Double-spin asymmetry of J/ψ production in polarized pp collisions

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(Received 29 January 1997; revised manuscript received 3 July 1997)

We calculate the color-octet contribution to the double spin asymmetry of J/ψ hadroproduction with nonzero transverse momenta at fixed target energies $\sqrt{s}\simeq 40$ GeV. It is shown that the color-octet contribution is dominant in the asymmetries. The expected asymmetries and statistical errors in a future option of DESY HERA with longitudinally polarized protons at HERA-$\vec{N}$ should allow one to distinguish between different parametrizations for the polarized gluon distribution in the proton. [S0556-2821(97)04321-X]

PACS number(s): 13.85.Ni, 12.38.Bx, 13.88.+e, 14.40.Gx

I. INTRODUCTION

Presently the most accurate way to measure the polarized gluon distribution function in the nucleon is to study those processes which can be calculated in the framework of perturbative QCD (PQCD), i.e., for which the involved production cross sections and subprocess asymmetries can be predicted. One of the cleanest ways to probe QCD is to investigate heavy quarkonia production processes. Heavy quark pair production processes can be controlled perturbatively due to a large mass of constituents. On the other hand, heavy quark systems are mainly produced in gluon fusion processes, and, therefore, asymmetries are expected to be sensitive to the polarized gluon distribution in the nucleon. Investigation of heavy quarkonia production processes in polarized experiments would also yield further information about the quark-antiquark pair hadronization phase.

The two-spin asymmetry in J/ψ production has been studied in the framework of the so-called color singlet model (CSM) [1] by Morii and collaborators [2]. But as was shown in the last years, the color singlet model does not describe satisfactorily the heavy quarkonium hadroproduction at the Fermilab Tevatron and also at fixed target energies. While the CSM gives a reasonable description of the J/ψ production cross section distribution shapes over p_T or x_F at fixed target energies, it completely fails in the explanation of the integrated cross section (a K factor of 7–10 is needed to explain experimental data) [3]. There is also an essential discrepancy between theoretical predictions [4] and experimental data [5,6] for the relative production of different charmonium states J/ψ, χ_1, and χ_2. In particular, the leading twist QCD calculations [4] predict that the ratio of direct J/ψ and χ_{c2} production is about three times as small as the experimental value from πN collision data [5,6]. The discrepancy for χ_{c1} and χ_{c2} relative yield is larger; CSM predicts a ten times smaller value for $\sigma(\chi_{c1})/\sigma(\chi_{c2})$ then that observed experimentally [5,6]. In paper [4] it was also shown that leading twist calculations (in the CSM) of J/ψ polarization could not reproduce the existing experimental data [7–9] even after introducing different K factors for direct J/ψ, χ_1, and χ_2 states production. The anomalously large cross section [10] of J/ψ production at large transverse momenta at the Tevatron revealed another negative feature of the CSM. Within the framework of the CSM it is impossible to explain the anomalously large ψ' [11] and direct J/ψ production [12] in the Collider Detector at Fermilab (CDF) experiment at the Tevatron.

The CSM is a nonrelativistic model where the relative velocity between the heavy constituents in a bound state is neglected. But discrepancies between experimental data and the CSM predictions hint that $O(v)$ corrections as well as other mechanisms of quarkonium production, which do not appear in the leading order in v, should be considered. Expansion of quarkonium cross sections and decay widths in powers of relative velocity v of heavy quarks in a bound state has recently been realized in terms of nonrelativistic QCD (NRQCD) [13]. This formalism implies not only color-singlet processes but the new color-octet mechanism, when a quark-antiquark pair is produced on small time scales in color octet states and evolves into a hadron by emission of soft gluons. The color octet mechanism takes into account the complete structure of the quarkonium Fock space while in the CSM only the dominant Fock state is considered, which consists of a color singlet quark-antiquark pair in a definite angular-momentum state (higher order Fock states are suppressed by powers of v). According to the factorization approach based on the NRQCD, the production cross section for a quarkonium state H in the process

$$A+B\to H+X \tag{1}$$

can be written as

$$\sigma_{ij}=\sum_{i,j}\int_0^1 dx_1 dx_2 f_{i/A}(x_1) f_{j/B}(x_2)\hat{\sigma}(ij\to H),$$

$$\hat{\sigma}(ij\to H)=\sum_n C^{ij}[n]\langle 0|\mathcal{O}^H[n]|0\rangle, \tag{2}$$

where $f_{i/A}$ is the distribution function of the parton i in the hadron A. The subprocess cross section is separated into two parts: short distance ($C^{ij}[n]$) coefficients and long distance matrix elements $\langle 0|\mathcal{O}^H[n]|0\rangle$. The $C^{ij}[n]$ is the production cross section of a heavy quark-antiquark pair in the i and j parton fusion. It should be calculated in the framework of

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PQCD. The $[n]$ state can be either a color singlet or a color octet state. The $\langle 0|\mathcal{O}^H[n]|0\rangle$ describes the evolution of a quark-antiquark pair into a hadronic state. These matrix elements cannot be computed perturbatively. But the relative importance of long distance matrix elements in powers of velocity v can be estimated by using the NRQCD velocity scaling rules [14].

Shapes of the p_T distribution of short distance color-octet matrix elements indicate that the new mechanism can explain the Tevatron data of direct J/ψ and ψ' production at large p_T [15]. However, but unlike color-singlet matrix elements connected with the subsequent hadronic nonrelativistic wave functions at the origin, color octet long distance matrix elements are unknown and should be extracted from experimental data. The color octet contribution to the J/ψ photoproduction has been analyzed in papers [16,17]. Recently, the J/ψ hadroproduction at fixed target energies has been studied by including the color-octet mechanism [18–20]. Large discrepancies between experimental data and the CSM predictions for the total cross section of J/ψ hadroproduction were explained. The color octet contribution is dominant in the J/ψ hadroproduction at energies $\sqrt{s}\simeq 30-60$ GeV. The color octet model (COM) prediction for the ratio $\sigma(J/\psi)_{\rm dir}/\sigma(J/\psi)\simeq 0.6$ is also in a good agreement with experiment [21]. The analyses carried out in papers [16–20] demonstrate that fitting the photoproduction and hadroproduction data at low energies requires smaller values for some long distance matrix elements than those extracted from prompt J/ψ production at CDF at the Tevatron [15]. Possible reasons for such discrepancies have recently been analyzed in papers [19,22]. Despite the obvious successes, some problems still remain unsolved in the framework of the COM. In particular, the theoretical predictions disagree with the J/ψ and ψ' polarization data at fixed target energies [19,21]; the COM prediction for relative yield of χ_{c1} and χ_{c2} states remains too low [19]. These discrepancies indicate that ''higher-twist'' corrections can give a significant contribution at low p_T productions of charmonium states and should be added to the color octet contributions [4]. On the other hand, expected ''higher-twist'' corrections lead to uncertainties in fitting color-octet parameters at fixed target energies. This fact does not allow us to exactly check the universality of NRQCD factorization mechanism using the values of long-distance matrix elements extracted from J/ψ photoproduction at low p_T and fixed target experiments. The remaining uncertainties in the numerical values of the COM parameters reduce the ''predictive power'' of the proposed model.

The existing uncertainties stimulate us to look for other processes and consequently additional possibilities for testing the underlying J/ψ-production dynamics, and in particular, the color octet mechanism. The observation of J/ψ asymmetries can be used for these purposes as well as measuring the J/ψ polarization in the unpolarized hadron-hadron collisions [4,23].

In the present paper, we consider the color octet contribution to the double spin asymmetry of J/ψ hadroproduction. Unlike previous calculations [24], we consider the $(c\overline{c})$ color octet and color singlet pair production in $2\to 2$ subprocesses to obtain asymmetries at nonzero transverse momenta ($p_T>1.5$ GeV). Such values of p_T can not be caused by internal motion of partons in the nucleon and hence transverse momentum distributions of the production cross section and asymmetries are calculable perturbatively. The double spin asymmetries in parton collisions are presented in Sec. II. Since a heavy quarkonium is mainly produced in the gluon-gluon fusion subprocesses, the J/ψ production asymmetry should be sensitive to the polarized gluon distribution function in the proton. We have calculated the expected asymmetry of J/ψ production at HERA-$\vec{N}$, one of the future options of the DESY ep collider HERA [25]; an experiment utilizing an internal polarized nucleon target in the polarized HERA beam with energy 820 GeV would yield $\sqrt{s}\simeq 39$ GeV. For comparison, we also considered the expected asymmetry of J/ψ production in similar spin physics experiments at much higher energies at the BNL Relativistic Heavy-Ion Collider (RHIC) [26]. We shall consider the possibility of the extraction of information (even indirect) about the polarized gluon distribution function in the nucleon and values of long distance color-octet matrix elements.

II. DOUBLE SPIN ASYMMETRIES AT SUBPROCESS LEVEL

Let us discuss the two-spin asymmetry A_{LL} for the inclusive J/ψ production which is defined as

$$A_{LL}^{J/\psi}(pp)=\frac{d\sigma(p_+p_+\to J/\psi)-d\sigma(p_+p_-\to J/\psi)}{d\sigma(p_+p_+\to J/\psi)+d\sigma(p_+p_-\to J/\psi)}=\frac{Ed\Delta\sigma/d^3p}{Ed\sigma/d^3p},\tag{3}$$

where $p_+(p_-)$ stands for the helicity projection sign on the proton momentum direction.

The cross section of J/ψ production can be written as

$$\sigma_{J/\psi}=\sigma(J/\psi)_{\rm dir}+\sum_{J=0,1,2}B(\chi_{cJ}\to J/\psi X)\sigma_{\chi_{cJ}}+B(\psi'\to J/\psi X)\sigma_{\psi},\tag{4}$$

where $B((c\overline{c})\to J/\psi X)$ denotes the branching ratio of the corresponding $(c\overline{c})$ state into J/ψ. The production of each quarkonium state is contributed both by the color octet and color singlet states, as in the case of direct J/ψ production:

$$\sigma(J/\psi)_{\rm dir}=\sigma_{J/\psi}^{\rm singl}+\sigma_{J/\psi}^{8}=\sigma(J/\psi)^{\rm singl}+\sum\ \sigma(Q\overline{Q}[^{2s+1}L_J^8])\times\langle 0|\mathcal{O}_8^{J/\psi}(^{2s+1}L_J)|0\rangle,\tag{5}$$

where the sum is over the states $^3P^8_{0,1,2}$, $^1S^8_0$, and $^3S^8_1$. We consider only the dominant sets of color octet states by the NRQCD velocity expansion for the direct S and P state charmonium production.

In a recent paper [24] the asymmetry of J/ψ hadroproduction has been considered in the color octet model exploiting only the lowest order subprocesses $[2\to(c\overline{c})]$ over the QCD coupling constant. Subprocesses $2\to 1$ contribute only to the production of a quarkonium state at the zero transverse momentum with respect to the beam axis. Transverse momentum distributions of $(c\overline{c})$ states and, consequently, the J/ψ meson are not calculable in the $p_T<\Lambda_{\rm QCD}$ region. To deal with the experimentally observable quantities (taking into account the kinematic restriction on the angle with respect to the beam axis at HERA-$\vec{N}$ and at collider experiments), we consider the subprocess $2\to 2$ which gives the leading contribution to the quarkonium production with p_T greater than 1.5 GeV. Such large transverse momenta cannot be caused by internal motion of partons in the nucleon and, respectively, subprocesses $2\to 1$ should not contribute to the production of quarkonia with $p_T > 1.5$ GeV. For calculating the expected asymmetries we consider the following subprocesses:

$$g+g\to(c\overline{c})+g,$$

$$g+q\to(c\overline{c})+q,$$

$$q+\overline{q}\to(c\overline{c})+g \tag{6}$$

for the color octet and singlet states of a $(c\overline{c})$ pair.

Using the symbolic manipulation program FORM [27], we have calculated the $(c\overline{c})$ states, the production cross sections for different helicity states of colliding partons. For the color octet states, the total cross sections have been calculated by Cho and Leibovich [15]. The total cross sections for color singlet states are presented in [28,29]; the results served for checking our calculations.

Figure 1 presents the values of the subprocess level asymmetries for the color octet and color singlet states production of a $(c\overline{c})$ pair depending on the two dimentionless quantities; $\eta=4m_c^2/\hat{s}^2$ and $x_T=p_T/p_{\max}$, where $p_{\max}$ is the maximum momentum of the produced state in the subprocess. Figure 1 shows only the gluon fusion subprocess asymmetries because they give the main contribution to the hadronic level asymmetry. The cases of ${}^1S_0$ and ${}^3S_1$ singlet states are omitted in Fig. 1. The ${}^1S_0$ state does not contribute to J/ψ production and analytic expressions for the corresponding cross sections for the ${}^3S_1$ state are given in [2].

As can be seen from Figs. 1 and 2, the asymmetries are very similar for color octet and color singlet states with the same spin-orbital quantum numbers. It is worth mentioning that in the limit $4m_c^2/s\to 1$ (i.e., at the threshold of heavy quark pair production) $\hat{a}_{LL}$ for the scalar and tensor states tends to 1 and -1, respectively. The limit $4m_c^2\to s$ means that the emitted gluon in the $2\to 2$ subprocess $[gg\to(c\overline{c})g]$ becomes soft and the helicity properties of the amplitude should be the same as those of the amplitude of the $2\to 1$ process[1] $[gg\to(c\overline{c})]$. It is easy to show that the asymmetries for the process $2\to 1$ for scalar and tensor states are 1 and -1, respectively. The existence of such limits serves as an additional test for our analytic calculations of cross sections $\Delta\hat{\sigma}$.

[1]The same reason makes the asymmetry less sensitive to the radiative corrections than spin-averaged cross section, as the K factor is dominated by the contributions of virtual, soft, and collinear gluons.

III. MATRIX ELEMENTS

For the calculation of the hadronic level asymmetries of J/ψ production we used the long distance matrix elements fitted from various experimental data. All color singlet matrix elements are related to the radial quarkonium wave functions at the origin and their derivatives. As in paper [15] for this purpose we used the Buchmüller-Tye wave functions at the origin tabulated in Ref. [19]. The color octet matrix elements were fitted from the J/ψ and higher charmonium state production data in various experiments. Unfortunately, there are some discrepancies between the values of color octet matrix elements extracted from different experiments.

The number of color octet long distance matrix elements should be reduced by using the NRQCD spin symmetry relations

$$\langle 0|\mathcal{O}_8^H({}^3P_J)|0\rangle=(2J+1)\langle 0|\mathcal{O}_8^H({}^3P_0)|0\rangle, \tag{7}$$

$$\langle 0|\mathcal{O}_8^{\chi_{cJ}}({}^3S_1)|0\rangle=(2J+1)\langle 0|\mathcal{O}_8^{\chi_{c0}}({}^3S_1)|0\rangle. \tag{8}$$

These relations are accurate up to v^2.

After using these relations we have only three independent matrix elements $\langle\mathcal{O}_8^{J/\psi}({}^3S_1)\rangle$, $\langle\mathcal{O}_8^{J/\psi}({}^3P_0)\rangle$, and $\langle\mathcal{O}_8^{J/\psi}({}^1S_0)\rangle$, which give the main contributions to the direct J/ψ hadroproduction cross section. From the Tevatron, the fixed target experiments, and the J/ψ photoproduction data it is possible to extract only the combinations of $\langle\mathcal{O}_8^{J/\psi}({}^1S_0)\rangle$ and $\langle\mathcal{O}_8^{J/\psi}({}^3P_0)\rangle$ parameters. From the direct J/ψ production data at the CDF (the Tevatron) Cho and Leibovich obtained [15]

$$\langle 0|\mathcal{O}_8^{J/\psi}({}^1S_0)|0\rangle+\frac{3}{m_c^2}\langle 0|\mathcal{O}_8^{J/\psi}({}^3P_0)|0\rangle=6.6\times 10^{-2}\ \mathrm{GeV}^3. \tag{9}$$

Values for other combinations are extracted from the J/ψ photoproduction and fixed target hadroproduction data [16–19]:

$$\langle 0|\mathcal{O}_8^{J/\psi}({}^1S_0)|0\rangle+\frac{7}{m_c^2}\langle 0|\mathcal{O}_8^{J/\psi}({}^3P_0)|0\rangle =2\times 10^{-2}\ \mathrm{GeV}^3\ \ [19],$$

$$\langle 0|\mathcal{O}_8^{J/\psi}({}^1S_0)|0\rangle+\frac{7}{m_c^2}\langle 0|\mathcal{O}_8^{J/\psi}({}^3P_0)|0\rangle =3\times 10^{-2}\ \mathrm{GeV}^3\ \ [16,17]. \tag{10}$$

If one assumes that $\langle 0|\mathcal{O}_8^{J/\psi}({}^1S_0)|0\rangle=\langle 0|\mathcal{O}_8^{J/\psi}({}^3P_0)|0\rangle/m_c^2$, the photoproduction and fixed target hadroproduction values (‘‘low-energy’’ values) are an order smaller than the Tevatron value (‘‘high-energy’’ value). Possible sources for such a discrepancy are discussed in [19,22]. In paper [19] it is mentioned that the mass of the produced hadronic final state (or intermediate color octet state) must be higher than that of the J/ψ meson–$M_{J/\psi}=2m_c$, because the intermediate octet state emits gluons with energy $2m_c v^2$ before transition into a color singlet state. But a charmonium is not a truly nonrelativistic system, the average relative velocity of constituents in J/ψ is not very small—$v^2\simeq 0.23-0.3$ and emitted gluons

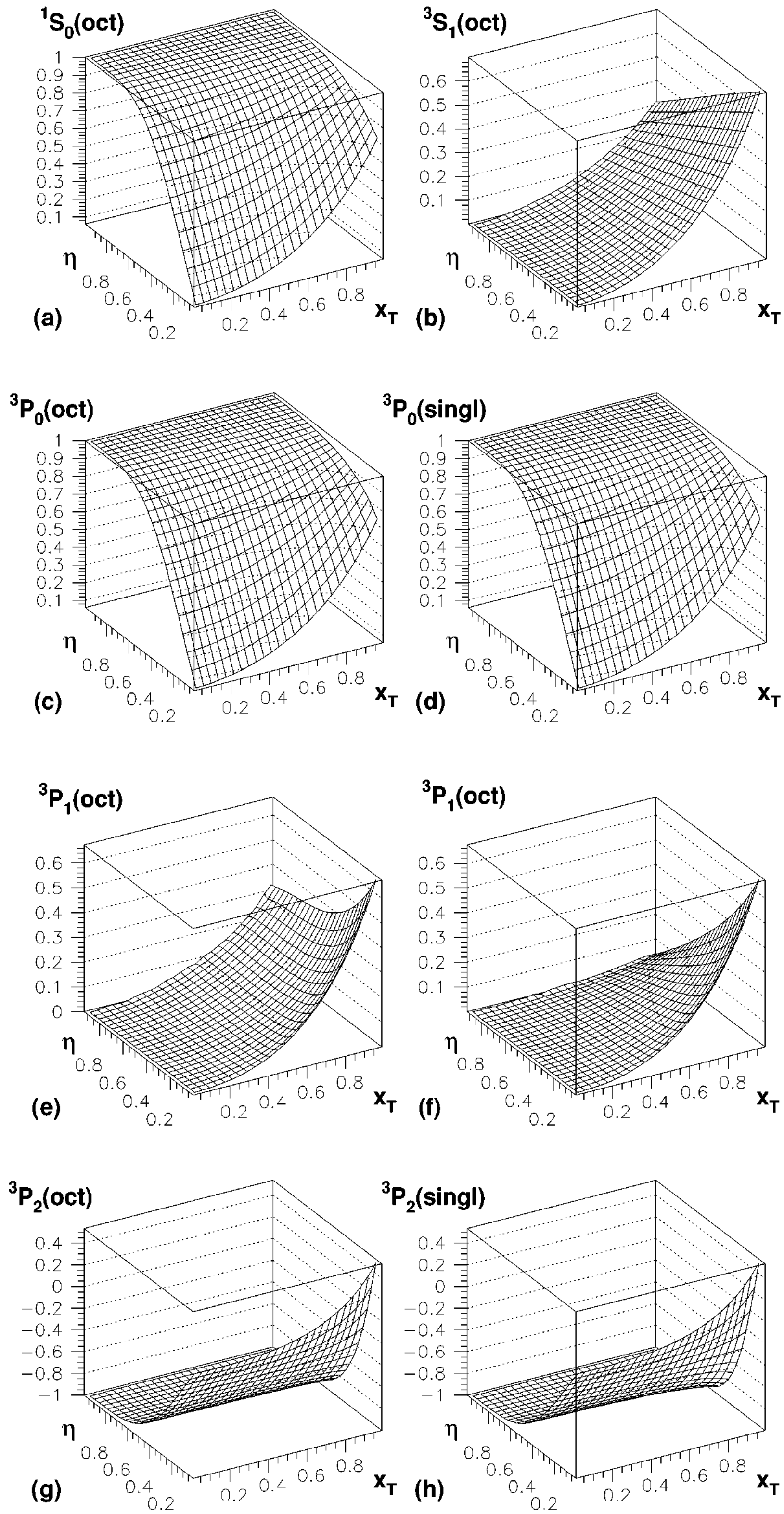

FIG. 1. Partonic level double spin asymmetries for the $^1S_0$ and $^3S_1$ color octets and $^3P_0$,1,2 color octet and singlet states versus η and x_T (see the text for the definitions of η and x_T).

in the $c\bar{c}$ pair hadronization phase have the energy 0.7–GeV. Therefore the mass of the hadronic final state is about 4 GeV. At fixed target energies, increasing the mass of the produced hadronic state reduces partonic luminosity because of a steeply falling gluon distribution function. Consequently, the production cross section of the $(c\bar{c})$ color octet state should be smaller. So, the ''true'' color octet long distance matrix elements must be larger than those extracted by using $M_{J/\psi}$ as mass of the intermediate octet state [19].

Another possible source of uncertainty was mentioned in paper [22] and should be connected with the choice of different parametrizations for the gluon distribution function in

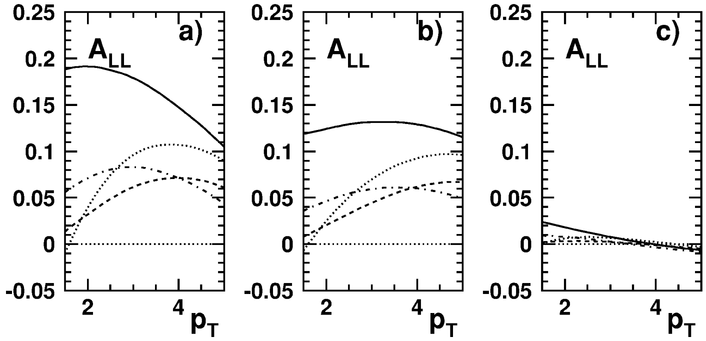

FIG. 2. The expected asymmetries at HERA-$\vec{N}$ ($\sqrt{s}=39$ GeV) for different color octet states production. Solid lines indicate asymmetries for the ${}^1S_0^{(8)}$ state, dashed lines for the combination of ${}^3P_J^{(8)}$ states (see text), and dash-dotted lines for the ${}^3S_1^{(8)}$ octet state. Dotted lines correspond to J/ψ production in the CSM; (a) for the the old Gehrmann and Stirling parametrization for polarized PDF (set A) [35], (b) for the new version of Gehrmann and Stirling parametrization (NLO set A), and (c) for (LO set A) [36].

fitting the direct J/ψ production data at CDF [15]. Cho and Leibovich in their calculations used the Martin-Roberts-Stirling set D0 (MRSD0) parametrization for parton distribution functions. At small values of $p_T\simeq 5$ GeV, using a more reliable parametrization for small partonic x [Glück-Reya-Vogt (GRV) leading order (LO) or GRV higher order (HO) [30]] leads to 1.5–1.6 times higher cross sections for the ${}^3P_0$ and ${}^1S_0$ color octet state production than those obtained by using the MRSD0 parametrization [15]. Hence the fitted value of combination (9) should be approximately 1.5–1.6 times smaller:

$$\langle 0|\mathcal{O}_8^{J/\psi}({}^1S_0)|0\rangle+\frac{3}{m_c^2}\langle 0|\mathcal{O}_8^{J/\psi}({}^3P_0)|0\rangle$$
$$=4-4.4\times 10^{-2}\ \mathrm{GeV}^3\ \ [22]. \qquad (11)$$

At large $p_T\simeq 10-15$ GeV all parametrizations give practically the same magnitude for the color octet states cross sections. Hence if we use the new combination (11), we need a larger value of the parameter $\langle 0|\mathcal{O}_8^{J/\psi}({}^3S_1)|0\rangle$ to explain the experimental data for the J/ψ cross section at $p_T\simeq 10-15$ GeV:

$$\langle 0|\mathcal{O}_8^{J/\psi}({}^3S_1)|0\rangle\simeq 10\times 10^{-3}\ \mathrm{GeV}^3. \qquad (12)$$

This suggestion was confirmed in the detailed analysis of the CDF data of J/ψ and ψ' production by Beneke and Krämer. Using the GRV LO (1994) parametrization the following values for three main matrix elements were obtained [23]:

$$\langle 0|\mathcal{O}_8^{J/\psi}({}^3S_1)|0\rangle=1.06\pm 0.14^{+1.05}_{-0.59}\times 10^{-2}\ \mathrm{GeV}^3, \quad (13)$$

$$\langle 0|\mathcal{O}_8^{J/\psi}({}^1S_0)|0\rangle+\frac{3.5}{m_c^2}\langle 0|\mathcal{O}_8^{J/\psi}({}^3P_0)|0\rangle$$
$$=3.9\pm 1.15^{+1.46}_{-1.07}\times 10^{-2}\ \mathrm{GeV}^3 \qquad (14)$$

(in our further calculations we will use these values for parameters). The second errors correspond to the variation of the factorization scale μ from $0.5\sqrt{p_T^2+4m_c^2}$ to $2\sqrt{p_T^2+4m_c^2}$. From the errors indicated in Eqs. (13) and (14) it is obvious that variation of the renormalization and/or factorization scale leads to large uncertainties in fitting the color octet parameters. Another source of large uncertainties concerned the expected large higher-order perturbative corrections at high energies [31] and ‘‘higher-twist’’ corrections at fixed target energies [4]. The fitting values of long distance octet parameters can be affected also by higher v^2 corrections, the parameter of nonrelativistic expansion. In particular, the large uncertainties emerge when the matrix element $\langle O_8^{J/\psi}({}^3S_1)\rangle$ is extracted from the data of J/ψ production at large p_T at the Tevatron. In fitting the CDF data the energy of emitted soft gluons by a heavy quark-antiquark pair before transition into J/ψ is usually neglected [15,23,12]. So, the fragmentation function of gluon into J/ψ on the scale $2m_c$ has the form

$$D_{g\to\psi}(z,2m_c)=\frac{\pi\alpha_s(2m_c)}{24m_c^3}\,\delta(1-z)\langle O_8^{J/\psi}({}^3S_1)\rangle. \quad (15)$$

The δ function implies that J/ψ takes the whole energy of the fragmenting gluon (the energy taken by emitted soft gluons is neglected). Taking into account the realistic energy of soft gluons (of order m_cv^2) leads to softening of the fragmentation function. Hence the realistic cross section is smaller at large p_T and the fit value of the $\langle O_8^{J/\psi}({}^3S_1)\rangle$ matrix elements would be a factor of 2 larger [31–34]. Therefore, care is required while using the value for this parameter extracted from the CDF data at fixed target energies. The uncertainty connected to the ‘‘trigger bias’’ effect makes also impossible to use this value for testing NRQCD universality.

For the indirect J/ψ production via the ψ' and χ_{cJ} states decays we use the following values fitted from the CDF data:

$$\langle\mathcal{O}_8^{\chi_{c1}}({}^3S_1)\rangle=9.8\times 10^{-3}\ \mathrm{GeV}^3\ \ [15], \qquad (16)$$

$$\langle\mathcal{O}_8^{\psi'}({}^3S_1)\rangle=0.46\times 10^{-2}\ \mathrm{GeV}^3\ \ [23], \qquad (17)$$

$$\langle\mathcal{O}_8^{\psi'}({}^1S_0)\rangle+\frac{3.5}{m_c^2}\langle\mathcal{O}_8^{\psi'}({}^3P_0)\rangle=1.8\times 10^{-2}\ \mathrm{GeV}^3\ \ [23]. \qquad (18)$$

For the calculations of the expected asymmetries we assume that the first parameter is leading in the latter combination. In this case the discrepancy between the COM predictions and experimental data of ψ' polarization is smallest [21].

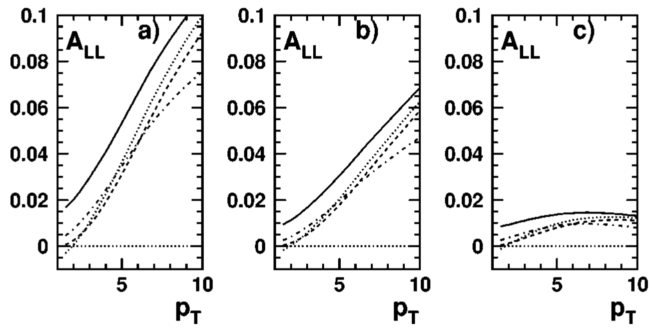

FIG. 3. The same as in Fig. 2 for the RHIC energy $\sqrt{s}=200$ GeV.

IV. RESULTS AND DISCUSSION

Figures 2 and 3 show the expected asymmetries for different states of a heavy quark-antiquark pair at $\sqrt{s}=40$ GeV (HERA-$\vec{N}$, Fig. 2) and $\sqrt{s}=200$ GeV (RHIC, Fig. 3). The asymmetries for ${}^1S_0^{(8)}$ and ${}^3S_1^{(8)}$ octet states are presented by solid and dotted lines, respectively. The dashed lines correspond to combined asymmetries of ${}^3P_J$ octet states, $\Sigma_{J=0,1,2}(2J+1){}^3P_J^{(8)}$. The dash-dotted lines show asymmetries of J/ψ production in the CSM including J/ψ production through decays of higher charmonium states (ψ' and χ_{cJ}). For unpolarized parton distribution functions (PDF's) we used the GRV LO parametrization [30]; for polarized parton densities, three different sets of parametrizations, the old version of the Gehrmann and Stirling parametrization (set A) [35] (as an example of large gluon polarization), and the new version of the Gehrmann-Stirling parametrizations next leading order (NLO) and LO (both set A) [36]. In Fig. 4 the

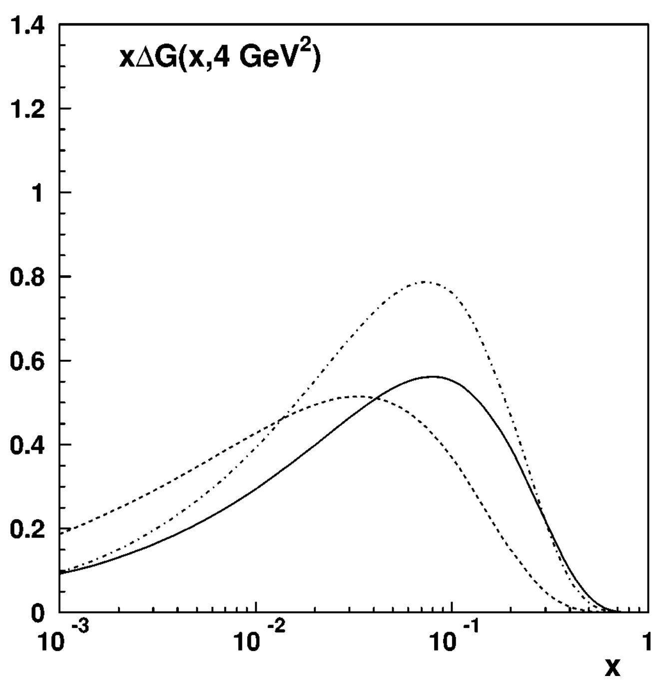

FIG. 4. Polarized gluon distributions in nucleon, used in the Figs. 2 and 3, at $Q^2=4$ GeV; the new Gehrmann and Stirling parametrization NLO set A (solid line), LO set A (dashed line) [36], and the old Gehrmann and Stirling parametrization (set A) (dash-dotted) [35].

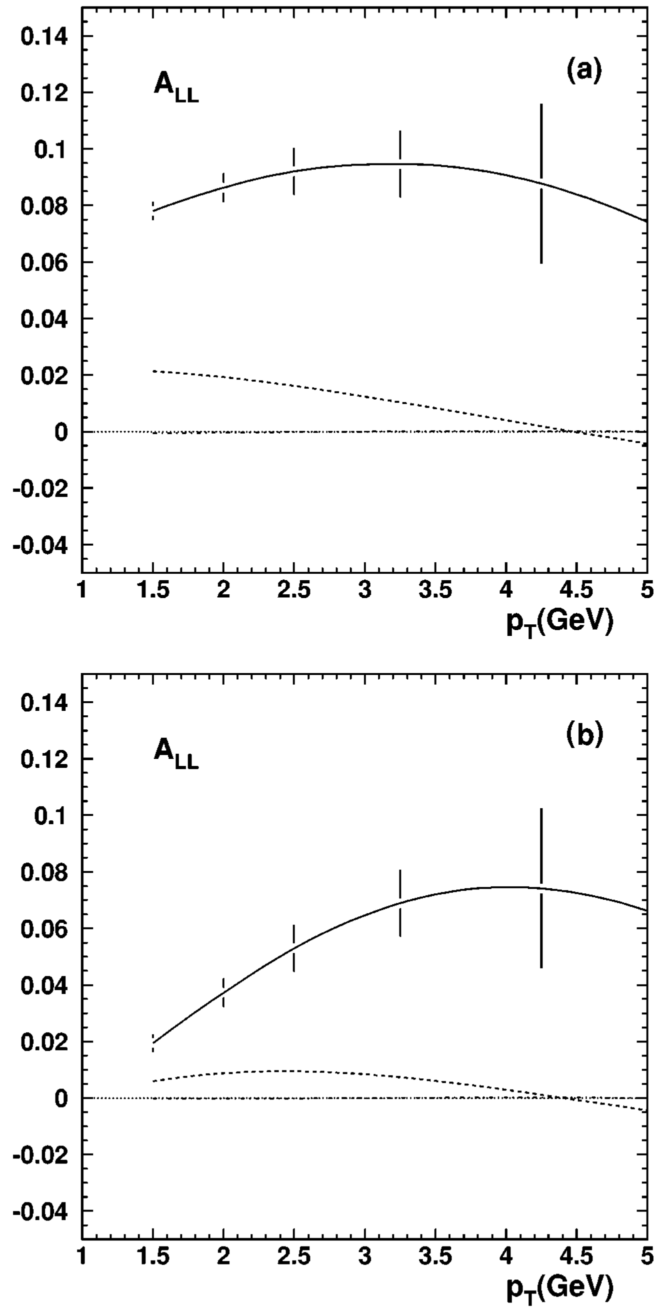

FIG. 5. The expected asymmetries versus transverse momentum at $\sqrt{s}=39$ GeV for the NLO set A (solid lines), set B (dashed lines), and set C (dash-dotted lines) of the new Gehrman-Stirling parametrization [36]; (a) $\langle 0_8^{J/\psi}|{}^3P_0|0\rangle=0$, (b) $\langle 0_8^{J/\psi}|{}^1S_0|0\rangle=0$.

polarized gluon densities from these parametrizations are presented at $Q^2=4$ GeV (the polarized gluon distribution functions of NLO set B and LO set A practically coincide at this value of Q^2). For all three parametrizations of the polarized PDF the gluon-gluon fusion gives the dominant contribution to $\Delta\sigma$; the quark-gluon subprocesses contribution is about 10% and the quark-antiquark annihilation subprocesses contribution is less than 1%. As one can see from Figs. 2 and 3, the expected asymmetries for all states strongly depend on the magnitude of the polarized gluon distribution function in the $x\simeq 0.1$ region. The observation of inclusive J/ψ asymmetry can give only indirect information about the gluon polarization in the nucleon.

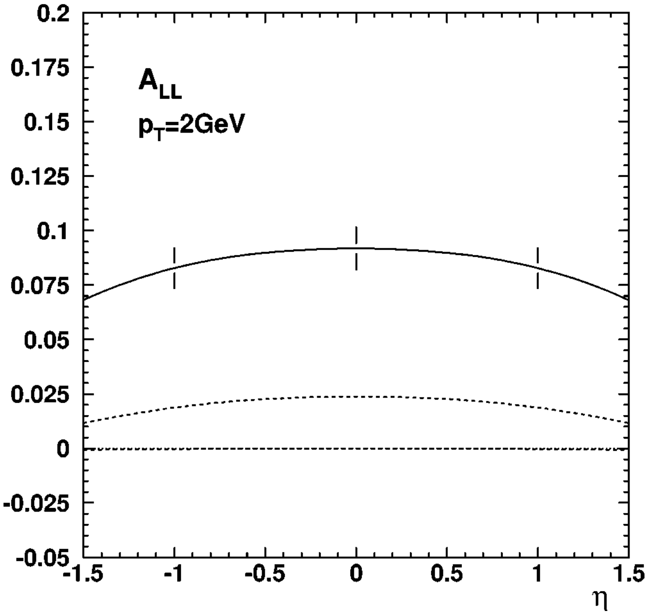

FIG. 6. The expected asymmetries versus J/ψ pseudorapidity $p_T=2$ GeV for the case $\langle 0_8^{J/\psi}|^3P_0|0\rangle=0$. The labels are the same as in Fig. 7.

Figure 5(a) shows the expected double spin asymmetries at the HERA-$\vec{N}$ energy as functions of transverse momentum of J/ψ for three different sets of new Gehrmann and Stirling NLO parametrizations, set A (solid curve), set B (dashed curve), and set C (dot-dashed curve). For the mass of charm quark the value $m_c=1.48$ GeV was taken. Parton distribution functions are evaluated on the factorization scale $\mu=\sqrt{p_T^2+4m_c^2}$. The strong coupling constant is calculated by the one-loop formula with four active flavors ($\Lambda_{\rm QCD}=200$ MeV). Figure 5(a) corresponds to the case when the first parameter in the combination (14), $\langle\mathcal{O}_8^{J/\psi}(^1S_0)\rangle$, is leading ($\langle\mathcal{O}_8^{J/\psi}(^3P_0)\rangle=0$). Figure 5(b) corresponds to the opposite case $\langle\mathcal{O}_8^{J/\psi}(^1S_0)\rangle=0$. In both the cases we use the following value for the third main parameter: $\langle\mathcal{O}_8^{J/\psi}(^3S_1)\rangle=20\times10^{-3}$ GeV^3 (the sensitivity of asymmetries to the value of this parameter will be considered below). Figures 5(a) and 5(b) also display the expected statistical errors. The statistical error δA_{LL} at HERA-$\vec{N}$ can be estimated from [25]

$$\delta A_{LL}=0.17/\sqrt{\sigma(\text{pb})}. \tag{19}$$

This relation has been determined by assuming an integrated luminosity of 240 pb^{-1} and beam and target polarizations $P_B=0.6$, $P_T=0.8$ [25]. The error bars are obtained by using integrated cross sections over bins $\Delta p_T=0.5$ GeV (for the first three points) and $\Delta p_T=1$ GeV (for the other two). The J/ψ decay branching ratio into the e^+e^- mode is also included. As can be seen from Figs. 5, the magnitude of asymmetries and expected errors allows one to distinguish between different parametrizations of polarized parton distribution functions. Figure 6 shows expected asymmetries depending on the pseudorapidity of J/ψ at $p_T=2$ GeV [for the case $\langle\mathcal{O}_8^{J/\psi}(^3P_0)\rangle=0$]. Statistical error bars correspond to the integrated cross section over bins $\Delta\eta=1$ and

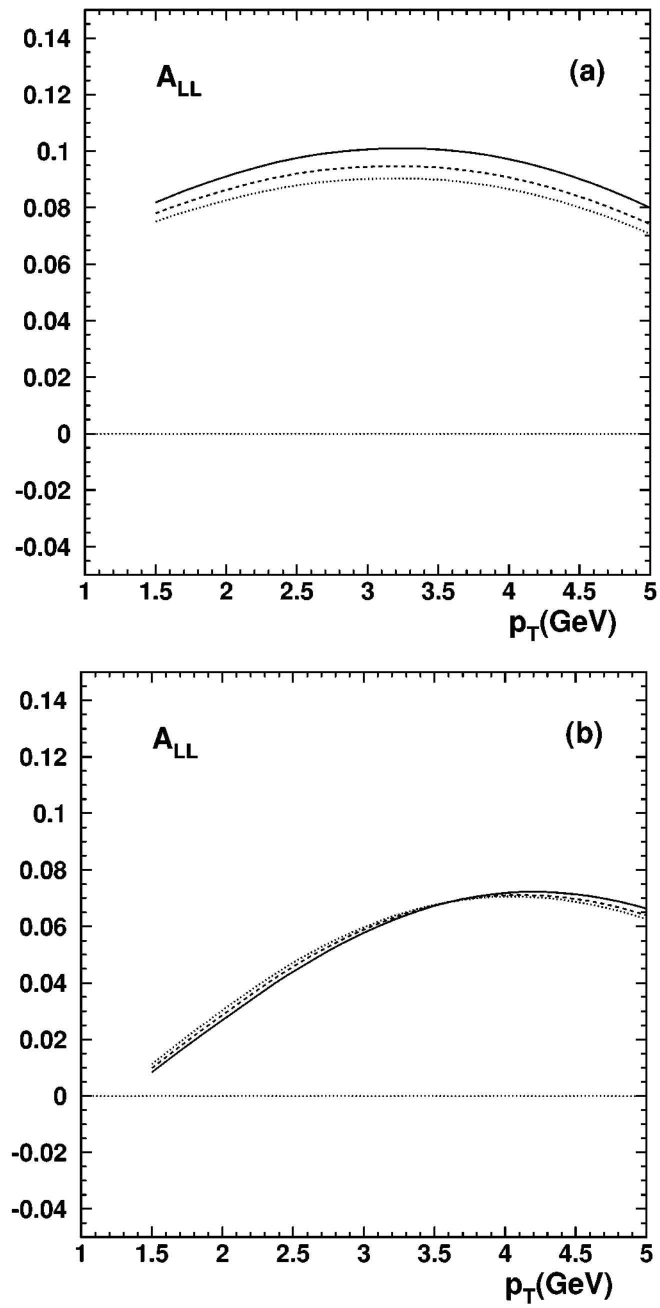

FIG. 7. The expected asymmetries at HERA-$\vec{N}$ for different values of $\langle\mathcal{O}_8^{J/\psi}(^3S_1)\rangle$ of the long-distance parameter. Solid line corresponds to the value 20×10^{-3} GeV^3, dashed line–10×10^{-3} GeV^3, and dotted line–30×10^{-3} GeV^3; (a) asymmetries for the case when $\langle 0_8^{J/\psi}|^3P_0|0\rangle=0$, (b) $\langle 0_8^{J/\psi}|^1S_0|0\rangle=0$.

$\Delta P_T=0.5$ GeV. As in the previous case, the errors are small in a wide pseudorapidity range and give a possibility to distinguish between different parametrizations for $\Delta g(x)$.

The direct access to the ratio $\Delta G(x)/G(x)$ is possible only in the double inclusive production processes (photon+jet or J/ψ+jet) [37]. The complete kinematics of the $2\to2$ subprocess can be reconstructed if the away-side jet in the production of J/ψ is measured as well. If the values of long distance matrix elements are established from experiments where the uncertainties connected with ‘‘higher twist’’ and other corrections are expected to be small (or negligible), the J/ψ+jet production asymmetry will serve as a good tool

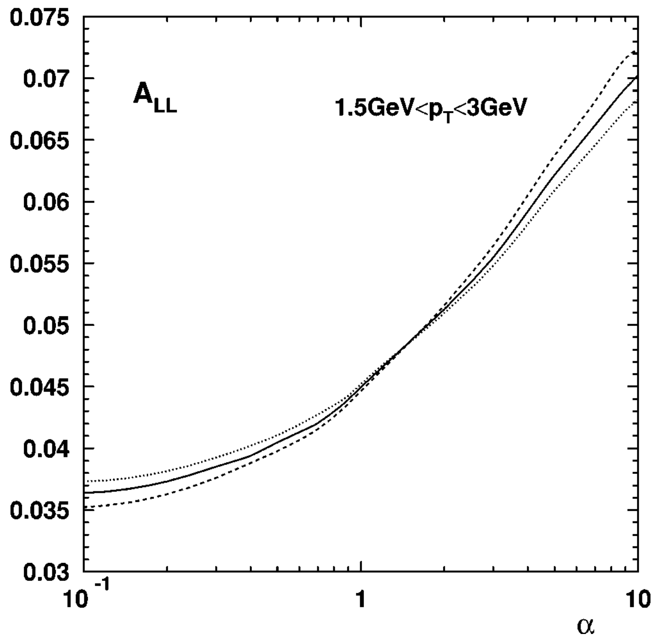

FIG. 8. The integrated double spin asymmetries versus the ratio of color octet parameters $\alpha=\langle \mathcal{O}_8^{J/\psi}(^1S_0)\rangle * m_c^2/\langle \mathcal{O}_8^{J/\psi}(^3P_0)\rangle$. Solid line corresponds to the value of $\langle \mathcal{O}_8^{J/\psi}(^3S_1)\rangle = 20\times 10^{-3}$ GeV^3, dashed line: 10×10^{-3} GeV^3, and dotted line: 30×10^{-3} GeV^3.

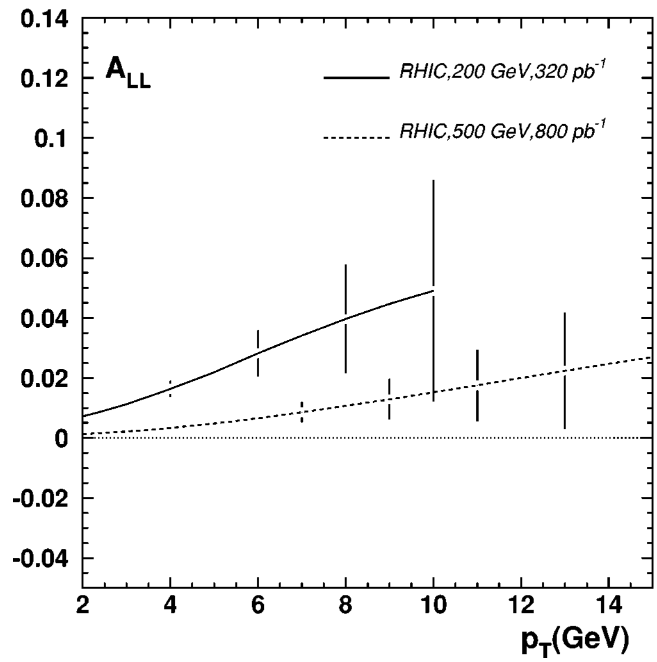

FIG. 10. Expected asymmetries and statistical errors at the RHIC for two different energies [$\sqrt{s}=200$ GeV and $\sqrt{(s)}=500$ GeV].

for extraction of the $\Delta G(x)/G(x)$ value at $x\simeq 0.1$ at HERA-$\vec{N}$ [37].

As soon as the polarized gluon distribution function is extracted from other modes (photon+jet, for example [37]) at HERA-$\vec{N}$ or RHIC, the observation of J/ψ asymmetry can be used for checking the NRQCD factorization scheme. For further calculations and analysis we use the new version of Gehrmann and Stirling parametrization for polarized PDF (NLO, set A) [36]. In Figs. 7(a) and 7(b), we present the expected asymmetries of J/ψ production for two radical choices of $\langle \mathcal{O}_8^{J/\psi}(^1S_0)\rangle$ and $\langle \mathcal{O}_8^{J/\psi}(^3P_0)\rangle$ squared amplitudes values. Figure 7(a) corresponds to the case when the parameter $\langle \mathcal{O}_8^{J/\psi}(^3P_0)\rangle$ tends to zero [$\langle \mathcal{O}_8^{J/\psi}(^1S_0)\rangle$ is the leading term in the combination (14)]. Figure 7(b) represents the other radical choice, when the second parameter $\langle \mathcal{O}_8^{J/\psi}(^1S_0)\rangle$ is zero. Because of the ''trigger bias'' effect the value of the third main parameter $\langle \mathcal{O}_8^{J/\psi}(^3S_1)\rangle$ is underestimated about twice. To check the sensitivity of expected asymmetries to the uncertainty caused by this effect, we used three different values for $\langle \mathcal{O}_8^{J/\psi}(^3S_1)\rangle$, $10\times 10-3$ GeV^3 from Eq. (13) (dashed lines in Figs. 7), 20×10^{-3} GeV^3 (solid line), and 30×10^{-3} GeV^3 (dash-dotted line). From comparison of Figs. 7(a), 7(b) it can be seen that the asymmetries depend strongly on relative values of the matrix elements $\langle \mathcal{O}_8^{J/\psi}(^1S_0)\rangle$ and $\langle \mathcal{O}_8^{J/\psi}(^3P_0)\rangle$, and practically do not depend on the value of $\langle \mathcal{O}_8^{J/\psi}(^3S_1)\rangle$. So, independently of the value the later parameter and consequently uncertainties caused by the ''trigger bias'' effect, measuring the J/ψ production asymmetry can be used for extraction of the ratio of the first two parameters. Of course, this suggestion is true only when the polarized gluon distribution function is known and is large enough to deal with observable magnitudes of J/ψ production asymmetries. In Fig. 8 we present the expected integrated asymmetries ($1.5<p_T<3$ GeV) at the HERA-$\vec{N}$ energy versus the ratio $\alpha=m_c^2\langle \mathcal{O}_8^{J/\psi}(^1S_0)\rangle/\langle \mathcal{O}_8^{J/\psi}(^3P_0)\rangle$ for the above-presented three different values of the third parameter. The expected statistical error for integrated asymmetries is about 2×10^{-3}. One of the main parameters of the model is the mass of the charm quark. Figure 9 shows the asymmetries of J/ψ production depending on m_c for two values of p_T for a large set of polarized parton parametrizations (set A). As displayed in Fig. 9, the expected asymmetries are practically insensitive to the quark mass above $m_c=1.5$ GeV. Therefore, the double spin asymmetry of J/ψ

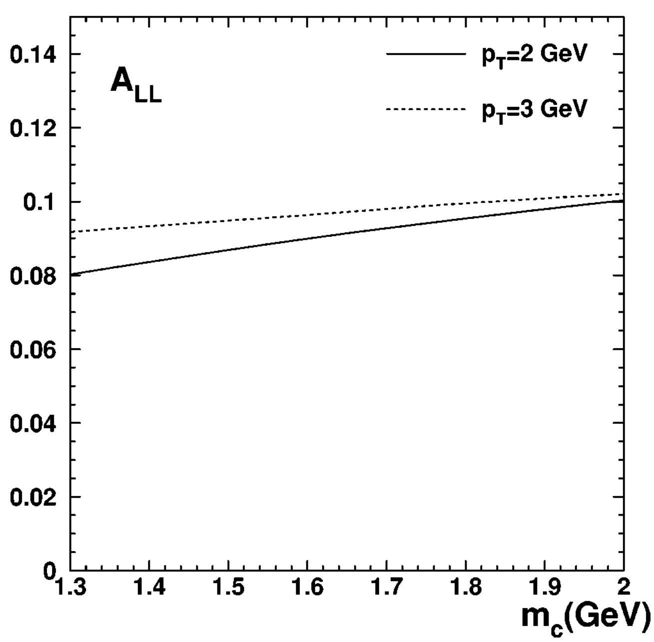

FIG. 9. Expected double-spin asymmetries at $\sqrt{s}=39$ GeV versus the mass of the charm quark.

production, unlike the cross section, should be free from uncertainties caused by the unknown mass of intermediate color octet states. We also note that asymmetries do not depend strongly on the renormalization scale unlike the J/ψ production cross sections [23].

For comparison we have also calculated the expected double-spin asymmetries of J/ψ production at RHIC energies. The results are given in Fig. 10 for two different values of energy. The expected statistical errors are calculated with the anticipated integrated luminosities at the corresponding energies. As we can see from Fig. 10, the expected asymmetry decreases with increasing c.m.s. energy. The statistical errors are calculated by integration over p_T with bins $\Delta p_T = 0.5$ GeV of the differential cross sections. It is worth mentioning that the study of double spin asymmetries separately for direct J/ψ- and χ_{cJ}-state production would provide further information for extraction the polarized gluon dencity in the nucleon and values of color octet long distance matrix elements. The estimation of the expected errors for direct J/ψ- and χ_{cJ}-state production asymmetries require the additional investigation of possibilities of the corresponding experiments to separate and reconstruct the particular charmonium state.

V. CONCLUSIONS

In this paper we investigated the expected double spin asymmetries of heavy quarkonium hadroproduction at HERA-$\vec{N}$ and RHIC. To deal with experimentally observed quantities and to reduce the contribution from ‘‘higher twist’’ corrections, we considered the J/ψ meson production at nonzero transverse momenta $p_T > 1.5$ GeV. Unlike the calculations of [24], where only the lowest order subprocesses were taken into account $(2 \rightarrow 1)$, we considered J/ψ production in subprocesses $2 \rightarrow 2$ because large values of p_T cannot be caused by internal motion of partons. We calculated the heavy quark pair color octet and color singlet S and P states production cross sections for different helicities of colliding partons. The FORTRAN codes for calculated cross sections are available by e-mail.

The magnitude of expected asymmetries and statistical errors at HERA-$\vec{N}$ allows one to distinguish between different parametrizations for polarized parton distribution functions (Gehrmann and Stirling, sets A, B, and C [36]). On the other hand, measuring the asymmetry would give a possibility to extract information about the color-octet long distance matrix elements $\langle \mathcal{O}_8^{J/\psi}(^1S_0) \rangle$ and $\langle \mathcal{O}_8^{J/\psi}(^3P_0) \rangle$ separately, and to check the universality of the factorization scheme. We also calculated the J/ψ production asymmetries at RHIC energies. By comparing the magnitudes of expected asymmetries at HERA-$\vec{N}$ and STAR, it becomes clear that the energy of the fixed target experiment is more preferable for the investigation of the charmonium production asymmetry.

ACKNOWLEDGMENTS

We are grateful to S. J. Brodsky and W.-D. Nowak for helpful discussions. This work was supported in part by the Russian Foundation for Fundamental Research under Grant No. 96-02-17631.

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