

Analyzing Powers for Forward $p_{\uparrow} + p \rightarrow \pi^0 + X$ at STAR

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Abstract. Preliminary results of the analyzing power for the production of forward, high-energy π^0 mesons from collisions of transversely polarized protons at $\sqrt{s} = 200$ GeV from STAR are presented. The kinematic ranges covered by the data are $x_F \approx 0.2 - 0.6$ and $p_T \approx 1 - 3$ GeV/c. The analyzing power at $\sqrt{s} = 200$ GeV is found to be comparable to that observed at $\sqrt{s} = 20$ GeV.

INTRODUCTION

Perturbative QCD makes a qualitative prediction that the single-spin transverse asymmetry, known as the analyzing power (A_N), for $2 \rightarrow 2$ parton scattering at large transverse momentum should be zero based on helicity conservation. In the late 1980's, the experiment E704 at Fermi National Laboratory measured A_N for the production of charged and neutral pions in $p_{\uparrow} + p$ collisions at $\sqrt{s} = 20$ GeV and $p_T = 1 - 3$ GeV/c over the Feynman- x range of $0 - 0.8$ [1, 2]. The analyzing power for π^+ mesons was found to increase as a function of Feynman- x from $A_N = 0$ at $x_F = 0$ to $A_N \approx 0.4$ at $x_F = 0.8$. For π^- mesons, the analyzing power was found to be approximately equal in magnitude and opposite in sign to the π^+ results, while for π^0 mesons, the analyzing power was found to be approximately half the size observed for π^+ mesons.

This result has inspired several theory groups to develop models to account for the observed large analyzing power. Most models attribute forward pion production to collisions between a quark in one proton and a gluon in the other. There are many different plausible mechanisms by which one might expect transverse spin effects, all of which could contribute to some degree. One perturbative QCD approach attributes transverse spin effects to twist-3 gluon correlations before or after the primary quark-gluon coupling [3, 4]. A second approach attributes A_N to the transversity distribution function and a T-odd Heppelmann-Collins fragmentation function [5]. Another approach is to include initial state interactions to introduce transverse spin effects before the primary quark-gluon coupling [6, 7]. All of these models predict the large analyzing power observed at E704 should persist to collision energies an order of magnitude greater [8, 9]. Here we present the measurement of the analyzing power for the production of π^0 mesons from the STAR experiment at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven Na-

¹ For the full author list and acknowledgements, see the appendix to these proceedings.

tional Laboratory, studying $p_{\uparrow} + p$ collisions with total energy $\sqrt{s} = 200\text{ GeV}$ available to the system.

EXPERIMENTAL CONDITIONS

The analyzing power for a reaction with a transversely polarized beam interacting with an unpolarized target is determined from a spin-dependent asymmetry,

$$\cos \phi P_{beam} A_N = \frac{N_+ - RN_-}{N_+ + RN_-}, \quad (1)$$

and requires the concurrent measurements of three independent quantities. The magnitude of the transverse polarization of the beam is P_{beam} . The number of measured π^0 events observed when the polarization direction is up(down) is $N_{+(-)}$. The relative luminosity is given by $R = \mathcal{L}_+ LT_+ / \mathcal{L}_- LT_-$, where $\mathcal{L}_{+(-)}$ is the luminosity and $LT_{+(-)}$ is the livetime of the detector for different polarization states. The spin-dependent asymmetry corresponds to the right-hand side of equation 1. The azimuthal angle between the polarization vector and the normal to the reaction plane is ϕ . Parity constrains the asymmetry to be zero when the π^0 is emitted along the direction of the polarization vector.

Data were collected during the polarized proton run at RHIC in January 2002, and, as such, resulted from the first observations of polarized protons in a collider environment. A typical RHIC fill lasted 6 – 8 hours with collision luminosities on the order of $10^{30}\text{ cm}^{-2}\text{ sec}^{-1}$ at the STAR interaction region. The so-called “yellow” proton beam rotated counterclockwise around RHIC when viewed from above, while the “blue” proton beam went clockwise. Each beam contained 55 filled bunches and 5 empty bunches which collided every 213 nsec at the STAR interaction region, resulting in 50 chances for collisions per revolution. The beam polarization vector was oriented vertically, perpendicular to the proton momentum direction. In the polarization pattern for the yellow beam, the polarization direction alternated every bunch, while the blue pattern alternated every second bunch. The data presented here refer to spin asymmetries with respect to the direction of the yellow polarization vector, averaging over the blue polarization.

The average beam polarization for each fill was given by the Coulomb-Nuclear Interference (CNI) polarimeter located at 12 o’clock in RHIC [10, 11]. This detector measured the asymmetry of elastic proton-carbon collisions by observing recoil carbon atoms at approximately 90 degrees. At the RHIC injection energy ($\approx 25\text{ GeV}$ per beam), the analyzing power of the CNI reaction has been measured [12] and can be used to deduce the absolute polarization of the proton beam. At RHIC collision energies ($\approx 100\text{ GeV}$ per beam), the analyzing power for this reaction has not yet been measured. Therefore, for these proceedings the beam polarization is determined by using the average value of the measured CNI asymmetry at collision energy within each fill, divided by the measured analyzing power of the CNI reaction at injection energy. With this assumption, the average luminosity-weighted beam polarization for the data presented here is $P_{beam} \approx 16\%$. As the asymmetry measured at collision energy was consistent with the asymmetry measured at injection energy for these runs, the P_{beam} quoted here represents

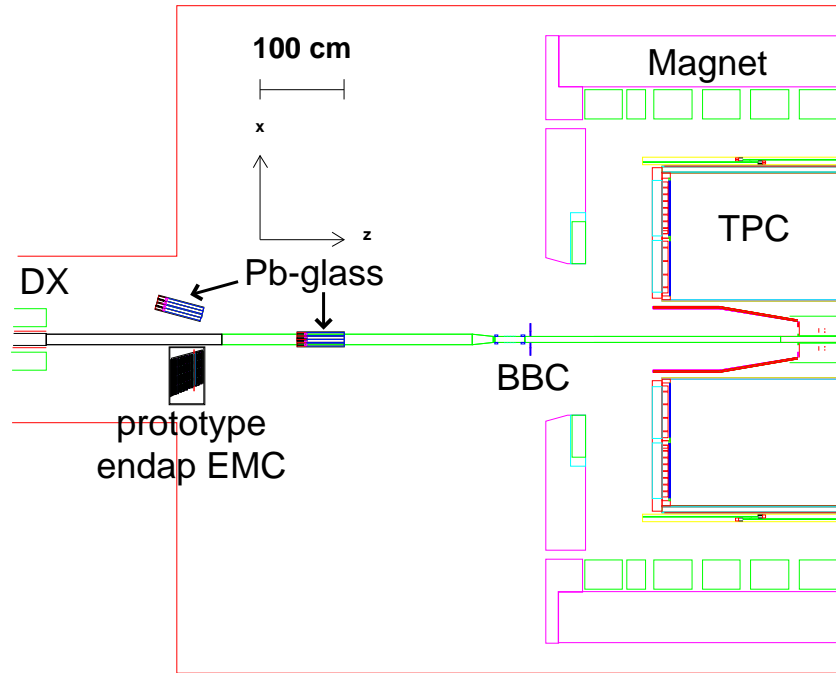


FIGURE 1. Schematic of the FPD and the east half STAR, looking from above. In this figure, the yellow beam moves from right to left, and collisions occur at the right-hand edge.

a likely upper limit at the collision energy, since the beam acceleration is not expected to enhance P_{beam} .

A forward π^0 detector (FPD) comprising four arms was installed at STAR approximately 750 cm from the interaction region and very close to the beam pipe (Fig. 1). Its location was such that significant energy deposition corresponded to positive x_F particle production with respect to the yellow beam. An electromagnetic Pb-scintillator sampling calorimeter of ≈ 21 radiation lengths subdivided into 12 towers was placed to the left of the oncoming yellow beam. This detector is a prototype of 1/60 of the endcap electromagnetic calorimeter (pEEMC), currently being installed at STAR. The pEEMC has two layers of preshower readout and a shower-maximum detector (SMD) made of orthogonal layers of finely segmented scintillator strips to measure the longitudinal and transverse profiles of photon showers. A 4×4 array of $3.8 \times 3.8 \times 45 \text{ cm}^3$ Pb-glass detectors was placed to the right of the oncoming beam as well as above and below the beam. Readout of all FPD calorimeters was triggered for events that deposited $\approx 20 \text{ GeV}$ electron-equivalent energy in any one calorimeter. The kinematic ranges covered by the FPD were $1 < p_T < 3 \text{ GeV}/c$ and $0.2 < x_F < 0.6$. A valid coincidence from scintillator annuli mounted around the beam on both sides of the STAR magnet was required in the offline analysis of the data. These scintillator annuli are called the STAR beam-beam counters (BBC) [13]. A dedicated beam study in which the beams were steered out of collision at the STAR interaction region determined that approximately 98% of the observed FPD triggers accompanied by a BBC coincidence came as a result of $p + p$ collisions.

DATA ANALYSIS

Neutral π mesons were reconstructed with the pEEMC from two cluster events in the SMD according to the formula,

$$M_{\gamma\gamma} = E_{\pi} \sqrt{1 - z_{\gamma}^2} \sin\left(\frac{\phi_{\gamma\gamma}}{2}\right) \approx E_{tot} \sqrt{1 - z_{\gamma}^2} \frac{d_{\gamma\gamma}}{2z_{vtx}}. \quad (2)$$

The energy of the π^0 , E_{π} , was taken to be the total energy deposited in all of the towers in the calorimeter, E_{tot} . The opening angle between the photons, $\phi_{\gamma\gamma}$, was determined by the measurement of two values: the vertex position, z_{vtx} , given by the time difference measured by the east and west STAR BBC's, and the distance between the two photons at the calorimeter, $d_{\gamma\gamma}$. Both $d_{\gamma\gamma}$ and the di-photon energy sharing parameter, $z_{\gamma} = |E_1 - E_2| / (E_1 + E_2)$, were measured by an analysis of the energy deposited in the strips of the two orthogonal SMD planes. Typical events had these SMD distributions fit with two peaks used to model the transverse profile of the electromagnetic shower from the incident photons. The value of $d_{\gamma\gamma}$ was determined from the fitted centroids of the peaks, while z_{γ} was determined from the fitted area under each peak. Background at low invariant mass was reduced by constraining z_{γ} as indicated in Figure 2, to ensure that both photons deposit significant energy in the SMD. This algorithm resulted in a mass resolution of $20 \text{ MeV}/c^2$ for π^0 energies from $20 - 80 \text{ GeV}$, limited by the measurement of $\phi_{\gamma\gamma}$ (Fig. 2). Due to the finite size of the collision diamond, making an assumption of a fixed value for $z_{vtx, fixed}$ would result in a mismeasurement of $\phi_{\gamma\gamma}$. The peak in the invariant mass distribution, reconstructed using $z_{vtx, fixed}$, was found to be linearly correlated with z_{vtx} as determined from charged tracks reconstructed with the STAR time projection chamber, with which a subset of the FPD data was accumulated [14]. This provides evidence that the observed π^0 mesons were produced in $p + p$ collisions.

The absolute energy scale for each tower was determined from the π^0 peak in the invariant mass distribution. The invariant mass was sorted according to the calorimeter tower with the greatest energy deposition in each event, and then the gain for each tower was adjusted to match the known mass of the π^0 meson. Since typical events involve multiple calorimeter towers, the gain matching procedure was iterative. After approximately five iterations, this procedure converged to a stable set of values for each fill with an absolute uncertainty better than 1%. Small drifts of the gain on the order of a few percent were observed for many towers. It has been checked that the position of the π^0 peak had negligible dependence on the spin-state of the yellow beam and was independent of π^0 energy, as shown in Figure 2. The energy calibration of the Pb-glass arrays were also performed with π^0 mesons, although the mass resolution was significantly worse since the positions of the photons at the detector were not as well measured.

The FPD data were compared with a simulation of $p + p$ collisions using PYTHIA together with a full GEANT simulation of the pEEMC response. Minimum-bias PYTHIA events with more than 25 GeV of energy within a box of size comparable to the pEEMC were run through GEANT. The simulated detector responses were processed through the analysis algorithm as if they were data. The simulation was found to compare well with the data for an over-determined set of kinematic variables, bolstering the evidence

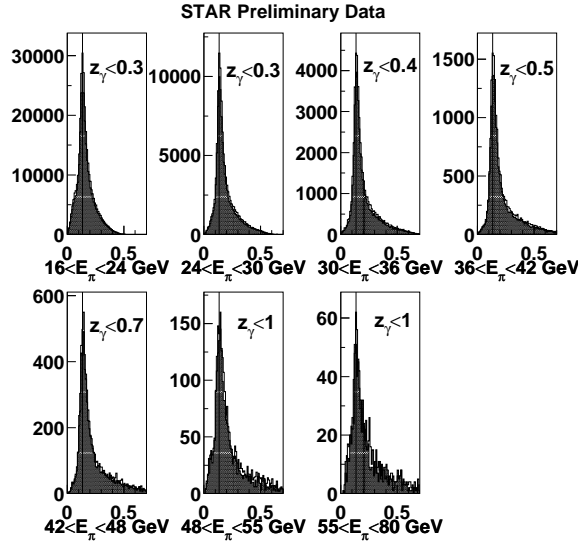


FIGURE 2. Preliminary distributions of the diphoton invariant mass spectra sorted into the energy bins used in the asymmetry analysis. The distributions are not corrected for acceptance or efficiency effects. The vertical line is drawn at $135 \text{ MeV}/c^2$. The absolute gain calibration of the pEEMC has been determined by the position of the mass peak in spin-summed distributions. Bin-by-bin constraints are applied to the energy sharing parameter to reduce background at small invariant mass. The filled area represents events collected when the yellow spin polarization direction is up, while unfilled represents spin down. There is negligible dependence of the peak position on either spin or energy.

that the FPD was measuring π^0 mesons resulting from $p - p$ collisions. A comparison of the data and the simulation for the p_T and the energy spectra can be seen in Figure 3.

The orientation of the yellow beam polarization for FPD triggered events was determined by measuring the time difference between the FPD trigger and spin direction bits provided by RHIC. The relative luminosity of collisions with polarization direction of the yellow beam oriented up or down was measured by counting the coincidences of charged particles fore and aft of the collision vertex by the STAR BBC sorted by the yellow beam spin direction bits [13]. The live time of the FPD data acquisition system was measured by counting the number of events acquired divided by the number of events which satisfied the trigger condition. No appreciable spin-dependence of the live time was observed. Correcting the π^0 yield by the luminosity and live time resulted in a normalized π^0 yield with fill-to-fill stability on the order of 15%. The value of the relative luminosity correction (R in Equation 1) was typically on the order of 1.15, and is understood to come from variations in the beam intensity from bunch-to-bunch [13].

RESULTS

The measured analyzing power is not strongly affected by cuts used to identify π^0 mesons. The A_N for the π^0 candidate events in the mass range $70 < M_{\gamma\gamma} < 300 \text{ MeV}/c^2$ shown in Figure 2 is consistent with A_N for the energy spectra observed with the

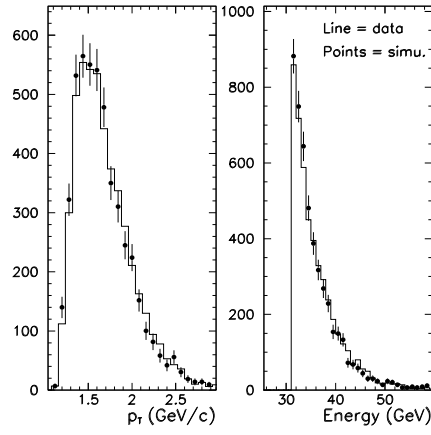


FIGURE 3. The spin-summed transverse momentum and energy distributions for events seen with the Pb-scintillator sampling calorimeter (pEEMC), uncorrected for efficiency or acceptance effects. The histogram is data from a single fill subjected to the data analysis algorithm described in the text. The points are a Monte-Carlo simulation using events generated from a PYTHIA minimum-bias sample together with a GEANT model of the pEEMC, subjected to identical analysis constraints as the data. The simulation agrees well with the data for virtually all observables, indicating minimal contributions from background sources other than $p + p$ collisions.

pEEMC. The value of Feynman- x is approximately $E_{tot}/100\text{GeV}$. A preliminary analysis of the simulation in Figure 3 indicates that events which trigger the FPD are composed of 95% photons, 95% of which are daughters from π^0 decay. Non-photon triggers predominantly come from hadron showers, while other photon triggers mostly come from other meson decays, such as the ω , η , and η' .

The analyzing power for the energy spectra in the pEEMC is shown in the upper-left plot in Figure 4. Also displayed in Figure 4 is A_N for the energy spectra measured with the Pb-glass arrays. The analyzing power observed on the left side with the Pb-scintillator sampling calorimeter is consistent with A_N measured with the Pb-glass array on the right side, even though systematic effects arising from hadronic contributions in these two detector arms are different. The analyzing powers observed above and below the beam pipe with Pb-glass arrays are consistent with zero.

The preliminary systematic uncertainty is taken to be constant throughout the energy range covered by the detectors, its value being $\delta A_N = 0.05$. This estimate has three primary, approximately equal, components: the average difference between the left and right detectors, the difference between the energy spectra asymmetry and the asymmetry for identified π^0 mesons, and the time dependence of the spin-dependent asymmetry seen with the pEEMC. The systematic uncertainty does not include the asymmetric normalization uncertainty from the beam polarization.

In summary, we have observed that the analyzing power for π^0 mesons at $\sqrt{s} = 200\text{GeV}$ is similar in magnitude and x_F dependence to that measured at collision energies an order of magnitude smaller.

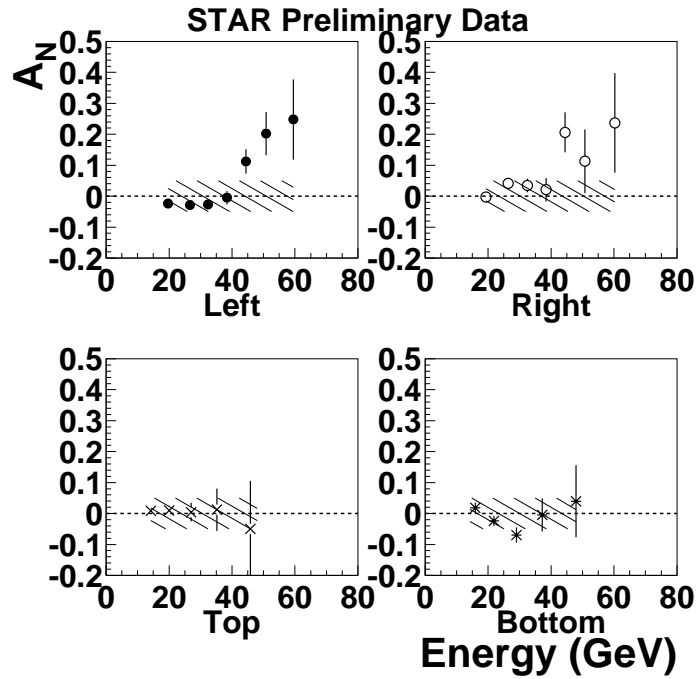


FIGURE 4. Preliminary results of the analyzing power for the energy spectra in the four arms of the FPD detector measured with a vertically polarized proton beam. The lines on the data points represent the statistical uncertainty, while the hatched area represents an estimate of the systematic uncertainty. The results from the Pb-scintillator sampling calorimeter to beam-left are consistent with the Pb-glass array to beam-right, while the Pb-glass arrays above and below the beam are consistent with zero. The analyzing power for identified π^0 mesons with the Pb-scintillator sampling calorimeter is consistent with these data, but with significantly larger statistical uncertainties. The size and shape of the analyzing power is similar to that seen for π^0 mesons at E704 [1, 2].

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