hep-ph/0207318

# Detect $\Delta G$ at BNL-RHIC via Double Quarkonium Production


Cong-Feng Qiao*

in collaboration with J. Kodaira

*Department of Physics, Faculty of Science,*
*Hiroshima University, Higashi-Hiroshima 739-8526, Japan*



### Abstract

The double spin asymmetry for the $J/\psi$ pair productions in the polarized $p\,p$ collisions is studied. We point out that the asymmetry measurement at RHIC-SPIN experiments is pretty realistic to extract the Polarized Gluon Distribution Function.


---


*JSPS Research Fellow. E-mail: qiao@theo.phys.sci.hiroshima-u.ac.jp

# I. INTRODUCTION

Intrigued by the measurement of the European Muon Collaboration in polarized-target experiment [1], an enormous amount of researches have been done on the nucleon spin structure both experimentally and theoretically. It is now clear that the gluon shares a large portion of the parent proton's momentum. However, whether the gluons share also the spin of proton is still an open question.

So far, almost all experimental measurements of the spin structure of the nucleon are about the polarization of quarks. It is expected that within few years the polarized proton-proton collisions at BNL heavy-ion collider RHIC will provide copious experimental data to unveil the polarized parton distributions. Since the major emphasis and strength of RHIC-Spin is to measure the gluon polarization, it is important and interesting to investigate various processes which are attainable experimentally to this aim.

Up to now, there are three main kinds of means in measuring the gluon polarization, which are thought to be feasible at RHIC technically. Those are:

---

[1]European Muon Collab., J. Ashman *et al.*, Phys. Lett. **B206**, 364 (1988).

- High-$p_T$ Prompt Photon Production
- Jet production
- Heavy Flavor Production

There are advantages and drawbacks in each of these schemes [2]. The prompt photon production with polarized beams at RHIC is a promising method to measure gluon polarization, but we must cooperate with the polarized deep inelastic scattering (DIS) results on quarks. For the jet and heavy flavor production, the tremendous effects of hadronization and higher order corrections are not yet well controlled theoretically. Therefore, to develop more practical ways for running RHIC spin project in measuring the gluon polarization is one of the urgent tasks in theory.

Quarkonium production and decays have long been taken as an ideal means to investigate the nature of Quantum Chromodynamics(QCD) and other phenomena. Due to the approximately non-relativistic nature, the description of heavy quark and antiquark system stands as one of the simplest applications of QCD. e.g., at

[2] G. Bunce, N. Saito, J. Soffer and W. Vogelsang, Ann. Rev. Nucl. Part. Sci. **50**, 525 (2000).

leading order in $v$ in NRQCD[3]

$$d\sigma(\psi + \mathrm{X}) = d\sigma(c\bar{c}_1(^3S_1) + \mathrm{X})|\mathrm{R}_\psi(0)|^2.$$

The very clean signals of quarkonium leptonic decays make the experimental detection with a high precision,

$$\Gamma(\psi_n \to l\bar{l}) \approx \frac{4\alpha^2}{9m_c^2}|R_{\psi_n}(0)|^2,$$

and therefore quarknoium plays a crucial role in investigating other phenomena as well, e.g. in detecting the parton distribution, the QGP signal, and even new physics.

Although we know that in explaining the high-$p_T$ $\psi$ surplus production discovered by CDF group [4] [5] [6] at the Fermilab Tevatron, the color-octet scenario [7] is still playing a central role, it encounters difficulties in confronting other phenomena [8]. And, due to a recent discovery [9], large uncertainties in color-octet matrix elements may

---

[3]G.T. Bodwin, E. Braaten, and G.P. Lepage, Phys. Rev. D**51**, 1125 (1995); **55**, 5853(E) (1997).

[4]CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **69**, 3704 (1992).

[5]CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **79**, 572 (1997).

[6]CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **79**, 578 (1997).

[7]E. Braaten and S. Fleming, Phys. Rev. Lett. **74**, 3327 (1995).

[8]For recent reviews see, for example: I. Rothstein, Hep-ph/9911276; M. Krämer, Hep-ph/0106120.

[9]Cong-Feng Qiao, Hep-ph/0202227.

still survive.

During the past years, a series of efforts have been made on detecting polarized parton distributions through the quarkonium production process [10] [11] [12] [13] [14]. Unfortunately, most of the previous investigations are not directly applied to the RHIC physics and are spoiled by the uncertainties aforementioned.

We found that double heavy quarkonium production in the polarized proton-proton collision would provide an ideal means of detecting the polarized gluon distributions, and which may at least play a supplemental role to the presently proposed program at RHIC to this end. The double $J/\psi$ production has several advantages in reducing the theoretical uncertainties mentioned above:

- By considering double production, the relativistic corrections and color-octet uncertainties, which only involve in significantly at high-$p_T$, are reasonable highly suppressed, especially without or with a lower transverse momentum cut [15].

---

[10] A.V. Batunin and S.R. Slabospitsky, Phys. Lett. **B188**, 269 (1987).

[11] J.L. Cortes and B. Pire, Phys. Rev. D**38**, 3586 (1988).

[12] M.A. Doncheski and R.W. Robinett, Phys. Lett. **B248**, 188 (1990).

[13] T. Morii, S. Tanaka, and T. Yamanishi, Phys. Lett. **B372**, 165 (1996).

[14] R.L. Jaffe and D. Kharzeev, Phys. Lett. **B455**, 306 (1999).

[15] Cong-Feng Qiao, Hep-ph/0206093, to appear in Phys. Rev. D.

- The total contribution from the higher excited states are also doubly suppressed.
- The higher order QCD correction can be well controlled by applying a suitable $p_T$ cut for the produced Charmonium.
- Since the prevailing partonic process is the gluon-gluon fusion into double quarkonium, it stands as very sensitive method in measuring the gluon polarization. In the RHIC energy region, and $p\ p$ collision the $q\bar{q}$ initiated process is negligible.

There were discussions of detecting the gluon polarization by means of double $J/\psi$ production in literature [16] [17]. However, their main emphasis were not on RHIC physics, and the analytical expressions were not given, since their expressions are too long to be presented in a journal paper.

---

[16] S.P. Baranov and H. Jung, Z. Phys. C**66**, 467 (1995).

[17] T. Gehrmann, Phys. Rev. D**53**, 5310 (1996).

## II. FORMALISM

The concerned process, $g + g \to J/\psi + J/\psi$, is shown in Figure I. When calculating the helicity-dependent matrix elements, one needs to project onto definite helicity states of initial gluons.

$$\epsilon_\mu(k_1,\, \lambda)\, \epsilon^\star_\nu(k_1,\, \lambda) = \frac{1}{2}\left[ -g_{\mu\nu} + \frac{k_{1\mu}k_{2\nu} + k_{1\nu}k_{2\mu}}{k_1 \cdot k_2} \right. \\ \left. + \, i\, \lambda\, \epsilon_{\mu\nu\alpha\beta} \frac{k_{1\alpha}k_{2\beta}}{k_1 \cdot k_2} \right] , \qquad (1)$$

The measurable double spin asymmetry $A_{LL}$ for $J/\psi$ pair production is defined as,

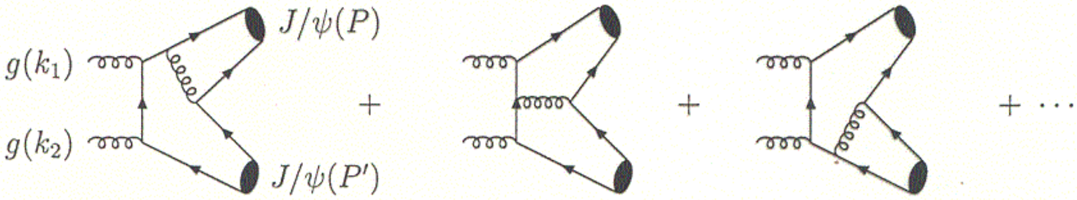
$$A^{2J/\psi}_{LL} = \frac{d\sigma(p_+p_+ \to J/\psi J/\psi) - d\sigma(p_+p_- \to J/\psi J/\psi)}{d\sigma(p_+p_+ \to J/\psi J/\psi) + d\sigma(p_+p_- \to J/\psi J/\psi)} \\ = \frac{E d\Delta\sigma/d^3p}{E d\sigma/d^3p} , \qquad (2)$$

where $p_+$ and $p_-$ denote the helicity projection of the incident protons being positive and negative, respectively. In terms of the gluon densities and the partonic cross sections, this asymmetry reads,

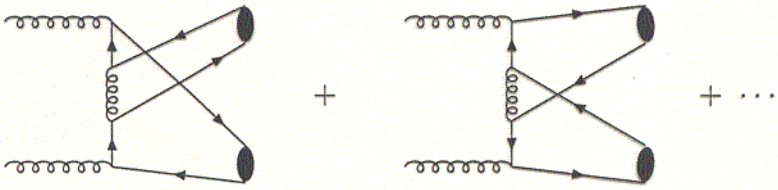
$$A^{2J/\psi}_{LL} = \frac{\int dx_1 dx_2 d\Delta\hat{\sigma} \Delta G(x_1) \Delta G(x_2)}{\int dx_1 dx_2 d\hat{\sigma} G(x_1) G(x_2)} \qquad (3)$$

where $\Delta G(x) = G_+(x) - G_-(x)$ and $G(x) = G_+(x) + G_-(x)$ are the polarized and unpolarized gluon distributions. The quantities

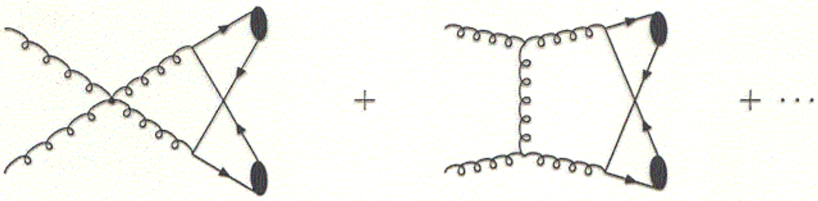
$$\hat{\sigma} = \frac{1}{4} \sum_{\lambda,\lambda'} \hat{\sigma}\,(\lambda,\, \lambda'),\; \Delta\hat{\sigma} = \frac{1}{4} \sum_{\lambda,\lambda'} \lambda\lambda'\, \hat{\sigma}\,(\lambda,\, \lambda'). \qquad (4)$$




$(A)$




$(B)$




$(C)$

- The asymmetric partonic differential cross section:

$$
\begin{aligned}
\frac{d\Delta\hat{\sigma}}{dt} &= \frac{-16\alpha_s^4\pi|R(0)|^4}{81s^8(m^2-t)^4(m^2-u)^4} \times [\,2744m^{24} \\
&- 15240m^{22}(t+u) + m^{20}(32110t^2 + 90076tu + 32110u^2) \\
&- 16m^{18}(2025t^3 + 12673t^2u + 12673tu^2 + 2025u^3) \\
&+ 2t^4u^4(349t^4 - 908t^3u + 1374t^2u^2 - 908tu^3 + 349u^4) \\
&+ 4m^{16}(3903t^4 + 57292t^3u + 117766t^2u^2 + 57292tu^3 \\
&+ 3903u^4) - 4m^{14}(510t^5 + 36713t^4u + 135685t^3u^2 \\
&+ 135685t^2u^3 + 36713tu^4 + 510u^5) + m^{12}(-1461t^6 \\
&+ 58600t^5u + 364313t^4u^2 + 594840t^3u^3 + 364313t^2u^4 \\
&+ 58600tu^5 - 1461u^6) + 4m^2t^2u^2(9t^7 - 505t^6u + 44t^5u^2 \\
&- 556t^4u^3 - 556t^3u^4 + 44t^2u^5 - 505tu^6 + 9u^7) \\
&+ 2m^{10}(381t^7 - 7111t^6u - 83783t^5u^2 - 180639t^4u^3 \\
&- 180639t^3u^4 - 83783t^2u^5 - 7111tu^6 + 381u^7) \\
&+ m^8(-79t^8 + 1272t^7u + 54526t^6u^2 + 156224t^5u^3 \\
&+ 163850t^4u^4 + 156224t^3u^5 + 54526t^2u^6 + 1272tu^7 - 79u^8) \\
&+ m^4tu(-36t^8 + 1471t^7u + 9764t^6u^2 + 12863t^5u^3 \\
&+ 7196t^4u^4 + 12863t^3u^5 + 9764t^2u^6 + 1471tu^7 - 36u^8) \\
&- 2m^6(2t^9 + 17t^8u + 5151t^7u^2 + 25947t^6u^3 + 24439t^5u^4 \\
&+ 24439t^4u^5 + 25947t^3u^6 + 5151t^2u^7 + 17tu^8 + 2u^9)\,]
\end{aligned}
$$

- The symmetric partonic differential cross section:

$$
\begin{aligned}
\frac{d\hat{\sigma}}{dt} = & \frac{16\ \alpha_s^4\ \pi\ |R(0)|^4}{81 m^2 s^8 (m^2-t)^4 (m^2-u)^4} \Big[ 2680 m^{24} - 14984 m^{22}(t+u) \\
& + m^{20}(31406t^2 + 89948tu + 31406u^2) - 16m^{18}(1989t^3 + 12661t^2u \\
& + 12661tu^2 + 1989u^3) + 2t^4u^4(349t^4 - 908t^3u + 1374t^2u^2 \\
& - 908tu^3 + 349u^4) + 4m^{16}(4417t^4 + 57140t^3u + 117714t^2u^2 \\
& + 57140tu^3 + 4417u^4) - 4m^{14}(1793t^5 + 38340t^4u + 134119t^3u^2 \\
& + 134119t^2u^3 + 38340tu^4 + 1793u^5) + 2m^{12}(1478t^6 + 38203t^5u \\
& + 180812t^4u^2 + 285950t^3u^3 + 180812t^2u^4 + 38203tu^5 + 1478u^6) \\
& + 4m^2t^2u^2(9t^7 - 586t^6u - 37t^5u^2 - 394t^4u^3 - 394t^3u^4 - 37t^2u^5 \\
& - 586tu^6 + 9u^7) - 2m^{10}(397t^7 + 15391t^6u + 91227t^5u^2 + 167593t^4u^3 \\
& + 167593t^3u^4 + 91227t^2u^5 + 15391tu^6 + 397u^7) + m^8(47t^8 + 7642t^7u \\
& + 73146t^6u^2 + 150334t^5u^3 + 132502t^4u^4 + 150334t^3u^5 + 73146t^2u^6 \\
& + 7642tu^7 + 47u^8) + 2m^6(10t^9 - 411t^8u - 8951t^7u^2 - 29063t^6u^3 \\
& - 17653t^5u^4 - 17653t^4u^5 - 29063t^3u^6 - 8951t^2u^7 - 411tu^8 + 10u^9) \\
& + m^4(t^{10} - 66t^9u + 2469t^8u^2 + 12874t^7u^3 + 11928t^6u^4 + 1164t^5u^5 \\
& + 11928t^4u^6 + 12874t^3u^7 + 2469t^2u^8 - 66tu^9 + u^{10}) \Big]
\end{aligned}
$$

## III. RESULTS

In the numerical calculation, we take Gehrmann and Stirling's parameterization [18] for the polarized gluon distributions, and for consistency the unpolarized gluon distribution is taken to be the MRST parameterization [19]. We have:

1) Spin Asymmetry versus transverse momentum for different set of GS polarized parton distributions at colliding energy $\sqrt{s} = 500$ GeV.

2) Angular differential asymmetry distribution of the $J/\psi$ pair in the parton interaction c.m. frame at RHIC with colliding energy of 500 GeV.

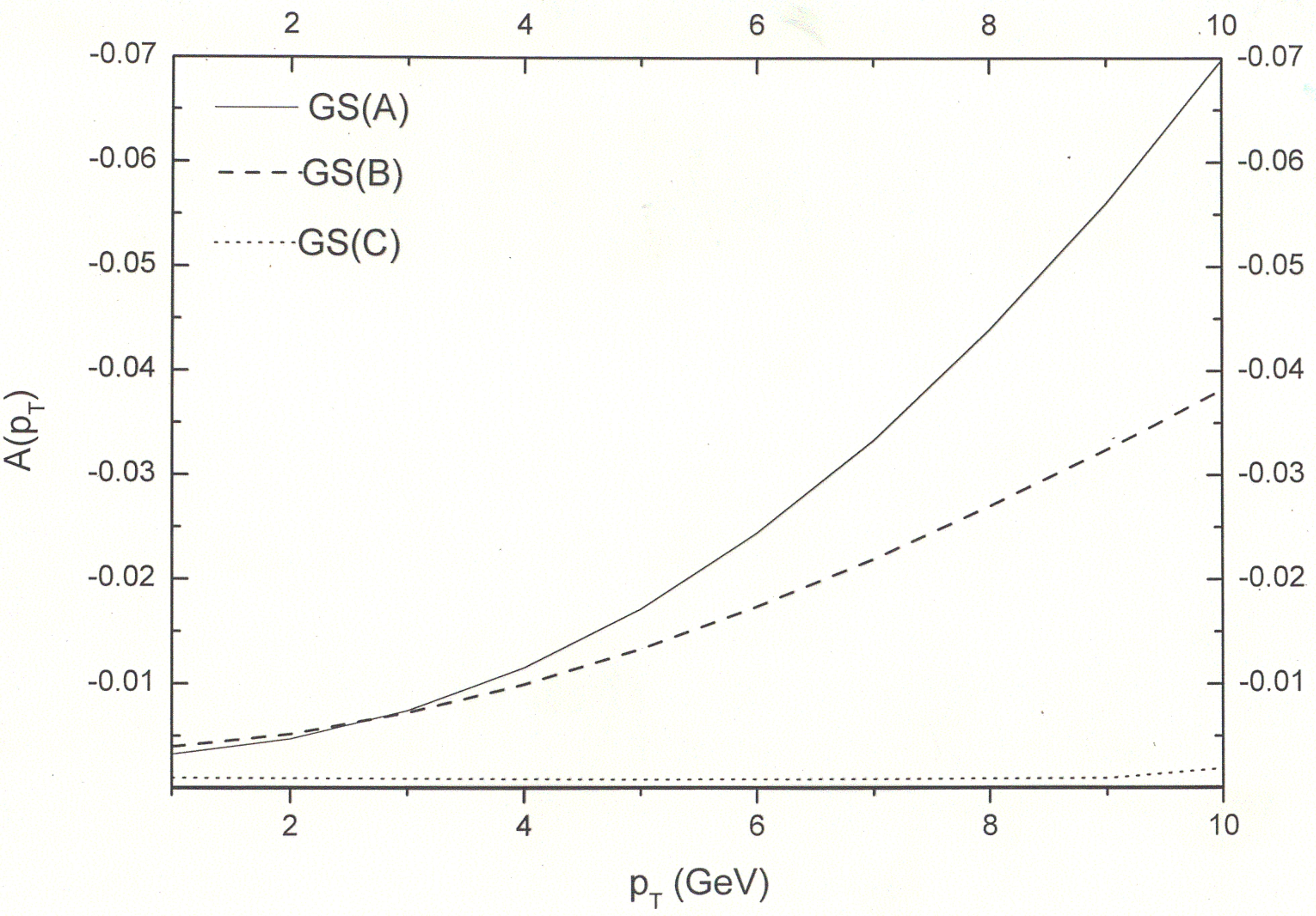
3) The differential cross-section of $J/\psi$ pair production versus $p_T$ at the Tevatron. Solid line comes from the Color-Singlet calculation of this paper; the dashed line from the Color-Octet calculation read from Ref.[20].

---

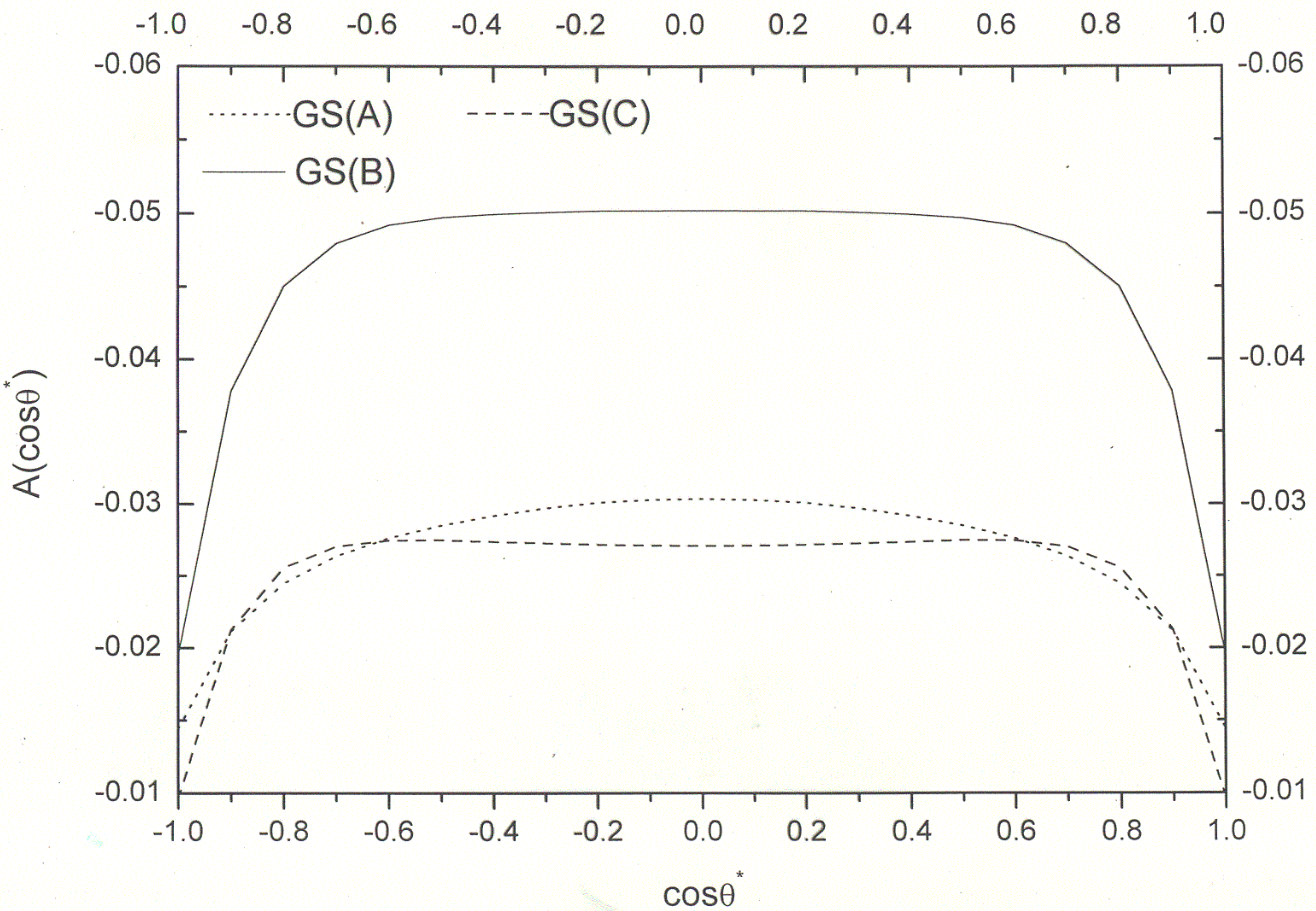
[18] T. Gehrmann and W.J. Stirling, Phys. Rev. **D53**, 6100 (1996).

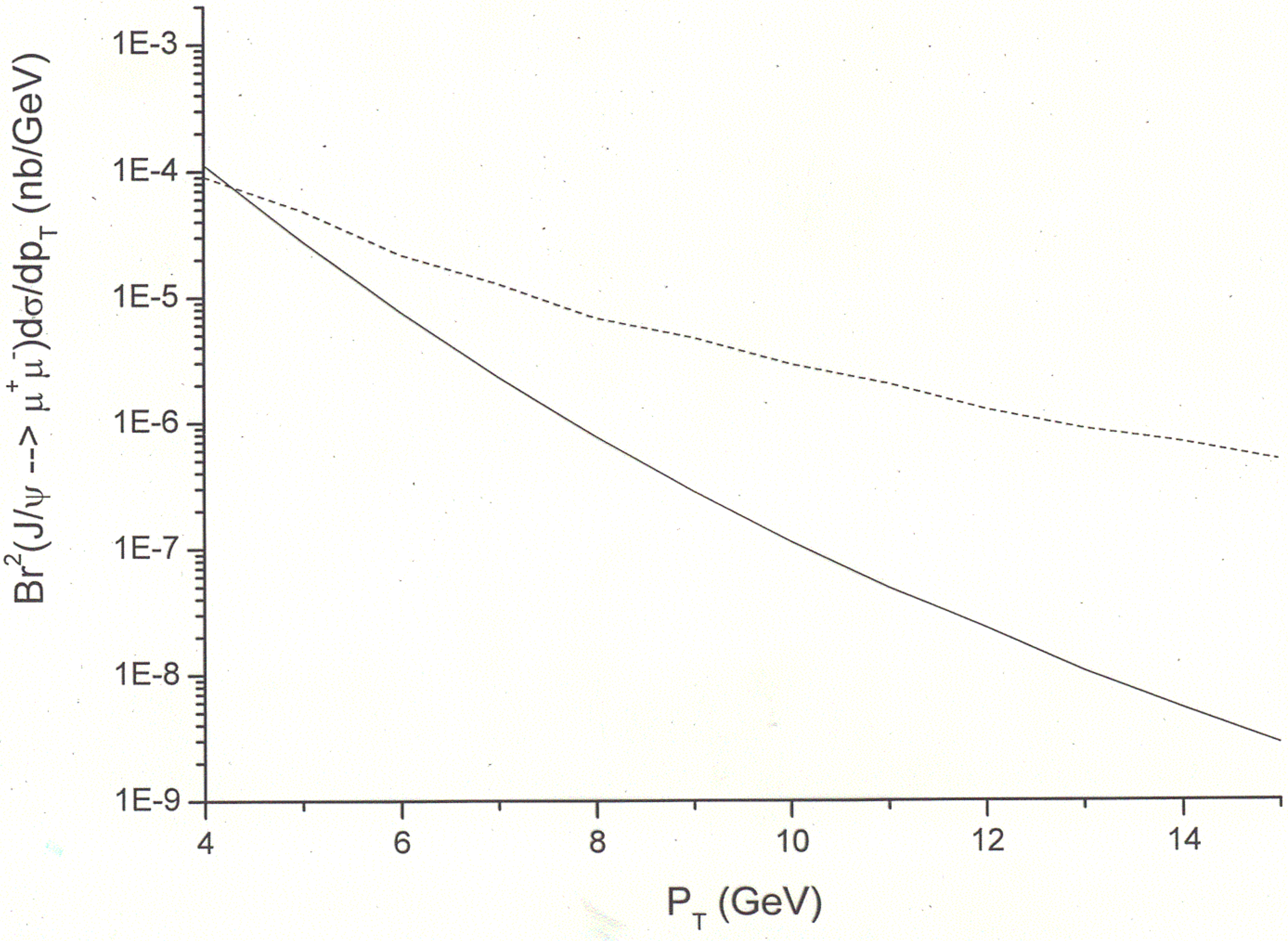
[19] A.D. Martin, R.G. Roberts, W.J. Stirling, R.S Thorne, Eur. Phys. J. **C14**, 133 (2000).

[20] V. Barger, S. Fleming, and R.J.N. Phillips, Phys. Lett. **B371** (1996) 111.



GS(A)
GS(B)
GS(C)
A(p_T)
p_T (GeV)
2
4
6
8
10
-0.07
-0.06
-0.05
-0.04
-0.03
-0.02
-0.01


GS(A)
GS(C)
GS(B)
A(cosθ*)
cosθ*



1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
4
6
8
10
12
14
$Br^2(J/\psi \dashrightarrow \mu^+\mu^-)d\sigma/dp_T$ (nb/GeV)
$P_T$ (GeV)

TABLE I. Total cross sections for $J/\psi$ pair production at RHIC at $\sqrt{s} = 500$ GeV, evaluated with different parton distributions.

| | $\sigma^{tot}_{\mu^+\mu^-}$ | $\sigma_{\mu^+\mu^-}(\lvert p_T\rvert > 1$ GeV) |
|---|---|---|
| CTEQ5L[21] | 11.8 pb | 7.3 pb |
| MRST[22] | 6.5 pb | 4.3 pb |
| GRV [23] | 7.4 pb | 4.7 pb |

$$\sigma^{tot}_{\mu^+\mu^-} \equiv Br^2(J/\psi \to \mu^+\mu^-)\,\sigma^{tot}$$

---


21) CTEQ Collaboration, H.L. Lai *et al.*, Eur. Phys. J. C12, 375 (2000).

22) A.D. Martin, R.G. Roberts, W.J. Stirling, R.S Thorne, Eur. Phys. J. C**14**, 133 (2000).

23) M. Glück, E. Reya, and A. Vogt, Z. Phys. C**67**, 433 (1995).

## IV. CONCLUDING REMARKS

- We have given out the analytical expressions for the dominant $J/\psi$ pair production process in polarized proton-proton collision.
- $J/\psi$ pair production in polarized proton-proton collision is sensitive to the polarized gluon distributions. We have shown that the $J/\psi$ pair production at RHIC may stand as an independent means in detecting the gluon spin asymmetry within the hadron.
- The illustrative figures of spin asymmetry distributions versus transverse momentum and angular are given based on some sets of polarized gluon distribution parameterizations.
- It should be noted that for the time being the accumulated data at RHIC detectors are far from enough for the analyzing of this process in the aim of measuring the gluon helicity distributions. However, in the following run, that is to say with colliding energy of 500 GeV and 800 $pb^{-1}$ of integrated luminosity, thousands of $J/\psi$ pair events could be detected and the gluon polarization would be measured.
- With the expected upgrade of RHIC in the future, the concerned process would show up to be as more important means in chasing the goal of uncovering the nucleon spin structures.