Fermi National Accelerator Laboratory

FERMILAB-Pub-91/14-E
[E-581/E-704]

High-x_t Single-Spin Asymmetry in π^0 and η Production at $x_F = 0$ by 200-GeV Polarized Antiprotons and Protons *

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P.O. Box 500
Batavia, Illinois 60510

January 7, 1991

* Submitted to *Phys. Rev. Lett.*

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

High-x_t Single-Spin Asymmetry in π^0 and η Production at x_F = 0 by 200-GeV Polarized Antiprotons and Protons*

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Abstract

The single-spin asymmetry A_N in inclusive π^0 production at $x_F = 0$ by 200-GeV transversely-polarized protons on a liquid hydrogen target shows the transition of the production process from a "low-x_t" regime with $A_N = 0$ to a "high-x_t" regime with $A_N > 0.3$. The transition, with an intermediate region of negative asymmetry, occurs at $x_t = 0.4$ and is consistent with x_t-scaling of A_N in pion production with polarized beams or targets from $s^{1/2} = 5.2$ to 19.4 GeV. We also present results for A_N in η production and in π^0 production by antiprotons.

We have measured the single-spin asymmetry A_N, the left-right asymmetry of the production cross sections, in inclusive π^0 and η production at $x_F = 0$ by 200-GeV vertically-polarized protons and antiprotons incident on a liquid hydrogen target. The measurements were carried out in the Fermilab polarized proton (antiproton) beam[1] arising from lambda (antilambda) decays. The incident beam and the 100-cm liquid hydrogen target were the same as used for the measurements of Refs. 2 and 3.

Photons from the decay of neutral mesons produced in the target are detected in the "Central Electromagnetic Calorimeters" CEMC-1 and CEMC-2, shown in Fig.1, located symmetrically to the left and to the right of the beam axis at 10 m from the target. Each calorimeter is comprised of 504 lead-glass counters in an array of 21 columns by 24 rows. The dimensions of each lead-glass block are 3.81 cm x 3.81 cm x 18 radiation lengths. Each array covers polar angles of $(5.5 \pm 2.2)^o$ in the laboratory frame, where 5.5^o corresponds to 90^o in the C.M., and azimuthal angles of $\pm 25^o$ with respect to the horizontal plane containing the beam axis. Details on the CEMC detectors and on the "high-p_t" π^0 event triggers are given in Ref. 4.

A total of 2×10^7 events was recorded with incident protons. The fraction of empty target background triggers was close to 10 %. A total of 2×10^6 events was recorded with incident antiprotons.

All combinations of photon pairs satisfying the following conditions were selected as π^0 or η candidates:

(1) The energy asymmetry $|E_1 - E_2| / (E_1 + E_2)$ between the two shower was less than 0.8 for π^0s and less than 0.6 for ηs;

(2) Both photons were contained within a distance of more than one counter width from the edge of the calorimeter;

(3) The two-photon invariant mass was between 80 and 200 MeV/c^2 for π^0s and between 500 and 700 MeV/c^2 for ηs;

(4) The transverse momentum p_t of the π^0 or η was 0.3 GeV/c above the trigger threshold (to avoid trigger bias);

(5) The x_F value was between -0.1 and 0.1.

The analysis yielded 930,000 π^0 events and 10,600 η events satisfying these conditions, produced by beam protons tagged with average polarizations[5,6] of +45 % or -45 %, and an approximately equal number produced by protons tagged with average polarization of zero. The analysis of the events produced by polarized antiprotons yielded 170,000 π^0s.

The two-photon invariant-mass distributions for π^0s produced by protons, given in Fig.2(a), and by antiprotons, in Fig.2(b), show that the mass resolution is ±5% as expected from the calibration with 30 GeV positrons. The background under the π^0 peaks decreases from 15 % at low p_t to 5 % at higher p_t. The η peaks in the two-photon invariant-mass distributions are shown in Fig.2(c). The mass distributions from CEMC1 and CEMC2 are identical, demonstrating that the absolute calibrations and the energy resolutions were the same for the two detectors.

In principle, one of the CEMC detectors, one of the two polarized parts of the beam, and polarization reversal by the spin-rotating magnets in the beam line are sufficient to determine the asymmetries. The two parts of the beam with opposite polarizations and the left-right symmetric detector apparatus represent two levels of redundancy. Consistency among the four possible methods to calculate the asymmetry provides a check of instrumental errors specific to each method. Furthermore, we calculate the false asymmetry for the events tagged with average beam polarization of zero as described in Ref. 2. Possible false asymmetries are estimated to be less than $\Delta A_N = 0.03$ at the largest p_t values and less than $\Delta A_N = 0.01$ at $p_t < 3$ GeV/c. The relative systematic error proportional to A_N is estimated to be 10 % and is due principally to the uncertainty in the beam polarization. A small contribution comes from possible errors in subtracting the background in the two-photon invariant-mass distributions, due to uncorrelated photon pairs and neutral mesons produced outside the target volume.

The results for A_N as a function of p_t in π^0 production by protons are presented in Table I and Fig.3(a). Only the statistical errors are shown. The "false asymmetry" shown in Fig.3(b) is representative of the systematic errors.

The results for A_N are consistent with zero up to p_t = 3.1 GeV/c. In the p_t interval from 3.1 to 3.8 GeV/c, the values are negative, with $A_N = -0.13 \pm 0.03$. At $p_t > 3.8$ GeV/c, we observe a large positive asymmetry of $A_N = 0.37 \pm 0.09$. At the highest p_t values attained in this experiment, protons polarized vertically-upward produce more than twice as many π^0s to the left as to the right. The transition from the low-p_t regime with zero asymmetry to a different regime with large positive asymmetry involves an intermediate region with a negative asymmetry.

The possible origin of single-spin asymmetries in pion production has been discussed in a variety of theoretical approaches and a recent review is given in Ref. 7. In Ref. 8, the effect has been interpreted as a manifestation of the gluon polarization. In Ref. 9, a prediction using a Lund-type model states that the asymmetry at large p_t should be proportional to the slope of the inclusive differential cross section as a function of p_t. According to Ref. 10, an asymmetry in the transverse-momentum distributions, due to orbital angular momentum of the constituents in a polarized proton, is the possible origin of the single-spin asymmetries A_N. An alternate suggestion in Ref. 11 invokes transverse forces that are generated when rotating color charges in the spinning proton interact with the gluon field of the target. As yet, no explanation has been formulated for the p_t-dependence of A_N at $p_t > 3$ GeV/c observed in the present experiment.

The data for A_N in π^0 production by polarized antiprotons are given in Table II and Fig.4(a). Small asymmetries are found in the "low p_t" region, with an indication for a possible negative asymmetry in the transition region.

The results for A_N in η production by protons are given in Table III and Fig.4(b). At the lower transverse momenta, we observe again small values for A_N. In the region $3.5 < p_t < 5$ GeV/c, the data do not exclude a possible change from negative to positive asymmetries, as found for π^0 production.

The data for π^0 production by antiprotons at $p_t > 3.2$ GeV/c and for η production at $p_t > 3.5$ GeV/c have large statistical errors. These three data points do not exclude identical asymmetries for π^0s produced by antiprotons and by protons (charge conjugation of beam and produced particle), and also identical asymmetries for η and π^0s ($u\text{-}\bar{u}$) states), as had been observed in production by 40-GeV negative pions on a polarized proton target[12].

We now compare the present results for the p_t dependence of A_N in π^0 production by 200-GeV polarized protons with the results from four previous measurements of inclusive pion production at $x_F = 0$ and $p_t < 3$ GeV/c, with transversely-polarized proton targets or beams at energies from 13 to 40 GeV. The Brookhaven experiment[13] had studied π^+ production at 13.3 GeV and 18.5 GeV with the AGS polarized proton beam incident on an unpolarized target. The CERN-PS[14] and Serpukhov[15] experiments had measured π^0 production on polarized proton targets by 24-GeV protons and 40-GeV negative pions, respectively. In all of these experiments the asymmetry was small at low p_t and then rose to relatively large positive values. A positive sign of A_N corresponds to a larger production cross-section to the beam-left (beam-right) when the beam (target) proton spin is vertically-upward. The similarity between π^+ and π^0 production asymmetries may be expected considering that both involve valence u-quark scattering[12]. It had been noticed[15,16] that, at energies from 13.3 to 40 GeV, the rise of A_N to large positive values ocurred at a fixed value of the transverse scaling variable $x_t = 0.4$. The present experiment establishes that this x_t-scaling behavior of A_N is a high energy phenomenon. Also, the magnitude of A_N at large x_t is of the same order as that at the lower energies. The onset of the rise shown in Fig.5 is defined by the p_t value where a linear fit to the data with positive asymmetry extrapolates back to $A_N = 0$. At 200 GeV, this corresponds to a change from negative asymmetries at about $0.32 < x_t < 0.4$ to positive values at higher x_t. At 13.3, 18.5 and 24 GeV, the data below $x_t \approx 0.35$ are consistent with $A_N = 0$ within the statistical errors. The data at 40 GeV show some indication[17] that the onset of the rise corresponds to a change of sign, as at 200 GeV.

The cross sections for inclusive π^0 and π^+ production at $x_F = 0$ in different reactions and in a wide range of energies depend in a similar way on the transverse spin state of the beam or target proton when the pion is produced at sufficiently large p_t. The kinematical region where this effect appears is characterized at all energies by the transverse scaling variable x_t, as would be expected for parton scattering. On the other hand, the existence of a nonzero single-spin asymmetry A_N by itself had been presented as evidence against parton scattering, since $\hat{A}_N = 0$ for parton 2 => 2 interactions in lowest-order perturbative QCD. This argument assumes that the only possible origin of hadronic asymmetries is the spin dependence of the parton scattering amplitudes, but alternate origins such as transverse momentum asymmetry[10] would invalidate this argument. Because of the x_t-scaling behavior of A_N, one may ask if other data, in particular the spin-averaged cross sections for inclusive π^0 and π^+ production, also show evidence for parton scattering processes at $x_F > 0.4$.

In summary, the p_t dependence of A_N for inclusive π^0 production at $x_F = 0$ presented here shows a transition at $x_t = 0.4$ from a "low x_t" regime with zero or small asymmetries to a new regime with large asymmetries. The compiled data for $5.2 < s^{1/2} < 19.4$ Gev suggest a mechanism that depends neither on s nor on p_t, but on x_t since the onset of a rise to large positive values of A_N occurs at $x_t \approx 0.4$ for all energies. The results reported here show that for the "hardest" interaction at the highest energy attained to date in a spin experiment, the invariant π^0 production cross sections for opposite beam transverse-spin states differ by a factor of two or more. This large single-spin effect is observed at $s^{1/2} = 19.4$ GeV and at $p_t = 4.5$ GeV/c. The lowest-order PQCD-amplitudes for parton scattering do not generate single-spin asymmetries. Several theoretical approaches have been proposed to reconcile the experimental situation with QCD. The literature on this subject demonstrates the general difficulty for the parton picture to describe transverse spin, as compared to helicity.

We would like to acknowledge useful discussions of theoretical issues with colleagues at our respective institutions. We gratefully acknowledge the assistance of the staff of Fermilab and of all the participating institutions. This research was supported by the U.S.S.R. Ministry of Atomic Power and Industry, the Ministry of Education, Science, and, Culture in Japan, the U.S. Department of Energy, the Commissariat a l'Energie Atomique and the Institut de Physique Nucleaire et de Physique des Particules in France, and the Istituto di Fisica Nucleare in Italy.

* This work was performed at the Fermi National Accelerator Laboratory, which is operated by University Research Assocoiates, Inc., under contract DE-AC02-76CH03000 with the U.S. Department of Energy.

Work supported in part by the U.S. Department of Energy, Division of High Energy Physics, Contracts W-31-109-ENG-38, W-7405-ENG-36, DE-AC02-76ER02289, DE-AS05-76ER05096.

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FIGURE CAPTIONS

Fig.1 Layout of the experimental apparatus.

Fig.2 The two-photon invariant-mass distributions for π^0 production by (a) protons and (b) antiprotons, and (c) for η production by protons, for different regions of p_t.

Fig.3(a) The asymmetry parameter A_N in the reaction $P + P \Rightarrow \pi^0 + X$ at 200 GeV as a function of p_t at $x_F = 0$. The dotted line is added to guide the eye. $\sigma\uparrow / \sigma\downarrow$ is the ratio of the π^0 production cross sections for opposite beam spins.

Fig.3(b) The "false asymmetry" calculated for events with average beam polarization of zero, as a function of p_t at $x_F = 0$.

Fig.4 The asymmetry parameter A_N as a function of p_t at $x_F = 0$ for the reactions (a) $P + P \Rightarrow \pi^0 + X$ and (b) $P + P \Rightarrow \eta + X$ at 200 GeV. $\sigma\uparrow / \sigma\downarrow$ is the ratio of the π^0 production cross sections for opposite beam spins.

Fig.5 Plot of the onset of the rise of A_N to large positive values (closed circles) for different C.M. energies, showing data from this experiment and from the previous experiments (see Refs. 13, 14, and 15) at lower energies.

TABLE I. The asymmetry parameter A_N for inclusive π^0 production by 200-GeV polarized protons measured in the reaction, $p\uparrow + p \rightarrow \pi^0 + X$, as a function of p_T for $x_F \approx 0$.

p_T (GeV/c)	$\langle p_T \rangle$ (GeV/c)	A_N (%)	No. π^0 Events
1.0 – 1.2	1.05	0.3 ± 0.5	
1.2 – 1.4	1.25	0.3 ± 0.6	
1.4 – 1.6	1.45	0.4 ± 0.6	750 000
1.6 – 1.8	1.65	0.7 ± 0.7	
1.8 – 2.0	1.85	−0.6 ± 0.8	
2.0 – 2.2	2.05	−1.6 ± 0.9	
2.2 – 2.4	2.25	−0.7 ± 1.3	
2.4 – 2.6	2.45	2.5 ± 1.8	175 000
2.6 – 2.8	2.65	−1.2 ± 2.5	
2.8 – 3.1	2.88	−1 ± 3	
3.1 – 3.3	3.15	−10 ± 4	
3.3 – 3.5	3.35	−17 ± 6	4 500
3.5 – 3.8	3.58	−15 ± 7	
3.8 – 4.1	3.88	34 ± 11	
4.1 – 4.6	4.23	44 ± 18	500
3.1 – 3.8	3.28	−13 ± 3	
3.8 – 4.6	4.00	37 ± 9	

TABLE II. The asymmetry parameter A_N for inclusive π^0 production by 200-GeV polarized antiprotons measured in the reaction, $\overline{p}\uparrow + p \rightarrow \pi^0 + X$, as a function of p_T for $x_F \approx 0$.

p_T (GeV/c)	A_N (%)	No. π^0 Events
1.0 − 1.2	0.0 ± 1.0	
1.2 − 1.4	1.0 ± 1.2	
1.4 − 1.6	−0.7 ± 1.3	158 000
1.6 − 1.8	−1.2 ± 1.6	
1.8 − 2.0	−0.6 ± 2.2	
2.0 − 2.2	−5.2 ± 3.2	
2.2 − 2.6	−6.5 ± 3.6	11 000
2.6 − 3.2	−2.4 ± 5.8	
3.2 − 3.8	−32 ± 18	150

TABLE III. The asymmetry parameter A_N for inclusive η production by 200-GeV polarized protons measured in the reaction, $p\uparrow + p \rightarrow \eta + X$, as a function of p_T for $x_F \approx 0$.

p_T (GeV/c)	A_N (%)	No. η Events
2.3 – 2.6	−2 ± 5	6 350
2.6 – 3.0	−3 ± 7	2 950
3.0 – 3.5	−3 ± 9	950
3.5 – 4.0	−30 ± 14	260
4.0 – 5.0	56 ± 22	90

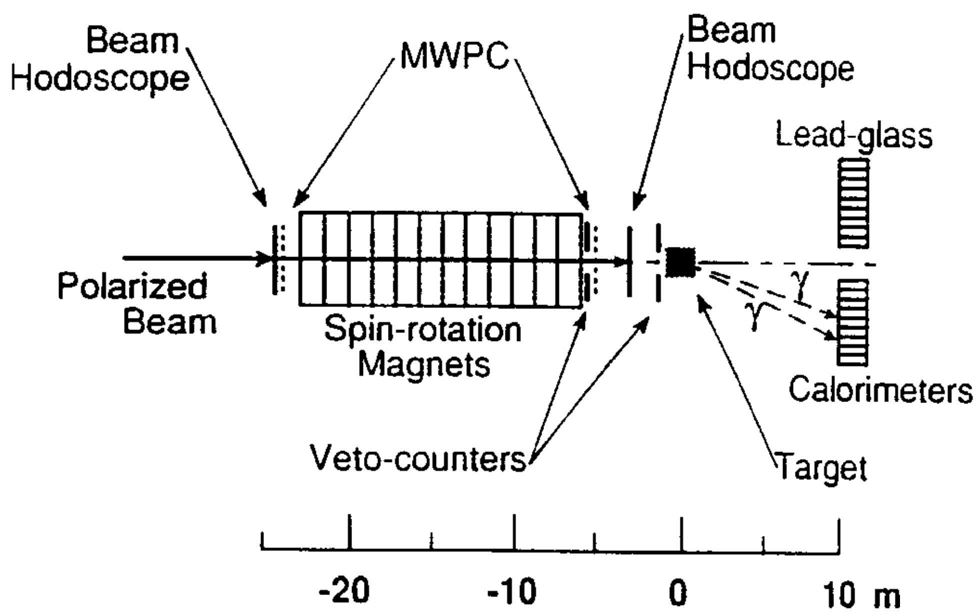

Beam
Hodoscope
MWPC
Beam
Hodoscope
Lead-glass
Polarized
Beam
Spin-rotation
Magnets
γ
γ
Calorimeters
Veto-counters
Target
-20
-10
0
10 m

Figure 1

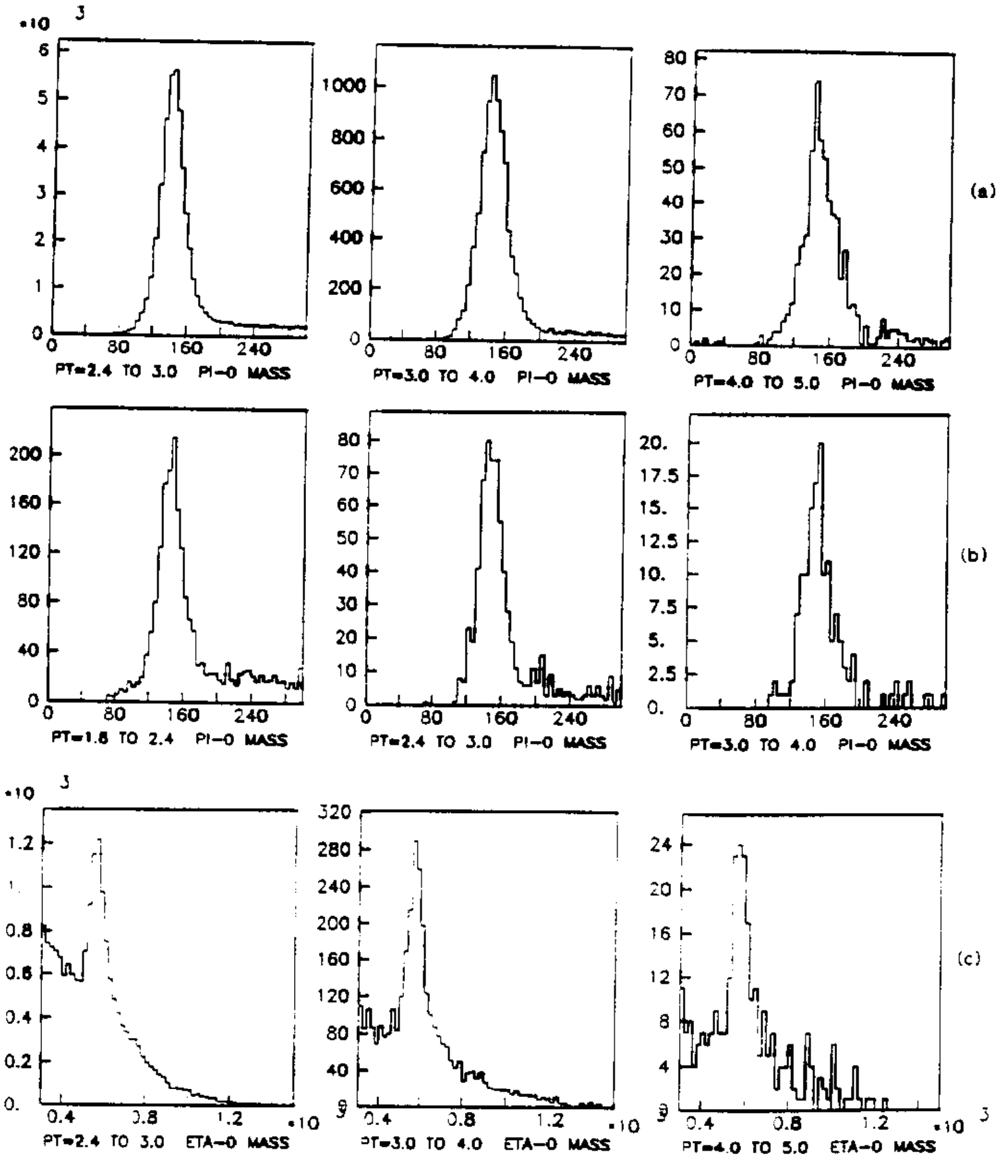

(a)
(b)
(c)
PT=2.4 TO 3.0 PI-0 MASS
PT=3.0 TO 4.0 PI-0 MASS
PT=4.0 TO 5.0 PI-0 MASS
PT=1.8 TO 2.4 PI-0 MASS
PT=2.4 TO 3.0 PI-0 MASS
PT=3.0 TO 4.0 PI-0 MASS
PT=2.4 TO 3.0 ETA-0 MASS
PT=3.0 TO 4.0 ETA-0 MASS
PT=4.0 TO 5.0 ETA-0 MASS

Figure 2

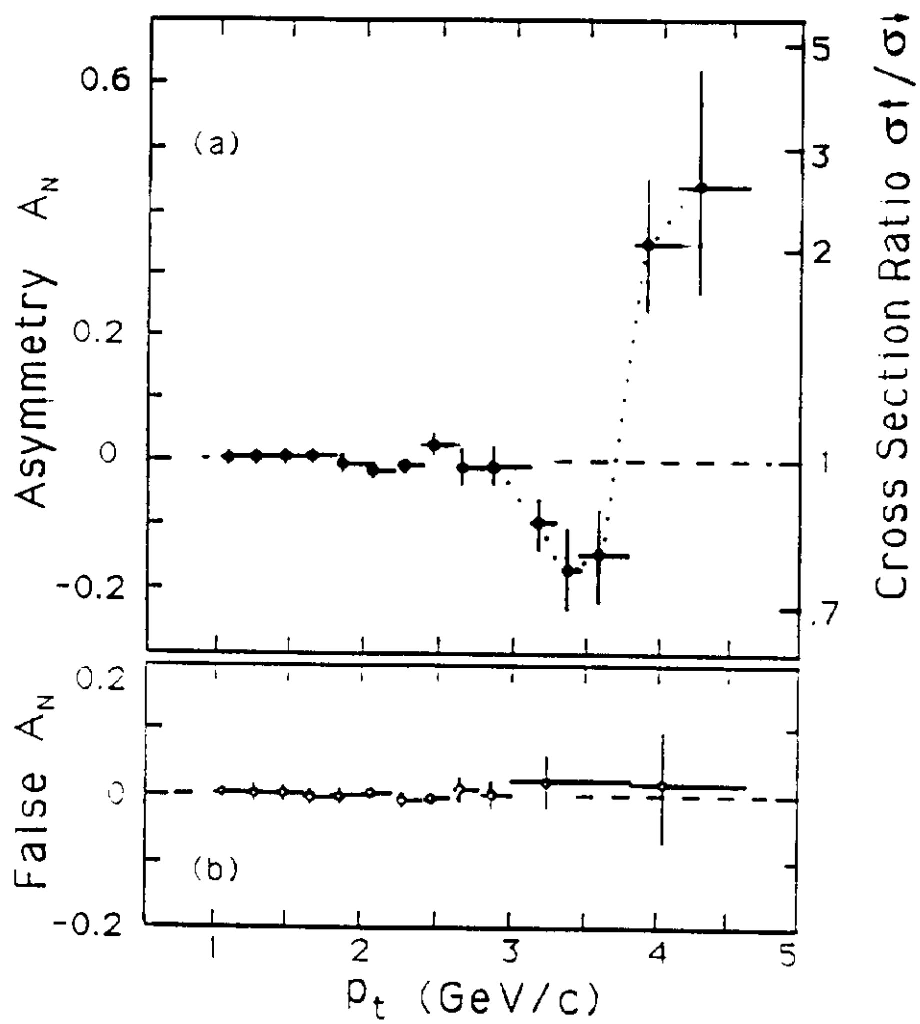
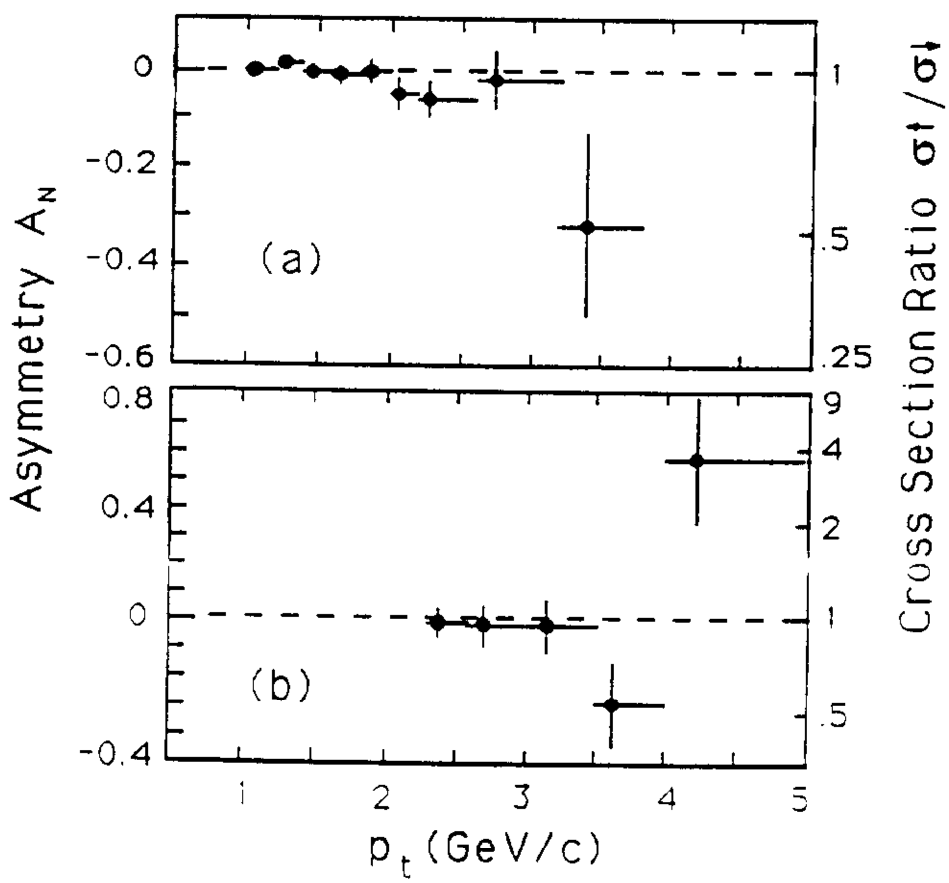
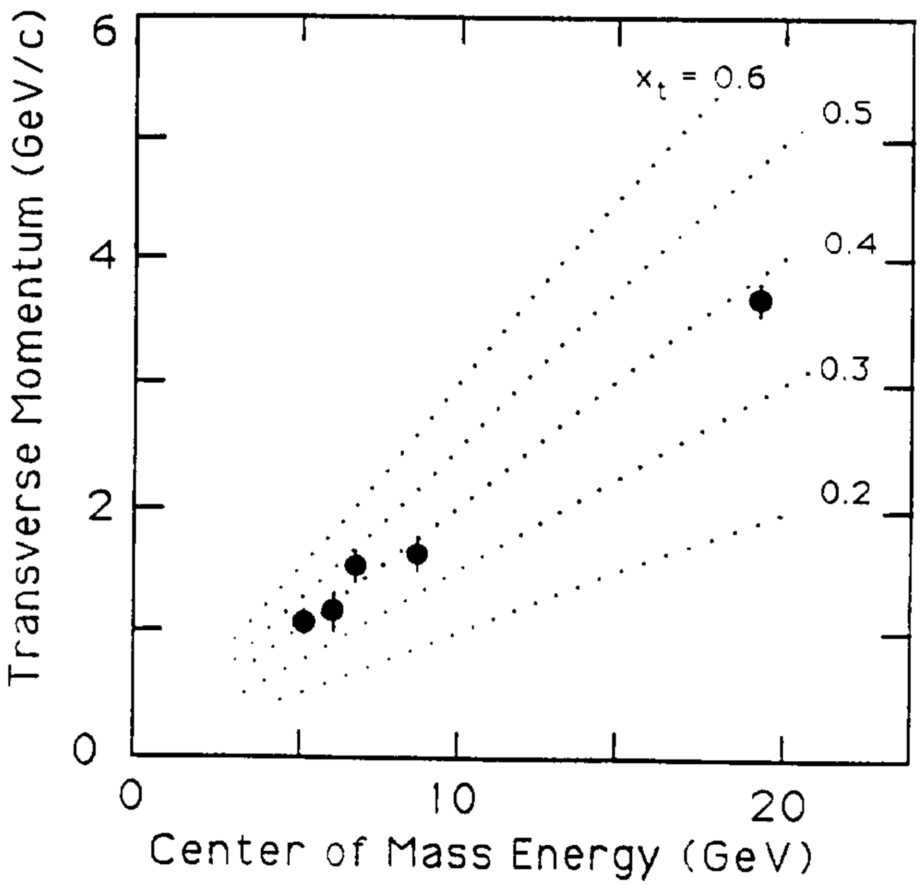

(a)
(b)
Asymmetry A_N
False A_N
Cross Section Ratio σ↑/σ↓
p_t (GeV/c)
0.6
0.2
0
-0.2
5
3
2
1
.7
1
2
3
4
5

Figure 3



Asymmetry A_N
Cross Section Ratio $\sigma\uparrow/\sigma\downarrow$
(a)
(b)
0
-0.2
-0.4
-0.6
0.8
0.4
0
-0.4
1
.5
.25
9
4
2
1
.5
1
2
3
4
5
p_t (GeV/c)

Figure 4



Transverse Momentum (GeV/c)
0
2
4
6
0
10
20
Center of Mass Energy (GeV)
x_t = 0.6
0.5
0.4
0.3
0.2

Figure 5