SPIN EFFECTS IN FORWARD $\pi^0$-PRODUCTION IN POLARIZED PROTON-PROTON COLLISIONS AT STAR

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We report some results in large pseudo rapidity $\pi^0$-production in polarized proton collisions at $\sqrt{s} = 200$ GeV. The single spin asymmetry for positive Feynman $x$ ($x_F$) is consistent with zero up to $x_F \sim 0.35$, then increases with increasing $x_F$. This behavior can be described by phenomenological models including the Sivers effect, Collins effect or twist-3 contributions in initial and final states. The asymmetry is found to be zero for negative $x_F$ ($-0.6 < x_F < -0.2$). It has been observed that inclusive $p + p \rightarrow \pi^0 + X$ cross sections at $\eta = 3.3, 3.8$ and 4.0 are consistent with next-to-leading order perturbative QCD calculations.

1 Introduction

At present Quantum Chromodynamics (QCD) can not explain the origin of significant transverse single spin asymmetry ($A_N$) in partonic interactions. Collinear factorized perturbative QCD (pQCD) calculations at leading twist predict these analyzing powers to be entirely negligible, due to chirality in the theory. However, experimental data\cite{1,2,3} shows that $A_N$ for inclusive particle production is on the order of 10% independent of the center of mass energy ($\sqrt{s}$). To improve the situation theorists develop several models in a generalized version of the QCD factorization scheme, which allows for intrinsic transverse motion of partons inside hadrons, and of hadrons relatively to fragmenting partons. This adds new possibilities of spin effects, absent for collinear configurations. Sivers\cite{4} proposed as a source of spin effects to be a flavor dependent correlation between the proton spin ($S_p$), momentum ($P_p$) and transverse momentum ($k^\perp$) of the unpolarized partons inside the proton. This results in the new polarized parton distribution function:

$$f_{q/p}^t(x, k^\perp; S_p) = \hat{f}_{q/p}(x, k^\perp) + \frac{1}{2} \Delta^N f_{q/p}(x, k^\perp) \frac{S_p \cdot (P_p \times k^\perp)}{|S_p||P_p||k^\perp|},$$

\begin{equation}
(1)
\end{equation}

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where \( \tilde{f}_{q/p}(x, k^\perp) \) - unpolarized distribution function, \( \Delta^N f_{q/p}(x, k^\perp) \) - Sivers function and \( x \) is the Bjorken scaling variable. Also significant \( A_N \) could be produced by the correlation between the quark spin (\( s_q \)), momentum (\( p_q \)) and transverse momentum (\( k^\perp \)) of the pion in the final state. Such an approach has been introduced by Collins\(^5\). Then the fragmentation function of transversely polarized quark \( q \) takes the form:

\[
D_{\pi/q^\uparrow}(z, k^\perp; s_q) = \frac{1}{2} \Delta^N D_{\pi/q^\uparrow}(z, k^\perp) \frac{s_q \cdot (p_q \times k^\perp)}{|p_q \times k^\perp|},
\]

where \( D_{\pi/q}(z, k^\perp) \) - unpolarized fragmentation function, \( \Delta^N D_{\pi/q^\uparrow}(z, k^\perp) \) - Collins function and \( z \) is longitudinal component of pion momentum. Along with Collins and Sivers mechanisms there are higher twist effects in either initial\(^6\) or final\(^7\) state which may cause the observed analyzing powers.

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab (BNL) has begun to provide collisions of polarized protons at highest energy \( \sqrt{s} = 200 \) GeV. The Solenoidal Tracker at RHIC (STAR\(^8\)) consists mainly of a large volume TPC, Forward TPC, Beam Beam Counters (BBC), Endcap Electromagnetic Calorimeter (EEMC), Barrel Electromagnetic Calorimeter (BEMC) and Forward Pion Detector (FPD). This contribution will focus on results from FPD and BBC, which located in the very forward region of STAR coverage. BBC are segmented scintillator detectors surrounding the beam pipe. It provides the minimum bias trigger, absolute luminosity and relative luminosity for our experiment. In addition BBC coincidences are used to suppress beam gas background. FPD is a set of eight calorimeters of lead glass cells with size of \( 3.8 \, \text{cm} \times 3.8 \, \text{cm} \times 45 \, \text{cm} \). It provides triggering and reconstruction of neutral pions. Four of them are left-right detectors and 7 \( \times \) 7 arrays cells. Four others are top-bottom 5 \( \times \) 5 arrays and are useful for systematics studies.

### 2 Single Spin Asymmetry at STAR/FPD

By definition single spin asymmetry is: \( A_N = \frac{1}{L_{\text{Beam}}} \frac{d\sigma^{\uparrow}}{d\sigma^{\downarrow}} \), where \( L_{\text{Beam}} \) - polarization of transversely polarized beam, \( d\sigma^{\uparrow(\downarrow)} \) - differential cross section of \( \pi^0 \) when incoming proton has spin up(down). One can measure \( A_N \) by two different ways. First with the use of single arm calorimeter: \( A_N = \frac{1}{L_{\text{Beam}}} \frac{N^\uparrow - R N^\downarrow}{N^\uparrow + R N^\downarrow} \), where \( N^\uparrow(\downarrow) \) - the number of pions detected when the polarization of the beam is oriented up(down) and \( R = \frac{L^\uparrow}{L^\downarrow} \) is the spin dependent relative luminosity measured by BBC. Second with the use of two arms calorimeter (cross ratio method): \( A_N = \frac{1}{L_{\text{Beam}}} \frac{\sqrt{N^\uparrow N^\downarrow} - \sqrt{N^\downarrow N^\uparrow}}{\sqrt{N^\uparrow N^\downarrow} + \sqrt{N^\downarrow N^\uparrow}} \), where \( N^\uparrow_{L(R)} \) - number of pions detected by the left (right) calorimeter while the beam has spin up and \( N^\downarrow_{L(R)} \) - number of pions detected by the left (right) calorimeter while the beam has spin down. In this method one does not need the relative luminosity. The asymmetries from these two measurements were found to be consistent and are combined. Positive (negative) \( x_F \) is defined when the pion is observed with the same (opposite) longitudinal momentum as the polarized beam. Positive \( A_N \) is defined as more \( \pi^0 \) going left of the upward polarized beam. In the 2002 proton run 0.15 \( pb^{-1} \) of integrated luminosity was collected for transversely polarized proton collisions at \( \sqrt{s} = 200 \) GeV at an average polarization of 16%. In 2003 run the integrated luminosity and average polarization have been increased to 0.5 \( pb^{-1} \) and 25% respectively. The polarization was measured by pC CNI polarimeter.\(^10\) Fig.\(^11\) shows \( A_N \) versus \( x_F \) for \( \pi^0 \) mesons. Left plot represents published 2002 data for \( < \eta > = 3.8 \) \( \pi^0 \). Result is consistent with measurements at lower \( \sqrt{s} = 20 \) GeV (E704 experiment) and increasing with \( x_F \). It also can be described by all theoretical predictions mentioned above due to statistical uncertainties. Results from run 2002 and preliminary results from run 2003 at \( < \eta > = 4.1 \)\(^12\) are compared on the right plot. The analyzing power for positive \( x_F \) at...
$< \eta > = 4.1$ is consistent with zero up to $x_F \sim 0.35$, then increases with increasing $x_F$. The first measurement of $A_N$ at negative $x_F$ has been done, and is found to be zero. Negative $x_F$ results may give an upper limit on the gluon Sivers function. This work is in progress.

### 3 Differential cross sections for forward $\pi^0$-Production

The inclusive differential cross section for $\pi^0$ production for $30 < E_\pi < 55$ GeV at $< \eta > = 3.8$ was previously published. The result at $< \eta > = 3.3$ in 2002 run also have been extracted. In 2003 run new calorimeters and readout electronics have been installed to allow measurements of the differential cross section at $< \eta > = 4.0$. The results are shown in Fig. 2.

On the left plot the cross sections are shown versus pion energy and are compared with NLO pQCD calculations evaluated at $\eta = 3.3$, 3.8 and 4.0. Two sets of fragmentation functions are used. The model calculations are consistent with the data in contrast to the data at lower $\sqrt{s}$ (NLO pQCD calculations at $\sqrt{s} = 20$ GeV underpredict measured cross sections). As $\eta$ increases, systematics regarding the comparison with NLO pQCD calculations begin to emerge. The data at low $p_T$ are more consistent with the Kretzer set of fragmentation functions. Similar trend was observed at mid-rapidity. On the right plot the data is represented as in earlier experiments. The outer picture shows cross section as a function of $p_T$ at fixed $x_F$. The inner one – cross section as a function of $(1 - x_F)$ at fixed $p_T = 2$ GeV/c. Invariant cross section falls with $p_T$ at fixed $x_F$ with exponent (value $\sim 6$) independently on $x_F$. Data also show exponential dependence on $x_F$ with fixed $p_T = 2$ GeV/c. The value of the fitted exponent ($\sim 5$) may be sensitive to the interplay between hard and soft scattering processes. One note should be stated regarding systematics of this separated $x_F$ and $p_T$ dependencies. Data were accumulated in different conditions in different running years: with different calorimeters, with different readout electronics, taken in different kinematical regions.
Figure 2: Left: invariant cross section for $\pi^0$ produced in $pp$ collisions at $\sqrt{s} = 200$ GeV versus pion energy ($E_\pi$) at average pseudorapidities ($< \eta >$) 3.3, 3.8 and 4.0. The error bars are point-to-point systematic and statistical errors added in quadrature. Right: invariant cross section as a function of $p_T$ at fixed $x_F$ (outer) and as a function of $(1 - x_F)$ at fixed $p_T = 2$ GeV/c (inner). Lines are fits by the functions showed in the plot.

4 Summary

Large spin effects have been observed at forward $\pi^0$ production in polarized $pp$ collisions at highest energy $\sqrt{s} = 200$ GeV at STAR FPD. The single spin asymmetry for positive $x_F$ is consistent with zero up to $x_F = 0.35$, then increases with increasing $x_F$. The asymmetry is found to be zero for negative $x_F$. The inclusive differential cross section for forward $\pi^0$ production at $\sqrt{s} = 200$ GeV is consistent with NLO pQCD calculations in contrast to what was observed at lower energy. First try to map the cross section in $x_F - p_T$ plane was performed.

The near-future plans are to increase the statistics with the present FPD in order to measure the $p_T$ dependence of $A_N$ at fixed $x_F$, and to extract the gluon Sivers function. In the longer term, plans include an increase of the angular coverage of the electromagnetic calorimetry in the forward direction, with a goal to disentangle the dynamical origin of transverse single spin asymmetries.

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