Heavy-Flavor Production via Single Muon Detection in the PHENIX Detector at $\sqrt{s} = 200$ GeV

M. L. Brooks and J. M. Moss
Los Alamos National Laboratory
Los Alamos NM 87545

August 1997

Abstract. We show that the spectrum of single muons with $p_t > 2$ GeV in the PHENIX muon endcaps is dominated by heavy-quark decays. Additionally, muons from pion and kaon decays have an asymmetric distribution of decay vertices, permitting a statistical subtraction of this background from the prompt muon signal which has a symmetric distribution. Hence high- p_t single muons may be used to measure the rate of production of heavy quarks in *pp*, *p*-nucleus, and nucleus-nucleus collisions in the early operational years of PHENIX. We have examined two applications of this technique: (1) Determination of the average gluon shadowing factor, and (2) Measurement of the gluon polarization, ΔG, via gluon-gluon fusion in polarized *pp* collisions. The shadowing factor is a straightforward measurement in *p*-nucleus collisions. In polarized *pp* collisions for modest p_t, cancellations in the analyzing power in the process $g + g \rightarrow Q + Q$ due to kinematic averages at the parton level result in rather small asymmetries. When higher luminosity polarized operation becomes feasible, detection of muons with $p_t > 6$ GeV will significantly improve the sensitivity to ΔG.

INTRODUCTION

It has been recognized for many years that heavy-quark production would be large in the RHIC energy range and, for a variety of theoretical reasons, that it would be interesting to study. The PHENIX conceptual design report highlights the measurement of open charm production through the distinctive *e*-*μ* coincidence channel. It is likely that a few years of operational experience with PHENIX will be required in order to fully exploit this capability.

In this report we focus on the potential for single-muon detection as a means of measuring a global signal for heavy-quark production with PHENIX. This goal is important both for the quark-matter and spin programs. The major results of our simulations are: (1) Open heavy flavor production followed by semileptonic decay into muons at $p_t > 2$ GeV competes favorably with the principal backgrounds — muons from pion and kaon decay, (2) A shifted distribution of decay vertices of muons from pion and kaon decays permits a statistical subtraction of this background from the interesting prompt muon signal, and (3) Single muons from J/ψ and Drell-Yan (DY) production are less important than open heavy-flavor decay.

The ease of triggering (penetration to muon ID plane 6) and large count rates for single high- p_t muons suggest that this measurement could have a large impact early in the PHENIX physics program when machine luminosity is low.

EVENT GENERATION

Heavy-Flavor Production

For charm and beauty production we used the PYTHIA(5.6)/JETSET(7.3) package [1] with the GRV leading order structure functions. Figure 1 shows the PYTHIA results compared to the E706 data [2], $\pi^- + N \rightarrow D^\pm$ at 515 GeV. The intrinsic p_t parameter of PYTHIA was set to 2 GeV. It is well known that an adjustment of this type is required in order to fit the p_t distribution of charm production [3,4]. In leading order calculations this is sometimes accomplished via an intrinsic p_t and sometimes via the use of a fragmentation function harder than the standard Peterson form. With the same parameters we were able to reproduce the D0 [5] single muon production data at 1.8 TeV (Fig. 2). For the $\sqrt{s}$ = 200 GeV calculations all muons with p_t > 1.5 GeV resulting from the decay of charm and beauty quarks were stored in PAW ntuples for the comparisons described below. With the PYTHIA/JETSET parameters fixed, only the total cross sections remain to be chosen. We adopted a value intermediate within the range explored by McGaughey et al. [6], σ(charm) = 200 μbarns. The same *K* factor yields σ(beauty) = 2 μbarns.

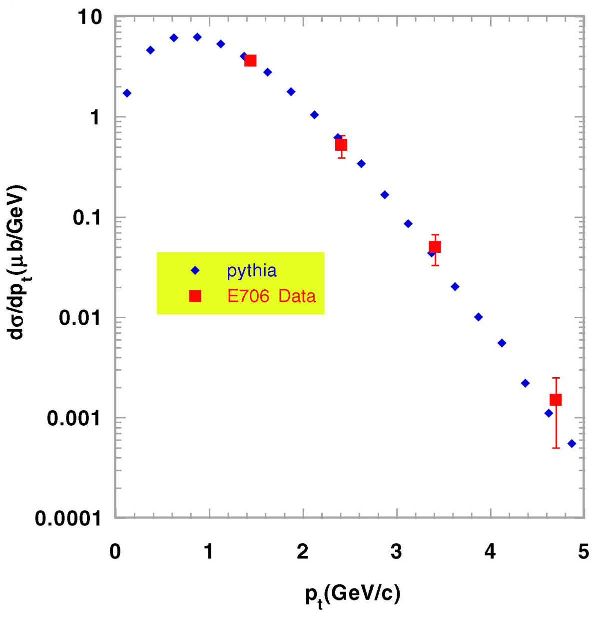

Fig. 1. Data from Fermilab E706 [2] compared with a PYTHIA calculation. The calculation was normalized at p_t = 1.4 GeV.

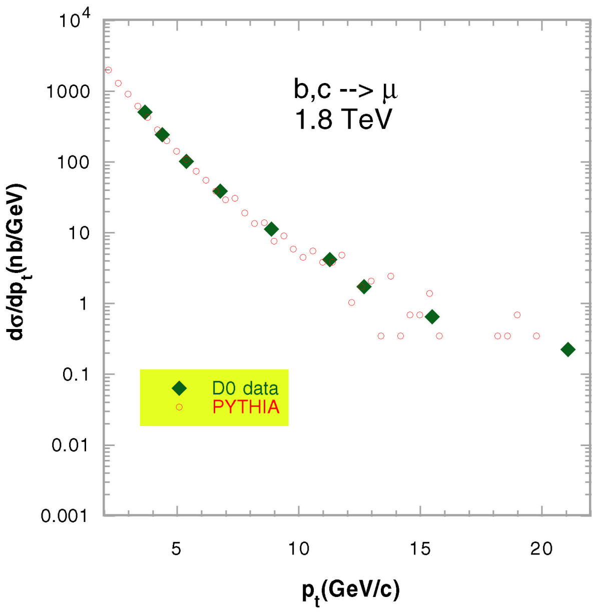

Fig. 2. Data from the D0 collaboration [5] compared with a PYTHIA calculation. The calculation was normalized at p_t = 4 GeV.

Pion and Kaon Production

Pion and kaon production has not been measured at $\sqrt{s}$ = 200 GeV in *pp* collisions. In the past many PHENIX simulations employed the UA1 parameterization of pion production based on central $\bar{p}p$ interactions at $\sqrt{s}$ = 200 GeV [7]. This parameterization is based on *y* ~ 0 production data only and does not contain *y*-dependent terms. Because the PHENIX muon system detects particles at larger rapidities, we chose a global parameterization due to Hans

Boggild [8], which reproduces a large set of charged-particle production data in the range, $7 < \sqrt{s} < 63$ GeV. It can be used for kaons as well as pions, and is parameterized versus energy, rapidity, and p_t. Figure 3 shows that its extrapolation to $\sqrt{s}$ = 200 GeV is in good accord with the UA1 parameterization in the limited rapidity range of the latter. Within the aims of the present document, the Boggild parameterization can probably be counted on for accuracy at the level of factors of 2–3. Similar uncertainties likely also plague the open heavy flavor calculations as well as the J/ψ simulations described below.

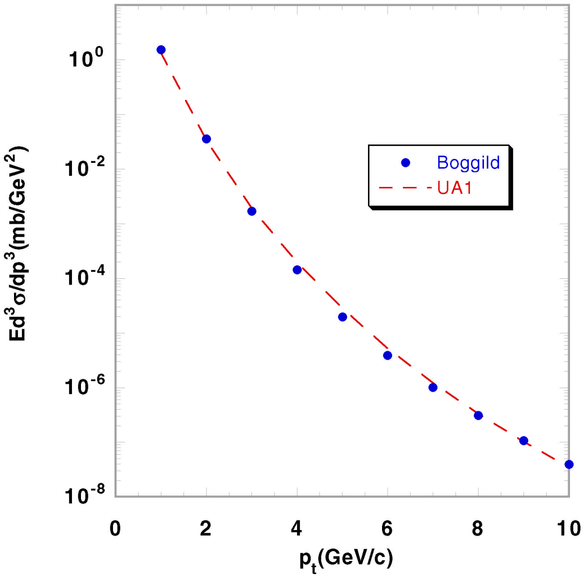

Fig. 3. Comparison of the UA1 [7] and Boggild [2] parameterizations of pion production in *pp* collisions at $\sqrt{s}$ = 200 GeV.

J/ψ and Drell-Yan Production

The energy dependence of quarkonium production has been studied extensively by Vogt [9]. A parameterization based on this work was used in the preparation of the PHENIX CDR. We used a slightly modified version of this generator which reproduces the measured cross section for $p + N$ J/ψ production at 800 GeV [10] — data not available at the time of the original parameterization. This results in a ~ 50% reduction in cross section at $\sqrt{s}$ = 200 GeV, σB = 0.078 μbarns. The event generation used the p_t parameterization determined by E789 [10] and rapidity distribution at $\sqrt{s}$ = 200 GeV recently determined by Vogt [11]. Finally, the cross section for Drell-Yan pair production above M = 3 GeV is only about 0.003 μbarns at $\sqrt{s}$ = 200, and can therefore be safely neglected in single muon detection.

SIMULATIONS

The studies described below employed both simple acceptance calculations and more complex modeling based on the PISA/PISORP package.

Much of the simulation was accomplished using a simple acceptance calculation based on single muons from the above sources contained in the solid angle of the PHENIX south arm acceptance, 12° < θ < 35°. For the prompt muons from open heavy flavor and J/ψ, this involves only simple cuts which can be performed in PAW. Pion and kaon decays, in contrast, occur over extended distances with varying decay kinematics. These simulations were carried out via Monte Carlo FORTRAN routines which followed the decay kinematics exactly but treated hadron absorption in the following approximate way. The pions and kaons are generated over a *z*-vertex distribution of σ = 22 cm. A uniform distribution of decays then occurs along a path from a given vertex (with the variation in solid angle taken into account) to the hadron-absorbing nose cone and for 15 cm into the nose cone — an approximate representation of the hadronic absorption length. Beyond this point all hadrons are assumed to be absorbed. The main results

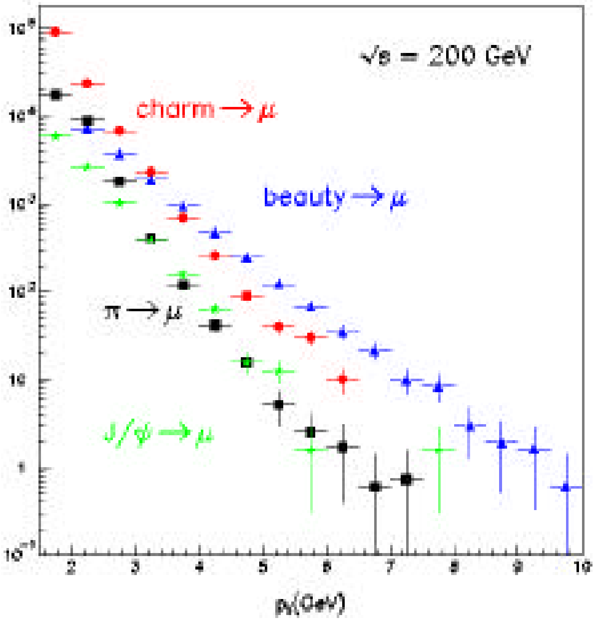

Fig. 4. Spectrum of single muons in the PHENIX south arm using the generators and acceptance codes described in the text. The symbols are: beauty – triangles, charm – circles, pion – squares, *J*/ψ –stars.

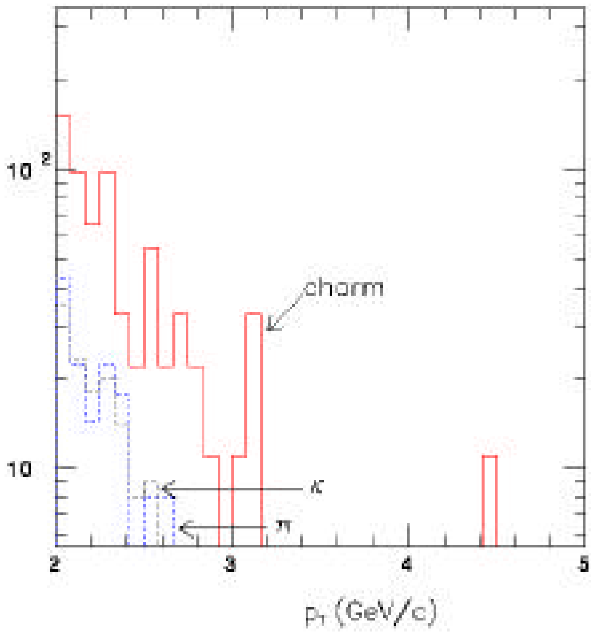

Fig. 5. Spectrum of single muons in the as determined by the PISA/PISORP code, using the event generators described in the text.

are shown in Fig. 4. Muons from kaon decays, which are not shown (see PISA calculation described below), are comparable to those from pion decays.

These results are similar to those obtained with a much more elaborate (and less statistically precise) calculations using PISA/PISORP package (Fig. 5). Here particles are required to meet the criteria listed below in Table I.

Table I. PISORP Tracking and Muon Identification Requirements

1. Hits in 3 tracking stations with momenta consistent with μID depth penetration
2. Tracks point to the interaction vertex region
3. Particles penetrate to μID plane 3
4. Particles satisfy μID trigger “road” condition

The charm decay results are obtained by entering the four-momenta of the decay muons from the PYTHIA calculations directly in PISA. The pion and kaon decay calculations rely on the cross sections generated by the Boggild parameterization. Here, however, the four-momenta of the hadrons is the initial data for the PISA(GEANT) transport in the muon arm. Statistical precision is difficult to obtain since most of the hadrons are absorbed before decaying. The main result is of course that semileptonic decay of charm dominates the single muon spectrum above p_t = 2 GeV, in accord with the acceptance calculations. Similar results were found at higher p_t at the Fermilab collider [5,12].

The extended interaction vertex in PHENIX offers a means of further reducing the contribution of pion and kaon decays. As is evident in Fig. 6, the vertex distribution for pion (and kaon) decays is significantly shifted to the side away from the muon endcap. The

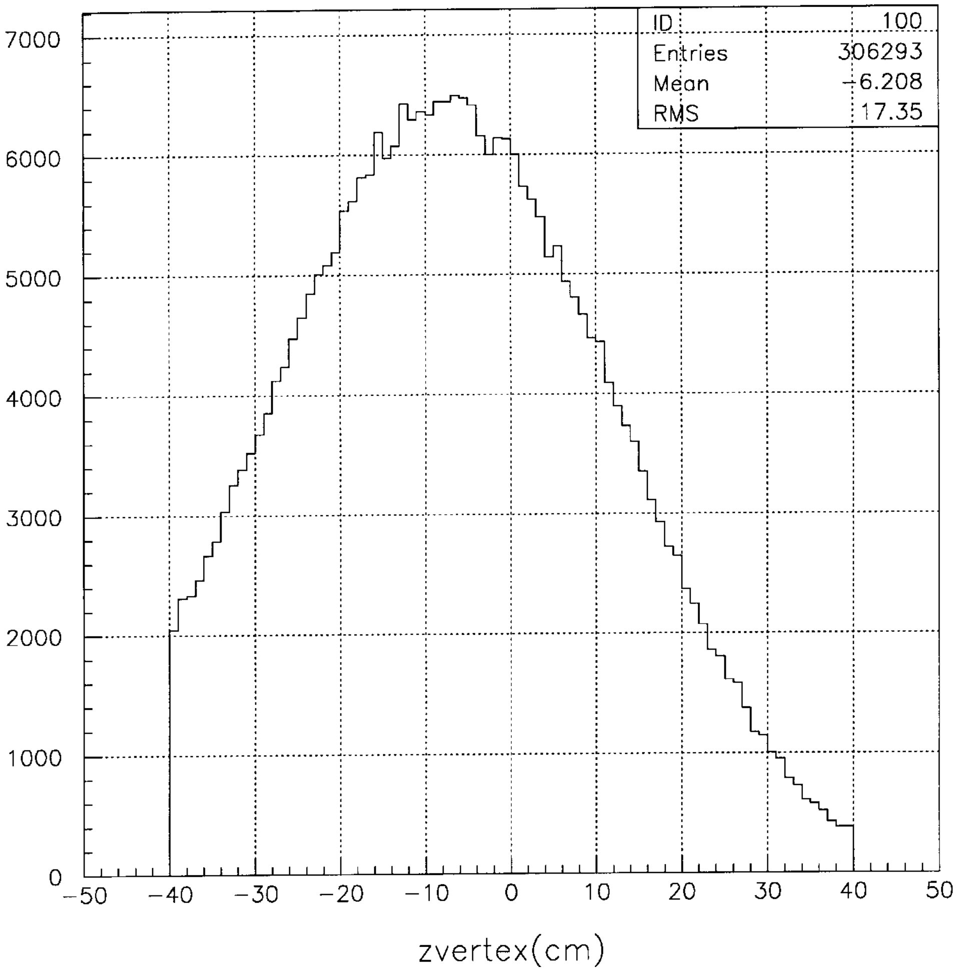

Fig. 6. Distribution of vertices from pions decaying into muons.

asymmetry is due to an increase in decay path, which more than compensates the small decrease in solid angle. The centroid shift from the limited statistics PISA calculation is –5.8 cm, in good accord with the –6.2 cm found with the acceptance code. In principal it is possible to achieve great statistical accuracy in the determination of the composite (heavy flavor plus pions and kaons) centroid, and thereby correct the total single muon spectrum for long-lived decays. One also has to consider various sources of systematic errors in this procedure. This requires a much more detailed model than we currently use. For simplicity, in the sections below, we have assumed that the single muon spectrum with $p_t > 2$ GeV is free from pion and kaon decay background.

EVENT RATES IN *p-p* AND Au-Au COLLISIONS

Table II shows the number of events expected for charm and beauty decay based on the above simulations. They are calculated for the south muon arm acceptance (assuming 100% detection) efficiency, a luminosity of 10^{30} cm^{-2}sec^{-1} for equivalent *pp* collisions — roughly 10% of bluebook luminosity for both *pp* or gold-gold collisions, and a running time of 10^6 sec (~11 days).

Table II. Heavy Quark Decays into Muon Accepted by the PHENIX South Muon Arm. Integrated luminosity is 10^{36} cm^{-2}, corresponding to a 10^6 sec run at 10% of the RHIC “bluebook” value for both *p-p* and gold-gold collisions.

p_t (GeV/c)	charm	beauty
> 2	37300	32500
> 4	700	2370
> 6	21	222

Event totals for central gold-gold collisions would be about 10% of the numbers below assuming $A^{4/3}$ scaling for hard collisions.

Heavy quark production has been suggested as a sensitive measure of the thermalization time in the transition to the quark-gluon plasma [13]. So far, explicit calculations have been done only for charm production [13–15]. It is clear, however, that the above totals coupled with the finding that backgrounds from long-lived decay are not large, imply that a significant measurement of the total cross section of heavy-quark production in central collisions could be carried out in the early years for RHIC/PHENIX operation.

OPEN HEAVY-FLAVOR PRODUCTION AND GLUON SHADOWING

Shadowing of the gluon structure function is known to be a critical factor in calculations of the dynamics of the hot hadronic matter in central relativistic heavy-ion collisions. Depending on the assumptions made, gluon shadowing reduces the initial gluon density by factors of 2–4. There is currently minimal data on shadowing in purely hadronic reactions [16], and no data interpretable in terms of gluon shadowing. Open heavy-flavor production at RHIC is clearly the best way to provide this crucial piece of information. Muon-electron coincidences have been analyzed by Lin and Gyulassi [17] as a possible means of providing these data. We believe that inclusive single muon production offers an easier solution.

The most straightforward way to measure shadowing is via a nuclear dependence experiment. Figure 7 shows the x_1-x_2 correlation produced by single muons from charm decay as would be detected by the PHENIX south muon arm. The mean kinematic quantities are listed in Table III.

Clearly one of the two gluon momenta is well below the threshold for shadowing — usually taken to be $x_2 \sim 0.07$ — while the other is well above the threshold. Thus in a *p*+A measurement with the ion beam directed toward the endcap, no shadowing is seen. With the beams in the opposite direction the nuclear dependence could be used to calculate the shadowing factor,

$$R_{g/A} = \frac{g_A(x)}{A \cdot g_N(x)} \quad . \tag{1}$$

Determination of $R_{g/A}$ would require accurate luminosity monitoring, or better, a comparison of yields in both muon arms. The ideal would be *p*+A combined with A+*p* running to cancel the different acceptances of the two muon arms. There is, of course, no way to determine the parton momenta, nor whether the muon originated from charm or beauty decay.

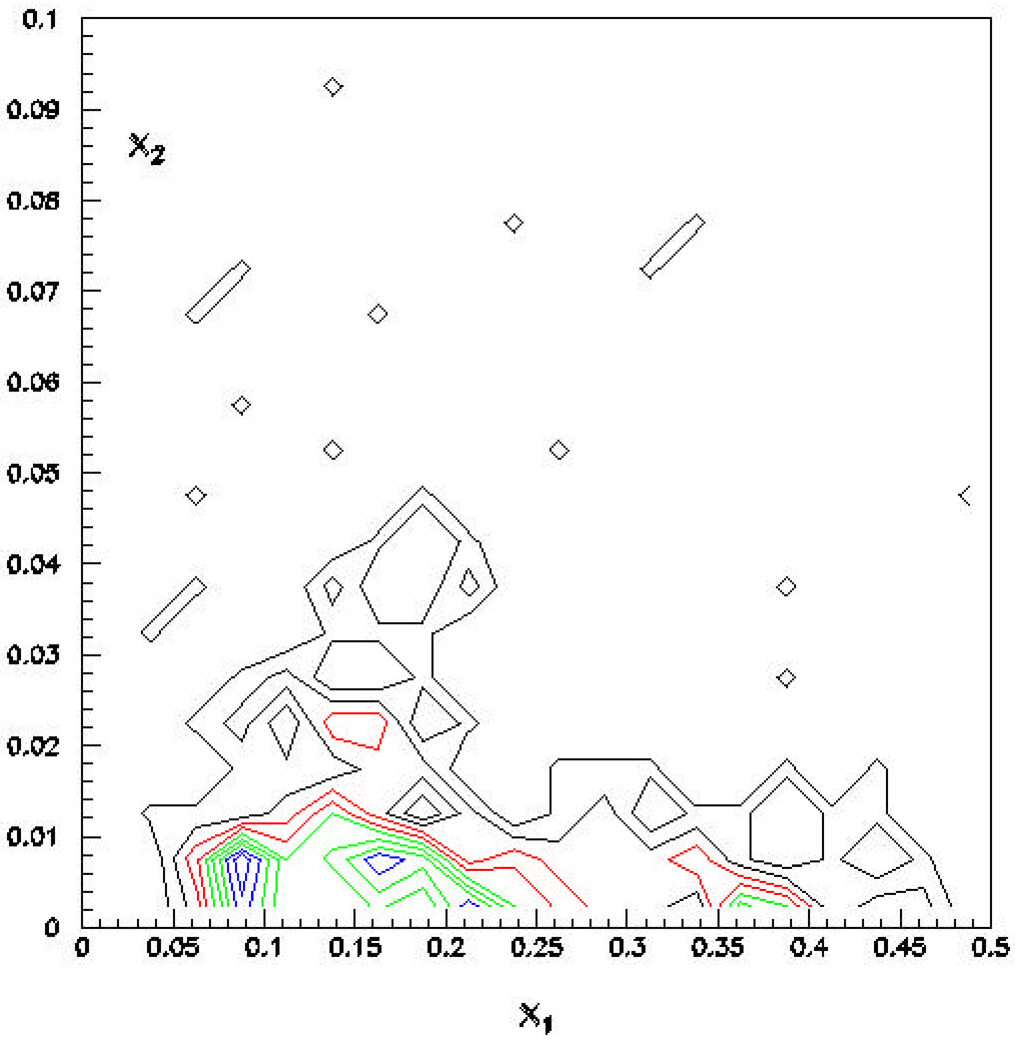

Fig. 7. x_1-x_2 correlation in charm production cut on single muons detected in the PHENIX south arm.

Table III. Mean Values of Gluon Momentum Fraction for Muons with p_t > 2 GeV. The shadowing factors were computed for the impact-parameter averaged values of x_1 and x_2 with the parameterization of Müller and Wang [13] for p+Au collisions.

	x_1	x_2	$R_{g/A}$
charm	0.22	0.016	0.63
beauty	0.24	0.048	0.70

DETERMINATION OF ΔG FROM OPEN HEAVY-FLAVOR PRODUCTION

Heavy flavor production in polarized p-p collisions has been suggested [18–20] as a means of investigating the exciting but extremely difficult problem of determining, ΔG, the polarization of the gluon structure function. In leading order, the dominant diagram, two-gluon fusion leading to $Q\bar{Q}$ production, has an analyzing power given by [21],

$$\hat{a}=\frac{-(32y^2-16y^4-8x^2-8x^2y^2+8x^2y^4+x^4-x^4y^4)}{32-32y^2-16y^4+8x^2-8x^2y^2+8x^2y^4+x^2-x^4y^4}\ . \tag{2}$$

where $x=\sqrt{\hat{s}}/m_Q$, $\hat{s}=sx_1x_2$, $y=\cos(\theta)$, and m_Q is the mass of the heavy quark. As can be seen in Fig. 8, the parton level analyzing power becomes large provided $\sqrt{\hat{s}}>>m_Q$.

Now, assuming the dominance of the two-gluon fusion, one has,

$$A_{LL}(x_1,x_2)\cong\frac{\Delta G}{G}(x_1)\cdot\frac{\Delta G}{G}(x_2)\cdot\hat{a}\ . \tag{3}$$

Because of the very inclusive nature of the measurement, there is little sensitivity to the initial kinematics of gluon fusion. Thus only the integrated values of A_{LL} have significance. The values obtained, performed with the simple acceptance code, are summarized in Table IV for two sets of polarized gluon distributions from Gehrmann and Stirling (GS) [22]. The gluon polarization from these sets, although both derived from existing data, show different x-dependencies, as is seen in Fig. 9. Errors were calculated assuming beam polarizations of 0.7 and the integrated counts of Table II.

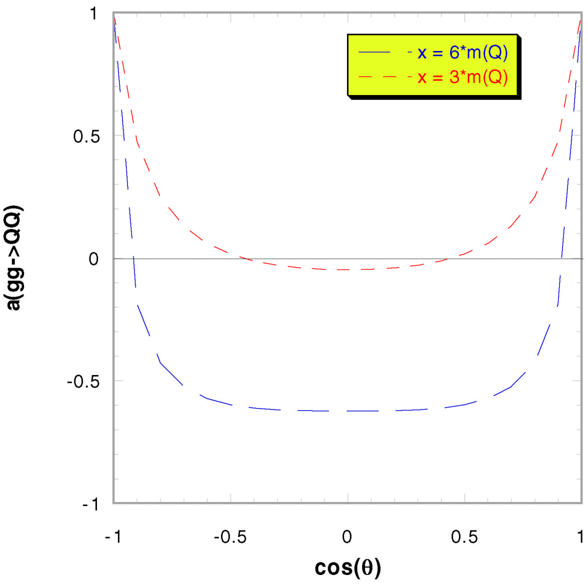

Fig. 8. Parton-level helicity asymmetry for $g+g\to Q+\bar{Q}$ for two different values of x (Eq. 2).

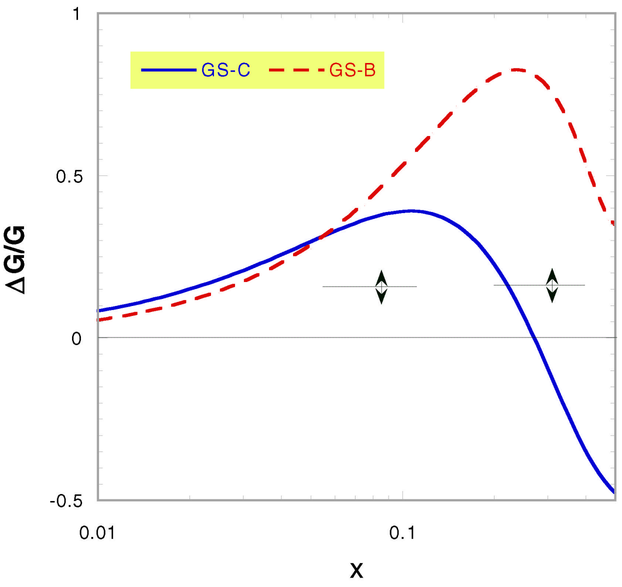

Fig. 9. Gluon polarization for two sets of structure functions from Gehrmann and Stirling [22].

Table IV. Acceptance Calculations for Charm and Beauty Production in Polarized Proton Collisions at $\sqrt{s}$ = 200 GeV. The kinematic quantities are based on acceptance into the PHENIX south muon arm with the integrated luminosities of Table II (L = 10^{-36} cm^{-2}).

p_t (GeV)	Quark	$\hat{a}$	A_{LL} (GS-B)	A_{LL} (GS-C)	δA_{LL}
> 2	c	–0.254	–0.044	–0.006	0.01
> 2	b	0.146	0.018	0.006	0.01

> 4	b	–0.135	–0.032	0.006	0.04
> 6	b	–0.501	–0.122	0.020	0.14

For modest p_t, it is evident from Table IV that there is a great deal of cancellation in the averaging over kinematic variables [x and y of Eq. (2)] resulting in a small net value of $\hat{a}$. Only for p_t > 6 GeV is $\hat{a}$ sufficiently large that the measurement may be considered robust. Figure 10 shows the distribution of $\hat{a}$ for p_t > 6 GeV. Here one has a convolution of ΔG at $\langle x_1 \rangle = 0.33$ and $\langle x_2 \rangle = 0.085$, indicated by arrows in Fig. 9, yielding a very significant difference in A_{LL} for the two sets of GS structure functions. The integrated luminosity needs to be ~ 100 beyond that assumed for RHIC startup operations — $L \approx 10^{38}\mathrm{cm}^{-2}$ in order to use very high-p_t single muons. Fortunately this should be easily achievable with the projected luminosities and running times for polarized operations of RHIC after one or two years.

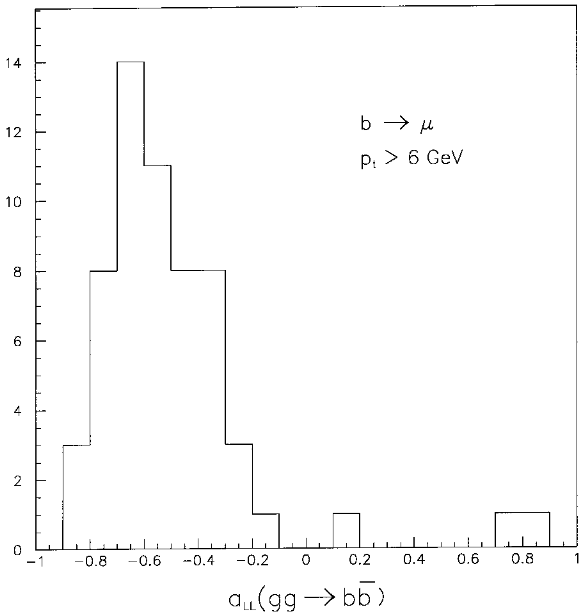

Fig. 10. Distribution of $\hat{a}_{LL}$ for $b \to \mu$ with p_t > 6 GeV.

REFERENCES

1. T. Sjöstrand, Computer Physics Commun. **39**, 347 (1986).
2. L. Apanasevich et al., Phys. Rev. **D56**, 1391 (1997).
3. S. Frixione et al., Nucl Phys. **B431**, 453 (1994).
4. J. A. Appel, Annu. Rev. Nucl. Part. Sci. **42**, 367 (1992).
5. S Abachi et al. (D0), Phys. Rev. Lett. **74**, 3548 (1995).
6. P. L. McGaughey et al., J. Mod. Phys. **A10**, 2999 (1995).
7. C. Albajar et al. (UA1), Nucl. Phys. **B335**, 261 (1990).
8. H. Boggild, private communication.
9. R. Vogt, Atom. Nucl. Data Tabl. **50**, 343 (1992).
10. M. H. Schub et al., Phys. Rev. **D52**, 1307 (1995).
11. R. Vogt, private communivation.
12. F. Abe et al. (CDF), Phys. Rev. Lett. **71**, 2397 (1993).
13. B. Mueller and X.-N. Wang, Phys. Rev. Lett. **68**, 22437 (1992).
14. P. Levai, B. Mueller, and X.-N. Wang, Phys. Rev. **C51**, 3326 (1995).
15. W. Lin and M. Gyulassy, Phys. Rev. **C51**, 2177 (1995); erratum-ibid. **C52**, 440 (1995).
16. D. M. Alde et al., Phys. Rev. Lett. **64**, 2479 (1990).
17. Z. Lin and M. Gyulassi, preprint, CU-TP 714 (1995).
18. A. P. Contogouris et al., Phys. Lett. **B246**, 523 (1990).
19. M. Karliner and R. W. Robinett, Phys. Lett. **B324**, 209 (1994).
20. PHENIX/Spin proposal, October 1994, http://phnxmu.lanl.gov/Files/muon/ spin/spin2.html.
21. Derived from the equations of Ref. [19].
22. T. Gehrmann and W. J. Stirling, Z. Phys. **C65**, 461 (1995).