Transverse momentum dependence of forward neutron single spin asymmetries in polarized $p^+ + p$ collisions at $\sqrt{s} = 200$ GeV$^\dagger$

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The PHENIX Collaboration has, for the first time, explicitly measured the transverse momentum ($p_T$)-dependent single spin asymmetries ($A_N$) for inclusive neutrons produced in the forward region of the PHENIX detector with $\eta > 6.8$ using 2015 data. During this time, a proton with transverse polarization collided with another proton at $\sqrt{s} = 200$ GeV. Owing to the limited acceptance and resolution of the detector, the measured quantities were considerably smeared. We, therefore, corrected for the smearing in the measured $p_T$ and azimuth ($\phi$) using unfolding.$^1$

As the physics of forward neutron production is not clearly understood, we performed detailed simulations using different event generators as input to a full GEANT3 simulation.$^2$ The generators DPMJET3.1, PYTHIA6.1, and PYTHIA8.2 were used because diffractive processes are very differently handled. Another generator was an empirical distribution of forward neutrons in $p_T$, mimicking a one-pion exchange (OPE) model in which a pion balancing the momentum between the incoming proton and outgoing neutron collided with the other proton beam using PYTHIA 8. Ultra-peripheral collisions (UPCs) also play a role in forward neutron production.$^3$ The distribution of photons was, therefore, simulated using the STARLIGHT$^4$ generator, and the photons collided with the proton beam using PYTHIA 8. As all Monte Carlo (MC) generators were intrinsically spin independent, we simulated spin effects by re-weighting events as a function of the generated $p_T$ ($p_{T,g}$) and azimuth ($\phi_g$) with the spin states ($\uparrow$) and ($\downarrow$) randomly assigned. Furthermore, as the shape of $p_T$-dependent $A_N$ is not precisely known, we used three weight forms to provide as much flexibility as possible. The weight ($w$) based on a polynomial of third order (Pol3), power law, and exponential forms is given by Eqs. (1), (2), and (3), respectively, with Pol3 being the most general one:

$$w = (a \cdot p_{T,g} + b \cdot p_{T,g}^2 + c \cdot p_{T,g}^3) \sin(\phi_g + \lambda \cdot \pi), \quad (1)$$

where $\lambda$ ($\pm 1$) is the spin state and $a$, $b$, and $c$ are free parameters. Accordingly, the power-law weight is,

$$w = (a \cdot p_{T,g}^b) \sin(\phi_g + \lambda \cdot \pi), \quad (2)$$

and the last parameterization is an exponential form, which eventually decays asymptotically as

$$w = a \left( 1 - e^{b \cdot p_{T,g}} \right) \sin(\phi_g + \lambda \cdot \pi). \quad (3)$$

The performance of parameters, functional form, and MC generator in reproducing $A_N$ values was evaluated by the minimum $\chi^2$ between the measured MC and data asymmetries. The 2D spin-dependent neutron yields in $p_T$ and $\phi$ were then unfolded using the TSV-DUnfold class based on a singular value decomposition (SVD)$^5$ of the smearing response matrix. Overall $A_N$ values were finally calculated from the unfolded yields using the left-right $A_N$ formula$^5$ after fitting a sine modulation having magnitude and phase as free parameters. In Fig. 1, overall $A_N$ values rapidly increase at low $p_T$ ($< 0.1$ GeV/$c$) and slowly level off at high $p_T$. With this result, the first reliable tests of mechanisms producing these asymmetries can be performed.

References