Nuclear Dependence of the Transverse Single-Spin Asymmetry in the Production of Charged Hadrons at Forward Rapidity in Polarized $p+p$, $p+\mathrm{Al}$, and $p+\mathrm{Au}$ Collisions at $\sqrt{s_{NN}} = 200$ GeV

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We report on the nuclear dependence of transverse single-spin asymmetries (TSSAs) in the production of positively charged hadrons in polarized $p^\uparrow + p$, $p^\uparrow + \mathrm{Al}$, and $p^\uparrow + \mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV. The measurements have been performed at forward rapidity ($1.4 < \eta < 2.4$) over the range of transverse momentum ($1.8 < p_T < 7.0$ GeV/c) and Feynman x ($0.1 < x_F < 0.2$). We observed positive asymmetries for positively charged hadrons in $p^\uparrow + p$ collisions, and significantly reduced asymmetries in $p^\uparrow + A$ collisions. These results reveal a nuclear dependence of TSSAs for charged-hadron production in a regime where perturbative techniques are applicable. These results provide new opportunities to use $p^\uparrow + A$ collisions as a tool to investigate the rich phenomena behind TSSAs in hadronic collisions and to use TSSAs as a new handle in studying small-system collisions.

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Understanding the transverse-single-spin asymmetries (TSSAs) that describe the azimuthal-angular dependence of particle production relative to the transverse-spin direction of the polarized proton in the reaction $p^\uparrow + p \to h + X$ has been a long-standing puzzle. The first observations in pion production at large Feynman x (x_F) [1] showed measured TSSAs that were considerably larger than early theoretical predictions (in the collinear leading twist approach) [2]. Surprisingly large measured TSSAs continued to persist in hadronic collisions at high energies up to $\sqrt{s} = 500$ GeV [3–14]. To explain these large TSSAs, two approaches were proposed within perturbative quantum chromodynamics (pQCD). One approach is called transverse-momentum-dependent factorization, in which TSSAs are generated by correlations between the nucleons transverse spin direction and the transverse momentum of a parton in the polarized nucleon (Sivers effect [15,16]), and from the fragmentation of a transversely polarized parton into a final-state hadron (Collins effect [17]). Another approach, directly applicable to single-hadron production (with $p_T \gg \Lambda_{\mathrm{QCD}}$) presented in this Letter is the twist-3, collinear-factorization framework [18]. The full description of TSSAs in $p^\uparrow + p \to h + X$ in the twist-3 collinear factorization includes twist-3 functions from the polarized proton, the unpolarized proton, and the parton fragmentation into final-state hadrons. The twist-3 functions describe quark-gluon-quark correlations and trigluon correlations in the polarized proton and have been studied in detail [19–27]. Recently, calculations of the twist-3 contribution from parton fragmentation have been carried out and have shown this to be an important mechanism for understanding TSSA measurements [28–30].

The Relativistic Heavy Ion Collider (RHIC) is a unique facility that can accelerate polarized protons and collide them with other (polarized) protons or nuclei [31]. The extension of TSSA measurements to $p^\uparrow + A$ collisions not only gives us a crucial tool for understanding the nature of TSSAs, but also provides a new handle for studying $p + A$ collisions and the parton dynamics inside nuclei, where many emergent effects remain to be understood. These include the so-called "Cronin" effect, an enhancement in the inclusive hadron p_T spectrum with respect to $p + p$ collisions at moderate p_T of approximately $2 < p_T < 6$ GeV/c that is proposed to be due to multiple scattering effects in the nuclear medium and modified hadronization mechanism [32–35]. Another exciting observation is that the collective behavior across large pseudorapidity ranges in high multiplicity $p + A$ collisions may indicate quark-gluon-plasma formation [36–38]. Furthermore, when hadron production is measured in the proton-going direction, the properties of nuclear gluons in the small-x region can be probed, where x is the fraction of the proton's longitudinal momentum carried by the parton. The dynamics of gluons in the small-x regime, where the gluon density is predicted to increase drastically, can be described by the color-glass condensate (CGC) formalism [39] at the saturation scale Q_s, where $Q_{sA}^2 \propto A^{1/3}$ for the target nucleus [40,41]. In recent years, substantial attention has been given to an interplay between small-x physics and spin physics by studying TSSAs in transversely polarized proton and ion collisions ($p^\uparrow + A$) and gluon saturation effects in a nucleus are taken into account for various calculations of TSSAs in $p^\uparrow + A$ collisions [40–51]. An A dependence of TSSAs can arise from the A dependence of Q_s when the probe is at or below Q_s, while TSSAs are expected to be A independent at higher scales [42,43,49–51]. Therefore, experimental data on hadron TSSAs measured in $p + A$ collisions with varying A size will provide valuable information testing these models and bring new insights in understanding the dynamics of the $p + A$ collisions.

We report here on the observation of a nuclear dependence of TSSAs of positively charged-hadron production at forward rapidity ($0.1 < x_F < 0.2$ and $1.4 < \eta < 2.4$, probing $0.004 \lesssim x \lesssim 0.1$ in the nuclei) in collisions between transversely polarized protons and unpolarized protons or nuclei, $p^\uparrow + p$, $p^\uparrow + \mathrm{Al}$, $p^\uparrow + \mathrm{Au}$ at $\sqrt{s_{NN}} = 200$ GeV measured with the PHENIX detector. The positively charged hadron is preferred in the nuclear-dependence measurement because the significance of TSSAs for negatively charged hadrons will be reduced by the partial cancellation of the asymmetry due to opposite signs of TSSAs for π^- and K^- in $p^\uparrow + p$ collisions [8,10]. In this measurement, we follow the convention to quantify TSSAs as A_N, where A_N is the modulation of the azimuthal angle of the hadron (ϕ_h) relative to the azimuthal angle of the transverse spin of the proton (ϕ_{pol}), i.e., hadron-production cross section $\sigma \propto 1 + A_N \sin(\phi_{\mathrm{pol}} - \phi_h)$.

The data from transversely polarized $p^\uparrow + p$, $p^\uparrow + \mathrm{Al}$, and $p^\uparrow + \mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV were collected with the PHENIX detector during the RHIC 2015 running period. Proton beams were polarized vertically with respect to the beam direction with an average polarization of 58% (clockwise beam) or 57% (counterclockwise beam) for $p^\uparrow + p$, 58% for $p^\uparrow + \mathrm{Al}$, and 61% for $p^\uparrow + \mathrm{Au}$ collisions, with a relative uncertainty of 3% due to uncertainty in the polarization normalization. The beams are bunched. To minimize systematic effects due to time dependence of machine and detector performance, the spin configuration of the colliding bunches is alternated every 106 ns.

The PHENIX detector comprises two central arms at midrapidity and two muon arms at forward rapidity [52,53]; only reconstructed tracks from the muon arms are used for this analysis. The two muon spectrometers cover $1.2 < \eta < 2.4$ (polarized p-going direction) and $-2.2 < \eta < -1.2$ (A-going direction) in pseudorapidity with full azimuthal angle coverage. Each muon arm has 7.5 nuclear interaction lengths (λ_I) of hadron absorber followed by a muon tracker (MuTr), which is a set of three stations of cathode strip chambers for momentum measurements of charged particles. The MuTr determines the momentum of a charged particle in a radial magnetic field of $\int B dl = 0.72$ T m with a momentum resolution of $\delta p/p \approx 0.05$ for hadrons in the kinematic range of this analysis. A muon identifier (MuID), located behind the MuTr, comprises five layers of stainless-steel absorbers ($\sim 5\lambda_I$ total) and Iarocci tube planes. The MuID helps to identify muons and hadrons based on the penetration depth of the tracks at $p_z \gtrsim 3.5$ GeV/c [54].

The beam-beam counters (BBCs) [55], at $z = \pm 144$ cm from the nominal interaction point, comprise two arrays of 64 quartz Cherenkov detectors and cover the full azimuth and the pseudorapidity range $3.1 < |\eta| < 3.9$. The BBCs are used to determine the collision vertex z position ($|z| < 30$ cm cut was used in this analysis) as well as to provide a minimum-bias (MB) trigger with efficiencies of 55% for $p + p$, 72% for $p + \mathrm{Al}$, and 84% for $p + \mathrm{Au}$ collisions. The A-going side of the BBC is also used to determine the event centrality based on the distribution of the charge sum [56]. The recorded events are sampled by the MB trigger combined with muon triggers to enrich good muon and hadron tracks. The MuID provides a trigger for events containing one or more hadron or muon candidates. Momentum-sensitive triggering is provided by hit information from the MuTr to enrich tracks with $p_T > 3$ GeV/c [57].

This analysis uses only charged tracks that stop in the middle of the MuID planes (third or fourth plane out of five planes) due to a hadronic interaction with the absorber material. In the kinematic region of $0.1 < x_F < 0.2$, where the longitudinal momentum of particles is larger than 10 GeV/c, positively charged hadron candidates mostly comprise π^+ and K^+.

The particle composition in the measured charged-hadron sample was estimated with a method developed in Refs. [54,58], based on identified charged-hadron spectra measured at midrapidity in $p + p$ and $d + \mathrm{Au}$ collisions at RHIC [35,59,60], and extrapolated to PHENIX muon arm rapidity region of $1.2 < \eta < 2.4$ for $p + p$, $p + \mathrm{Al}$ and $p + \mathrm{Au}$ collisions using PYTHIA [61] and HIJING [62] event generators. The K^+/π^+ ratio of ~ 0.35, as measured at RHIC at midrapidity at $p_T \sim 2$ GeV/c (typical for our data) [35,59,60], was found approximately unchanged when extrapolated to forward rapidity in both $p + p$ and $p + A$ collisions. The p/π^+ ratio of ~ 0.25 (~ 0.35) at midrapidity in $p + p$ ($d + \mathrm{Au}$) collisions [35,59,60] was extrapolated to the value of ~ 0.3 (~ 0.5) at the muon arm rapidity, with ratios in $p + \mathrm{Al}$ and $p + \mathrm{Au}$ collisions being in between values for $p + p$ and $d + \mathrm{Au}$ collisions. The initial charged hadron composition is significantly modified due to particle interaction in the detector material, which according to Geant4-based [63] detector simulation modifies the initial K^+/π^+ (p/π^+) ratio by a factor of 2.7 (0.4), which varies by $\approx 5\%$ for different hadron interaction models [63]. As a result, the $\pi^+/K^+/p$ particle composition in our measured positively charged-hadron sample is evaluated to be 45%/47%/5% in $p + p$ collisions, with increased proton fraction to 7% (9%) in $p + \mathrm{Al}$ ($p + \mathrm{Au}$) collisions.

The unbinned maximum-likelihood method for extracting A_N was established in a previous study [64] that used the same detectors. Compared to binned approaches, this method is robust even for low-statistics data. The extended log-likelihood is defined to be

$$\log \mathcal{L} = \sum_i \log[1 + P A_N \sin(\phi_{\mathrm{pol}} - \phi_h^i)] + \mathrm{const}, \quad (1)$$

where ϕ_h^i is the azimuthal angle of the ith hadron with respect to the direction of the polarized proton beam, $\phi_{\rm pol}$ is the azimuthal angle for the beam polarization direction, which in the 2015 PHENIX run takes the values $+/-(\pi/2)$ for $\uparrow/\downarrow$ spin-signed beam bunches, respectively, and P is the beam polarization. The asymmetry A_N is determined by maximizing $\log \mathcal{L}$. For $p^\uparrow + p$ collisions, both beams are polarized; therefore the values of A_N were measured separately for each beam, found to be consistent, and were averaged in the final result. For $p^\uparrow + A$ collisions, only the clockwise proton beam was polarized. The statistical uncertainty was calculated from the second derivative of the log-likelihood estimator,

$$\sigma^2(A_N) = \left(-\frac{\partial^2\mathcal{L}}{(\partial A_N)^2}\right)^{-1}. \quad (2)$$

The A_N calculated from the likelihood method is compared with the following azimuthal-fitting method based on the polarization formula [65]:

$$A_N(\phi) = \frac{\sigma^\uparrow(\phi) - \sigma^\downarrow(\phi)}{\sigma^\uparrow(\phi) + \sigma^\downarrow(\phi)} = \frac{1}{P}\frac{N^\uparrow(\phi) - RN^\downarrow(\phi)}{N^\uparrow(\phi) + RN^\downarrow(\phi)}, \quad (3)$$

where $A_N(\phi)$ is the simple count-based transverse single-spin asymmetry in each of the 16 azimuthal ϕ-bins, $\sigma^\uparrow$, $\sigma^\downarrow$ are cross sections for each polarization of spin up or down, $N^\uparrow$, $N^\downarrow$ are yields, and $R = L^\uparrow/L^\downarrow$ is the luminosity ratio (relative luminosity) between bunches with spin up and down, determined from the number of sampled MB triggers corresponding to different spin orientations. From this, A_N is extracted from the fit of Eq. (3) with a function $A_N \sin(\phi_{\rm pol\uparrow} - \phi)$, where $\phi_{\rm pol\uparrow} = \pi/2$ is the azimuthal direction of the upward polarized bunches. Because every detector element is simultaneously used for the measurements with spin-up and -down, the possible systematic effects from acceptance nonuniformity and acceptance variation versus time are largely canceled. The relative variation between this method and the log likelihood method is included in the systematic uncertainty.

Figure 1 shows the reconstructed azimuthal modulation of positively charged hadrons for $0.1 < x_F < 0.2$ and $1.8 < p_T < 7.0$ GeV/c in $p^\uparrow + p$, $p^\uparrow + $Al, and $p^\uparrow + $Au collisions at $\sqrt{s_{NN}} = 200$ GeV, as calculated using Eq. (3). The relatively larger statistical uncertainty in the bin at $\phi \sim 0.6$ rad is caused by a known detector inefficiency. The χ^2/NDF of the fits are 10.1/15 for $p^\uparrow + p$, 13.5/15 for $p^\uparrow + $Al, and 9.8/15 for $p^\uparrow + $Au. The $p^\uparrow + p$ results show a clear nonzero modulation, while the $p^\uparrow + $Al results show a weaker modulation. In $p^\uparrow + $Au collisions, the modulation is consistent with zero within the statistical uncertainty.

The finite momentum and azimuthal angle ϕ resolution in the MuTr and the interactions of particles with the materials prior to entering the MuTr lead to a kinematic smearing for the A_N measurement. This smearing effect was studied and corrected with a full detector Geant4 simulation. The effect due to the ϕ smearing was found to be negligible. The momentum smearing effect was evaluated by resolving a set of linear equations connecting A_N for the true x_F bins ($A_N^{\rm truth}$) and A_N for the reconstructed x_F bins ($A_N^{\rm reco}$):

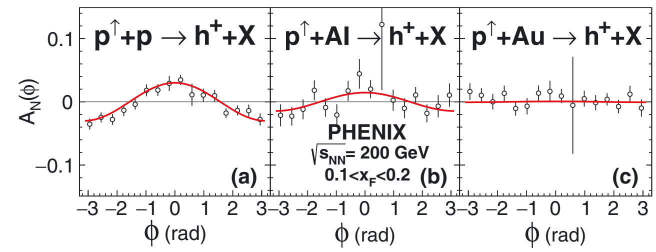

FIG. 1. Azimuthal modulation of positively charged hadrons for $1.4 < \eta < 2.4$, $0.1 < x_F < 0.2$, and $1.8 < p_T < 7.0$ GeV/c in (a) $p^\uparrow + p$, (b) $p^\uparrow + $Al, and (c) $p^\uparrow + $Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

$$A_N^{{\rm reco},m} = \sum_i f^{i\to m} \cdot A_N^{{\rm truth},i}, \quad (4)$$

where $A_N^{{\rm reco},m}$ is A_N for the m-th reconstructed x_F bin from this measurement and $A_N^{{\rm truth},i}$ is that for the ith true x_F bin. $f^{i\to m}$ represents the fraction of charged particles whose true x_F at the collision vertex belongs to the ith true x_F bin and is reconstructed as being in the mth x_F bin. $f^{i\to m}$ is obtained from the Geant4 detector simulation. For calculating $A_N^{\rm truth}$ by solving Eq. (4), the $A_N^{\rm reco}$ is measured in a wider x_F range $0.035 < x_F < 0.3$, by including two bins at lower x_F and one bin at higher x_F. The resulting smearing-corrected $A_N^{\rm truth}$ of the positively charged hadrons in bin $0.1 < x_F < 0.2$ are shown in Table I. The difference between the obtained $A_N^{\rm truth}$ and the measured $A_N^{\rm reco}$ is small compared to the statistical uncertainty and is accounted for in the systematic uncertainty.

Table I also summarizes the systematic uncertainties for the A_N measurements. The difference of A_N extracted with two methods, Eqs. (1) and (3), is shown as $\delta A_N^{\rm method}$. The difference between the obtained $A_N^{\rm truth}$ and measured $A_N^{\rm reco}$

TABLE I. A_N and sources of systematic uncertainty for positively charged hadrons for $1.4 < \eta < 2.4$, $0.1 < x_F < 0.2$, and $1.8 < p_T < 7.0$ GeV/c in $p^\uparrow + p$, $p^\uparrow + $Al, and $p^\uparrow + $Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

	$p^\uparrow + p$	$p^\uparrow + $Al	$p^\uparrow + $Au
A_N	3.14×10^{-2}	1.42×10^{-2}	0.12×10^{-2}
$\delta A_N^{\rm stat}$	0.37×10^{-2}	0.72×10^{-2}	0.55×10^{-2}
$\delta A_N^{\rm syst}$	${}^{+0.05}_{-0.18} \times 10^{-2}$	${}^{+0.02}_{-0.02} \times 10^{-2}$	${}^{+0.06}_{-0.06} \times 10^{-2}$
$\delta A_N^{\rm method}$	${}^{+0.05}_{-0.05} \times 10^{-2}$	${}^{+0.02}_{-0.02} \times 10^{-2}$	${}^{+0.06}_{-0.06} \times 10^{-2}$
$\delta A_N^{\rm smear}$	${}^{+0.00}_{-0.17} \times 10^{-2}$	${}^{+0.01}_{-0.00} \times 10^{-2}$	${}^{+0.01}_{-0.00} \times 10^{-2}$

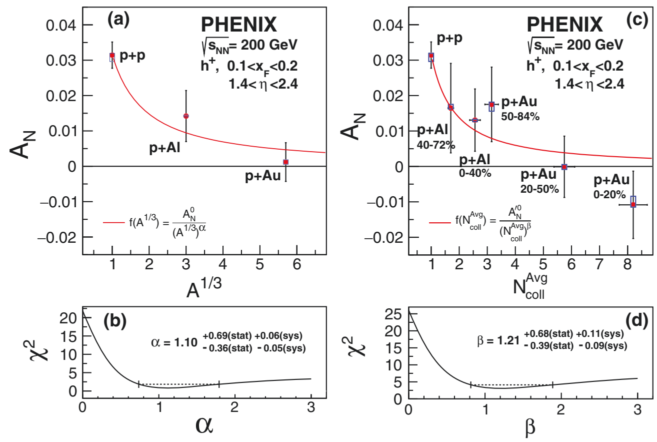

FIG. 2. Upper panels are A_N of positively charged hadrons for $0.1 < x_F < 0.2$, $1.8 < p_T < 7.0$ GeV/c, and $1.4 < \eta < 2.4$ in $p^\uparrow + p$, $p^\uparrow + \text{Al}$, and $p^\uparrow + \text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV as a function of (a) $A^{1/3}$ and (c) $N_{\text{coll}}^{\text{avg}}$. The fit functions, $A_N^0/(A^{1/3})^\alpha$ and $A_N'^0/(N_{\text{coll}}^{\text{avg}})^\beta$ are shown as solid [red] curves. Vertical bars (boxes) represent statistical (systematic) uncertainties. A 3% scale uncertainty due to polarization uncertainty is not shown. Lower panels show χ^2 distributions as a function of power parameters (b) α and (d) β, taking into account the statistical uncertainty only. Dashed lines represent the range of α and β for $\Delta\chi^2 < 1$.

is assigned as a conservative systematic uncertainty due to the smearing effect, $\delta A_N^{\text{smear}}$. The total systematic uncertainty δA_N^{syst} is calculated as a quadratic sum of these two uncertainties.

Figure 2 shows A_N of positively charged hadrons in $p^\uparrow + p$, $p^\uparrow + \text{Al}$, and $p^\uparrow + \text{Au}$ collisions vs $A^{1/3}$ and the average number of nucleon-nucleon collisions $N_{\text{coll}}^{\text{avg}}$. The $N_{\text{coll}}^{\text{avg}}$ is calculated using the Glauber model [66] for each centrality class in $p^\uparrow + A$ collisions [56]. The figure caption and legends denote the ranges of parameters and give the determined values of the power parameters α and β. Panels (b) and (d) show the χ^2 distributions with only statistical uncertainties included.

The recent efforts to calculate A_N in $p^\uparrow + p$ and $p^\uparrow + A$ collisions, accounting for gluon saturation effects [30, 49–51] suggested that A_N could be A independent or $A^{-1/3}$ dependent for the different contributions to A_N in the region where $p_T < Q_s$. However, $\langle p_T \rangle \sim 2.9$ GeV/c in our results is much larger than the saturation scale in the Au nucleus ($Q_s^{\text{Au}} \sim 0.9$ GeV) for the kinematics of this measurement and would lead to no strong A dependence of TSSAs under these models, as calculated in Ref. [51]. Nevertheless, the results in this Letter strongly disfavor the A-independent scenario.

The $N_{\text{coll}}^{\text{avg}}$ dependence of A_N also suggests the decrease of A_N is related to the density of nuclear matter inside the target nucleus which the projectile proton traverses. This $N_{\text{coll}}^{\text{avg}}$ dependence of A_N could be related to novel effects in $p + A$ collisions, such as multiple scattering of partons in the initial and/or final stages of the hard scattering, which is also indicated in the recent results of the nuclear modification of single hadron production and transverse momentum broadening in dihadron correlations in $p + A$ collisions [35,67,68]. Another possibility is interaction of the parton with hot QCD matter produced in $p + A$ collisions, as suggested by recent results in small systems [36–38].

We note preliminary results from the STAR Collaboration [69] of measured A_N for π^0 in $p^\uparrow + p$ and $p^\uparrow + \text{Au}$ collisions in more forward kinematics at $2.6 < \eta < 4.0$, $0.2 < x_F < 0.7$, and $p_T > 1.5$ GeV/c that show small or no A dependence. The dramatic difference in A-dependence of TSSAs in different particle species and kinematic range emphasizes the importance of further detailed studies of A_N for different particle species over wide kinematics.

To summarize, we have reported A_N of positively charged hadrons for $1.4 < \eta < 2.4$, $0.1 < x_F < 0.2$, and $1.8 < p_T < 7.0$ GeV/c in $p^\uparrow + p$, $p^\uparrow + \text{Al}$, and $p^\uparrow + \text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV. For the first time, we observed an A dependent A_N in light hadron production in $p + A$ collisions, with the asymmetry values dropping from ~3% in $p + p$ collisions to a value consistent with zero in $p + \text{Au}$ collisions. These results may provide new insights into the origin of A_N and a unique tool to investigate the rich phenomena behind TSSAs in hadronic collisions and to use TSSAs as a new approach to studying the small-system collisions.

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