Title

Impact Parameter Dependence of J/ψ and Drell-Yan Production in Heavy Ion Collisions at $\sqrt{s_{NN}} = 17.3$ GeV

Authors

Emel'yanov, V
Khodinov, A
Klein, SR
et al.

Publication Date

1998-09-01

Peer reviewed

LBNL-42170, August 12 1998

Impact Parameter Dependence of J/ψ and Drell-Yan Production in Heavy Ion Collisions at $\sqrt{s_{NN}} = 17.3$ GeV

V. Emel'yanov[1], A. Khodinov[1], S. R. Klein[2] and R. Vogt[2,3]

[1]*Moscow State Engineering Physics Institute (Technical University), Kashirskoe ave. 31, Moscow, 115409, Russia*

[2]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

[3]*Physics Department, University of California, Davis, CA 95616, USA*

Abstract

In heavy-ion collisions, J/ψ and Drell-Yan production are expected to be affected by nuclear modifications to the free nucleon structure functions. If these modifications, known as shadowing, are proportional to the local nuclear density, the per nucleon cross sections will depend on centrality. Differences in quark and gluon shadowing will lead to a new source of impact parameter dependence of the J/ψ to Drell-Yan production ratio. We calculate this ratio in the CERN NA50 acceptance with several shadowing parameterizations to explore its centrality dependence.

A significant 'anomalous' suppression of J/ψ production has been observed in Pb+Pb collisions. The ratio of J/ψ to Drell-Yan production is lower in central Pb+Pb collisions than extrapolations from more peripheral collisions, lighter ion interactions, and pA collisions suggest [1]. Centrality is inferred from the transverse energy, E_T.

Almost all calculations of J/ψ and Drell-Yan production in nuclear collisions to date have been based on position independent nucleon [2] or nuclear structure functions [3]. However, nuclear shadowing should depend on the parton's location inside the nucleus. If shadowing is due to gluon recombination [4], nuclear binding or rescaling [5], or other local phenomena, it should be proportional to the local nuclear density. The only studies of spatial dependence have relied on qualitative measurements of impact parameter, such as dark tracks in emulsion [6], to find evidence for such a spatial dependence.

This letter presents calculations of the impact parameter dependence of nuclear shadowing on J/ψ and Drell-Yan production in heavy ion collisions. This spatial dependence has an important effect on the E_T dependence of J/ψ and Drell-Yan production. Since J/ψ suppression is a predicted signature of quark-gluon plasma formation [7], interpretations [2] of the anomalous suppression in the NA50 Pb+Pb data [1] should include the spatial dependence of the structure functions on the J/ψ and Drell-Yan rates. We focus on the effects of shadowing and neglect J/ψ absorption mechanisms.

At leading order (LO), J/ψ production is dominated by gluon fusion while Drell-Yan production is due to $q\overline{q}$ annihilation. Thus if the quark and gluon distributions are affected differently by shadowing, and if shadowing has a spatial dependence, the J/ψ to Drell-Yan ratio can vary with impact parameter. We present results in the acceptance of the CERN NA50 experiment [1].

To be consistent with the NA50 analysis, we calculate J/ψ and Drell-Yan production at leading order, LO. The LO cross section for nuclei A and B colliding at impact parameter b with center of mass energy $\sqrt{s_{NN}}$ and producing a particle V (J/ψ or γ^*) with mass m at scale Q is

$$\frac{d\sigma_{AB}^V}{dydm^2d^2bd^2r} = \sum_{i,j}\int dz\,dz' F_i^A(x_1,Q^2,\vec{r},z)F_j^B(x_2,Q^2,\vec{b}-\vec{r},z')\frac{d\widehat{\sigma}_{ij}^V}{dydm^2} \ , \tag{1}$$

where $\widehat{\sigma}_{ij}^V$ is the partonic $ij \to V$ cross section. The nuclear parton densities, F_i^A, are the product of momentum fraction, x, and Q^2 independent nuclear densities, ρ_A; position and atomic mass, A, independent nucleon parton densities, f_i^N; and a shadowing function, S^i:

$$F_i^A(x,Q^2,\vec{r},z) = \rho_A(s)S^i(A,x,Q^2,\vec{r},z)f_i^N(x,Q^2) \ , \tag{2}$$

where $s = \sqrt{r^2+z^2}$. In the absence of shadowing, $S^i(A,x,Q^2,\vec{r},z) \equiv 1$. The nuclear density is given by a Woods-Saxon distribution, $\rho_A(s) = \rho_0(1+\omega(s/R_A)^2)/(1+e^{(s-R_A)/d})$ where electron scattering data [8] are used to fix R_A, d, ω and ρ_0.

We use the color evaporation model of J/ψ production [9] so that

$$\begin{aligned} f_i^N(x_1,Q^2)f_j^N(x_2,Q^2)\frac{d\widehat{\sigma}_{ij}^{J/\psi}}{dydm^2} &= K_{\rm th}\left\{ f_g^N(x_1,Q^2)f_g^N(x_2,Q^2)\frac{\sigma_{gg}(m^2)}{m^2} \right. \\ &+ \left. \sum_{q=u,d,s}[f_q^N(x_1,Q^2)f_{\overline{q}}^N(x_2,Q^2) + f_{\overline{q}}^N(x_1,Q^2)f_q^N(x_2,Q^2)]\frac{\sigma_{q\overline{q}}(m^2)}{m^2}\right\} \ . \end{aligned} \tag{3}$$

The LO partonic $c\overline{c}$ cross sections are defined in [10] and $m^2 = x_1x_2s_{NN}$. The fraction of $c\overline{c}$ pairs that become J/ψ's is fixed at next-to-leading order (NLO) [9]. The ratio of the NLO to LO cross section is given by $K_{\rm th}$. We use the GRV LO [12] nucleon parton distributions with $m_c = 1.3$ GeV and $Q = m_c$ as well as the MRS A$'$ densities [13] with $m_c = 1.2$ GeV and $Q = 2m_c$ where m_c and Q are chosen to agree with data [9].

The LO Drell-Yan cross section depends on isospin since $\sigma_{pp}^{\rm DY} \neq \sigma_{pn}^{\rm DY} \neq \sigma_{np}^{\rm DY} \neq \sigma_{nn}^{\rm DY}$

$$\begin{aligned} & f_i^N(x_1,Q^2)f_j^N(x_2,Q^2)\frac{d\widehat{\sigma}_{ij}^{\rm DY}}{dydm^2} = K_{\rm exp}\frac{4\pi\alpha^2}{9m^2s_{NN}} \\ & \times \sum_{q=u,d,s} e_q^2\left[\left\{\frac{Z_A}{A}f_q^p(x_1,Q^2) + \frac{N_A}{A}f_q^n(x_1,Q^2)\right\}\left\{\frac{Z_B}{B}f_{\overline{q}}^p(x_2,Q^2) + \frac{N_B}{B}f_{\overline{q}}^n(x_2,Q^2)\right\} + q \leftrightarrow \overline{q}\right] \ , \end{aligned} \tag{4}$$

where Z_A and N_A are the number of protons and neutrons in the nucleus. We assume that $f_u^p = f_d^n$, $f_d^p = f_u^n$ *etc.* In Eqs. (3) and (4), $x_{1,2} = Qe^{\pm y}/\sqrt{s_{NN}}$ and $Q = m$. The factor $K_{\rm exp}$ accounts for the rate difference between the calculations and the data.

Three parameterizations of shadowing, based on nuclear DIS [14], are used. The first, $S_1(A,x)$, treats quarks, antiquarks, and gluons equally without Q^2 evolution [15]. The other two evolve with Q^2 and conserve baryon number and total momentum. The second, $S_2^i(A, x, Q^2)$, modifies the valence quarks, sea quarks and gluons separately for $2 < Q < 10$ GeV [16]. The most recent, $S_3^i(A, x, Q^2)$, evolves each parton distribution separately for $Q \geq 1.5$ GeV [17]. The S_3 initial gluon distribution shows important antishadowing in the region $0.1 < x < 0.3$ with sea quark shadowing in the same x range. In contrast, S_2 has less gluon antishadowing and essentially no sea quark effect.

Since we assume that shadowing is proportional to the local nuclear density, the spatial dependence is defined as

$$S^i_{\rm WS} = S^i(A, x, Q^2, \vec{r}, z) = 1 + N_{\rm WS}[S^i(A, x, Q^2) - 1]\frac{\rho(s)}{\rho_0} \ , \qquad (5)$$

where $N_{\rm WS} =$ is chosen so that $(1/A) \int d^3s \rho(s) S^i_{\rm WS} = S^i$, similar to [18]. For lead, $N_{WS} = 1.32$. At large radii, $s \gg R_A$, $S^i_{\rm WS} \rightarrow 1$ while at the nuclear center, the modifications are larger than the average S^i. An alternative parameterization, $S^i_{\rm R}$, proportional to the thickness of a spherical nucleus [19], leads to a slightly larger modification in the nuclear core.

We model our calculations to the NA50 experimental acceptance with center of mass rapidity $0 < y_{\rm cm} < 1$ and decay angle in the Collins-Soper frame $|\cos\theta_{\rm CS}| < 0.5$ [1]. The Drell-Yan spectrum is measured for $m > 4.2$ GeV and the factor $K_{\rm exp}$ is extracted by comparing to Eq. (4) calculated with the GRV LO distributions [12]. The ratio $\sigma^{J/\psi}/\sigma^{\rm DY}$ is formed by extrapolating the calculations to $2.9 < m < 4.5$ GeV with the same $K_{\rm exp}$ because J/ψ and ψ' decays dominate the region $2.7 < m < 3.5$ GeV. Table I give the impact parameter averaged cross sections per nucleon pair for the GRV LO and MRS A$'$ distributions, for pp, Pb+Pb and S+U interactions. The numbers show the effects of isospin and shadowing at $\sqrt{s_{NN}} = 17.3$ GeV. With the MRS A$'$ set, the isospin correction is quite small in the extrapolated region [20]. Because isospin is unimportant in J/ψ production, only the Pb+Pb cross section is shown. However, the J/ψ data suggests that the AB dependence might be stronger if shadowing could be removed from the data. Although the choice of parton densities influences the isospin effect and $K_{\rm exp}$, the average Drell-Yan shadowing is changed by less than 1% while the difference in J/ψ shadowing can be as large as 5%, largely because the gluon distribution is imprecisely measured. The table shows that the dependence on the nuclear species is weak. The change in the shadowing is also $\sim 1\%$ when $\sqrt{s_{NN}} = 19.4$ GeV. Most important is the mass interval: shadowing is 5% stronger in the measured region than the extrapolated region.

To illustrate how shadowing could affect the interpretation of J/ψ suppression, Fig. 1 shows the Drell-Yan mass distribution for $m > 2.9$ GeV in three impact parameter bins relative to no shadowing, $S = 1$. Shadowing changes the slope of the spectrum, producing a $\sim 20\%$ change in the predicted rate at $m \approx 9$ GeV. The absence of Q^2 evolution causes the S_1 results to decrease faster with mass than S_2 or S_3. Including only spatially-averaged shadowing increases $K_{\rm exp}$ over that needed for $S = 1$ in the measured region relative to the extrapolated region, shown in Table I, as well as further increase the discrepancy in central collisions while overestimating $K_{\rm exp}$ in peripheral collisions. At small radii, Fig. 1(a), $d\sigma^{\rm DY}/dm$ drops more rapidly than the impact parameter averaged spectra. When $b \approx R_A$, Fig. 1(b), the averaged and spatial dependent spectra approximately coincide. At large radii, Fig. 1(c), shadowing is reduced, approaching the unshadowed spectra. These results show that using a calculation to extrapolate to an unmeasured region is problematic.

Figure 2 shows the impact parameter dependence of the J/ψ and Drell-Yan cross sections. The x_2 ranges of the two processes nearly coincide: the Drell-Yan region $2.9 < m < 4.5$ GeV corresponds to $0.062 < x_2 < 0.26$ while the J/ψ cover $0.066 < x_2 < 0.18$. Since all three parameterizations assume some gluon antishadowing in this region, $\sigma^{J/\psi}$ is always enhanced in Pb+Pb collisions. Because S_1 is the same for quarks and gluons, J/ψ and Drell-Yan are equally affected by shadowing. On other hand, $S^{\overline{q}}_{2,3} \leq 1$, reducing $\sigma^{\rm DY}$.

In Fig. 3, $\sigma^{J/\psi}/\sigma^{\rm DY}$, calculated in Eqs. (1)-(4), is presented as a function of E_T. The correlation between E_T and b is based on the number of nucleon participants [2], in agreement with the most recent NA50 E_T distributions [20]. The Drell-Yan cross section is corrected for isospin and $\sigma^{J/\psi}/\sigma^{\rm DY}$ is calculated at $\sqrt{s_{NN}} = 19.4$ GeV. After these adjustments, with $S = 1$, $\sigma^{J/\psi}/\sigma^{\rm DY} \sim 40.3$, in agreement with the published NA50 data [1]. The combined

Drell-Yan shadowing and J/ψ antishadowing in Fig. 2 increases $\sigma^{J/\psi}/\sigma^{\rm DY}$to 40.6 with S_1, 44.5 for S_2 and 54.4 using S_3. The S_1 ratio is independent of E_T because the b dependence cancels. However, S_2 and S_3 vary with E_T. The S_2 ratio rises about 7% while the S_3 ratio increases $\approx 11\%$ as $\langle E_T \rangle$ grows from 14 GeV to 120 GeV. These enhancements are opposite to the observed drop at large E_T and small b [1], neglecting shadowing.

Because of uncertainties in the gluon shadowing parameterization, it is difficult to draw detailed conclusions. However, S_1 should represent a lower limit and S_3 an upper limit. A stronger spatial dependence such as $S^i_{\rm R}$ would slightly increase the effect with E_T while parameterizations based on *e.g.* nuclear binding [5] might predict a smaller effect.

In conclusion, we have studied the impact parameter dependence of the ratio $\sigma^{J/\psi}/\sigma^{\rm DY}$ using a spatially dependent shadowing model. We find that the ratio increases at small b (large E_T) compared with more peripheral collisions. The magnitude of the effect depends on the chosen parameterization. Neglecting shadowing could lead to an increased $K_{\rm exp}$ at $\sqrt{s_{NN}} = 17.3$ GeV since the measured cross section is more strongly affected by shadowing than the extrapolated cross section. In addition, using an impact parameter averaged spectra in central collisions would tend to underestimate the total number of Drell-Yan pairs, increasing $\sigma^{J/\psi}/\sigma^{\rm DY}$. If this effect could be identified and corrected for in the data, then $\sigma^{J/\psi}/\sigma^{\rm DY}$ would rise $\sim 10\%$ at low E_T and drop $\sim 4\%$ at high E_T, enhancing the discrepancy between absorption models and the data. At higher $\sqrt{s_{NN}}$, such as at future heavy-ion colliders, the shadowing effect will be larger [21] since these colliders probe lower x values.

V.E. and A.K. would like to thank the LBNL RNC group for hospitality and M. Strikhanov and V.V. Grushin for discussions and support. R.V. would like to thank J. Schukraft for discussions. We also thank K.J. Eskola for providing the shadowing routines and for discussions. This work was supported in part by the Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U. S. Department of Energy under Contract Number DE-AC03-76SF00098.

REFERENCES

[1] M.C. Abreu *et al.* (NA50 Collab.), Phys. Lett. **B410**, 337 (1997); Phys. Lett. **B410**, 327 (1997).

[2] For a recent review, see R. Vogt, LBNL-41758 (1998), to appear in Phys. Rep.

[3] S. Gupta and H. Satz, Z. Phys. **C55** 391, (1992); N. Hammon *et al.*, hep-ph/9807546.

[4] L.V. Gribov, E.M. Levin, and M.G. Ryskin, Phys. Rep. **100** 1, (1983).

[5] S. Kumano and F.E. Close, Phys. Rev. C **41**, 1855 (1990).

[6] T. Kitagaki *et al.*, Phys. Lett. **B214**, 281 (1988).

[7] T. Matsui and H. Satz, Phys. Lett. **B178** 416 (1986).

[8] C.W. deJager, H. deVries, and C. deVries, Atomic Data and Nuclear Data Tables **14** 485, (1974).

[9] R.V. Gavai *et al.*, Int. J. Mod. Phys. **A10** 3043 (1995); G.A. Schuler and R. Vogt, Phys. Lett. **B387** 181, (1996).

[10] B.L. Combridge, Nucl. Phys. **B151** 429, (1979).

[11] S. Gavin *et al.*, Int. J. Mod. Phys. **A10** 2961 (1995).

[12] M. Glück, E. Reya, and A. Vogt, Z. Phys. **C53** 127, (1992).

[13] A.D. Martin, R.G. Roberts and W.J. Stirling, Phys. Lett. **B354** 155, (1995).

[14] M. Arneodo, Phys. Rep. **240** 301 (1994); M.R. Adams *et al.*, Phys. Rev. Lett. **68** 3266, (1992).

[15] K.J. Eskola, J. Qiu, and J. Czyzewski, private communication.

[16] K.J. Eskola, Nucl. Phys. **B400** 240, (1993).

[17] K.J. Eskola, V.J. Kolhinen and P.V. Ruuskanen, hep-ph/9802350, Nucl. Phys. **B** in

press; K.J. Eskola, V.J. Kolhinen and C.A. Salgado, hep-ph/9807297.

[18] P. Castorina and A. Donnachie, Z. Phys. C **49**, 481 (1991).

[19] V. Emel'yanov, A. Khodinov, S.R. Klein and R. Vogt, Phys. Rev. Lett **81**, 1801 (1998); V. Emel'yanov, A. Khodinov, S.R. Klein and R. Vogt, Phys. Rev. **C56**, 2726 (1997); V. Emel'yanov, A. Khodinov and M. Strikhanov, Yad. Fiz. **60**, 539 (1997) [Phys. of Atomic Nuclei, **60** 465, (1997)]; V. Emel'yanov and A. Khodinov, Yad. Fiz. **60**, 1489 (1997) [Phys. of Atomic Nuclei, **60** 1352, (1997)].

[20] A. Romana *et al.* (NA50 Collab.), in Proceedings of the 33$^{\rm rd}$ Rencontres de Moriond, *QCD and High Energy Hadronic Interactions*, Les Arcs, France, 1998.

[21] V. Emel'yanov, A. Khodinov, S.R. Klein and R. Vogt, in preparation.

TABLES

	Drell-Yan ($2.9 < m < 4.5$ GeV)			Drell-Yan ($4.2 < m < 9$ GeV)			J/ψ
	σ_{pp} (pb)	$\sigma_{\rm PbPb}$ (pb)	$\sigma_{\rm SU}$ (pb)	σ_{pp} (pb)	$\sigma_{\rm PbPb}$ (pb)	$\sigma_{\rm SU}$ (pb)	$\sigma_{\rm PbPb}$ (nb)
				GRV LO			
$S = 1$	16.6	12.7	13.3	2.31	1.66	1.76	1.61
$S = S_1$	–	12.8	13.5	–	1.61	1.72	1.64
$S = S_2$	–	12.5	13.1	–	1.56	1.67	1.84
$S = S_3$	–	11.9	12.6	–	1.48	1.61	2.04
				MRS A$'$			
$S = 1$	18.8	18.3	19.0	2.15	2.17	2.29	1.53
$S = S_1$	–	18.6	19.4	–	2.10	2.26	1.58
$S = S_2$	–	18.1	18.9	–	2.03	2.19	1.74
$S = S_3$	–	17.2	18.1	–	1.93	2.10	1.85

TABLE I. The Drell-Yan extrapolated and measured cross sections in pp, Pb+Pb and S+U collisions and the J/ψ cross section in Pb+Pb collisions in the NA50 acceptance with the GRV LO and MRS A$'$ parton densities at $\sqrt{s_{NN}} = 17.3$ GeV. We have not included $K_{\rm exp} = 2.4$ for GRV LO and 1.7 for MRS A$'$.

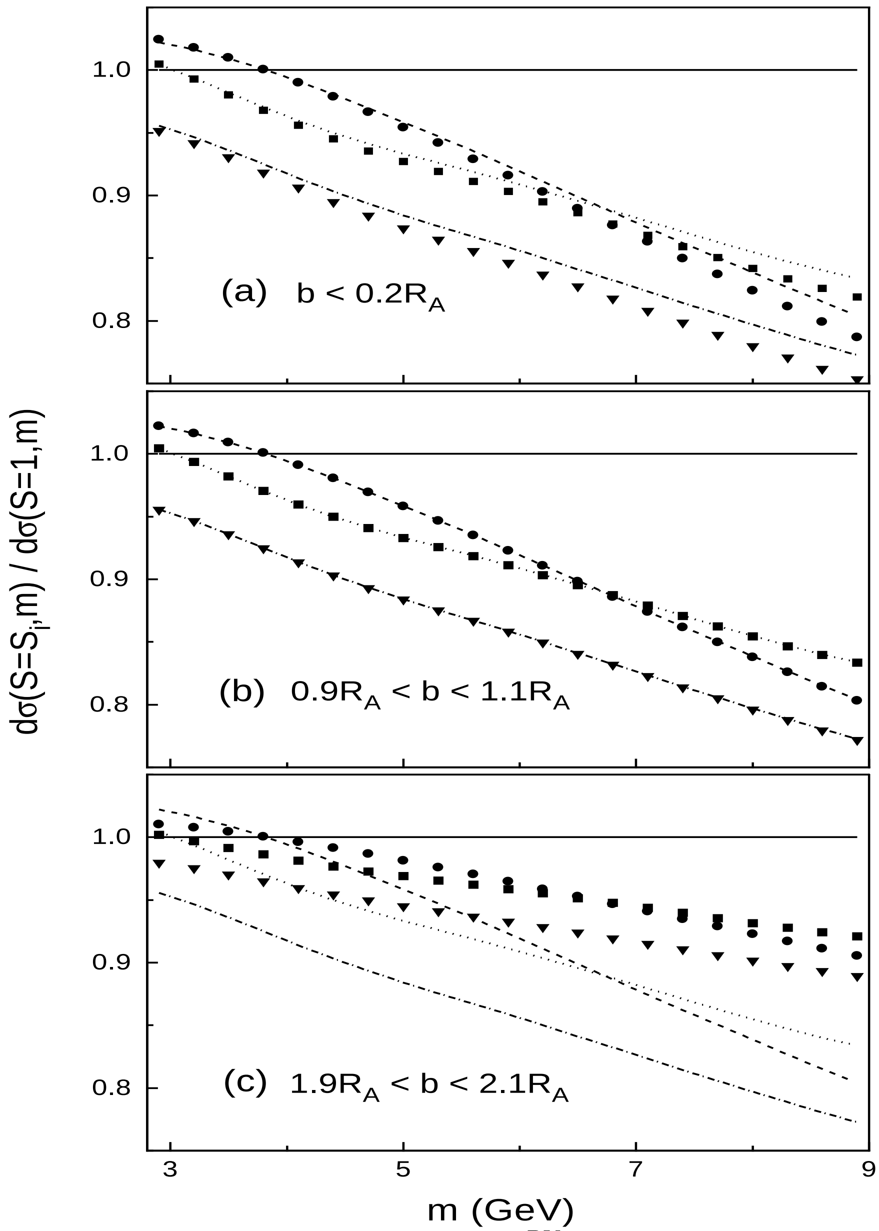

FIG. 1. The Drell-Yan dilepton mass spectrum, $d\sigma^{\rm DY}/dM$, without and with spatial dependence relative to $S = 1$. The curves correspond to b-averaged results with S_1 (dashed), S_2 (dotted) and S_3 (dot-dashed). The spatial dependence is illustrated for $S_{1,{\rm WS}}$ (circles) $S_{2,{\rm WS}}$ (squares) and $S_{3,{\rm WS}}$ (triangles). The impact parameter ranges are (a) $0 < b < 0.2R_A$ fm, (b) $0.9R_A < b < 1.1R_A$ fm and (c) $1.9R_A < b < 2.1R_A$ fm respectively.

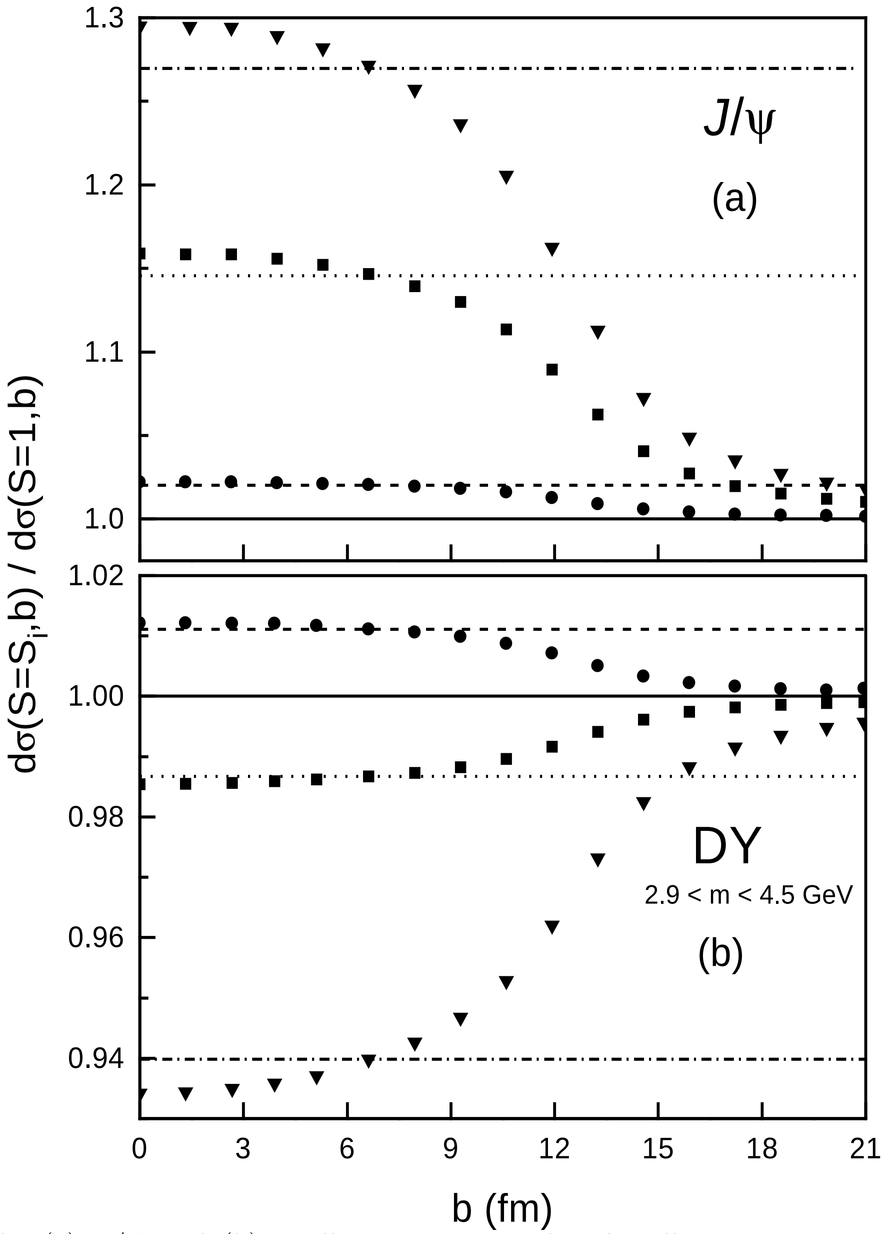

FIG. 2. The (a) J/ψ and (b) Drell-Yan rates in Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV relative to production without shadowing, $S = 1$, as a function of impact parameter. The curves and symbols are defined in Fig. 1.

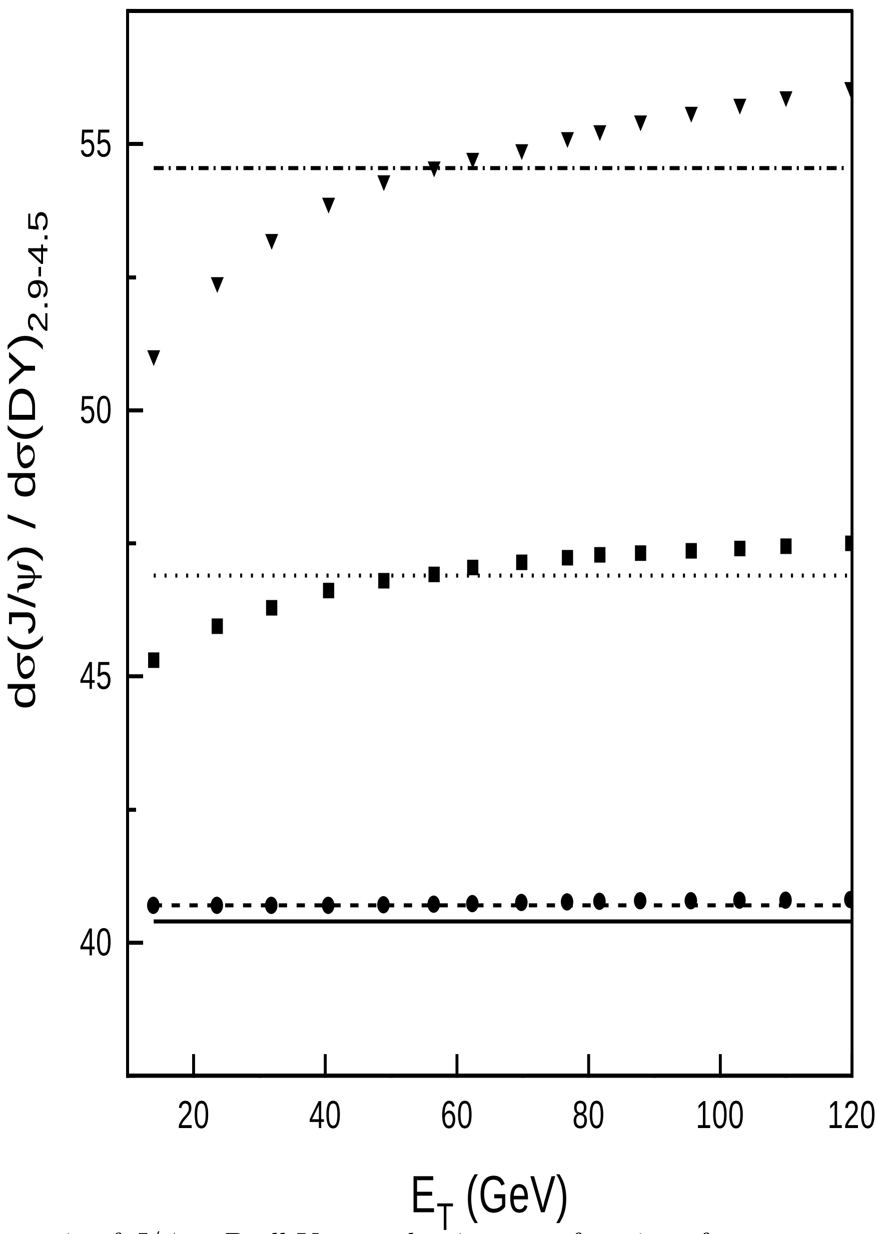

FIG. 3. The ratio of J/ψ to Drell-Yan production, as a function of transverse energy, E_T. The curves and symbols are defined in Fig. 1.