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DILEPTONS FROM NUCLEI AT INTERMEDIATE ENERGIES

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1.Introduction

Extensive experimental and theoretical studies of lepton pair production in hadron-nucleus and nucleus-nucleus collisions continue now in a wide kinematical range [1,2,3,4]. It is worth to emphasize that the main interest here is connected with some evidence that in these processes it a noticeable nuclear enhancement of the dileptons yield is possible which may be interpreted as a signal of the creation of new exotic phases of the nuclear matter: quark gluon plasma at ultrarelativistic energies[5,6,7] and (super)heated and (super)dense hadronic phase in a state of thermodynamic equilibrium at energies of about a dozen GeV[8,9,10]. It is clear that in this case the crucial moment is the correct extraction of the background mechanism such as the direct dilepton emission. Moreover, the theoretical investigation of direct dileptons production is very interesting itself, since a great amount of different sources contribute to the dileptons spectrum[10]: hard annihilation of partons existed in the colliding nuclei before the interaction, i.e. the Drell-Yan (DY) mechanism; annihilation of secondary partons (quarks, mesons) produced in the collision; decay of vector mesons; Dalitz decays of η, ω, tensor mesons and Δ-isobar; internal conversion of virtual photons produced by bremsstrahlung of quarks and hadrons during the collision etc.. As well as, some theoretical models for concrete numerical calculations of dileptons production in the kinematical range of their masses $\sim 1GeV/c^2$ have been established in refs.[11,12,13,14]. But up to now the problem of a clear understanding of the dilepton spectrum at low masses remains open.

Especially quite a complicate kinematical region is that of the dilepton mass below $0.3GeV/c^2$. Bremsstrahlung from nucleon-nucleon collisions and rescattering as well as Dalitz decays give the main contributions there[15,16]. Since in the resonance region the contribution of the vector mesons decays dominates, a possible enhancement of the dilepton yield in nuclear reactions in comparison with the proton-proton collisions becomes the central problem. This region seems to be more interesting owing to some unexpected predictions[6] about the rate of $\rho_0-, \omega-, \phi-$ meson yields in nuclear collisions.

Annihilation of the "primary" partons existing inside the systems before collisions and the "secondary" ones seems to be the main origin of the nuclear enhancement, whereas the annihilation of the pure secondary partons ought to give a smaller effect (for direct pairs) since each parton is produced in its own separate space-time volume. Further, for simplicity, annihilation of secondary and primary partons will be called the nuclear enhanced mechanism. This mechanism has been considered in the framework of "the soft annihilation models"[10,11,12], however it is still open for further extension because one of these models does not include all aspects of the space time evolution of the collision process and another one contains unknown phenomenological parameters of secondary - parton distributions fixed from comparisons with the same experimental data on dilepton productions.

Obviously the naive extrapolation of the DY model into the low dilepton mass and low initial energies is absolutely incorrect from the point of view of perturbative QCD. But now there are many phenomenological parton models (so called "quark gluon jets models" [17,18,19]) which have been proposed to take into account different characteristics of the nuclear collisions in a wide energy range with a low limit up to few of GeV/nucleon and which phenomenologicaly include nonperturbative QCD effects. So, working in the framework of the same phenomenology it is useful to modify the DY model in order to use it at low energies.

The aim of this work is the examination of the real yield of direct dileptons and nuclear enhanced effects at energies $\sim 10GeV/nucleon$ on the basis of the ideas of quark parton fragmentation models with paramefers fixed from independent experiments. The paper is organized as follows: in sect.2 we discuss the vector meson decays contribution; in sect.3 we define the quark distributions in nuclei and consider nuclear enhancement of the dilepton yield owing the quark-quark and pion-pion annihilation. In the last case we assume annihilation of secondary pions and exchanged pions inside nuclei (meson exchange currents (MEC) - contribution). Results of calculations and comparison with the available experimental data are given in sect.4. Here we restrict our consideration to the proton nucleus collision. Generalization to the nucleus-nucleus case will be done later.

2. Decays of vector mesons

The mechanism of the vector mesons decays contribution into the dilepton yield is depicted in fig. 1.

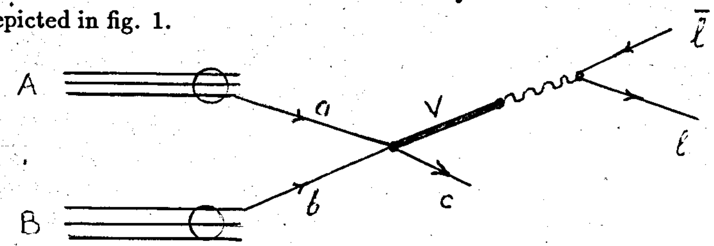

Fig.1 Vector meson decay contribution.

Parton model gives a simple formula for the cross section of this process:

$$\frac{d\sigma^{AB\to l^+l^-}}{dM^2dyd\mathrm{p_t}} = \sum_{ab}\int_{x_0}^{1} dx_a[G_{a/A}(x_a)G_{b/B}(x_b) + G_{b/A}(x_a)G_{a/B}(x_b)]\frac{x_ax_b}{x_a - x_1}\left(\frac{d\sigma}{\pi dt}\right)^{ab\to V\to l^+l^-} \quad (1)$$

$$x_b = \frac{(x_ax_1 - M^2/s)}{(x_a - x_1)};\, x_0 = \frac{(x_1 - M^2/s)}{(1 - x_2)};\, x_{1,2} = \tau e^{\pm y};\, \tau^2 = \frac{M_t^2}{s},$$

where $G_{c/C}(x)$ is the probability of finding, in the hadron C, a parton c with momentum fraction x; $M, y, \mathrm{p_t}$ are the mass, rapidity and transverse momentum of the virtual photon respectively; $M_t^2 = \mathrm{p_t}^2 + M^2$; s is the nucleon-nucleon center of mass energy squared; and the cross section of the elementary subprocess $ab \to V \to l^+l^-$ is as follows:

$$\frac{d\sigma^{ab\to V\to l^+l^-}}{dt} = \frac{(1 - 4\mu^2/M^2)^{\frac{1}{2}}}{32s_{ab}^2(2\pi)^3} \mid T_{ab\to V\to l^+l^-} \mid^2 \quad (2)$$

where μ is the lepton mass. The amplitude T_{ab} can be taken in a general form:

$$T_{ab} = f_\mu \frac{g_{\mu\nu} - p_\mu p_\nu/p^2}{p^2 - m_V^2 + im_V\Gamma_V} g_{V\gamma} \frac{u_{\sigma_1}(p_1)\gamma_\nu v_{\sigma_2}(p_2)}{p^2}, \quad (3)$$

where m_V and Γ_V are the mass and width of the resonance; f_μ is the vertex form factor $ab \to V$; u_σ, v_σ are spinors of the leptons with momenta $p_{1,2}$ and polarization σ and the coupling constant $g_{V\gamma}$, which can be obtained from the V-meson decay into l^+l^--pair:

$$\Gamma_V^{l^+l^-} = \frac{4\pi\alpha^2}{3}\frac{g_{V\gamma}^2}{m_V^3}. \quad (4)$$

Substituting cross section (2) into eq.(1) and using eqs.(3, 4) one can obtain

$$\frac{d\sigma^{AB\to l^+l^-}}{dM^2dyd\mathrm{p_t}} = \sum_{ab}\int_{x_0}^{1} dx_a[G_{a/A}(x_a)G_{b/B}(x_b) + G_{b/A}(x_a)G_{a/B}(x_b)]\frac{x_ax_b}{x_a - x_1}$$
$$\cdot \frac{(1 + 2\mu^2/M^2)\mathrm{f}^2 - 6(\mu/M)^4 f_0^2}{16\pi^3 s_{ab}^2} \frac{\Gamma_V^{em}(1 - 4(\mu/M)^2)^{\frac{1}{2}}}{M^2((M^2 - m_V^2)^2 + (m_V\Gamma_V)^2)} \cdot \quad (5)$$

The cross section of the "V"- meson creation can be found similarly:

$$\frac{d\sigma^{AB\to V}}{dyd\mathrm{p_t}} = \sum_{ab}\int_{x_0}^{1} dx_a[G_{a/A}(x_a)G_{b/B}(x_b) + G_{b/A}(x_a)G_{a/B}(x_b)]\frac{x_ax_b}{x_a - x_1}\frac{\mathrm{f}^2}{16\pi^2 s_{ab}^2}. \quad (6)$$

Eqs.(5, 6) allow us to express the cross section of pair production in a proton nucleus collision ($A = p$) with the cross section of vector meson creation in pp- interaction in the limit of $\mu^2 \ll M^2$:

$$\frac{d\sigma^{AB\to l^+l^-}}{dM^2dyd\mathrm{p_t}} = \sum_V R_{AB}^V \frac{1}{\pi}\frac{\Gamma_V^{em} b(\mu)}{M^2((M^2 - m_V^2)^2 + (m_V\Gamma_V)^2)}\frac{d\sigma^{pp\to V}}{dyd\mathrm{p_t}}, \quad (7)$$

where R_{AB}^V is a projectile - target factor, and $b(\mu) = (1 - 4(\mu/M)^2)^{\frac{1}{2}}$. This relation has a general character in spite of that it has been obtained in the parton model which is correct at ultrarelativistic energies.

Thus, the central problem becomes to obtain $d\sigma^{pp\to V}/dyd\mathrm{p}_t$. The fragmentation models overestimate this cross section. For example the widely popular Lund model gives $\sigma^{pp\to\rho_0}$=6.3 mb [20] at $E = 24GeV$ which is about twice the experimental value $(3.5 + 0.4mb)$[20,21]. Of course one can "improve" the model by correcting of its parameters or by addinq of the new ones. But for our aim the straight way is to use an analytical approximation of the experimental data[21]. So we take

$$\frac{d\sigma^{pp-V}}{dyd\mathrm{p}_t} = 3.32(1-x_R)^{2.4}exp(-3.6p_t^2)[mb];\ x_R = \frac{E}{E_{max}} = \frac{M\cosh(y)}{E_{max}} \tag{8}$$

which gives the following values for the total cross sections: $\sigma^{\rho_0}(E = 24\ \mathrm{GeV})$=3.44 mb, $\sigma^{\rho_0}(E = 12\ \mathrm{GeV})$=1.8 mb, $\sigma^{\rho_0}(E = 5\ \mathrm{GeV})$=0.26 mb. The creation of ϕ- mesons consisted of two strange quarks is suppressed by the factor δ^2, where δ is the ratio of K^+/π^+ - yield: $\delta \approx 0.1$.

Note that equation (7) is determined in the vicinities of resonances and can give a wrong prediction outside of it.

3. Nuclear enhancement

Let assume that dynamical nuclear enhancement occurs because of annihilation of the secondary partons quarks - q^* and pions - π^* with the primary nuclear quarks and exchanged pions inside the nucleus respectively. Annihilation among the secondary partons is neglected because they are produced in different space - time volumes and the corresponding contribution to the dileptons yield seems to be negligible.

Annihilation q^*q

The parton model gives the following expression for q^*q- annihilation:

$$\frac{d\sigma^{q^*q}}{dM^2dyd} = R^*_{AB}\frac{4\pi\alpha^2}{9M^4}b(\mu)\sum_{ab} e_i^2 x_a x_b[\overline{q}^*_{a/A}(x_a)q_{b/B}(x_b) + q_{b/A}(x_a)\overline{q}^*_{a/B}(x_b) + \overline{q} \leftrightarrow q] \tag{9}$$

where $q^*_{i/C}(x)$ is the distribution of a i-th quark produced by the fragmentation of the hadron (nucleus) C , R^*_{AB} is the nuclear factor.

At lab. energies below one hundred GeV/nucleon the hadronization length is of the order of magnitude of the mean nucleon-nucleon separation in a nucleus or smaller [22]. This means that all secondary quarks are confined in "quark - gluon strings" and the distribution $q^*_{i/C}(x)$ can be found in a convolution approach:

$$q^*_{i/C}(x) = \int q_{i/s}(z)s_C(y)\delta(x-yz)dydz \tag{10}$$

where $q_{i/s}$ is the quark distribution in the "string" and s_C is the distribution of the "strings" which can be calculated in the fragmentation models. It was found that

s_C practically coincides with the distribution of the secondary pions. So we choose: $q_{i/s}(x) = q_{i/\pi}(x)$ and $s_C(x) = \pi^*_C(x)$, where $q_{i\pi}(x)$ is the quark distribution in a pion and $s_C(x) = \pi^*_C(x)$ is the pion spectrum

$$\pi^*_C(x) = \frac{1}{\sigma_{tot}}\frac{d\sigma^{C\to\pi}}{dx} \ . \tag{11}$$

For further numerical calculation we have employed the following expressions for $d\sigma^{p\to\pi}$ [23,24,25]:

$$\frac{1}{\sigma_{tot}}E_\pi\frac{d\sigma^{pp\to\pi^+}}{d\mathrm{p}_\pi} = \begin{cases} 1.88(1-0.86x)^{3.3}(1-x)^{0.2}z_l(p_t),\ E \sim 10GeV \\ 1.50(1-x)^{3.4}z_h(p_t),\ E \sim 100GeV \end{cases}$$

$$z_l(p_t) \simeq e^{-6.1p_t},\ z_h(p_t) \simeq e^{-4.1p_t};\ \frac{d\sigma^{p\to\pi^-}}{d\sigma^{p\to\pi^+}} \simeq 0.3e^{-0.51x};\ x = \frac{E_\pi}{E_{\pi max}} \ . \tag{12}$$

Using eqs.(9, 10) one can obtain the final result for the q^*q - annihilation contribution in the form:

$$\frac{d\sigma^{q^*q}}{dM^2dy} = R^*_{1B}\frac{4\pi\alpha^2}{9M^4}b(\mu)\sum_i e_i^2\int_{x_1/a}^1 dz\pi^*(z)\frac{x_1x_2}{az}[q_{i/\pi}(\frac{x_1}{az})(q_{i/B}(x_2) + \overline{q}_{i/B}(x_2)] \tag{13}$$

$$x_{1,2} = \frac{M}{\sqrt{s}-2M_N}e^{\pm y}, \tag{14}$$

where M_N is a nucleon mass, E_π is a pion energy. Definition of the scale variables $x_{1,2}$ given by eq.(14) takes into account the mass correction which becomes essential at low energies and assumes that the partons energy is limited not by the total but kinetic energy of a hadron. Using eq.(14) instead of usual DY- scale variables leads to a more sharp decrease of the cross section (13) with increasing M. The coefficient a in eq.(13) couples the scale variable x_1 and the radial variable $z = E_\pi/E_{\pi max}$: $a = 2E_{\pi max}/(\sqrt{s} - 2M_N)$.

Quark distributions for the free nucleons can be taken from the analysis of deep inelastic scattering and in our further calculations we have used the following expressions [26]:

$$\begin{aligned} u_p(x) = d_n(x) &= 2.69x^{-0.42}(1-x)^{2.7} + 0.2(1-x)^7/x \\ d_p(x) = u_n(x) &= 1.56x^{-0.42}(1-x)^{3.7} + 0.2(1-x)^7/x \qquad (15) \\ \overline{u}_{p,n} = \overline{d}_{p,n} &= 0.2(1-x)^7/x \\ q_{i/\pi}(x) = \overline{q}_{i/\pi}(x) &= 0.75(1-x)/\sqrt{x} + 0.15(1-x)^5/x \ . \qquad (16) \end{aligned}$$

The quark distribution in a nucleus normalized to the atomic weight differs from the corresponding distribution in a free nucleon because of the influence of the nuclear Fermi motion and multinucleon (multiquark) correlations at short distances which are essential in the vicinity of $x \sim 1$ [25,27]. So following the papers [25,27] we choose:

$$q_A(x) = \sum_{k=1} P_k^A q_k(x), \tag{17}$$

where

$$q_1(x) = \frac{1}{A} \int\limits_{x/A}^{1} \frac{dy}{y} q_N(\frac{x}{Ay}) N_1^A(y) \tag{18}$$

is the quark distribution in a intranuclear nucleon smeared by the Fermi motion - $N_1^A(y)$, and $q_k(x)$ $(k \geq 2)$ is the contribution of the short-range multinucleon correlations which exist in the nucleus with the probability $P_k^A \approx (r_\xi/r_0)^{3(k-1)}/(k-1)!$ $(2 \leq k \ll A)$:

$$q_k(x) = \frac{1}{k} \int\limits_{x/k}^{1} \frac{dy}{y} q_N(\frac{x}{ky}) N_k(y) \tag{19}$$

$$N_k(y) = N y^\gamma (1-y)^{2k-\beta}, \quad \int N_k(y) dy = 1 \, .$$

The momentum distribution $N_1^A(y)$ has been calculated in the framework of the "coherent fluctuation" model [25,28] which describes the main characteristics of nuclei, and the result is close to the theoretical values obtained by other authors[29] in their microscopical calculations, including nucleon-nucleon correlations. All the other parameters of $q_A(x)$ have been chosen as to obtain the best description of the deep inelastic lepton - and hadron - nuclei scattering data, and they are: $\gamma = 0, \beta = 1.5, (r_\xi/r_0) = 0.42$. Note that in the range of $x \leq 0.8$ the distributions $q_A(x)$ and $q_N(x)$ are almost the same with an accuracy of the order of the nuclear EMC - effect or about few per cents.

Annihilation $\pi^*\pi$

In this case the additional dileptons are created in annihilation of the secondary pions produced in hadron nucleus interaction with the exchanged meson field in the nucleus. This MEC contribution can be calculated in the same way as in the deep inelastic scattering which has been widely discussed in the connection with the EMC - effect[30]. It was found that an enhancement of the meson field in a nucleus as compared with the free nucleons is small (about one percent per nucleon) but enough to be seen in the EMC - like processes. Here we use the result of papers [26,31], where a self - consistent method has been developed with taking into account all kinds of meson exchange diagrams. Self-consistency means that the same mesons (with their meson-nucleon vertices) define both the OBE - potential and the MEC diagrams. An enhanced meson field was found out. It may be treated as existence of the extra mesons (pions) in a nucleus and the result of the numerical calculation

may be represented by the analytical approximation:

$$\pi_A(x) = \int dp_t \pi_A(x, p_t) \approx 3.61 x^{1.4} (1-x)^{10}. \tag{20}$$

Then, the contribution of the $\pi^*\pi$- annihilation to the dilepton production can be written as:

$$\frac{d\sigma^{\pi^*\pi}}{dM^2 dy} = R_{1B}^* \frac{4\pi\alpha^2}{3M^4} b(\mu) A(M^2) [\frac{x_1 x_2}{az} \pi^*(\frac{x_1}{az}) \pi_B(x_2)] (1 - \frac{4m_\pi^2}{M^2}), \tag{21}$$

where $A(M^2)$ is the sum of $\pi^+\pi^- \to \rho, \pi^+\pi^- \to \rho'$ vertex form factors squared [7]:

$$A(M^2) \approx \frac{1.2}{(M^2 - m_\rho^2)^2 + m_\rho^2 \Gamma_\rho^2} + \frac{0.12}{(M^2 - m_{\rho'}^2)^2 + m_{\rho'}^2 \Gamma_{\rho'}^2} \, .$$

The nuclear enhancement mechanism described by eqs.(13, 21) with their own atomic weight dependence occurs only in nuclear reactions and disappears in *pp*-collisions.

4. Results and discussion

The calculations of the dilepton (e^+e^-) yields from proton-nucleus $(p - {}^9Be)$ collisions were performed for different dilepton sources and the results are shown in Figs.2,3 for two energies. Parameters of the resonances were taken from ref.[32]. The target factors R_{p,A_T}^V, R_{p,A_T}^* in eqs.(7),(13), (21) are determined by the total inelastic nucleon-nucleon cross section $\sigma_{in} \approx 32mb$, the total cross section of the interaction of the secondary partons (q^*, π^*) with a nucleon - σ^*, nuclear density $\rho_{A_T}(r)$ and in the Glauber approximation have the usual form:

$$R_{p,A}^V = \int\limits_0^R 2\pi b db \int\limits_{-\infty}^{\infty} dz \rho_A(b,z) e^{-\sigma_{in} \int_{-\infty}^{z} \rho_A(b,z')dz'} \tag{22}$$

$$R_{p,A}^* = \int\limits_0^R 2\pi b db \int\limits_{-\infty}^{\infty} dz \rho_A(b,z) e^{-\sigma_{in} \int_{-\infty}^{z} \rho_A(b,z')dz'} \sigma^* \int\limits_z^{\infty} \rho_A(b,z')dz' \tag{23}$$

which in the constant density approximation $(\rho_A(r) = \rho_0 \theta(R-r), \; R = r_0 A^{\frac{1}{3}}, \; \rho_0 = 0.17(fm^{-3}), r_0 = 1.12 fm)$ transfer to the simple expressions:

$$R_A^V = \frac{A^{\frac{2}{3}}}{a} \int\limits_0^1 dt (1 - e^{-b(A,t)}) \tag{24}$$

$$R_A^* = \frac{A^{\frac{2}{3}}}{a} c \int\limits_0^1 dt (1 - (1 + b(A,t) e^{-b(A,t)}) \tag{25}$$

where $a = (4/3)\sigma_{in}\rho_0 r_0 \approx 0.81, b(A,t) = 1.5aA^{\frac{1}{3}}\sqrt{1-t}, c = \sigma^*/\sigma_{in} \sim 1$. Note that the eqs.(24, 25) give the result which is very close to the prediction of eqs.(22,23) with using of realistic Woods-Saxon nuclear density distribution.

All calculations take into account the nucleon Fermi motion in the target nucleus on the base of the prescription done by eq.(18).

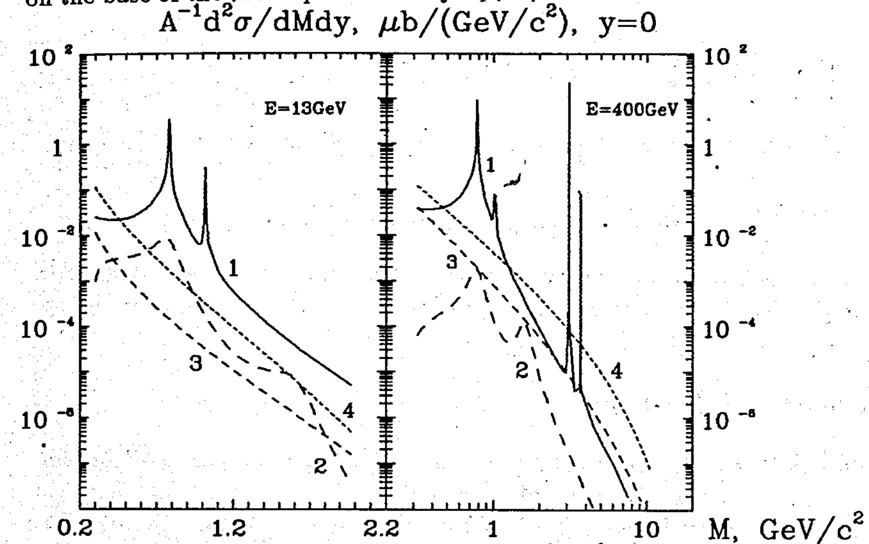

Fig.2. The dilepton (e^+e^-) invariant mass distribution. Curves: 1-vector meson decay, 2-MEC contribution, 3-qq-annihilation, 4-naive DY extrapolation.*

One can see that the main contribution in the resonant range comes from the vector mesons decays - curves 1 in Fig.2. At high energy, for completeness, eq.(7)has been added by the contribution of the J/ψ and ψ' decays which has been calculated with cross sections $d\sigma^{pp\to V}$ taken in the form [33]:

$$\frac{d\sigma^{J/\psi}}{dy} \simeq 7.1(1-x)^{4.3}B^{-J/\psi}[nb]; \ \frac{d\sigma^{J/\psi}B^{J/\psi}}{d\sigma^{\psi'}B^{\psi'}} = 0.017; \ B^V = \frac{\Gamma_V^{em}}{\Gamma_V} \cdot$$

The contribution of the MEC is shown by curves 2, and curves 3 correspond to the dilepton yield from q^*q- annihilation. Curves 4 represent an illustration of the naive extrapolation of the DY prediction with the mass correction (eq.(14)). The contribution of MEC reaches its maximum value at $x \approx 0.25$. This means that at $M \approx m_\rho$ the maximum contribution will come at an initial energy $E \sim 12GeV$ and is order of values smaller than the resonant contribution. At high energies the contribution of MEC is negligible. The relative dilepton yield from the q^*q- annihilation has an opposite tendency - increases at high energies and becomes very small at low

ones. It should be noted that in the vicinity of the resonances this prediction is correct with the accuracy of an order of magnitude. The picture should be completed by nonperturbative $\bar{q}q$- annihilation form factor. Its incorporation may intensify the corresponding yield, but nevertheless it seems to contribute a very small correction.

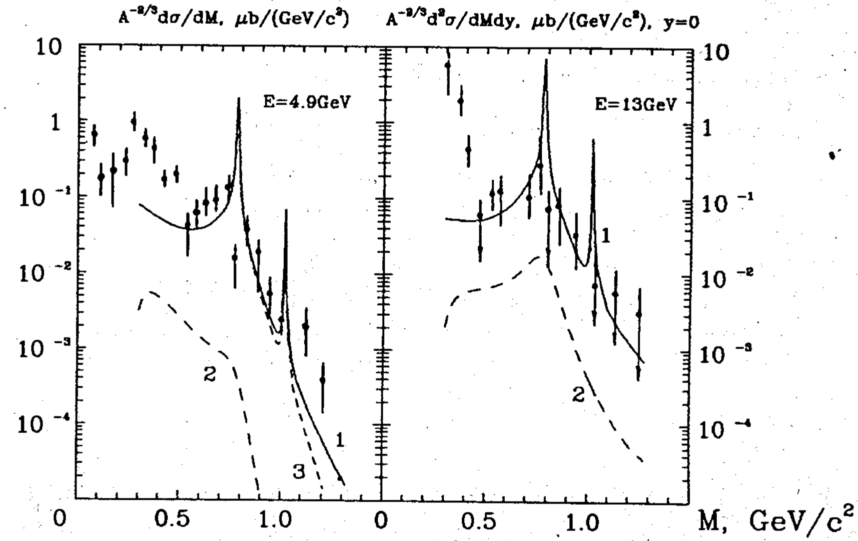

Fig.3. The dilepton (e^+e^-) invariant mass distribution. Curves: 1-vector meson decay, 2-MEC contribution, 3 - calculation without Fermi-motion. Experimental data are taken from refs.[2,3]

Fig.3 shows the comparison with the available experimental data refs.[2,3]. Curves 1 correspond to the vector mesons decay contribution and curves (2) are the MEC calculation. Dashed line is when the Fermi motion is excluded.

The calculation predicts sharp ω, ϕ- resonances peaks which have not been seen experimentally. Except of the comparably narrow regions around resonances one can see a qualitative agreement between the calculation and experimental data at $Mc^2 \geq 0.4GeV$. At the lower mass the bremsstrahlung photons and Dalitz decays must be included[13,14,15,16].

Further investigations seem to be important with an improvement of the acceptance in order to observe the narrow resonances, to study the vector-meson creation and to search for the collective phenomena.

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