What Causes ψ Suppression in Pb+Pb Collisions?

R. Vogt[a*]

[a]Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720
and
Physics Department, University of California at Davis, Davis, CA, 95616

A reexamination of hadronic comover scattering indicates that this mechanism cannot explain the observed ψ suppression in Pb+Pb interactions. The possibility of quark-gluon plasma formation is therefore considered. Implications for RHIC and LHC are also discussed.

The agreement of the NA50 Pb+Pb data [1] with naive comover models is reassessed. Previous work [2] is reanalyzed and expanded to include feeding of the ψ' and χ_c states to the ψ. The effect of color screening is also investigated. Only the ψ/Drell-Yan(DY) ratios are discussed here, for more details, see Ref. [3]. The ψ/DY ratio as a function of E_T is

$$\frac{B\sigma_\psi}{\sigma_{\mu^+\mu^-}} = \frac{B\sigma_{pp\to\psi}\int d^2b\int d^2s\, T_A^{\rm eff}(b)\, T_B^{\rm eff}(|\vec{b}-\vec{s}|)\, S_{AB}(b,s)\, p(E_T;b)}{\sigma_{pp\to\mu^+\mu^-}\int d^2b\int d^2s\, T_A(b)\, T_B(|\vec{b}-\vec{s}|)\, p(E_T;b)}\ . \tag{1}$$

The ψ, ψ' and χ_c are assumed to interact with nucleons while in $|c\bar{c}g\rangle$ color octet states with a lifetime of ≈ 0.3 fm [4]. The common survival probabilities for $|c\bar{c}g\rangle$ nucleon interactions are given by $T_A^{\rm eff}$ and $T_B^{\rm eff}$. Because the final charmonium state has formed by the time it interacts with comovers, the $\sim 30\%$ χ_c [5] and $\sim 12\%$ ψ' [6] decay contributions to ψ production are considered separately. The survival probability S_{AB}, including comovers and plasma screening, is

$$S_{AB}(b,s) = 0.58\, S_\psi^{\rm co}(b,s)\, S_\psi^{\rm QGP}(\epsilon) + 0.3\, S_{\chi_c}^{\rm co}(b,s)\, S_{\chi_c}^{\rm QGP}(\epsilon) + 0.12\, S_{\psi'}^{\rm co}(b,s)\, S_{\psi'}^{\rm QGP}(\epsilon) \tag{2}$$

where now

$$S_\psi^{\rm co}(b,s) = \exp\left\{-\langle\sigma_{\psi{\rm co}}v\rangle a n_{AB}(b,s)\ln\left(\frac{\tau_I(b)}{\tau_0(b,s)}\right)\right\} \tag{3}$$

depends on the participant density. Figure 1(a) shows the S+U ψ/DY ratios for $\sigma_{\psi N} = 7.3$ mb [7] and 4.8 mb [2]. Comovers are included for $\sigma_{\psi N} = 4.8$ mb with $\sigma_{\psi{\rm co}} \approx 2\sigma_{\psi N}/3 = 3.2$ mb $\sigma_{\psi'{\rm co}} \approx 3.8\sigma_{\psi{\rm co}}$, $\sigma_{\chi_c{\rm co}} \approx 2.4\sigma_{\psi{\rm co}}$, and $a = 0.21$ in S+U and Pb+Pb collisions [3].

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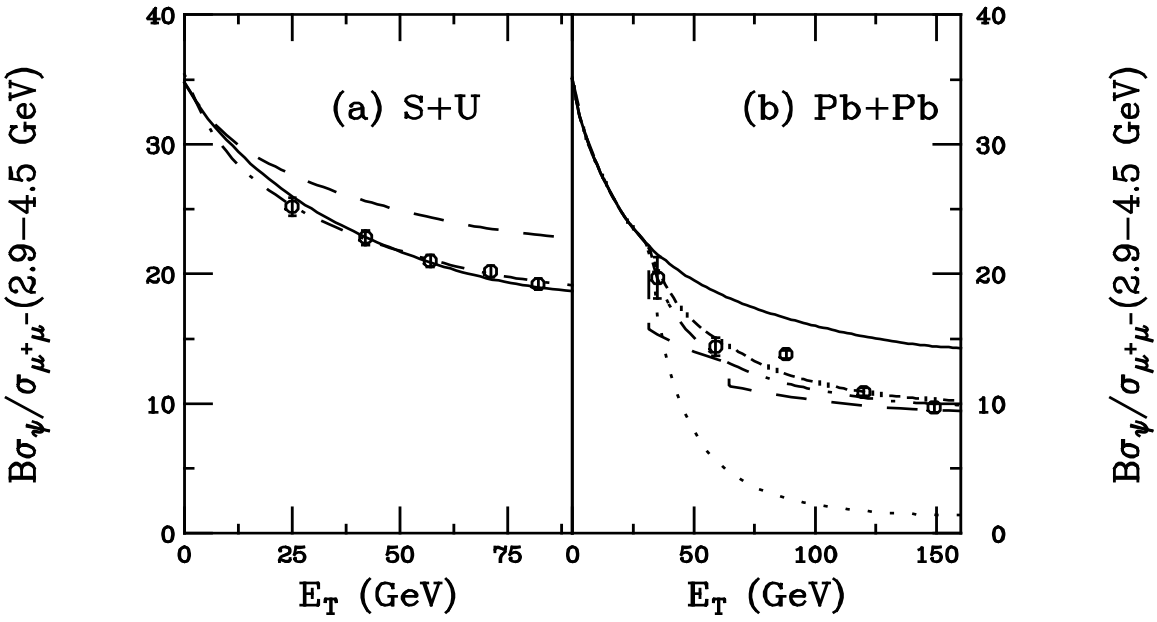

Figure 1. The ψ/DY calculations are compared with data from S+U [8] (a) and Pb+Pb [9] (b) interactions, both at 200 GeV. The solid curve shows $\sigma_{\psi N} = 4.8$ mb and $\sigma_{\psi\mathrm{co}} = 3.2$ mb with $a = 0.21$. The dashed and dot-dashed assume $\sigma_{\psi\mathrm{co}} = 0$ for $\sigma_{\psi N} = 4.8$ mb and $\sigma_{\psi N} = 7.3$ mb [7], respectively. In (b), plasma screening is included. The dashed and dot-dot-dashed-dashed curves illustrate case I assuming total suppression and $R = R_{\mathrm{Pb}}$ respectively. The dot-dashed and dotted curves correspond to cases II and III with $R = R_{\mathrm{Pb}}$.

The conclusions that can be drawn from Fig. 1 differ from those reached in Ref. [2] since the Pb+Pb result now disagrees with the data. The major difference lies in the normalization of the ψ/DY ratio to the *pp* ratio in the NA50 phase space. The angular adjustment to $|\cos\theta_{\mathrm{CS}}| < 0.5$ was left out of the Pb+Pb calculation, resulting in a 23% lower normalization in Ref. [2]. The results now suggest that the suppression is inconsistent with the assumption of the same maximum comover density in S+U and Pb+Pb interactions [2] although agreement in alternative models is not ruled out [10].

In light of this conclusion, color screening effects are investigated. The quarkonium potential is expected to be modified at finite temperatures by the screening mass $\mu(T)$ [11]. We assume that $\mu^2(T) = (6 + n_f)\, g^2(T) T^2/6$ where $g^2(T) = 48\pi^2/[(33 - 2n_f)\ln F^2]$ with $F = K(T/T_c)(T_c/\Lambda_{\overline{MS}})$ [12]. In SU(3) gauge theory, $T_c = 260$ MeV [13], $T_c/\Lambda_{\overline{\mathrm{MS}}} = 1.03 \pm 0.19$ [14] and a fit to the heavy quark potential at high temperatures yields $K \approx 33.8$ [12]. Lattice results with n_f =2 and 4 suggest $T_c = 170$ MeV and $T_c/\Lambda_{\overline{\mathrm{MS}}} = 1.05$ [14]. If the SU(3) value of K is applicable when $n_f > 0$, then the χ_c and ψ' break up while the ψ itself would not. Since the high temperature limit is probably invalid at the SPS, we also use a fit to lattice results for $T \geq T_c$ [12] which gives lower values of K, suggesting the χ_c, ψ' and ψ break up at T_c. Thus, the ψ/DY ratio could exhibit one or two thresholds as a function of E_T. We choose three illustrative cases: I) $n_f = 3$, sequential χ_c and ψ'

break up; II) $n_f = 4$, χ_c and ψ' break up at T_c; and III) all charmonium states break up at T_c. Cases I and II assume $K \approx 33.8$ while case III takes K from the fit for $T \geq T_c$ [12].

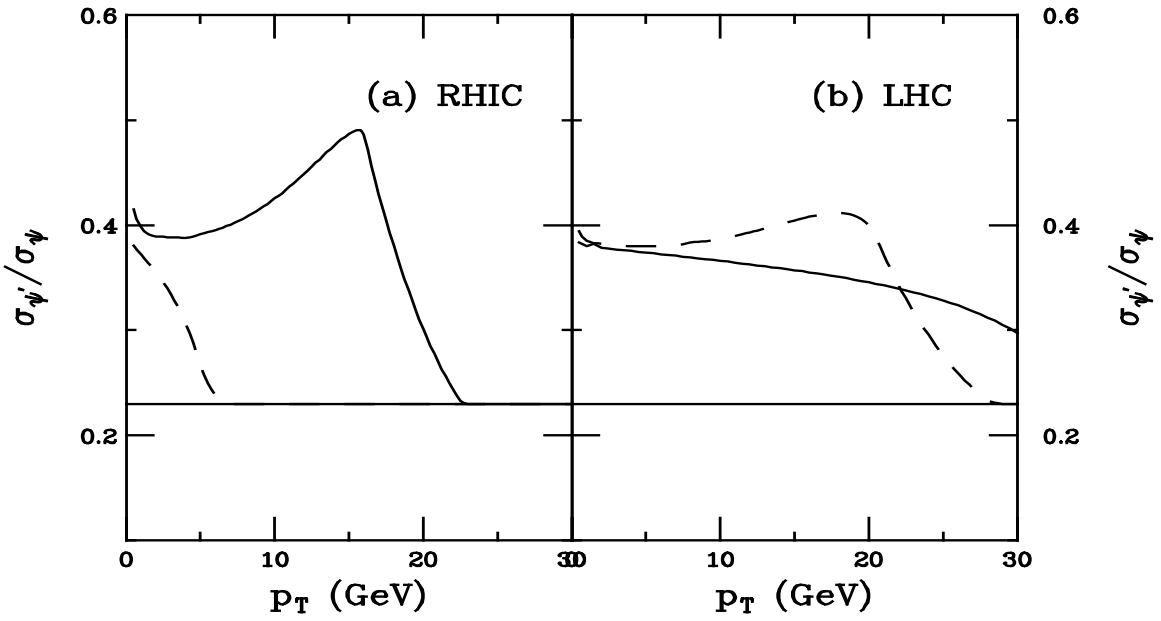

Figure 2. The direct or prompt ψ'/ψ ratio as a function of p_T is shown for several choices of initial conditions at RHIC and LHC assuming case I above. In (a), RHIC parton gas results are shown with $R = R_{\rm Pb}$ (solid) and $R = 1$ fm (dashed). In (b) the LHC results are given with $R = R_{\rm Pb}$ for the parton gas (solid) and a minijet plasma (dashed).

Calculations with plasma screening are shown with the Pb+Pb data in Fig. 1(b) assuming $R = R_{\rm Pb}$ and $p_T \approx 0$ except for the dashed curve where the suppression is assumed to be total above the break-up temperature. Realistic models do not show sharp thresholds due to the finite size of the system and fluctuations of E_T and b, noted also in [15,16]. A sudden change of slope, not predicted by hadronic models, appears when the plasma suppression begins, even without the assumption of total suppression. Note that case III overpredicts the suppression and that the thresholds introduced in case I are somewhat low relative to the data [1]. With $R = 1$ fm, case III is comparable to cases I and II with $R = R_{\rm Pb}$ when $p_T \approx 3$ GeV, somewhat higher than measured at the SPS [1], perhaps suggesting that only the χ_c and ψ' are suppressed. Similar results are obtained if $\sigma_{\psi N} = 7.3$ mb and comovers are not included.

At RHIC and LHC, perturbative QCD processes will influence the initial conditions, producing very hot, dense systems. The parton gas [17], dominated by kinetic equilibration, will have a longer lifetime than the initially hotter minijet plasma [18] produced by semi-hard scatterings. A high statistics study of ratios such as ψ'/ψ and Υ'/Υ as a function of p_T may conclusively determine the initial conditions as well as the temperature dependence of $\mu(T)$ [19]. In Fig. 2 the direct ψ'/ψ ratio is shown for case I at RHIC and LHC, following Ref. [19]. Other cases show a different p_T dependence. Therefore,

if plasma screening is found to be the source of the current ψ suppression, the precise behavior of the ψ'/ψ and Υ'/Υ ratios at RHIC and LHC would place severe constraints on the initial conditions.

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