

# Energy and transverse momentum dependence of single-spin asymmetry of very forward neutron in polarized pp collision

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## Abstract.

We measured energy ( $\sqrt{s}$ ) and transverse momentum ( $p_T$ ) dependence of single-spin asymmetry ( $A_N$ ) of very forward neutron in transversely polarized proton collisions with  $\sqrt{s}$  from 62 to 500 GeV. The observed asymmetry linearly increases with  $p_T$  up to  $\simeq 0.3$  GeV/c. On the other hand,  $\sqrt{s}$  dependence, which shows higher asymmetry for higher  $\sqrt{s}$ , can be interpreted as due to  $p_T$  dependence. A one-pion exchange model fails to reproduce the data. This suggests that the mechanism for forward neutron production is not understood yet, and that we need to consider more processes for forward neutron production.

## 1. Introduction

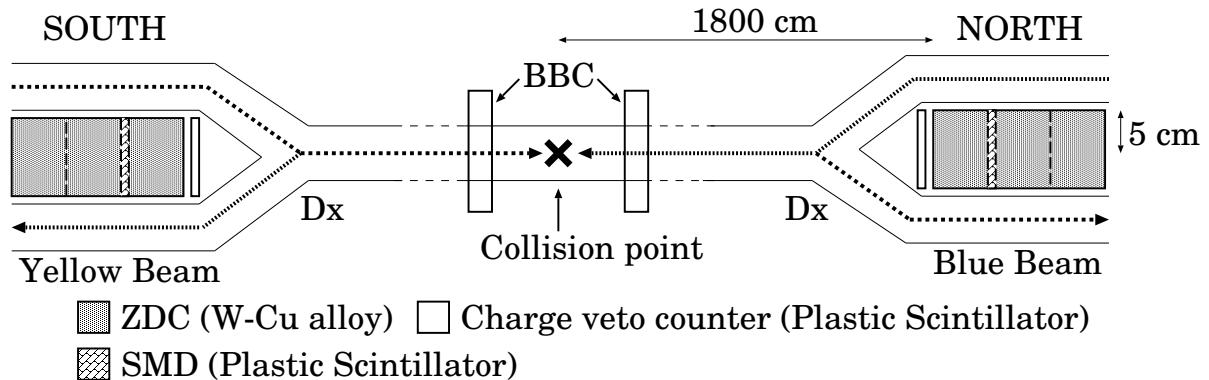
With first polarized proton collision at  $\sqrt{s} = 200$  GeV at Relativistic Heavy Ion Collider (RHIC), a large single transverse spin asymmetry ( $A_N$ ) for neutron production in very forward kinematics was discovered [1]. The discovery shed new light on the production mechanism of such leading baryons in the region where perturbation is not applicable.

The cross sections for inclusive production of zero-degree neutrons for unpolarized  $pp$  collisions are measured at ISR from  $\sqrt{s} = 7$  to 64 GeV [2, 3]. The  $x_F$  spectrum of the shows a peak around  $x_F \sim 0.8$  and is found to have almost no  $\sqrt{s}$  dependence. The preliminary cross-section at  $\sqrt{s} = 200$  GeV we reported earlier [4] is consistent with the ISR result. These features are reasonably explained by one pion exchange (OPE) models, in which the incoming proton emits a pion which scatters on the other proton [5, 6].

In this article, we report the  $\sqrt{s}$  and  $p_T$  dependence of  $A_N$  for very forward neutron in transversely polarized proton collisions with  $\sqrt{s}$  from 62 to 500 GeV. It is interesting to see if the OPE mechanism can explain  $A_N$  as well, especially its transverse momentum ( $p_T$ ) dependence, because  $A_N$  gives information to separate spin-flip and spin-non-flip amplitudes.

## 2. Experimental Setup

A plan view of the experimental setup for very forward neutron measurement at PHENIX is shown in Figure 1. Neutrons have been measured by Zero-Degree Calorimeter (ZDC) with a position-sensitive Shower-Max Detector (SMD) [7]. ZDC is composed of copper-tungsten alloy absorbers with optical fibers and each module has 1.7 interaction length ( $\lambda_I$ ). A photomultiplier collects Cherenkov lights via the optical fibers in each module. Three ZDCs are located in



**Figure 1.** A plan view of the experimental setup at PHENIX (not to scale). Principle components for the leading neutron measurement are shown.

series ( $5.1 \lambda_I$  in total) at  $\pm 1800$  cm away from the collision point within the small acceptance, covering 10 cm in the transverse plane. SMD consists of  $x$ - $y$  scintillator strip hodoscopes and is inserted between the first and second ZDC modules at the position of maximum hadronic shower approximately. The  $x$ -coordinate (horizontal) is sampled by 7 scintillator strips of 15 mm width, while the  $y$ -coordinate (vertical) is sampled by 8 strips of 20 mm width, tilted by 45 degrees. These detectors are located down stream of the RHIC-DX magnet so that charged particles from collisions are expected to be bent away. A forward scintillation counter, covering  $10 \times 12$  cm, has been installed in front of the ZDC to remove charged particle backgrounds.

The data was collected by two sets of triggers for the neutron measurement. One is the ZDC trigger for neutron inclusive measurements by requiring energy deposit in either side of the ZDC (the north side or the south side) above 5 GeV. The other is a coincidence trigger of the ZDC trigger with hits in Beam Beam Counter (BBC), which consists of 64 sets of quartz Cherenkov counters covering  $\pm (3.0\text{--}3.9)$  in pseudorapidity and  $2\pi$  in azimuthal angle.

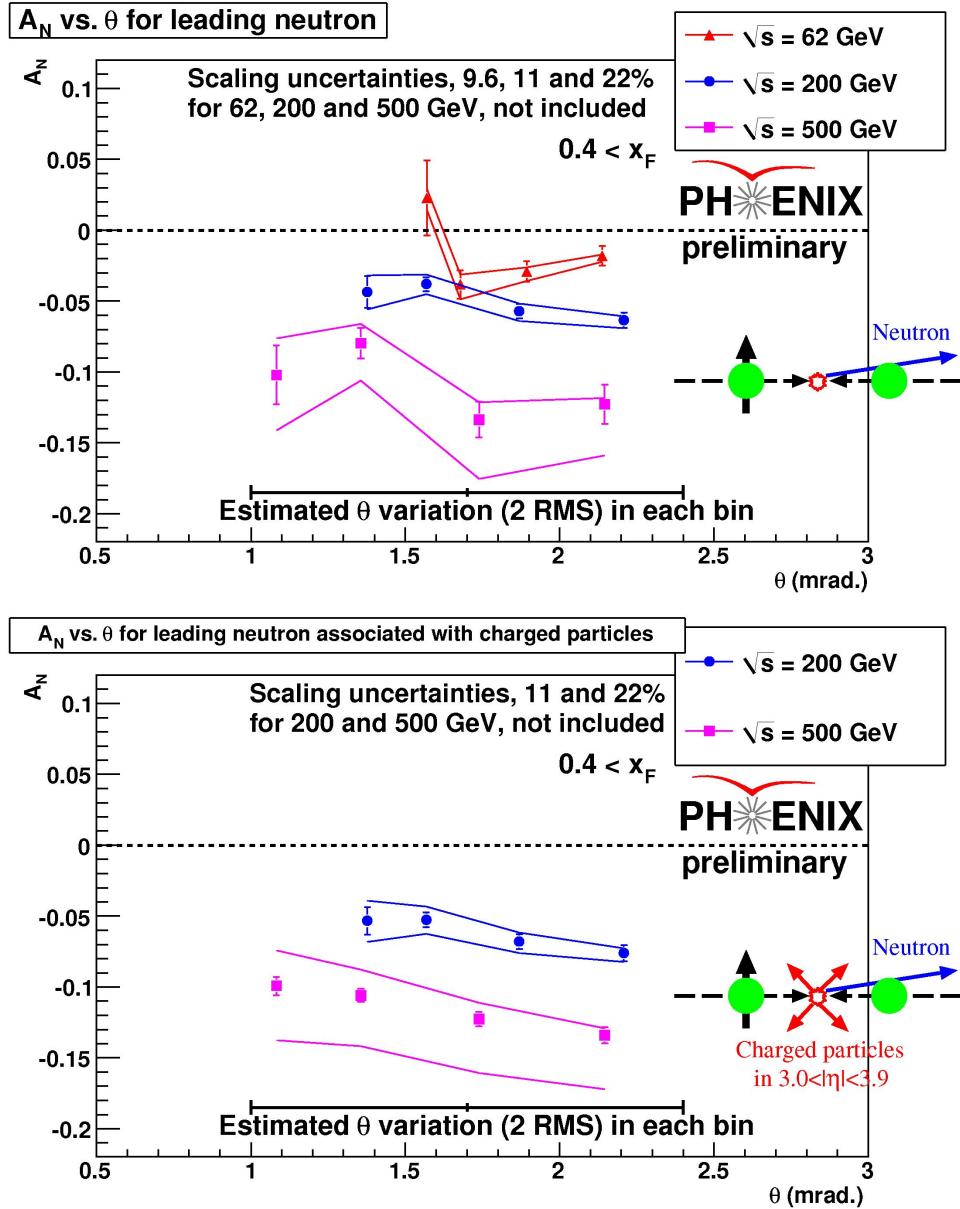
An absolute scale for the energy measurement is determined by the 100 GeV single neutron peak from peripheral heavy ion collisions. The response of the detectors was studied by GEANT3 with GHEISHA, which well reproduced the response of the prototype ZDC. The energy resolution obtained from the simulation can be described by  $\Delta E/E = 65/\sqrt{E} \text{ (GeV)} + 15 \text{ (\%)}$ , which is consistent with the observed width of one neutron peak at 100 GeV.

Neutron position is reconstructed by the energy deposit in SMD scintillators with the centroid method. The position resolutions were estimated by the simulation to be around 1 cm for the neutron energy at 100 GeV. The reliability of the position measurement was checked by comparing hadron shower shapes of the real and simulation data. Then, based on the obtained position and neutron energy ( $E_n$ ),  $p_T$  was calculated as  $p_T = E_n \sin \theta_n \sim E_n r/d$ , where  $\theta_n$  is the reaction angle,  $r$  is the distance from the beam center to the hit position at ZDC, and  $d = 1800$  cm is the distance from the collision point to the ZDC. The single-spin asymmetry,  $A_N$ , was calculated using the square-root-formula. Smearing due to finite position resolution and finite acceptance is corrected for using simulations.

### 3. Results and Discussions

The obtained  $A_N$  for forward neutrons are plotted in Figure 2, as functions of reaction angle. Significant neutron energy ( $x_F$ ) dependence was not observed [4].  $A_N$  for backward neutrons are all consistent with zero.

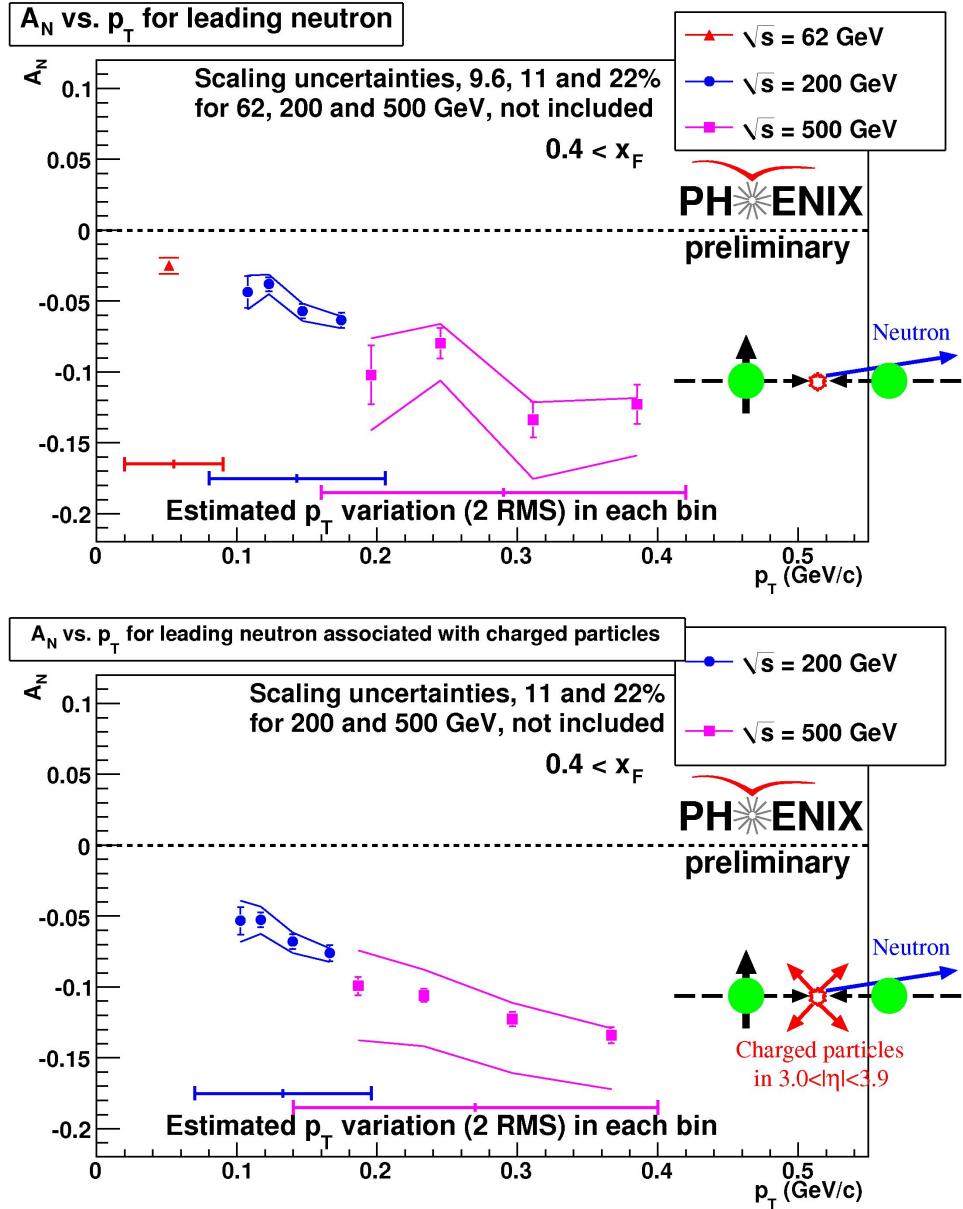
The observed  $\sqrt{s}$  dependence could be interpreted as  $p_T$  dependence, as shown in Figure 3, which shows a linear increase of  $A_N$  with respect to  $p_T$ . As  $p_T$  is proportional to  $\sqrt{s}$  for the



**Figure 2.** The measured asymmetries for forward neutrons as functions of reaction angle. Top: for inclusive neutrons (ZDC single trigger). Bottom: for neutrons with associated particles (ZDC-BBC coincidence trigger). Neutrons with  $x_F > 0.4$  are selected. For the horizontal axis, the plotted positions give the average angles and their variation is also plotted as horizontal bars.

same  $\theta_n$  and  $x_F$ , the asymmetry could be larger for higher  $\sqrt{s}$  even if there would be no actual  $\sqrt{s}$  dependence.

On the theory side, Kopeliovich *et al.* give their calculation for  $\sqrt{s} = 200$  GeV based on a OPE model [8]. They obtained small asymmetries ( $|A_N| < 0.01$ ) for  $p_T < 0.2$  GeV/c which is the range of our measurement at  $\sqrt{s} = 200$  GeV, and thus failed to reproduce our result. Note that their calculation is for the  $x_F$  range between 0.6 and 0.9 which is narrower than



**Figure 3.** The measured asymmetries for forward neutrons as functions of  $p_T$ . Top: for inclusive neutrons (ZDC single trigger). Bottom: for neutrons with associated particles (ZDC-BBC coincidence trigger). Neutrons with  $x_F > 0.4$  are selected. For the horizontal axis, the plotted positions give the average  $p_T$  and its variation is also plotted as horizontal bars.

our measurement ( $x_F > 0.4$ ), but this difference would not have significant effect since  $x_F$  dependence was found to be small in our measurement [4]. Within their model, the smallness at low  $p_T$  is rather natural because both of the spin-flip amplitude and the relative phase vanish for  $p_T \rightarrow 0$ . Therefore, they argued that one should include other mechanisms beyond OPE, for instance, interference of pion and  $a_1$  exchanges.

#### 4. Summary

Single spin asymmetry for very forward neutron production in  $pp$  collision is measured for  $\sqrt{s} = 62, 200$ , and  $500$  GeV. A significant  $\sqrt{s}$  and  $p_T$  dependence was observed, while no  $x_F$  dependence was seen. The  $\sqrt{s}$  can be interpreted as due to  $p_T$  dependence. A model calculation based on OPE mechanism failed to reproduce the results. Therefore, the mechanism for the observed large  $A_N$  is still a mystery.

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