Event structure and double helicity asymmetry in jet production from polarized \( p + p \) collisions at \( \sqrt{s} = 200 \) GeV at PHENIX

Kenichi Nakano (for the PHENIX Collaboration)
Tokyo Institute of Technology, Rm. 158, Main Bldg., 2-12-1, Ookayama, Meguro-ku, Tokyo 152-8550, Japan
E-mail: knakano@bnl.gov

Abstract. We report on the event structure and double helicity asymmetry \( (A_{LL}) \) of jet production in longitudinally polarized \( p + p \) collisions at \( \sqrt{s} = 200 \) GeV. Photons and charged particles were measured by the PHENIX experiment at midrapidity \( J < 0.35 \) with the requirement of a high-momentum \( > 2 \) GeV/\( c \) photon in the event. Event structure such as \( p_T \) density were measured and compared with the pythia event generator and the geant detector simulation. The shape of jets and the underlying event were well reproduced at this collision energy. For the measurement of jet \( A_{LL} \), photons and charged particles were clustered with a seed-cone algorithm to obtain the cluster \( p_T \) sum \( (p_T^{\text{reco}}) \). The effect of detector response and the underlying events on \( p_T^{\text{reco}} \) was evaluated with the simulation. The production rate of reconstructed jets is satisfactorily reproduced with the NLO pQCD jet production cross section. We measured the jet \( A_{LL} \) for \( 4 < p_T^{\text{reco}} < 12 \) GeV/\( c \) with a beam polarization scale error of 9.4% and a \( p_T \) scale error of 10%. The measured \( A_{LL} \) is compared with predictions that assume various \( G(x) \) distributions based on the GRSV parameterization. The present result imposes the limit \( 1/R_0 < 0.02 \) at 95% confidence level or \( 1/R_0 < 0.05 \) at 99% confidence level.

1. Introduction
The motivation of this measurement is to understand the spin structure of the proton, particularly the contribution of the gluon spin \( (\Delta G) \) to the proton spin. The proton spin can be represented as

\[
\frac{1}{2}_{\text{proton}} = \frac{1}{2} \sum_f \Delta q_f + \Delta G + L_q + L_g, \tag{1}
\]

where \( \Delta G \) is the gluon spin, i.e. the integral of the polarized gluon distribution function, \( \Delta G = \int_0^1 dx \Delta G(x) \), \( \sum \Delta q \) is the quark spin, and \( L_q \) and \( L_g \) are the orbital angular momenta of quarks and gluons in the proton. It was found by the EMC experiment at CERN in 1987 that the quark spin contribution to the proton spin is only \((12 \pm 9 \pm 14)\% \) [1, 2]. After the EMC experiment many deep inelastic scattering (DIS) experiments have been carried out to measure \( \sum \Delta q \) more precisely. The recent analysis by the HERMES experiment [3] reported that \( \sum \Delta q = 0.330 \pm 0.011 \) (theo.) \( \pm 0.025 \) (exp.) \( \pm 0.028 \) (evol.) at a hard-scattering scale \( \mu^2 \sim 5 \) GeV\(^2\), which is only about 30% of the proton spin. Consequently, the majority of the proton spin should be carried by the remaining components.
Jet production from longitudinally-polarized $p + p$ collisions is suited for the measurement of $\Delta G$ because gluon-involved scatterings, such as $q + g \rightarrow q + g$ or $g + g \rightarrow g + g$, dominate the cross section. The double helicity asymmetry, $A_{LL} \equiv \frac{2 \sigma_{++} - \sigma_{+-} - \sigma_{-+} + \sigma_{--}}{\sigma_{++} + \sigma_{+-} + \sigma_{-+} + \sigma_{--}}$, is the asymmetry in cross section between two beam helicity states. In the $A_{LL}$ measurement, many systematic errors cancel out so that high precision can be achieved.

Another motivation of this measurement is to study the event structure of $p + p$ collisions. A high-energy $p + p$ collision produces not only hard scattered partons but also many particles that originate from soft interactions which we call the ‘underlying event’. The PYTHIA event generator phenomenologically models the underlying event on the Multi-Parton Interaction (MPI) scheme [4], and can reproduce the event structure of $p + \bar{p}$ collisions measured by the CDF experiment at $\sqrt{s} = 1.8$ TeV [5]. We present measurements of event structure at lower collision energy, $\sqrt{s} = 200$ GeV, and compare them with those simulated by PYTHIA in order to examine the validity of the PYTHIA MPI scheme.

One of the main goals of the PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) is the determination of $\Delta G$. PHENIX has published results on single particle production; the $A_{LL}$ of $\pi^0$ production was reported in [6, 7]. This paper reports a measurement of jet production. For $\Delta G$, it is valuable to determine the parton kinematics following the collision in order to better control the $x$ range. In this work we reconstruct jets, observing a larger fraction of the parton’s momentum. This allows improved reconstruction of the original parton kinematics and better statistical accuracy for higher $x$ gluons.

More detailed information on this measurement can be found in [8].

2. Experimental Setup
The PHENIX detector [9] can be grouped into three parts; the Inner Detectors, the Central Arms and the Muon Arms. The schematic drawing of the PHENIX detector is shown in Fig. 1. In this measurement, the Central Arms were used to detect photons and charged particles in jets, and the Inner Detectors to obtain the collision vertex and beam luminosity.

2.1. Inner detectors
The Inner Detectors include the Beam-Beam Counters (BBC) and the Zero-Degree Calorimeters (ZDC). The BBC is composed of two identical sets of counters placed at both the north and south sides of the collision point at a distance of 144 cm [10]. The BBC measures the number of charged particles in forward and backward regions to determine the collision time, collision $z$-vertex, and beam luminosity.

The ZDC is comprised of two sets of hadronic calorimeters placed at the north and south sides of the collision point at a distance of 18 m [11]. They measure neutrons in forward and backward regions and is used as a local polarimeter which assures that the beam polarization is correctly longitudinal or transverse at the interaction region.

2.2. Central Arms
The Central Arms consist of a tracking system and an electromagnetic calorimeter (EMCal). Pad chambers (PC) and drift chambers (DC) were used to detect charged particles in jets, and the EMCal was used to detect photons in jets.

The EMCal system [12] is located at a distance of 5 m from the interaction point. The system consists of four sectors in each of the East and West Arms, and each sector has a size of $2 \times 4$ m$^2$. The system is composed of two types of calorimeter, lead scintillator (PbSc) and lead glass (PbGl).

The DC system [13] is located in the region from 2 to 2.4 m from the interaction point to measure the position and momentum of charged particles. The DC system consists of one frame
in each of the East and West Arms. Each chamber has a size of 2.5 m×90° in z-φ direction with cylindrical shape.

The PC system [13] is composed of multi-wire proportional chambers in three separate layers, which are called PC1, PC2 and PC3, of the Central Arms tracking system. The PC1 is located behind the DC and is used for pattern recognition together with the DC by providing the z coordinate. Charged particle tracks are reconstructed using the information from the DC and the PC1 [14]. The magnetic field between the collision vertex and the DC is axial, and thus bends particles in the x-y plane. Because the field is sufficiently weak in the outer area from the DC, particle tracks can be assumed to be straight.

2.3. Trigger
The PHENIX experiment has various trigger configurations to efficiently select many type of interesting rare events. This measurement required the coincidence of two triggers; a minimum bias (MB) trigger issued by the BBC, and a high-energy photon trigger issued by the EMCal.

The MB trigger in p+p collisions requires one charged particle in both the north and south sides of the BBC. The reconstructed z-vertex is required to be within ± ∼ 30 cm. The high-energy photon trigger is fired when the sum of energy deposits in 4×4 EMCal modules (∆φ ∼ ∆η ∼ 0.04) is above a threshold of ∼ 1.4 GeV.

3. Analysis Methods
This analysis used 2.3 pb⁻¹ of data that were taken with the MB + high-energy-photon trigger in 2005. In addition, ∼0.3 pb⁻¹ of data that were taken with the MB trigger alone were used for systematic error studies. Photons were detected with the EMCal, and charged particles were detected with the DC and PC1. Measured particles in each PHENIX Central Arm were clustered using a cone method to form a ‘reconstructed jet’ and its transverse momentum (p_T^{reco}). Because of the finite size of the acceptance (|η| < 0.35), the cone size for the particle clustering were set to 0.3 at maximum. This is smaller than the typical cone size, 0.7, and raises two issues: First, a jet in an NLO calculation is usually defined with the same cone size and compared with the measured jet, but this is optimum when both jet energy and cone size are large since the jet spread due to hadronization becomes significant with small jet energy and cone size. Second, such a small cone is more sensitive to quark jets than gluon jets since gluon jets are broader and softer than quark jets. Because of the situation described above, the theory calculation and the simulation evaluations have been organized as follows.

The cross section and the A_{LL} of inclusive jet production were calculated as a function of jet transverse momentum (p_T^{NLO}) within the framework of a next-to-leading-order perturbative
Reconstructed jet ($p_{T}^{\text{reco}}$) | Hadronic jet made with measurable particles after hadronization with a cone size of $R = 0.3$.
---|---
Jet in PYTHIA ($p_{T}^{\text{PY}}$) | Partonic jet in PYTHIA without cone.
Jet in NLO calculation ($p_{T}^{\text{NLO}}$) | Partonic jet in NLO pQCD calc. with a cone size of $\delta = 1.0$.

Table 1. Definitions of jets adopted in this measurement.

QCD (NLO pQCD). This calculation predicted various $A_{LL}$’s by assuming various $\Delta G(x)$ distributions.

A simulation with the PYTHIA event generator [4] and the GEANT detector simulation package [15] was performed to understand the effects of the detector response, the underlying events and the jet-definition difference between the measurement and the theory calculation. PYTHIA simulates parton-parton hard scatterings in $p + p$ collisions at leading order (LO) in $\alpha_s$ with phenomenological initial and final-state radiation and hadronization. GEANT simulates the acceptance and response of the PHENIX detector. We define a jet and its $p_T$ ($p_{T}^{\text{PY}}$) at the partonic level in PYTHIA. The effect of the detector response and the underlying events was evaluated as the statistical relation between the jets defined in PYTHIA and the reconstructed jets. We assume $p_{T}^{\text{PY}} = p_{T}^{\text{NLO}}$ within an uncertainty, and then we obtained the relation between the NLO calculation and the measurement.

Two PYTHIA settings were used. One is the default setting of PYTHIA version 6.220, which we call ‘PYTHIA default’ in this paper. The other is the so-called ‘MPI tune A’ [5, 16] setting, which we call ‘PYTHIA MPI’ in this paper. The outputs of the two settings were compared to estimate the effect of the underlying event on this measurement.

To confirm that the simulation reproduces well the real data in terms of event structure, namely spatial distribution of particles in an event, quantities sensitive to event structure were measured. Those include particle multiplicity, transverse-momentum density, thrust distribution and jet-production rate. A comparison was made between the real data and the simulation output.

We derived the predictions of the measured $A_{LL}$ by converting the NLO calculation with the relation between $p_{T}^{\text{NLO}}$ and $p_{T}^{\text{reco}}$. A $\chi^2$ test between the measured and predicted $A_{LL}$’s was performed to determine the most-probable $\Delta G$.

The definitions and relations of jets in this measurement are summarized in Tab. 1 and Fig. 2. Figure 3 shows the ratio $p_{T}^{\text{reco}}/p_{T}^{\text{PY}}$ at each $p_{T}^{\text{reco}}$ bin, and Fig. 4 shows the mean value of the ratios as a function of $p_{T}^{\text{reco}}$. The ratio of the PYTHIA MPI output is $\sim 80\%$ on average and is larger than that of the PYTHIA default output due to the contribution from the underlying event. Figure 5 shows the fraction of $g + g$, $q + g$ and $q + q$ subprocesses as a function of $p_{T}^{\text{reco}}$. The dominant subprocess is $q + g$ throughout the $p_{T}^{\text{reco}}$ range.
4. Results and discussions

4.1. Event structure

The $p_T$ density, $D_{p_T}(\Delta \phi)$, is defined as

$$D_{p_T}(\Delta \phi) \equiv \left\langle \frac{1}{\delta \phi} \sum_{|\Delta \phi_i + \delta \phi|} p_{T_i} \right\rangle_{\text{event}},$$

where $\Delta \phi$ is $\phi$ angle with respect to the direction of a trigger photon in event, $\delta \phi$ is an area width in $\phi$ direction, and $p_{T_i}$ is transverse momentum of $i$-th particle in event. The measurement condition is illustrated in Fig. 6. The $p_T$ density means the area-normalized total transverse momentum in an area of $\delta \phi \times \delta \eta$ at a distance $\Delta \phi$ from trigger photon, where $\delta \eta$ is the width of the Central Arm acceptance.

Figure 7 shows the $D_{p_T}$ distributions for each $p_T^{\text{sim}}$ range. In the toward region ($\Delta \phi \sim 0^\circ$), the simulation outputs agree well with the real data. It shows that the shape of jets produced by the simulation is consistent with the real data. In the transverse region ($\Delta \phi \sim 90^\circ$), the PYTHIA default output is generally smaller than the real data. This is an indication that the PYTHIA default does not contain sufficient total $p_T$ of soft particles from the underlying event. The PYTHIA MPI output agrees with the real data well.
4.2. Jet production rate
The jet production rate \( \mathcal{Y} \), namely the yield of reconstructed jets per unit luminosity, is defined with measured quantities as

\[
\mathcal{Y}^i = \frac{N_{i \text{reco}}}{L \cdot f_{\text{MB}} \cdot f_{\text{ph}}},
\]

where \( L \) is the integrated luminosity; \( f_{\text{MB}} \) and \( f_{\text{ph}} \) are the efficiencies of the MB trigger (see Sec. 2.3) and the high-\( p_T \) photon trigger, respectively; \( N_{i \text{reco}} \) is the reconstructed-jet yield in a \( i \)-th \( p_T^{\text{reco}} \) bin. The high-\( p_T \) photon trigger efficiency \( f_{\text{ph}} \) was estimated to be 0.92 ± 0.02.

Figure 8 shows the jet production rate. The main uncertainties of the measurement are the BBC cross section and the EMCal energy scale. These errors are fully correlated bin-to-bin. The error on the EMCal energy scale includes both the change of \( p_T \) of individual photons and the change of the threshold of the high-\( p_T \) photon requirement. In comparing the measurement and the calculation, a 10% \( p_T \) scale uncertainty of the jet definitions in the PYTHIA simulation and the NLO pQCD theory makes a 30% error at low \( p_T \) or 70% at high \( p_T \), and is the largest source. The uncertainty of the renormalization and factorization scales in the NLO jet production cross section makes a 30% error. The calculation with PYTHIA MPI agrees with the measurement within errors over the measured range \( 4 < p_T^{\text{reco}} < 15 \text{ GeV}/c \).

4.3. Double helicity asymmetry \( A_{LL} \)
\( A_{LL} \) is expressed with measured quantities as

\[
A_{LL} = \frac{1}{|P_B| |P_Y|} \frac{(N_{++} + N_{--}) - R(N_{+-} + N_{-+})}{(N_{++} + N_{--}) + R(N_{+-} + N_{-+})}, \quad R = \frac{L_{++} + L_{--}}{L_{+-} + L_{-+}},
\]

where \( N_{++} \) etc. are reconstructed-jet yields with colliding proton beams having the same (++ or --) and opposite (+- or --) helicity; \( P_B \) and \( P_Y \) are the beam polarizations; \( R \) is the
relative luminosity, i.e. the ratio of the luminosity with the same helicity $(L_{++} + L_{--})$ to that with the opposite helicity $(L_{-+} + L_{+-})$.

Figure 9 shows measured $A_{LL}^{\text{reco}}$ and four prediction curves. The measured $A_{LL}$ is consistent with zero, as the $\chi^2$/n.d.f. between the data points and zero asymmetry ($A_{LL} = 0$) is $1.3/6$. The systematic error of the relative luminosity is much smaller than the statistical error on $A_{LL}$ and is negligible. On the prediction curves the systematic error related to the fractions of subprocesses are smaller than the 10% $p_T$ scale uncertainty by roughly an order of magnitude. Therefore it is not included in this plot.

Figure 10 shows the $\chi^2$ between the 6 data points and prediction curves as a function of the integral $\int_{0.02}^{0.3} dx \Delta G(x, \mu^2 = 1)$ for each prediction curve. The value of $\mu^2 = 1 \text{ GeV}^2$ has been arbitrarily chosen in order to show the value of the $\Delta G$ integral in horizontal axis. Actual $\mu^2$ used in the $A_{LL}$ calculation varies depending on jet $p_T$.

The minimum of the $\chi^2$ is $\sim 1.5$ at $\Delta G = 0.07$, namely the GRSV $\Delta G = 0$ input. The 95% and 99% confidence limits are where the $\chi^2$ increases from the minimum by 4 and 9, respectively. We obtained $-1.1 < \int_{0.02}^{0.3} \Delta G^{G_{RSV}}(x, \mu^2 = 1) < 0.4$ at 95% confidence level and $\int_{0.02}^{0.3} \Delta G^{G_{RSV}}(x, \mu^2 = 1) < 0.5$ at 99% confidence level. In the assumptions of the present approach, the error correlations between the normalization parameter and the shape parameters in $\Delta G(x)$ are not included.

5. Conclusion

We measured the event structure and the double helicity asymmetry ($A_{LL}$) in jet production at midrapidity ($|\eta| < 0.35$) in longitudinally polarized $p + p$ collisions at $\sqrt{s} = 200 \text{ GeV}$ were measured. The main motivation is to use this complementary approach to inclusive measurements to better understand the contribution of the gluon spin ($\Delta G$) to the proton spin. Because this measurement of $A_{LL}$ observes a larger fraction of the jet momentum, it reaches higher $p_T$ and thus higher gluon $x$.

The MPI-enhanced PYTHIA simulation agrees well with the real data in terms of the event
structure. The simulation well reproduces the shape of jets and the underlying event at this collision energy.

In the measurement of jet $A_{LL}$, measured particles were clustered by the seed-cone algorithm with a cone radius $R = 0.3$. The relation between $p_T^{NLO}$ and $p_T^{reco}$ was evaluated with PYTHIA and GEANT. The jet production rate was measured and satisfactorily reproduced by the calculation based on the NLO pQCD jet production cross section and the simulation. The jet $A_{LL}$ was measured at $4 < p_T^{reco} < 12$ GeV/c. The main systematic errors are a $p_T$ scale uncertainty of 10% and a beam polarization uncertainty of 9.4%. The measured $A_{LL}$ was compared with the predicted values based on the GRSV parameterization, and the comparison imposed the limit $-1.1 < \int^{0.3}_{0.02} dx \Delta G^{GRSV}(x, \mu^2 = 1) < 0.4$ at 95% confidence level or $\int^{0.3}_{0.02} dx \Delta G^{GRSV}(x, \mu^2 = 1) < 0.5$ at 99% confidence level. The theoretical uncertainties such as the parameterization of the polarized PDFs were not included in this evaluation.

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