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Associated $J/\psi + \gamma$ production as a probe of the polarized gluon distribution

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Associated production of J/ψ and a γ has recently been proposed as a clean probe of the gluon distribution. The same mechanism can be used to probe the polarized gluon content of the proton in polarized proton-proton collisions. We study $J/\psi + \gamma$ production at both polarized fixed target and polarized collider energies.

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Interest in high energy spin physics has been recently revived with the result from (and interpretations thereof) the European Muon Collaboration (EMC) collaboration [1] on polarized μ-p scattering. Processes in polarized pp collisions (such as achievable at an upgraded Fermilab fixed target facility or at a polarized collider [2]) sensitive to the polarized gluon content of the proton, such as jets [3–5], direct photons [5–7], and heavy quark production [8], have been discussed. Another intriguing suggestion, due to Cortes and Pire [9], is to consider $\chi_2(c\bar{c})$ production where the dominant lowest-order subprocess would be $gg \to \chi_2$. The partonic level asymmetries for χ_2/χ_0 production have been calculated in the context of potential models [11] and are large. Low transverse momentum quarkonium production in polarized pp collisions using other methods has also been considered [8, 12] as has high-p_T ψ production [13].

In all cases of charmonium production, the experimental signal is $\ell^+\ell^-$ ($\ell = e$ or μ) with the lepton-lepton invariant mass giving the J/ψ mass, since χ_J can decay radiatively to $J/\psi + \gamma$, and the J/ψ signature is quite clean. As has been noted [14], the question of extracting the gluon distribution is made less clean by the multitude of contributing processes: e.g.,

$$\begin{aligned}
&g + g \to \chi_{0,2}\ , \\
&g + g \to \chi_J + g\ , \\
&q + g \to \chi_{0,2} + q\ , \\
&q + \bar{q} \to \chi_{0,2} + g\ , \\
&g + g \to J/\psi + g\ , \\
&g + g \to b(\to J/\psi + X) + \bar{b}\ , \\
&q + \bar{q} \to b(\to J/\psi + X) + \bar{b}. \qquad (1)
\end{aligned}$$

The simplicity of the Cortes-Pire idea is now gone. A full $O(\alpha_s^3)$ calculation of the spin-dependent production of χ_J is necessary. At low p_T, χ_J production will also involve $q + g$ and $q + \bar{q}$ initial states, while at high p_T in addition the $2 \to 2$ kinematics make the extraction of parton distribution functions less direct. Furthermore, a very careful calculation is required because even processes with small cross section can have a large effect on the asymmetry. The extraction of $\Delta g(x, Q^2)$ using inclusive J/ψ will be a challenge.

Recently, J/ψ produced in association with a γ has been proposed as a clean channel to study the gluon distribution at hadron colliders [15]. The radiative χ_J decays can produce J/ψ at both low and high p_T, but the photon produced will be soft ($E \sim 400$ MeV). If we insist that the experimental signature consist of a J/ψ and γ, with large but equal and opposite p_T there is only one production mechanism

$$g + g \to J/\psi + \gamma. \qquad (2)$$

Following Ref. [15], this mechanism has been proposed in Ref. [16] to study the polarized gluon distribution in polarized fixed target experiments; we perform a more detailed analysis, including the analysis of this mechanism at the Brookhaven Relativistic Heavy Ion Collider (RHIC) at both 50 GeV and 500 GeV center of mass energy and at the Superconducting Super Collider (SSC). Polarized proton-proton operation is being considered for RHIC, for at least several months data collection, while the tunnel design of the SSC has been modified for the possible future inclusion of the Siberian Snakes needed for polarized proton-proton mode. Also, we list the full set of helicity amplitudes for this process, explicitly stating the Lorentz frame in which the J/ψ helicities are given.

The full helicity amplitudes for $g + g \to J/\psi + \gamma$ can be calculated following the approach of Gastmans, Troost, and Wu [17], with the addition of explicit helicity polarization vectors for the J/ψ. A convenient set of polarization vectors can be found in Böhm and Sack [18]. These polarization vectors reduce to the usual massive vector boson (+,−,0) polarization vectors in the parton center of mass frame, and so, although the expressions for the helicity amplitudes have Lorentz-invariant form, the (+,−,0) only refer to the J/ψ helicity in this one particular frame. We find only one independent helicity amplitude [$M(++,++)$, where the ++,++ refer to the helicity of $g_1 g_2, \gamma J/\psi$ respectively], and the remaining five nonzero helicity amplitudes can be found by crossing and parity symmetries:

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$$
\begin{aligned}
M(++,++) = M(--,--) &= C\frac{\hat{s}(\hat{s}-M^2)}{(\hat{s}-M^2)(\hat{t}-M^2)(\hat{u}-M^2)}\,, \\
M(+-,-+) = M(-+,+-) &= C\frac{\hat{u}(\hat{u}-M^2)}{(\hat{s}-M^2)(\hat{t}-M^2)(\hat{u}-M^2)}\,, \\
M(-+,-+) = M(+-,+-) &= C\frac{\hat{t}(\hat{t}-M^2)}{(\hat{s}-M^2)(\hat{t}-M^2)(\hat{u}-M^2)}\,,
\end{aligned} \tag{3}
$$

where $C = \frac{4e_q e g_s^2 R(0) M \delta^{ab}}{\sqrt{3\pi M}}$. Here, M is the J/ψ mass, $\hat{s}$, $\hat{t}$, and $\hat{u}$ are the usual Mandelstam variables, $R(0)$ is the radial wave function at the origin of the $c\bar{c}$ in the J/ψ, and a, b are the color indices of the incident gluons. Thus, the (spin and color) summed and averaged matrix element squared can be found [15]:

$$
\overline{|M(g+g\to J/\psi+\gamma)|^2} = \frac{(16\pi)^2 \alpha\alpha_s^2 M |R(0)|^2}{27}\left[\frac{\hat{s}^2}{(\hat{t}-M^2)^2(\hat{u}-M^2)^2} + \frac{\hat{t}^2}{(\hat{u}-M^2)^2(\hat{s}-M^2)^2} + \frac{\hat{u}^2}{(\hat{s}-M^2)^2(\hat{t}-M^2)^2}\right]. \tag{4}
$$

$|R(0)|^2$ can be related to the leptonic width of the J/ψ:

$$
\Gamma(J/\psi\to e^+e^-) = \frac{16\alpha^2}{9M^2}|R(0)|^2 = 4.72\ \text{keV}\,, \qquad |R(0)|^2 = 0.48\ \text{GeV}^3. \tag{5}
$$

We are interested in the longitudinal spin-spin asymmetry, defined as

$$
A_{LL} = \frac{\sigma(++)-\sigma(+-)}{\sigma(++)+\sigma(+-)}\,, \tag{6}
$$

where $\sigma(++)$ [$\sigma(+-)$] is the cross section for the collision of two protons with the same [opposite] helicities. This can be calculated in the parton model,

$$
A_{LL}\sigma = \int dx_1\, dx_2\, \hat{a}_{LL}\, \hat{\sigma}\, \Delta g(x_1,Q^2)\, \Delta g(x_2,Q^2)\,, \tag{7}
$$

where $\hat{\sigma}$ is the parton level cross section (related to $\overline{|M|^2}$ given earlier), $\Delta g(x,Q^2)$ is the polarized gluon distribution in the proton ($= [g^+(x,Q^2) - g^-(x,Q^2)]$ where $g^+(x,Q^2)$ [$g^-(x,Q^2)$] is the distribution for gluons with the same [opposite] helicity as that of the proton) and $\hat{a}_{LL}$ is the parton level asymmetry:

$$
\hat{a}_{LL} = \frac{\hat{\sigma}(++)-\hat{\sigma}(+-)}{\hat{\sigma}(++)+\hat{\sigma}(+-)}. \tag{8}
$$

Given the known helicity amplitudes for this process, the parton level asymmetry is simply

$$
\hat{a}_{LL} = \frac{\hat{s}^2(\hat{s}-M^2)^2 - \hat{t}^2(\hat{t}-M^2)^2 - \hat{u}^2(\hat{u}-M^2)^2}{\hat{s}^2(\hat{s}-M^2)^2 + \hat{t}^2(\hat{t}-M^2)^2 + \hat{u}^2(\hat{u}-M^2)^2}. \tag{9}
$$

Measurable quantities of interest are the p_T distribution and the joint p_T-y_1-y_2 distribution with $y_1 = y_2 = 0$, where $y_{1(2)}$ is the rapidity of the γ (J/ψ). In the latter case, both partons have the same Bjorken x (which is a function of p_T only). The corresponding asymmetries are given by

$$
\begin{aligned}
A_{LL}^1 &= \frac{\sigma(++)-\sigma(+-)}{\sigma(++)+\sigma(+-)}\,, \\
A_{LL}^2 &= \frac{\frac{d\sigma(++)}{dp_T} - \frac{d\sigma(+-)}{dp_T}}{\frac{d\sigma(++)}{dp_T} + \frac{d\sigma(+-)}{dp_T}}\,, \\
A_{LL}^3 &= \frac{\left.\frac{d\sigma(++)}{dp_T\,dy_1\,dy_2}\right|_{y_1=y_2=0} - \left.\frac{d\sigma(+-)}{dp_T\,dy_1\,dy_2}\right|_{y_1=y_2=0}}{\left.\frac{d\sigma(++)}{dp_T\,dy_1\,dy_2}\right|_{y_1=y_2=0} + \left.\frac{d\sigma(+-)}{dp_T\,dy_1\,dy_2}\right|_{y_1=y_2=0}}.
\end{aligned} \tag{10}
$$

Note that A_{LL}^3 is proportional to $[\Delta g(x(p_T),Q^2)]^2$. Another interesting theoretical concept (though not measurable experimentally) is the average $\hat{a}_{LL}$, or "resolving power." It is defined as

$$
\langle\hat{a}_{LL}\rangle\sigma = \int dx_1\, dx_2\, \hat{a}_{LL}\, \hat{\sigma}\, g(x_1,Q^2)\, g(x_2,Q^2). \tag{11}
$$

As we wish to determine if a given experimental scenario can shed light on the size of the polarized gluon in the proton, we need, in addition to calculating the asymmetry, to estimate the experimental uncertainty in the asymmetry. We will approximate the uncertainty by the statistical uncertainty, since ratios of cross sections should be relatively free of systematic uncertainties. The statistical uncertainty in the measurement of an asymmetry is given by δA, where

$$
\delta A = \frac{\sqrt{1-A^2}}{\sqrt{N}} \tag{12}
$$

and N is the number of events.

We examine this process in several different experimental settings. First, we consider an hypothetical fixed target experiment and, to be specific, take the proton beam energy to be 800 GeV (such as would exist at the upgraded Fermilab fixed target facility). In order to estimate the luminosity possible at such an experiment, we must make some assumptions. First, the Main Injector at Fermilab can provide $\sim 10^{14}$ (unpolarized protons)/sec, with a 65% duty cycle [19]. We will assume a 1 month run, at a much reduced proton rate (say, a factor of 100), combined with a small polarized gas (H_2) jet target (approximately 1 cm long). This will give, we think, a very conservative estimate of $\int \mathcal{L}\, dt = 50$ pb^{-1}. We place no cuts on the rapidity of the photon or J/ψ or on the p_T of the photon or leptons. We find a cross section of approximately 200 pb, most of which is at low p_T. The resolving power (or average $\hat{a}_{LL}$) is found to be about 28%. We use the polarized distributions of Bourrely, Guillet, and Chiappetta (BGC) [20]. They provide two sets of distributions, one with a large polarized gluon distribution and small polarized strange quark distribution (we will refer to it as the set BGC0) and one with a moderately large polarized gluon and moderately large polarized strange quark distribution (we will refer to this set as BGC1). The p_T distribution is shown in Fig. 1(a) (in cross section) and in Fig. 1(b) (in A^2_{LL}). We were also interested the asymmetry A^3_{LL} (technically, instead of taking y_1 and y_2 derivatives, we bin the events in the usual way, displaying the contents of the bin with $-0.1 \leq y_1, y_2 \leq 0.1$). The results are shown in Figs. 2(a) (distribution in cross section) and 2(b) (A^3_{LL} vs p_T). We present in Table I the total number of events expected (at all p_T and $y_{1,2}$ consistent with our cuts) as well as the "resolving power" and asymmetry A^1_{LL} and an estimate of the statistical uncertainty δA^1_{LL}. We also list the number of events in a single p_T bin (p_T given in the table caption), and A^2_{LL} and δA^2_{LL} for that particular p_T bin. Finally, we present the the number of events in the same p_T bin, further restricting the events to lie within $|y_{1,2}| \leq 0.1$, and the value of A^3_{LL} and δA^3_{LL} in the particular p_T bin. These are representative results. Higher statistics can be ob-

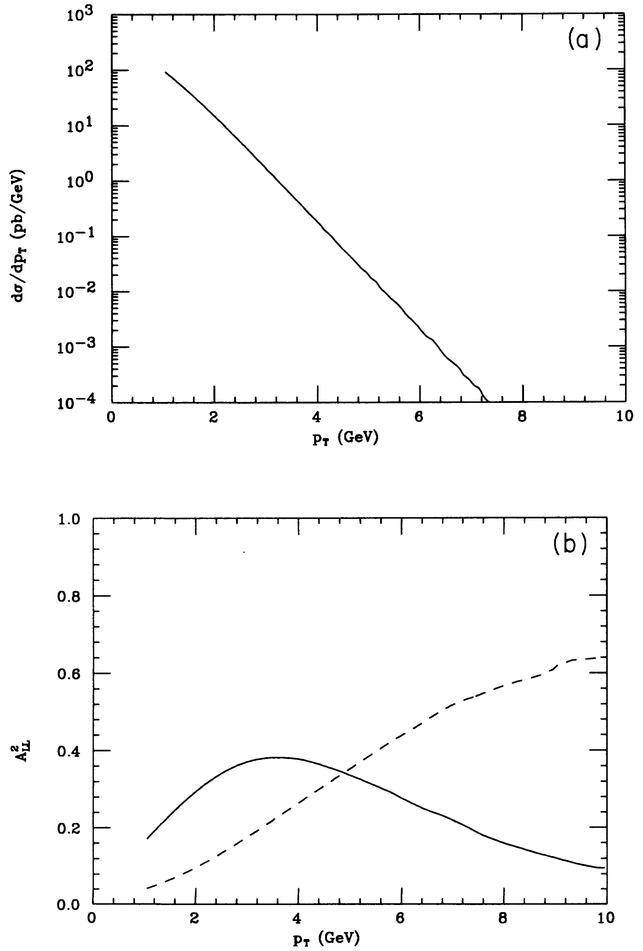

FIG. 1. p_T distribution $\frac{d\sigma}{dp_T}$ vs p_T (a) and A^2_{LL} vs p_T (b) for large $\Delta g(x,Q^2)$ (solid line) and for moderately large $\Delta g(x,Q^2)$ (dashed line) at fixed target.

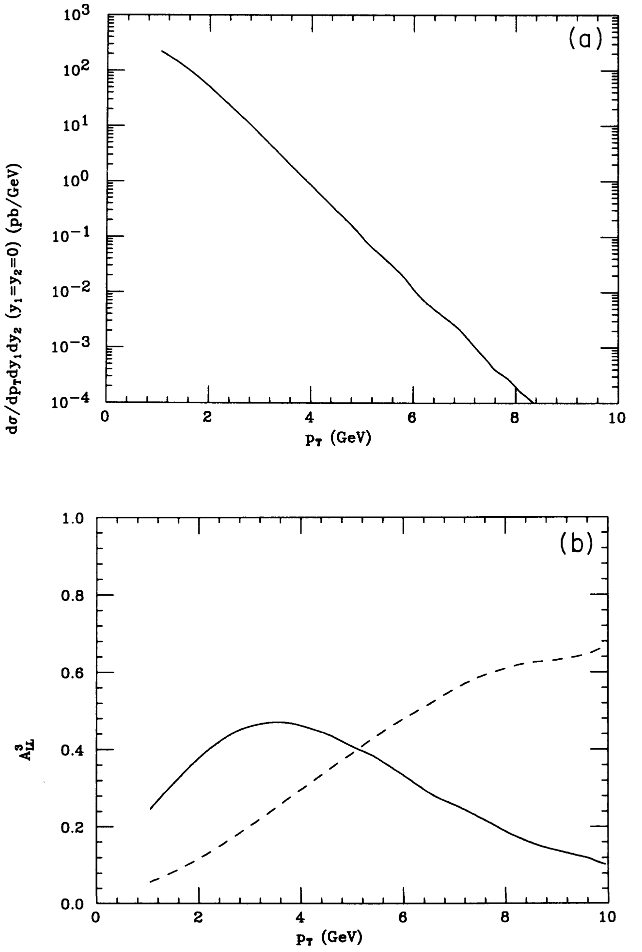

FIG. 2. $\frac{d\sigma}{dp_T dy_1 dy_2}|_{y_1=y_2=0}$ vs p_T (a) and A^3_{LL} vs p_T (b) for large $\Delta g(x,Q^2)$ (solid line) and moderately large $\Delta g(x,Q^2)$ (dashed line) at fixed target.

TABLE I. Summary of representative predictions for $J/\psi + \gamma$ production in polarized proton-proton interactions. $N_{\rm tot}$ is the total number of events above some minimum p_T (= 0 GeV for fixed target, 1 GeV for RHIC, and 10 GeV for the SSC). $\langle \hat{a}_{LL} \rangle$ is the "resolving power" as defined in the text (this is independent of the polarized parton distributions). A^i_{LL} and δA^i_{LL} are defined in the text; the upper entry corresponds to the large $\Delta g(x, Q^2)$ (set BGC0) and the lower entry corresponds to the moderately large $\Delta g(x, Q^2)$ (set BGC1). N_{p_T} is the number of events in the particular p_T bin (0.5–1.5 GeV for fixed target, 1–2 GeV for RHIC at 50 GeV, 3–5 GeV for RHIC at 500 GeV, and 10–20 GeV for the SSC).

	$N_{\rm TOT}$	$\langle \hat{a}_{LL} \rangle$	$A^1_{LL}(\delta A^1_{LL})$	N_{p_T}	$A^2_{LL}(\delta A^2_{LL})$	N_{p_T} $\lvert y_{1,2}\rvert \le 0.1$	$A^3_{LL}(\delta A^3_{LL})$
Fixed Target	10 500	28.4%	12.5% (1%) 3.2% (1%)	5000	16% (1.4%) 4% (1.4%)	200	22% (6%) 5% (6%)
RHIC 50 GeV	11 430	43.3%	19.1% (1%) 4.6% (1%)	4500	26% (1.5%) 8% (1.5%)	1080	32% (3%) 8% (3%)
RHIC 500 GeV	86 400	44.7%	0.4% (0.3%) 0.05% (0.3%)	4500	1.7% (1.5%) 0.2% (1.5%)	840	1.8% (3%) .3% (3%)
SSC	8835	60.2%	0.005% (1%) 0.0006% (1%)	3000	0.008% (2%) 0.001% (2%)	540	.01% (4%) .001% (4%)

tained by the inclusion of all p_T bins.

At this point, we would like to further address the work of Ref. [16]. The large asymmetries shown are surprising, and in our opinion not correct. The parton level asymmetry, making the replacements for $\hat{t}$ and $\hat{u}$ (i.e., working in the parton center of mass frame),

$$\hat{t} = -\frac{1}{2}(\hat{s} - M^2)(1 - \cos\theta) \ , \qquad \hat{u} = -\frac{1}{2}(\hat{s} - M^2)(1 + \cos\theta) \ , \tag{13}$$

reduces to

$$\hat{a}_{LL} = \frac{1 - \frac{1}{8}[(1 + 6\cos^2\theta + \cos^4\theta) + \frac{2M^2}{\hat{s}}(1 - \cos^4\theta) + \frac{M^4}{\hat{s}^2}(1 - \cos^2\theta)^2]}{1 + \frac{1}{8}[(1 + 6\cos^2\theta + \cos^4\theta) + \frac{2M^2}{\hat{s}}(1 - \cos^4\theta) + \frac{M^4}{\hat{s}^2}(1 - \cos^2\theta)^2]} . \tag{14}$$

Here $\cos\theta$ is measured in the parton center of mass frame. It is obvious that for $\cos\theta = \pm 1$, $\hat{a}_{LL}$ is a minimum (actually zero), and so, for any $\hat{s}$, the maximum of $\hat{a}_{LL}$ should be at $\cos\theta = 0$. In this limit, the asymmetry reduces to

$$\hat{a}_{LL}(\cos\theta = 0) = \frac{1 - \frac{1}{8}\left(\frac{\hat{s} + M^2}{\hat{s}}\right)^2}{1 + \frac{1}{8}\left(\frac{\hat{s} + M^2}{\hat{s}}\right)^2} . \tag{15}$$

Two further limiting cases are possible: namely, production at threshold ($\hat{s} = M^2$) which gives $\hat{a}_{LL} = \frac{1}{3}$ and production at very high energy ($\hat{s} \to \infty$) which gives $\hat{a}_{LL} = \frac{7}{9}$. For $\sqrt{\hat{s}} = \sqrt{s} = 38.75$ GeV (the fixed target energy considered both here and in Ref. [16]), the parton level asymmetry is near its maximum value. Since $\Delta g(x, Q^2)/g(x, Q^2) \le 1$ generally, the maximum observable asymmetry is bounded by the maximum parton level asymmetry. Thus we are unable to understand the prediction, in Ref. [16], that the observable asymmetry can be as large as 85%.

Next, we consider collider experiments at RHIC. RHIC is a high luminosity ($\mathcal{L} = 2 \times 10^{32}$ cm^{-2}sec^{-1} =6000 pb^{-1}/yr) collider capable of producing proton on proton collisions for center of mass energies between 50 and 500 GeV. A program of polarized proton on proton collisions, at full energy and luminosity, is being discussed [21]. We will assume a nominal running time of 2 months, at full luminosity, for 50 GeV and 500 GeV each. In order to be somewhat conservative, we will estimate event numbers based on 300 pb^{-1} integrated luminosity. We will assume a generic collider-type detector, and in order to simulate the acceptance we will require the photon and electrons observed to lie in the rapidity range $|y| \le 2$. (This simulates the acceptance of the proposed STAR detector at RHIC [22], level 2 for photons and electrons. We will not consider the possibility of the detection of the $\mu^+\mu^-$ final state at RHIC.) Furthermore, we will (rather arbitrarily) require the p_T of the photon larger than 1 GeV in the following discussion. We present our results for the p_T distribution in Fig. 3(a), and A^2_{LL} in Figs. 3(b) ($\sqrt{s} = 50$ GeV) and 3(c) ($\sqrt{s} = 500$ GeV). See Fig. 4(a) for $\frac{d\sigma}{dp_T dy_1 dy_2}$ vs p_T and Figs. 4(b) ($\sqrt{s} = 50$ GeV) and 4(c) ($\sqrt{s} = 500$ GeV) for A^3_{LL} vs p_T. The "resolving power" increases with energy (actually p_T), even though the observed asymmetry decreases. This is simply a consequence of the behavior of the polarized gluon distribution. Refer to Table I for some representative results.

Finally, we consider a collider experiment at the SSC. The luminosity of the SSC is $\mathcal{L} = 10^{33}$ cm^{-2} sec^{-1} = 30 000 pb^{-1}/yr. We will again assume a running time of 2 months at full luminosity and energy, and conservatively calculate event numbers based on 1500 pb^{-1} integrated luminosity. We require the photons and leptons to have $p_T \geq 10$ GeV and lie in the range $|y| \leq 2.5$ [these approximate the acceptances of the Solenoidal Detector Collaboration (SDC) detector [23]]. In this case, the resolving power is quite high, $\langle \hat{a}_{LL} \rangle = 60\%$, although because of the extremely small x probed the observed asymmetry A^1_{LL} is tiny. Similarly, A^2_{LL} and A^3_{LL} are both smaller

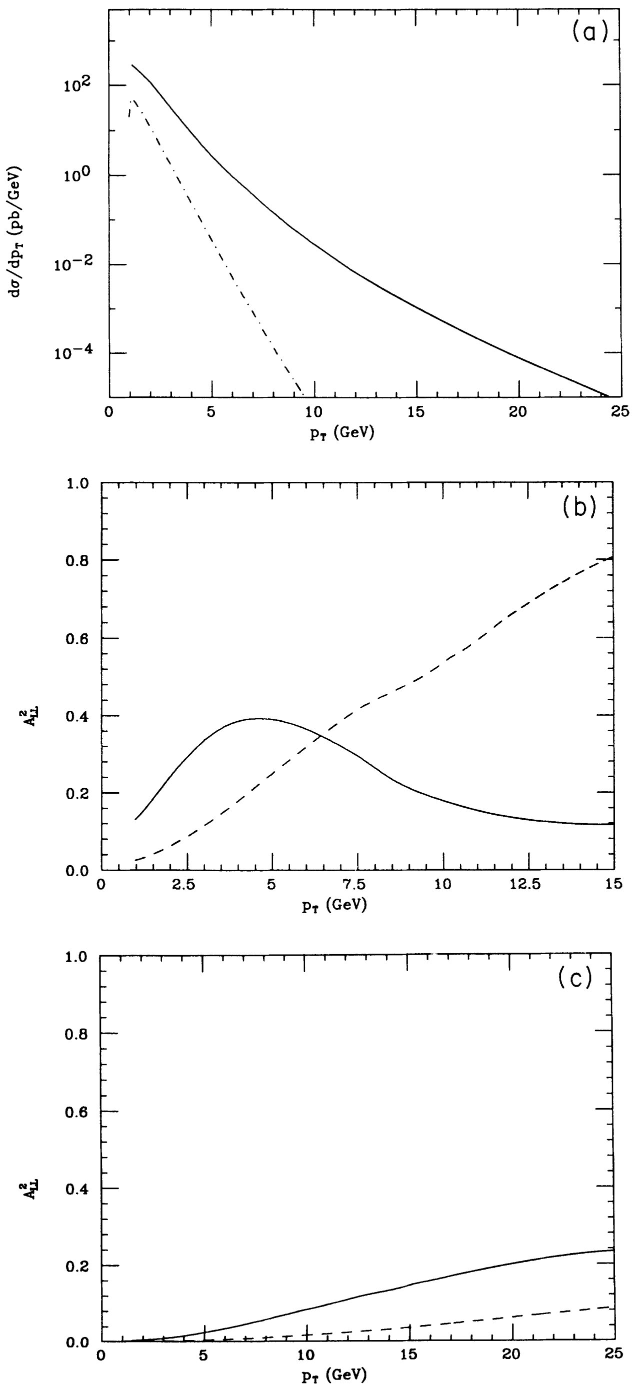

FIG. 3. p_T distribution, $\frac{d\sigma}{dp_T}$ vs p_T (a) for RHIC at $\sqrt{s}$ = 500 GeV (solid line) and at $\sqrt{s}$ = 50 GeV (dot-dashed line), and A^2_{LL} vs p_T for RHIC at $\sqrt{s}$ = 50 GeV (b) and at $\sqrt{s}$ = 500 GeV (c) for large $\Delta g(x, Q^2)$ (solid line) and for moderately large $\Delta g(x, Q^2)$ (dashed line).

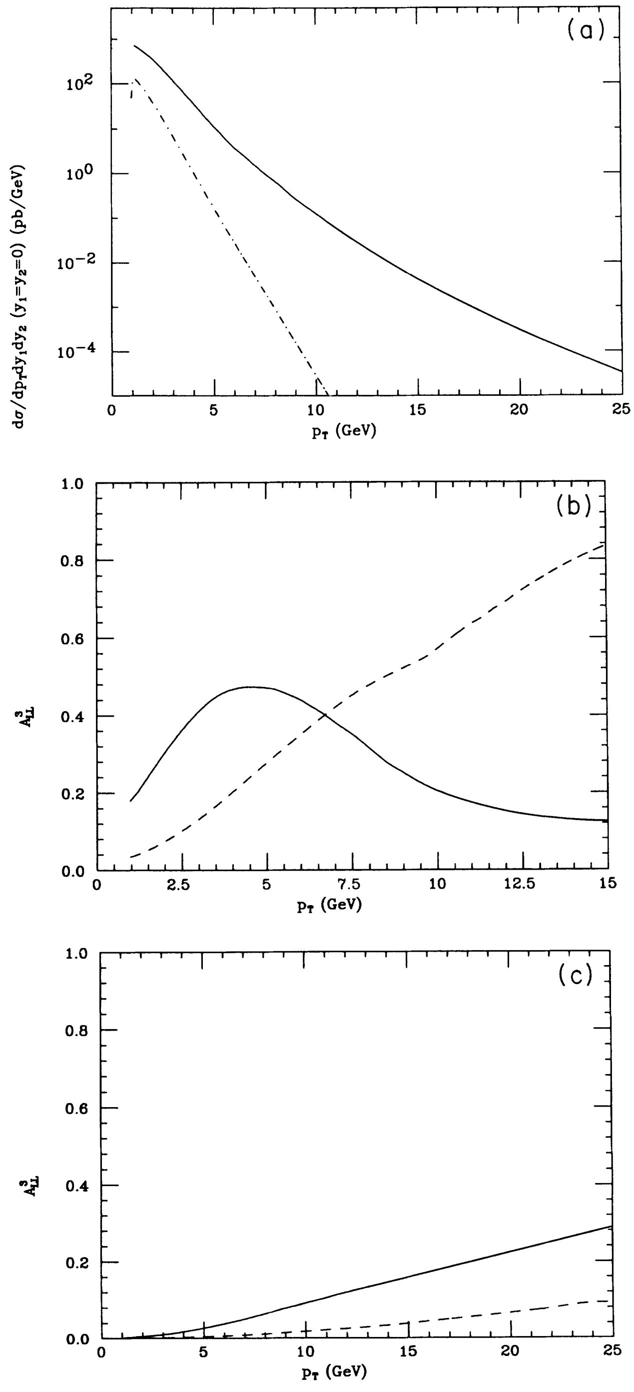

FIG. 4. $\frac{d\sigma}{dp_T dy_1 dy_2}|_{y_1=y_2=0}$ vs p_T (a) for RHIC at $\sqrt{s}$ = 500 GeV (solid line) and at $\sqrt{s}$ = 50 GeV (dot-dashed line), and A^3_{LL} vs p_T for RHIC at $\sqrt{s}$ = 50 GeV (b) and at $\sqrt{s}$ = 500 GeV (c) for large $\Delta g(x, Q^2)$ (solid line) and moderately large $\Delta g(x, Q^2)$ (dashed line).

than 1% for all $p_T < 125$ GeV, while there will only be a handful of events at (or beyond) $p_T \sim 25$ GeV, and so there is no observable asymmetry. Again, see Table I for some representative results.

In conclusion, we have studied the process $p + p \rightarrow J/\psi + \gamma + X$ in polarized proton-proton collisions. We first presented the necessary helicity amplitudes and discussed the calculation. Then we studied this process at polarized fixed target and in colliders, at polarized RHIC (50 and 500 GeV center of mass energy) and at the polarized SSC. Our results indicate that a polarized (double spin) fixed target program can be very useful in the determination of the polarized gluon distribution. It is unfortunate that no such experiment is planned. RHIC (especially at lower energies) is an excellent probe of the polarized gluon distribution. Since A^3_{LL} is directly proportional to $[\Delta g(x(p_T), Q^2)/g(x(p_T), Q^2)]^2$, this distribution provides an easy determination of the polarized gluon distribution at various x values. It will prove especially useful to measure this distribution at several center of mass energies. Even a measurement of A^2_{LL} can provide much useful information (though it is not clear whether the higher statistics involved in this measurement will outweigh the cleanliness of the extraction of the polarized gluon distribution in a measurement of A^3_{LL}). The SSC probes a much lower x in this process, and since $\Delta g(x, Q^2)/g(x, Q^2) \ll 1$ there is no measurable asymmetry. However, the "resolving power" at the SSC is still very large, and so the smallness of the asymmetry is purely a consequence of the small-x behavior of $\Delta g(x, Q^2)$. The polarized SSC can still be a useful tool for the study of high energy spin properties of the proton by utilizing a subprocess that will probe larger x (e.g., heavy Higgs boson production). We should also point out that we have considered only the color singlet model of heavy quarkonium production in this paper. A similar analysis can be performed using local duality, if it is determined at HERA that this mechanism contributes to $J/\psi + \gamma$ production [24]. Some slight modifications will be required, namely, the inclusion of charm in the proton (this effect should be small) and light $q\bar{q}$ fusion, and in addition the modification of the parton level asymmetries. As a final related comment, we plan to study $J/\psi + \gamma$ production at HERA using a polarized lepton beam and angular distributions of the final leptons to learn something of the polarized gluon distribution of the photon.

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