in the neighbouring tubes. When plasma starts to be formed, the excited regions of the neighbouring tubes form a common system, which evolves differently from the two subsystems taken

separately. This "collectivization" of energy densities in individual tubes can be seen experimentally. The calculations given below show that the r.h.s. in Eq. (2) increases approximately *linearly* with E_T and flattens at the highest E_T, whereas as shown by Hwa and Kajantie [9] the dilepton production from plasma is proportional to $N_\pi^2 = (\Sigma N_\pi^i)^2 \sim E_T^2 = (\Sigma E_T^i)^2$.
Thus *the signature for the onset of plasma formation is a transition from the linear to the quadratic dependence of the low mass dilepton production on E_T.*

We shall now present the calculation showing that the r.h.s. of Eq. (2) increases approximately linearly with E_T. The calculation takes into account the geometry of the heavy ion collision but neglects some fluctuations.

The average number $N_{mn}(b)$ of the m, n-type tube-tube collisions at a given value of b is ([10] and the references quoted there)

$$N_{nm}(b) = \int_0^{R_B} \frac{\mathrm{d}^2 s}{\sigma} \frac{(\sigma \varrho_B t_B(\mathbf{s}))^m}{m!} \mathrm{e}^{-\sigma \varrho_B t_B(s)} \frac{(\sigma \varrho_A t_A(\mathbf{b}+\mathbf{s}))^n}{n!} \mathrm{e}^{-\sigma \varrho_A t_A(b+s)} \tag{4}$$

and the average number of nucleon-nucleon collisions at this value of b is given as

$$N(b) = \sum_{mn} m \cdot n \cdot N_{mn}(b) = \int_0^{R_B} \frac{\mathrm{d}^2 s}{\sigma} (\sigma \varrho_B t_B(\mathbf{s})) \cdot (\sigma \varrho_A t_A(\mathbf{b}+\mathbf{s})), \tag{5}$$

where $t_B(\hat{s}) = 2\sqrt{R_B^2 - s^2}$, $t_A(\mathbf{b}+\mathbf{s}) = 2\sqrt{R_A^2 - (\mathbf{b}+\mathbf{s})^2}$ are the longitudinal distances within B and A at given values of $\mathbf{b}$ and $\mathbf{s}$. The cross-section for the low mass dilepton production in the BA collision with a given total transverse energy E_T is then

$$\frac{\mathrm{d}\sigma^{e^+e^-}}{\mathrm{d}m\,\mathrm{d}y\,\mathrm{d}E_T} = \alpha\mu^2 \int_0^{R_A+R_B} 2\pi b\,\mathrm{d}b \left[\sum_{mn} (mn)^2 N_{mn}(b)\right] P(E_T/N(b)), \tag{6}$$

where $P(E_T/N(b))$ is the probability distribution for producing the transverse energy E_T in $\Delta y = 1$ at $y^* = 0$ in a $N(b)$ nucleon-nucleon collision.
The cross-section for the transverse energy production becomes

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_T} = \int_0^{R_A+R_B} 2\pi b\,\mathrm{d}b P(E_T/N(b)). \tag{7}$$

The probability distribution $P(E_T/N(b))$ has the mean value $\langle E_T \rangle = 2T\mu N(b)$ with $T = 0.2\,\mathrm{GeV}$ and since it is obtained as a convolution of $\mu N(b)$ single particle distributions one can come to the conclusion that the variance of the distribution is [11] $\sigma^2 = T^2 2N(b)\mu$.

We can thus take as in approximation

$$P(E_T/N(b)) = \frac{1}{\sqrt{2\pi T^2 2N(b)\mu}} \exp\left[\frac{-(E_T - 2T\mu N(b))^2}{2T^2 2N(b)\mu}\right]. \quad (8)$$

Inserting Eq. (8) into (7) and calculating $N(b)$ from (5) we can compute $d\sigma/dE_T$. Taking $N_{mn}(b)$ from Eq. (4) we can compute also the $d\sigma^{e^+e^-}/dm\, dy\, dE_T$. In Fig. 4 we present the factor

$$R(E_T) = \frac{\int_0^{R_A+R_B} 2\pi b\, db \left[\sum_{mn} (mn)^2 N_{mn}(b)\right] P(E_T/N(b))}{\int_0^{R_A+R_B} 2\pi b\, db P(E_T/N(b))}.$$

Numerically it appears that $R(E_T)$ is approximately linear[3] below some value of E_T.

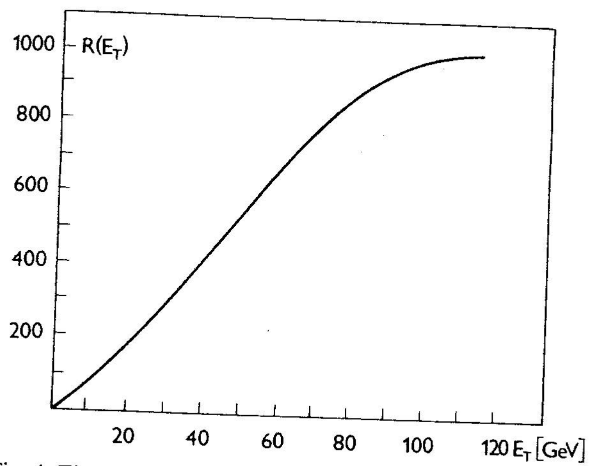

Fig. 4. The factor $R(E_T)$ given by Eq. (9) for the ^{16}O-Pb collision.

For the ^{16}O-Pb collision at the highest transverse energy $R(E_T)$ reaches the value of about 1100. This comes about as follows. A nucleon passing through the ^{16}O nucleus interacts on an average about twice. We can therefore imagine the ^{16}O nucleus as 8 tubes each containing $m = 2$ nucleons. A nucleon passing through the central region of Pb interacts on an average $2r/l$ times, where r is the radius of Pb and $l = 1/\sigma\varrho = 2.5$ fm is the mean free path. In this way we have $n = 2r/l = 6$. We have thus 8 tubes with $m = 2$ and $n = 6$. The $R(E_T)$ factor for the low mass dilepton production is $\Sigma(mn)^2 N_{mn}(b) \sim (6.2)^2 \cdot 8 = 1150$. The number of pions within the same rapidity bin is about $N(b)$ times higher than in a standart pp interaction. For the central ^{16}O-Pb interaction we have $N(b = 0) = 8.2 \cdot 6 \sim 100$ (in fact one bit lower). The e^+e^-/π ration for a central ^{16}O-Pb is by a factor of $R(E_T)/N(b = 0) = 10$ enhanced with respect to the case of a pp collision. The enhancement of the e^+e^-/π ratio by more than a factor of 10 would be a signature for the collectivizzation of energy produced in different tube-tube collisions.

[3]) The linearity would be exact for collisions of two cylinders of nuclear matter. This is a qualitative explanation for the numerically obtained approximately linear rise of $R(E_T)$.

III. COMMENTS AND CONCLUSIONS

The estimates presented above of the low mass dilepton production on the transverse energy in a specified rapidity window are, in fact, based on the assumption that the space-time evolution of this process is very similar to the one of a proton-proton collision. The only difference consists in taking into account the geometry of the collision and the increased energy density due to the Lorentz contraction of the colliding nuclei. The yield of the low mass dileptons is thus a sum of contributions from different tube-tube collisions.

If the energy density in tube-tube collisions increases above the critical density, the quark-gluon plasma will be formed and the dilepton yield will get a larger contribution. This will be further increased by the interactions of the pion gas formed after the phase transition of the quark-gluon plasma.

In this design our model corresponds to the transition region from the quark-gluon plasma to the pion gas. This transition region is that which corresponds to the soft annihilation model as applied to the proton-proton collision. If the energy density is insufficient for the production of the quark-gluon plasma, the quarks and antiquarks created during the collision recombine with the pion gas and the pion gas expands. The soft annihilation model describes in this situation the contribution to the dilepton production due to the transition from quarks and antiquarks to the meson (pion) gas.

In any case the soft-annihilation model as applied here to heavy ion collisions describes only a part of the contribution of the whole space-time evolution of the process to the low mass dilepton production. In this sense the results presented above represent only a lower bound of the low mass dilepton production in heavy ion collisions. Note that even this lower bound leads to the e^+e^-/π ratio in ^{16}O-Pb collisions about ten times higher than in a pp collision. The observation of a significantly larger e^+e^-/π ratio in heavy ion collisions would be a clear signal that the heavy ion collision is not just a simple sum of tube-tube collisions, which are in fact simple sums of nucleon-nucleon collisions.

There are a few points which deserve further study: 1) a detailed clarification of the connection between the soft annihilation model and the quark-gluon plasma → pion gas evolution of the heavy ion collision, 2) the estimates of the contributions of the expanding quark-gluon plasma and the pion gas to the low mass dilepton production as a function of the transverse energy released in the rapidity window in which low mass lepton pairs are detected.

The excess of the low mass dilepton production higher than the predictions of the soft annihilation model (extended to heavy ion collisions) will be experimental information about the contributions in a latter paper.

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ПРОДУКЦИЯ ДИЛЕПТОНОВ С МАЛОЙ МАССОЙ В СОУДАРЕНИЯХ ТЯЖЕЛЫХ ИОНОВ

В работе показано, что зависимость продукции дилептонов с малой массой (и фотонов с малым поперечным импульсом) представляет сигнатуру начала формирования кварк-глюонной плазмы. Приводятся сечения для продукции дилептонов с малой массой, соответствующие ситуации когда в столкновениях не возникает термализованной кварк-глюонной или адронной материи. Большие сечения — сигнатура появления коллективизированной материи.