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J/ψ SUPPRESSION AS EVIDENCE FOR HIGH DENSITIES IN NUCLEAR COLLISIONS*

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Abstract

We determine the hadron density necessary to account for J/ψ suppression in nuclear collisions by absorption, including the effects of nuclear stopping and J/ψ formation time. It is found that the suppression measured in central 200 GeV/A O-U and S-U collisions cannot be obtained from interactions of the J/ψ with the primary nucleons alone. It can be explained by absorption on primary and secondary hadrons, provided the density of the secondaries is at least 0.8 fm^{-3}, i.e., five times standard nuclear density.

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In the early stages of a high energy nucleus-nucleus collision, projectile and target nucleons interact strongly in a limited spatial region. Within this region we expect particle densities around $5-20\,\rho_0$, far above the density of nuclear matter $\rho_0 = 0.16\ \mathrm{fm}^{-3}$ [1]. It is therefore remarkable that no single measurement from the BNL and CERN light ion programs (with projectiles $A \leq 32$) stands out as unambiguous evidence of such extreme densities [2]. To separate genuine high density signals from background effects of other origins, a careful comparative study of hadron-nucleus and nucleus-nucleus data is needed. In this paper we want to carry out such a study for the case of J/ψ suppression as high density probe.

In the NA38 experiment at CERN, the suppression of the J/ψ relative to the dimuon continuum was measured in central nucleus-nucleus collisions with 200 GeV/A incident beams [3–7]. For central O-U and S-U collisions, it is observed that the ratio of cross sections $\sigma_\psi/\sigma_{\rm cont}$ is reduced by a factor of two compared to minimum bias pU results [7]. Such a suppression had been predicted as a consequence of color screening in a quark-gluon plasma [8]. On the other hand, scattering of the J/ψ with comoving hadrons can also provide suppression. Either of these two mechanisms is able to describe the AB data within the theoretical and experimental uncertainties [9–12]. One is therefore tempted to infer the presence of high densities from the observed J/ψ suppression, since both absorption and screening require this.

However, a strong suppression is also seen in hadron-nucleus collisions [13,14], where such high densities are not expected. The J/ψ production cross section per nucleon in pPt and pW interactions is 30 – 40% smaller than in pp collisions [13,14] and $\sigma_\psi/\sigma_{\rm cont}$ is found to fall by about 20% between pCu and pU [7]. This presence of J/ψ suppression in both pA and AB collisions has led different authors to search for a common explanation of the two cases in terms of J/ψ absorption on nucleons alone [15–19].

In this paper, we estimate the maximum contribution of absorption by nucleons to the observed J/ψ suppression in AB collisions. In a comparative study of pA and AB data, we show that nuclear absorption alone cannot account for the observed suppression. The additional suppression needed can, however, be obtained from J/ψ scattering with secondary hadrons at sufficiently high density.

To study the dependence of absorption on nucleon density, we consider the J/ψ's survival probablity,

$$S \;\equiv\; \mathrm{e}^{-W} \;=\; \exp\left\{-\int_0^L dz\,\rho(z)\sigma(z)\right\} \tag{1}$$

where L is the path length of the J/ψ through the medium, ρ the nucleon density, and σ the J/ψ absorption cross section on nucleons. In the conventional eikonal approach [15,19], it is assumed that the J/ψ propagates along the beam direction through undisturbed projectile and target nuclei of density $\rho(z) = \rho_0$. Furthermore, the absorption cross section is fixed at the value $\sigma(z) = \sigma_{\psi N}$ taken from pp interactions. We denote the resulting survival probability by S_0. Geometric arguments [20], together with the measured χ contribution for J/ψ production [21], give $\sigma_{\psi N}$=4 mb. In the case of minimum bias pU collisions this leads to

$$S_0(p\mathrm{U}) \;\simeq\; \exp\{-\rho_0\sigma_{\psi N}(3R_U/4)\} \;\simeq\; 0.72, \tag{2}$$

where the factor 3/4 is due to the average over impact parameter. For central S-U collisions we correspondingly find

$$S_0(\mathrm{SU}) \;\simeq\; \exp\{-\rho_0\sigma_{\psi N}[(3R_S/4) + R_U]\} \;\simeq\; 0.54. \tag{3}$$

The ratio of central S-U to minimum bias pU is then

$$[S_0(\mathrm{SU})/S_0(p\mathrm{U})] \;\simeq\; 0.75, \tag{4}$$

i.e., we get a decrease of only 25% instead of the observed 50%. To obtain a 50% suppression, it is necessary to increase the break-up cross section to about 10 mb. This not only contradicts geometric cross section arguments [20], but also leads to too much suppression for pU, resulting in a decrease of almost 60% between pp and pU. The conventional eikonal approach thus cannot provide a common explanation of both pA and AB data. With a realistic $\sigma_{\psi N}$ it also cannot account for the amount of suppression observed in central O-U and S-U interactions.

It is not evident, however, to what extent the assumptions of the eikonal approach are satisfied in actual interactions. Target and projectile nuclei are certainly affected by the collision since there is considerable stopping. In the framework of perturbative QCD [22], the break-up cross section attains its saturation value $\sigma_{\psi N}$ only after some formation time [23]. Both these factors should be included in a more realistic estimate of absorption.

We first show that stopping does not affect the eikonal description if the J/ψ is assumed to form instantaneously. Consider a J/ψ formed in a pA collision at the center of the target nucleus with lab rapidity $y_\psi > 0$. In the J/ψ rest system, the Lorentz-contracted target medium passes by with a rapidity $-y_\psi$, provided there is no stopping. With stopping, the participant target nucleons are accelerated, reducing their rapidity relative to the J/ψ. This increases the path length of the J/ψ in the medium. On the other hand, the medium appears less Lorentz-contracted and hence of lower density to the J/ψ. These two effects cancel each other.

Specifically, the nucleon-nucleon interactions during a pU collision slow down the projectile, shifting its rapidity by an average of $\Delta y \simeq 2.5$ units [24,25]. At the same time the N_A participant target nucleons are accelerated to an average rapidity $\delta y \simeq \Delta y/N_A$. There are approximately

$$N_A \;=\; 2\pi(r_{\rm tube})^2 R_A\,\rho_0 \;\simeq\; 0.82\ A^{1/3} \tag{5}$$

participant nucleons in a tube of nucleonic radius $r_{\rm tube} \simeq 0.8$ fm and length $2R_A$ in the lab; for pU, this gives $N_A \simeq 5$, and hence $\delta y \simeq 0.5$. Thus, a J/ψ of lab rapidity y_ψ encounters target participants with density $\gamma\rho_0$ over a longitudinal distance $d = L/\gamma$, where $\gamma \equiv \cosh(y_\psi - \delta y)$. The survival probability (1) thus becomes

$$S_{\delta y} \;=\; \exp\left\{-\int_0^{L/\gamma} \gamma\rho_0\sigma_{\psi N}\,dz\right\} = \exp\{-\sigma_{\psi N}\rho_0 L\}, \tag{6}$$

so that stopping effects indeed cancel.

Next, we discuss how the finite J/ψ formation time modifies nuclear absorption. We begin with a $c\bar{c}$ pair of rest mass $M_\psi = 3.1$ GeV formed in a pA collision at the center of the target with a lab rapidity y_ψ. The time needed for this pair to escape the nucleus is $t_{escape} \simeq R_A/\gamma\beta$, where $\gamma = \cosh y_\psi$. If this escape time is shorter than the formation time, the $c\bar{c}$ pair cannot form a J/ψ bound state until it is well outside the target nucleus. When first produced, the $c\bar{c}$ pair is essentially pointlike with a spatial extension of about $M_\psi^{-1} \simeq 0.06$ fm. In the $c\bar{c}$ rest frame, the pair requires about 0.9 fm to expand into a bound J/ψ with $r_\psi \simeq 0.23$ fm [26–28]. Roughly 70% of the observed J/ψ's are directly produced $1S$ states; the remaining 30% are decay products of $1P$ χ_c's [21], with $r_\chi \simeq 0.35$ fm and formation time 2.0 fm. Therefore, the observed J/ψ's have an average formation time $\tau_\psi \simeq 1.2$ fm, much larger than the escape time in most pA experiments. For example, a physical J/ψ at $\langle x_F \rangle \simeq 0.3$ in 800 GeV interactions appears 100 fm from the center of the target.

Brodsky and Mueller observed that the dissociation cross section for a color singlet $c\bar{c}$ pair is reduced relative to the hadronic cross section $\sigma_{\psi N}$, because the pre-hadronic pair is smaller than the hadronic bound state [23]. Assuming that the J/ψ and χ hadronic dissociation cross sections are given by the total geometric cross sections [20], and with a 70%–30% superposition of ψ and χ states, we obtain $\sigma_{\psi N} \simeq 4.0$ mb for the saturation cross section. For an estimate of the evolution effects, we assume that the cross section of the growing $c\bar{c}$ increases as a power of the pair's separation, so that

$$\sigma(\tau) \ = \ \sigma_{\psi N} \ (\tau/\tau_\psi)^k , \tag{7}$$

during the time $\tau < \tau_\psi$ in the $c\bar{c}$ rest system. In general $k \geq 0$; in our calculations, we shall set $k = 2$ [16,29]. The form (7) holds only for $\tau \leq \tau_\psi$; afterwards $\sigma(\tau) = \sigma_{\psi N}$.

Since $\sigma(\tau) \leq \sigma_{\psi N}$, it is clear that the introduction of the J/ψ formation time always reduces the amount of suppression. In other words, the eikonal form (3) provides an upper bound on the possible suppression. Using (7) to account for the cross section evolution in (1), we find the exponent

$$W = \sigma_{\psi N} \rho_0 \int_0^L dz \ (\tau/\tau_\psi)^2 \ \leq \ \sigma_{\psi N} \rho_0 L. \tag{8}$$

A $c\bar{c}$ pair moving with lab rapidity y_ψ covers a distance $z = \tau\gamma\beta$ in the lab system during the proper time τ, with $\beta\gamma = \sinh y_\psi$. The inequality (8) thus becomes

$$[\sigma_{\psi N} \rho_0 L] \left(\frac{1}{3}\right) \left(\frac{L}{d_\psi}\right)^2 \ \leq \ \sigma_{\psi N} \rho_0 L, \tag{9}$$

where $d_\psi \equiv \tau_\psi \sinh y_\psi$ is the distance the nascent J/ψ must cover in the lab system before reaching its full size. Relation (9) holds as long as $L \leq d_\psi$; subsequently, the saturation cross section is reached and the conventional eikonal form is valid.

In the presence of stopping, the finite formation time increases the suppression beyond the value given by the l.h.s. of inequality (9). The functional form remains as before, but the formation length

$$d_\psi(\delta y) = \beta\gamma\tau_\psi = \tau_\psi \sinh(y_\psi - \delta y) \tag{10}$$

is reduced in the lab system by the rapidity shift δy of the target participants. We then find

$$\sigma_{\psi N} \rho_0 L \ \geq \ [\sigma_{\psi N} \rho_0 L] \left(\frac{1}{3}\right) \left(\frac{L}{d_\psi(\delta y)}\right)^2 \ \geq \ [\sigma_{\psi N} \rho_0 L] \left(\frac{1}{3}\right) \left(\frac{L}{d_\psi}\right)^2 , \tag{11}$$

showing that the suppression is greatest in the conventional eikonal description and least for the case of no stopping, but with a finite J/ψ formation time.

We now consider the suppression obtained in a more realistic description of pU interactions, incorporating stopping and a finite J/ψ formation time. The survival probability is [30]

$$S_{\delta y}(p\text{U}) \ = \ \exp\{-\sigma_{\psi N} \rho_0 R_A \ [R_A/d_\psi(\delta y)]^2/3\} \tag{12}$$

For J/ψ's produced at $x_F = 0$ with a 200 GeV p beam, we find $S_{\delta y=0.5}(p\text{U}) \simeq 0.87$, instead of the value 0.72 obtained in eq. (2). For an 800 GeV p beam, eq. (12) gives $S_{\delta y=0.5}(p\text{U}) \simeq 0.98$. In both cases, the suppression is much less than the observed 30–40% [13,14]. We thus conclude that in a realistic scenario, absorption on primary nucleons cannot account for the observed J/ψ suppression in pA collisions. Additional absorption from comoving mesons may produce a sufficient effect [17,18], although the measured equality of J/ψ and ψ' suppression [36] poses a general problem for absorption. Other mechanisms may well come into play [18,31,32]; the situation at large x_F also remains unclear.

The extension of our considerations to AB interactions is straightforward, with

$$S(AB) \ = \ S_{\delta y_B}(A) \ S_{\delta y_A}(B), \tag{13}$$

where we use (12) to determine $S_{\delta y}$ for interactions with both the projectile A and the target B. We assume the average projectile and target rapidity shifts are $\delta y_A \simeq N_B \delta y$ and $\delta y_B \simeq N_A \delta y$, taking $\delta y = 0.5$ and $N_{A,B}$ from (5). We obtain

$$S(\text{SU}) \simeq 0.59, \tag{14}$$

a somewhat larger result than the eikonal value 0.54 of eq. (3). One cannot compare this result directly to data as in eq. (4) because, as we have just shown in eq. (12), absorption cannot account for the suppression measured in pU collisions, once stopping and J/ψ formation time are included. We therefore use the experimental value $S(p\text{U}) \simeq 0.71$ for 200 GeV incident protons [13]. This leads to

$$[S(\text{SU})/S(p\text{U})] \ \simeq \ 0.83 \tag{15}$$

as the J/ψ suppression predicted for S-U relative to pU collisions in a more realistic absorption description. As expected, stopping and J/ψ formation time have further decreased the amount of suppression, compared to the conventional eikonal result (4).

The estimate (15) depends on the description of stopping and formation time, and is therefore quite model dependent. However, one can exploit the eikonal bounding property (11) to determine in a model independent way the *maximum* contribution of nucleon absorption to the ratios measured by NA38,

$$\frac{B_{\mu\mu}\sigma_\psi}{\sigma_{\rm cont}} \equiv \frac{B_{\mu\mu}(d\sigma/dE_T^0)_{AB\to\psi}}{(d\sigma/dE_T^0)_{AB\to{\rm cont}}}, \tag{16}$$

where E_T^0 is the neutral transverse energy in the pseudorapidity interval $1.4 < \eta < 4.1$ and $B_{\mu\mu}$ is the J/ψ branching ratio into dimuons. The correlation of J/ψ production with transverse energy provides information on centrality. For collisions of a given impact parameter b, the differential cross section for J/ψ production is

$$\left(\frac{d\sigma}{d^2b}\right)_{AB\to\psi} = \sigma_\psi^{NN}\int d^2s dz dz'\, \rho_A(b,z)\rho_B(\vec{b}-\vec{s},z')\, S, \tag{17}$$

where $\rho_{A,B}$ are the nuclear densities, σ_ψ^{NN} is the cross section for $NN \to \psi + X$ and S is the J/ψ survival probability (1) for the AB collision. The dimuon continuum cross section has a similar form, but with $S \equiv 1$ and σ_ψ^{NN} replaced by $\sigma_{\rm cont}^{NN}$. We calculate the E_T^0 dependent cross sections,

$$\left(\frac{d\sigma}{dE_T^0}\right)_{AB\to\psi} = \int d^2b\, P(E_T^0,b)\left(\frac{d\sigma}{d^2b}\right)_{AB\to\psi}, \tag{18}$$

where $P(E_T^0,b)$ is the probability that an AB collision of impact parameter b produces transverse energy E_T^0 in NA38's acceptence. We use the empirical form of $P(E_T^0,b)$ from [17]. To demonstrate that $P(E_T^0,b)$ correctly describes the correlation between E_T and centrality, we show in Fig. 1 that our calculation of $d\sigma/dE_T^0$ for the S-U continuum is in good agreement with data [7].

To obtain a bound on the absorption, we assume that J/ψ's interact with their saturation cross section, $\sigma_{\psi N}$. We must specify $\sigma_{\psi N}$ in S and the overall prefactor $\mathcal{N} \equiv B_{\mu\mu}\sigma_\psi^{NN}/\sigma_{\rm cont}^{NN}$ to compute the ratio (15) using (16-17). In the context of the eikonal model, the upper limit of $\sigma_{\psi N}$ is that value needed to account for all the suppression observed in pA experiments. NA3 data from pPt and pp suggest that $\sigma_{\psi N} = 4.8$ mb, a value close to our geometrical expectations. Comparison to the NA38 pCu and pU data then implies $\mathcal{N} = 2.4$. Alternatively, a fit to NA38 data ignoring the high statistics NA3 results implies $\sigma_{\psi N} = 7$ mb and $\mathcal{N} = 2.8$. Note that the extracted nucleon-nucleon ratios are in rough agreement with the cross sections $B_{\mu\mu}\sigma_\psi = 4.9$ nb and $\sigma_{\rm cont} = 1.8$ nb calculated following [33] and [34,35], respectively. Reassuringly, the extracted $\mathcal{N}$ and $\sigma_{\psi N}$ are close to our theoretical expectations. As we have stressed, the application of the naive eikonal description (2) in pA interactions is not well founded.

The calculated J/ψ-to-continuum ratios for O-U and S-U are compared to data in Figs. 2 and 3. For both values of $\sigma_{\psi N}$, these results fall well above the data. Since we have shown that $\sigma_{\psi N}$ gives the maximum possible absorption by primary nucleons, our results indicate that another source of J/ψ absorption is needed for a complete description of the data.

One source of additional suppression is scattering with comoving pions and resonances [10–12]. The S of (17) is multiplied by the comover survival probability $S_{\rm co}$ to

illustrate the role of these comovers. To estimate $S_{\rm co}$, we rewrite (1) as a time integral in the J/ψ's rest frame with $\tau = z/v_{\rm rel}$, where $v_{\rm rel} \sim 0.6$ is the average relative velocity between the J/ψ and the comovers,

$$S_{\rm co} = \exp\left\{-\int d\tau\, v_{\rm rel}\sigma_{\rm co} n\right\}. \tag{19}$$

The cross section for J/ψ dissociation by comovers is assumed to be $\sigma_{\rm co} \sim 2\sigma_{\psi N}/3$. Furthermore, the comover density varies as $n = n(\tau_0)\tau_0/\tau$ from the comover formation time, $\tau_0 = 2$ fm, until interactions effectively cease at $\tau_F \simeq R_A/v_{\rm rel}$. In Figs. 2 and 3 we vary $n(\tau_0)$ to fit the NA38 O-U and S-U data to find that the $n(\tau_0) \sim 0.8$ fm^{-3} $\sim 5\rho_0$ gives reasonable agreement with the data. These results agree with $n \sim 1$ fm^{-3}, found in earlier J/ψ analyses [17,18]. Densities of this magnitude are quite consistent with the assumption that comovers are hadrons.

In summary, we have found that absorption due to scattering with nucleons alone cannot account for the J/ψ suppression measured in either pA or AB collisions. Current fixed-target pA experiments have studied production only at $x_F > 0$ [13,14] so that the J/ψ forms well outside the target, inhibiting interactions with nucleons [17,18]. It is therefore necessary to include the additional suppression from scattering by comoving secondary particles [17], nuclear effects associated with intrinsic charm [18], shadowing [31] or parton energy loss [32] to describe the pA data.

Our AB conclusion is independent of theoretical uncertainties in descriptions of both the J/ψ formation dynamics and the stopping of the projectile ion. Current models of intrinsic charm [18], shadowing [31] and energy loss [32] effects cannot account for the centrality dependence measured in O-U and S-U collisions. An additional increase in density from secondaries can, however, lead to a consistent description of the data, provided the density of the secondaries is at least five times nuclear density.

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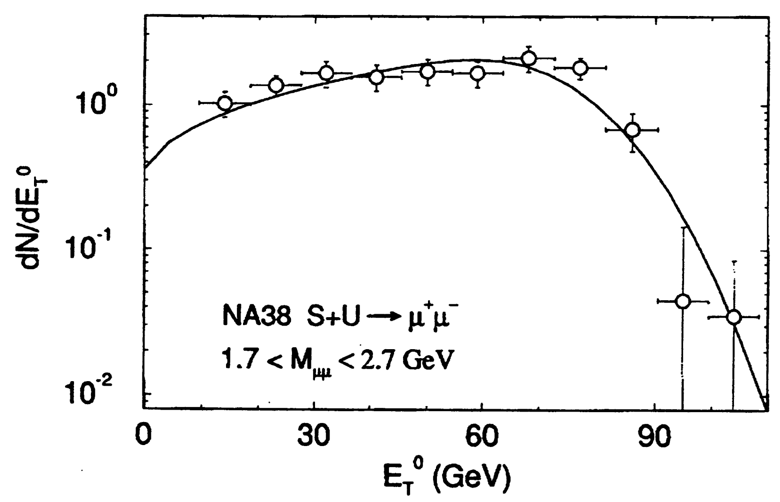
Figure Captions

Fig.1 The transverse energy dependence of continuum $\mu^+\mu^-$ pair production in 200 GeV S-U collisions. The data shown is from Ref. [5].

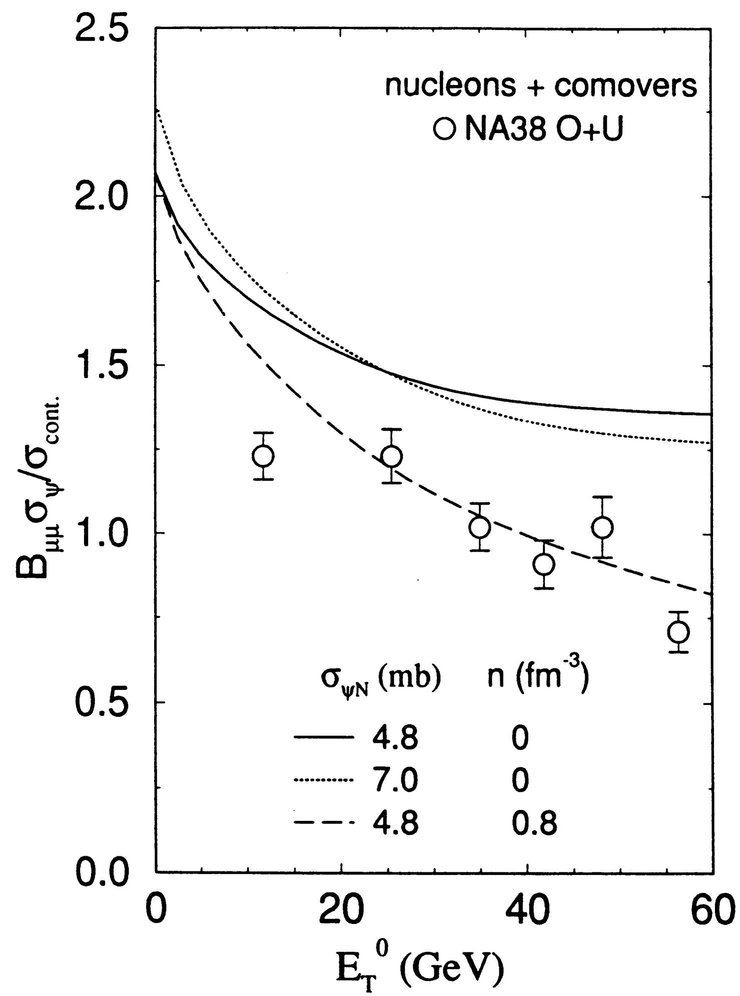
Fig.2 The contribution of nucleon absorption assuming $\sigma_{\psi N} = 4.8$ mb (solid curve) and 7 mb (dotted curve) are compared to NA38 O-U data. The dashed curve represents the combined contributions of nucleon and comover absorption for a comover density 0.8 fm^{-3}.

Fig.3 Same as Fig. 3 for S-U.



NA38 S+U → μ⁺μ⁻
1.7 < M_μμ < 2.7 GeV
dN/dE_T^0
E_T^0 (GeV)

Fig. 1



nucleons + comovers
○ NA38 O+U
σ_ψN (mb)   n (fm⁻³)
4.8   0
7.0   0
4.8   0.8
B_μμ σ_ψ/σ_cont.
E_T^0 (GeV)

Fig. 2

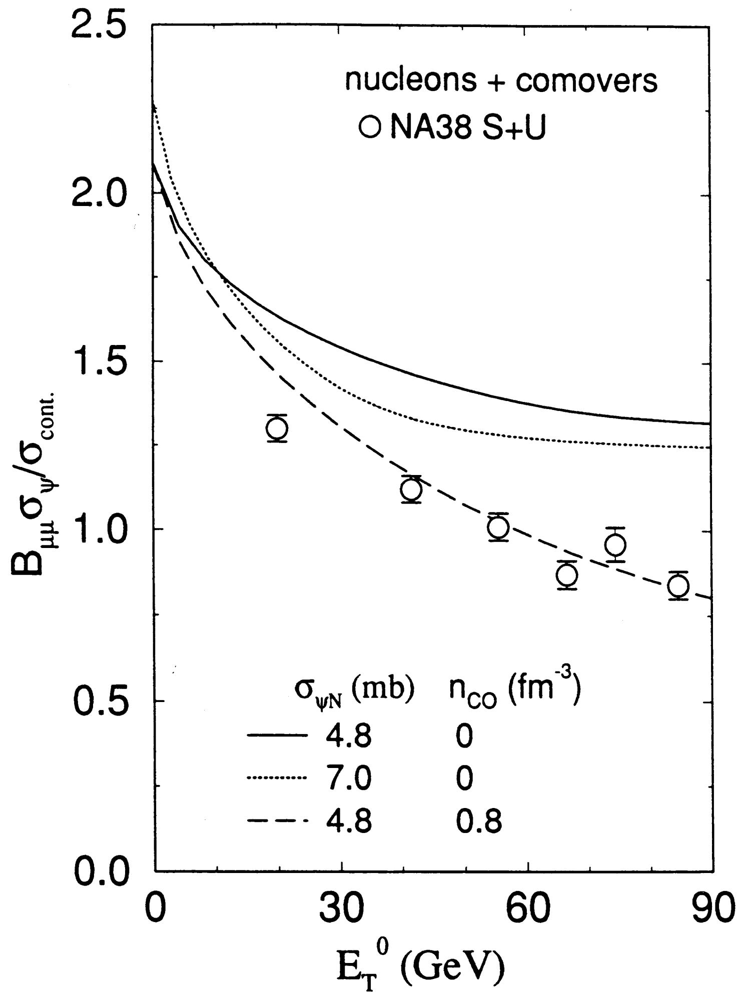

nucleons + comovers
NA38 S+U
$\sigma_{\psi N}$ (mb) n_{CO} (fm^{-3})
4.8 0
7.0 0
4.8 0.8
2.5
2.0
1.5
1.0
0.5
0.0
0
30
60
90
$B_{\mu\mu}\sigma_{\psi}/\sigma_{cont.}$
E_T^0 (GeV)

Fig. 3