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RECENT RESULTS AND FUTURE PROSPECTS FOR THE POLARIZED BEAM PROGRAM AT FERMILAB*

(For the Fermilab E-704 Collaboration*)

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ABSTRACT

We summarize activities concerning the Fermilab polarized beams. They include a brief description of the polarized-beam facility, measurements of beam polarization by polarimeters (Fermilab E-581), asymmetry measurements in the π° production at high $p_\perp$ and in the Λ (Σ°), $\pi^\pm$, π° production at large x_F, and $\Delta\sigma_L$(pp, $\bar{p}$p) measurements (Fermilab E-704). In future we plan to investigate the proton-spin crisis by determining the gluon spin distribution in inclusive production of direct gamma, χ2, and J/ψ.

INTRODUCTION

About ten years ago, we wrote several physics proposals in order to justify the construction of a polarized-beam line at Fermilab. They are as follows:

- P-581 Construction of a Polarized Proton Beam Facility in the Meson Area
- P-674 Asymmetries in Inclusive Pion and Kaon Production at Large-x with a Polarized Beam
- P-675 Asymmetry Measurements for Dimuon Production in the J/ψ Mass Region
- P-676 An Experiment to Measure $\Delta\sigma^{Tot}$ in p-p and $\bar{p}$-p Scattering Between 100 and 500 GeV/c
- P-677 A Study of the Spin Dependence in the Inclusive Production of Lambda Particles with the Polarized Beam at Fermilab
- P-678 Proposal to Study the Spin Dependence in Inclusive π° and Direct Gamma Production at High $p_\perp$ with the Polarized Proton Beam Facility at Fermilab
- P-682 Study of the p_T Dependence of $\pi^\pm$ Inclusive Production with a Polarized Proton Beam and Target
- P-688 Nuclear-Size Dependence of Single-Spin Asymmetries in High-p_T Hadron Production
- P-689 Measurement of the Asymmetry in Calorimeter Triggered High-$p_\perp$ Events Using a Polarized Proton Beam and Target

Among these an integration program was suggested as an initial experiment by the Fermilab management. Results were E-581, measurements of the beam polarization and E-704 integrating P-674, 676, 677, and 678.

The Fermilab polarized-beam facility at 200 GeV/c became operational in 1987. At that time, we mainly concentrated on the measurements of beam polarization by polarimeters and on the studies of beam polarization monitors. Recently we carried out the polarized-beam program designated as E-704 by an international collaboration.

We summarize these activities including the discussions of some preliminary data on $p_\perp$ and x_F dependence.

POLARIZED BEAM FACILITY

The Fermilab polarized-beam facility[1] was operated during the past TeV-II (fixed target) period which ended in February 1988.

An extracted beam from the Tevatron is delivered through the MP primary-beam line to the Meson Detector Building where a 0.73-interaction-length Be target is utilized to produce Λ and $\bar{\Lambda}$ at $\theta_{c.m.} \approx 0°$. Protons and antiprotons from the Λ and $\bar{\Lambda}$decays respectively are brought to a final target position in the MP hall through the MP secondary beam (200 GeV/c) line.

Polarized protons from the virtual sources as shown in Fig. 1 are focussed in the tagging section, where both the momentum and polarization are selected.[1]

The typical beam flux ($\Delta p/p = \pm 5\%$) for 3×10^{12} incident protons per 20-sec spill at 200 GeV/c were: (P_{av} is average polarization)

	Tagged Beam $P_{av} = 45\%$)	Total Protons (antiprotons)	Background π's
Protons	1.0×10^7	2.0×10^7	2.0×10^6
Antiprotons	5.0×10^5	1.0×10^6	5.0×10^6

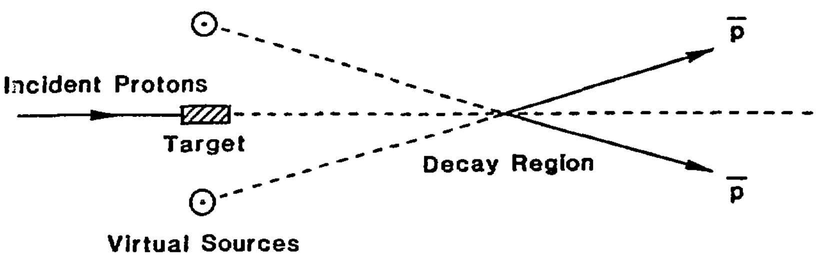

Figure 1 Virtual sources (top view).

PRIMAKOFF-EFFECT MEASUREMENT

The asymmetry of the nuclear coherent Coulomb π° production process ("Primakoff process"), was measured[2] for the first time with the use of the polarized-proton beam. The apparatus consisted of a lead-glass calorimeter for π° detection and a magnetic spectrometer for the scattered protons. A large asymmetry in the region of $|t'| < 0.001\ (\mathrm{GeV}/c)^2$ and $1.36 < M(\pi^\circ p) < 1.52\ \mathrm{GeV}/c^2$ was observed for the reaction $p + Pb \to p + \pi^\circ + Pb$, where the Coulomb process is predominant. The expected null asymmetry was observed in the larger $|t'|$ region where the diffractive-dissociation process is predominant.

The observed ϕ-angle dependence of the coherent π° production process may be expressed as $1 + (f\ T(\theta)\ P_B) \cos\phi$, where $T(\theta)$ is the analyzing power (target azimuthal asymmetry) for photoproduction of π° from a polarized proton target at c.m. polar angle θ, ϕ is the azimuthal angle, P_B is the transverse polarization, and the parameter f is a dilution factor caused by the diffractive dissociation. The raw asymmetry at ϕ is obtained as

$$A(\phi) = \{N^{\uparrow}(\phi) - N^{\downarrow}(\phi)\}/\{N^{\uparrow}(\phi) + N^{\downarrow}(\phi)\} = f\ T(\theta)\ P_B \cos\phi = \varepsilon \cos\phi,$$

where $N^{\uparrow}(\phi)$ and $N^{\downarrow}(\phi)$ are the number of events at ϕ for the up and down spin direction of the incident proton, respectively.

The measured asymmetry for the Coulomb process is consistent with the analyzing power (about -70%) of the π° production process deduced from existing low-energy $\gamma + p \to \pi^\circ + p$ data. The results demonstrate that the Primakoff process is useful for the measurement of proton and antiproton polarization at high energy.

COULOMB-NUCLEAR INTERFERENCE MEASUREMENTS

The analyzing power, A_N, of proton-proton, proton-hydrocarbon, and antiproton-hydrocarbon scattering in the Coulomb-nuclear region was measured with use of the polarized-proton and polarized-antiproton beams.[3] For the elastic scattering at small $|t|$, a set of scintillation counters was utilized to detect the recoil proton which stops within a very short range in the scintillator. The results at $|t| \sim 0.003\ (\mathrm{GeV}/c)^2$ show the value $A_N = (2.4 \pm 0.9)\%$ with the polarized-proton beam, and $A_N = (-4.6 \pm 1.9)\%$ with the polarized-antiproton beam both on a hydrocarbon target, and also $A_N = (4.5 \pm 2.8)\%$ of proton-proton scattering. These results are consistent with predictions[4-6] based on Coulomb-nuclear interference. Recently A_N measurements were repeated with much higher statistics than those mentioned above.

SINGLE-SPIN ASYMMETRY IN $p^{\uparrow}p \to \pi^{\circ}X$ AND $\bar{p}^{\uparrow}p \to \pi^{\circ}X$ AT HIGH $p_{\perp}$

This experiment is recently completed at incident proton momentum of 200 GeV/c. Preliminary data of the $p^{\uparrow}p$ reaction show that the asymmetry values (A_N) at $x_F \approx 0$ are approximately zero (or small negative) up to $p_{\perp}$ = 3.5 GeV/c and then begin to rise to ~ + 40% in the region of $p_{\perp}$ = 4 to 5 GeV/c as shown in Fig. 2. At lower energies as seen in the BNL[7] ($p^{\uparrow}p \to \pi^{+}X$), CERN[8] ($pp^{\uparrow} \to \pi^{\circ}X$),

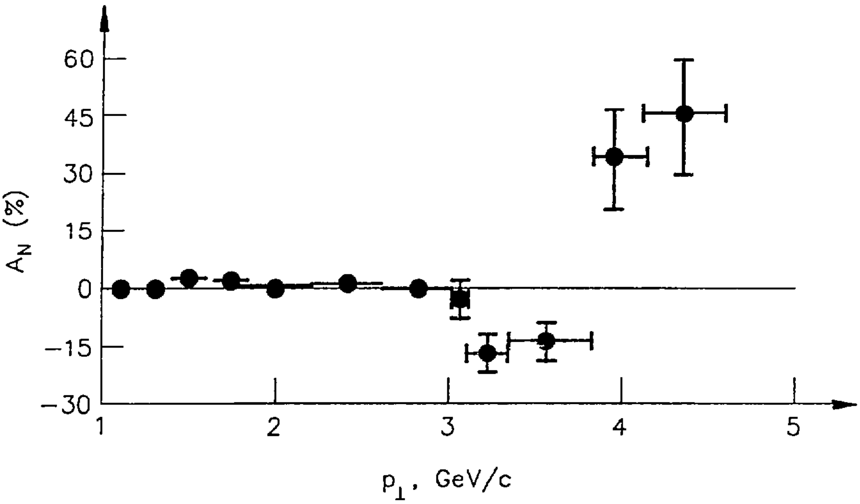

Figure 2 $p_{\perp}$ dependence of A_N at $x_F \approx 0$ (preliminary data).

Serpukhov[9] ($\pi^{-}p^{\uparrow} \to \pi^{\circ}X$) data, this rapid rise from zero to large positive values,* was also observed as shown in Fig. 3 although none of the data exceeded $p_{\perp}$ = 3 GeV/c. A new finding is that all the A_N data of π° or π^{+} production at $x_F \approx 0$ show the large positive asymmetries begin at $x_{\perp}$ = 0.4 in the region $\sqrt{s}$ = 5 to 20 GeV as shown in Fig. 4.

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* Data taken with polarized targets (Refs. 8 and 9) are normalized to the measurements with polarized beams, that is, the sign of A_N ($hp^{\uparrow} \to hX$, where h represents hadron) is reversed. Note that A_N ($p^{\uparrow}h \to hX$) = $-A_N$ ($hp^{\uparrow} \to hX$) at $x_F \approx 0$.

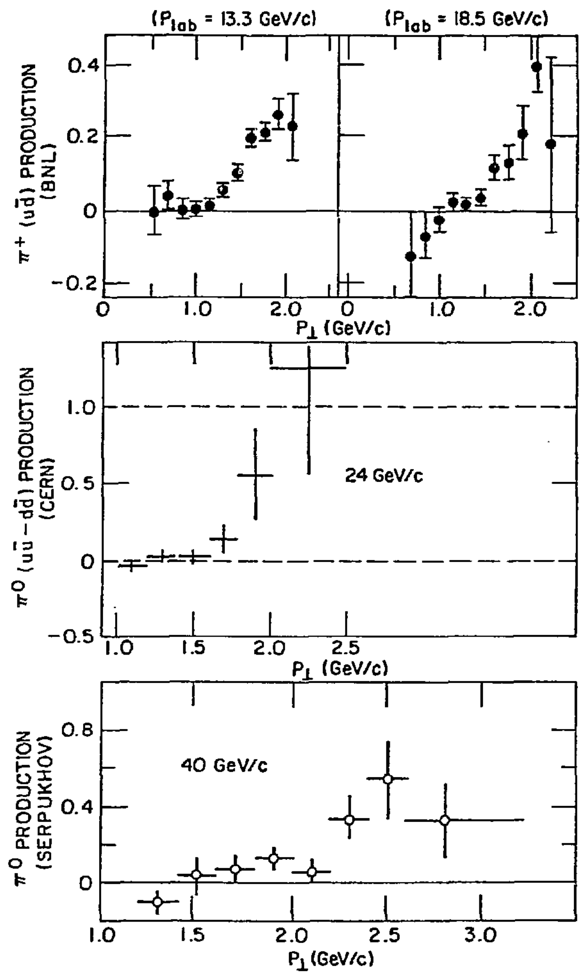

Figure 3 Asymmetry A_N(%) vs. $p_\perp$ at p_{lab} = 1.33 to 40 GeV/c

This is strong indication that we are indeed observing asymmetries caused by hard scattering. We note that the common crossing point $x_\perp = 0.4$ was pointed out in the Ref. 9 in the region $\sqrt{s}$ = 5 to 8.5 GeV/c. Theoretically single-spin asymmetries are discussed within the context of the QCD hard-scattering model.[10] By knowing the quark content of $\pi^+ = u\bar{d}$ and $\pi^\circ = (u\bar{u} - d\bar{d})/\sqrt{2}$, polarized u quark in the polarized proton beam is considered to be the career of the spin information.

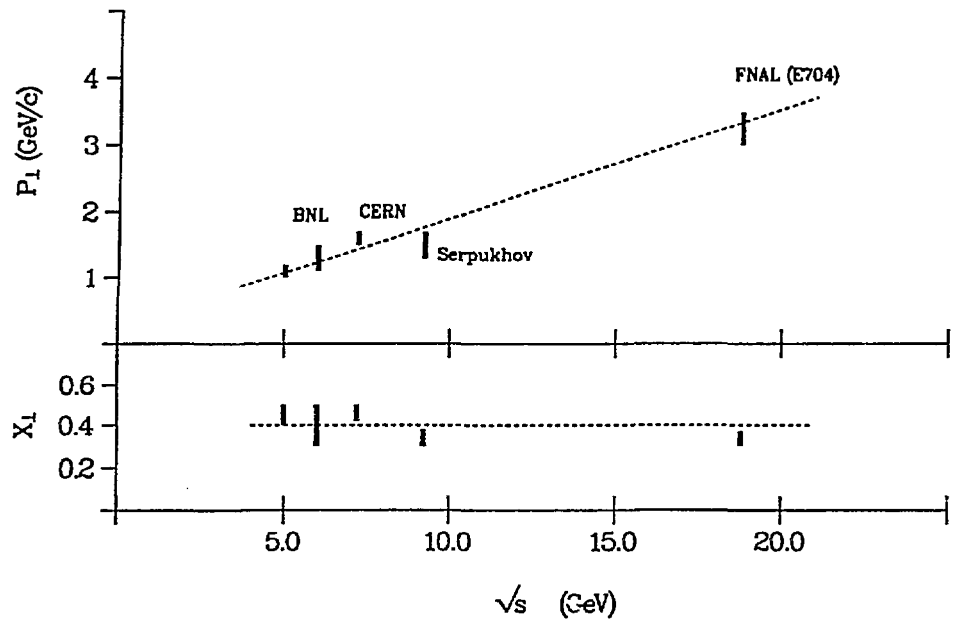

Figure 4 Onset of structure in A_N vs. $\sqrt{s}$.

Single-spin asymmetry in $\bar{p}^{\uparrow}p \to \pi^0 X$ shows a similar $p_\perp$ dependendce as the $p^{\uparrow}p$ case. However, data are limited only up to $p_\perp = 3.5$ GeV/c.

x_F DEPENDENCE OF SINGLE-SPIN ASYMMETRY IN $p^{\uparrow}p \to \pi^\circ X$ AND $\bar{p}^{\uparrow}p \to \pi^\circ X$

Measurements on the x_F dependence at 200 GeV/c covering $p_\perp$ up to 2 GeV/c were recently completed. Asymmetry values in the $p^{\uparrow}p$ reaction are consistent with zero up to $x_F = 0.3$ to 0.4, and then linearly increase to + 20% near $x_F = 1.0$ as shown in Fig. 5. The data suggest an influence of polarized u quarks at large x_F. Also they are consistent with earlier data[11] taken at $\langle x_F \rangle = 0.52$. This is the first x_F dependence data ever obtained in the π production. It is interesting to notice that our data resembled x_F dependence for Λ polarization in $pp \to \Lambda^{\uparrow}X$ where polarized s quarks were considered[12] to be responsible for high polarization.

Single-spin asymmetry in $\bar{p}^{\uparrow}$ $p \to \pi^\circ X$ shows a similar x_F dependence as $p^{\uparrow}p$ case.

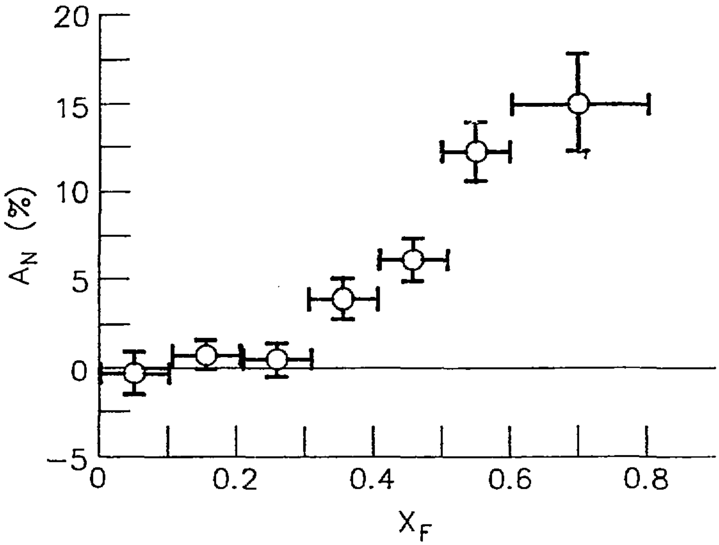

Figure 5

x_F dependence of A_N at $p_\perp$ = 0.5 to 2.0 GeV/c (preliminary data).

A SHORT SUMMARY ON $x_\perp$ AND x_F DEPENDENCE

There are two distinct common phenomena observed in the $x_\perp$ and x_F dependence of the one-spin asymmetries. The asymmetry values are zero or small for both $x_\perp$ and x_F < 0.3 to 0.4. Then there is a rise from zero to large positive values for $x_\perp$ and x_F > 0.3 to 0.4. It will be interesting to find out if these two phenomena are related. One strong hint is that polarized u quarks seem responsible to the rise in A_N at high $x_\perp$ and high x_F. It is interesting to investigate if these phenomena may be related to the origin of proton spin. High-$p_\perp$ and high -x_F scattering phenomena were interpreted as an indication for the existence of rotating color charges in polarized protons.[13]

$\Delta\sigma_L$ (pp and $\bar{p}$p), AND DOUBLE-SPIN ASYMMETRY IN $p^{\uparrow}p^{\uparrow} \rightarrow \pi^{\circ}X$ AND $\bar{p}^{\uparrow}p^{\uparrow} \rightarrow \pi^{\circ}X$

Difference in total cross sections for pure spin states, $\Delta\sigma_L$ (pp and $\bar{p}$p), was simultaneously measured at 200 GeV/c with the π° production up to $p_\perp$ = 3 GeV/c. Data are currently being analyzed.

$\pi^{\pm}$ AND HYPERON PRODUCTION ON HYDROGEN TARGET WITH POLARIZED BEAM

Measurements of $p^{\uparrow}p \rightarrow (\pi^{\pm}, \Lambda^{\circ}, \Sigma^{\circ}) + X$ at 200 GeV/c were completed and data are currently being analyzed.

FUTURE EXPERIMENTS

We have proposed the following simultaneous measurements using a polarized beam and a polarized target.

i) Spin dependence in direct-gamma production at high $p_\perp$.

To understand the basic question of the origin of proton spin, we may be able to determine the gluon spin distribution in the proton by measuring the spin correlation parameter A_{LL} in the direct-γ production at high $p_\perp$, with longitudinally polarized protons on longitudinally polarized target nucleons.

$$A_{LL} = (1/P_B P_T) \frac{N(\overset{\rightarrow}{\rightarrow}) - N(\overset{\leftarrow}{\rightarrow})}{N(\underset{\rightarrow}{\rightarrow}) + N(\underset{\rightarrow}{\leftarrow})} ,$$

where P_B is beam polarization, P_T is target polarization, and arrows indicate the spin direction in the laboratory system.

The QCD Compton effect, "gluon + quark → gamma + quark", is expected to be the dominant mechanism for direct-γ production at large $p_\perp$. The parameter A_{LL} is approximately proportional to the gluon polarization.[14,15]

Our plan is to carry out the A_{LL} measurements up to $p_\perp = 5$ GeV/c with reasonable statistical accuracy. Our main detectors consist of lead-glass counters and proportional wire chambers.

ii) Spin dependence of $\chi 2$ (3555) production.

We plan to measure the spin dependence of $\chi 2$ (3555) production, which will be simultaneously carried out with the above mentioned direct-gamma measurements. The double-spin asymmetry, A_{LL}, in $p^\uparrow p^\uparrow \rightarrow \chi 2$ (3555) $\rightarrow J/\psi + \gamma$ is also expected to provide a means to study the spin dependent gluon structure function. The 15% decay branching ratio of $\chi 2$ (3555) to $J/\psi + \gamma$ allows us to analyze the helicity of the charmonium state.

There is general agreement[16] theoretically that the $\chi 2$ (3555) state is mainly produced by gluon-gluon fusion as shown below and there are promising experimental results[17] suggesting that simple gluon fusion is sufficient to account for the $\chi 2$ (3555) production in proton interactions at 200 and 250 GeV/c. The measured two-spin asymmetries (as defined below) give information on the initial gluon polarization, which can be used to reconstruct the gluon spin distribution in the polarized proton.[18] By considering the fusion process, if the initial helicity state is (+-), that is $(\overset{\leftarrow}{\rightarrow})$, the $J_z = 2$ and this state produces $\chi 2$.

To be exact, the observable A_{LL} is related to the distribution function of a polarized gluon in a polarized proton expressed as $G_+(x)$ and $G_-(x)$ with same- and opposite-sign helicities respectively.[18]

$$A_{LL}(x_F) = (1-R)/(1+R)\left[\frac{\Delta G}{G}(x_1)\cdot\frac{\Delta G}{G}(x_2)\right],$$

where x_1, x_2, and x_F are the longitudinal-momentum fraction of gluons, R is the ratio of matrix elements f_+ (f_-) which are the squared matrix elements for the production of $\chi2$ out of two gluons with same- (opposite-) sign helicities, and $\Delta G/G\,(x) \equiv (G_+(x) - G_-(x))/(G_+(x) + G_-(x))$.

Theoretical predictions were recently made on A_{LL} (x_F) in both the J/ψ and χ production based on a perturbative QCD approach.[19,20]

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