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Further Evidence for Pomeron-Quark Interactions: Observation of Large Λ^0 Polarization in $pp \rightarrow (\Lambda^0 K^+)p$

(R608 Collaboration)

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Abstract

We report an analysis of the diffractive reaction $pp \rightarrow (\Lambda^0 K^+)p$, measured at $\sqrt{s} = 63$ GeV in an open geometry forward spectrometer experiment at the CERN Intersecting Storage Rings. In the rest frame of the $(\Lambda^0 K^+)$ system, which has nearly the beam momentum of 31.4 GeV, the Λ^0 is observed to be sharply peaked forward, similar to earlier observations in the reaction $pp \rightarrow (\Lambda^0 \phi^0 K^+)p$, which were interpreted as the first direct evidence for Pomeron-quark interactions. A smaller backward peak is also observed which may be evidence for Pomeron-diquark interactions. The polarization of the Λ^0 increases to more than 60% when the diffractive mass reaches ≈ 2.8 GeV.

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In an earlier Letter[1], the R608 collaboration at the CERN Intersecting Storage Rings presented evidence that the exchanged Pomeron in the exclusive diffractive reaction

$$pp \rightarrow (\Lambda^0 \phi^0 K^+)p \qquad (1)$$

interacts with a single valence quark in the beam proton, leading to a quark-diquark separation and subsequent hadronization (in Reaction 1, the bracketed system emerged along the beam direction with nearly the full beam momentum of 31.4 GeV). This evidence took the form of a striking linear structure of the $\Lambda^0\phi^0K^+$ system in its center of mass. Specifically, the K^+ which contains the interacting u-quark of the beam proton is sharply peaked backwards (with respect to the direction of the incident proton), and the Λ^0 which contains the "spectator" diquark is sharply peaked in the forward direction. The ϕ^0, which contains none of the beam proton valence quarks, remains at rest in the $\Lambda^0\phi^0K^+$ center of mass.

It was noted that this interpretation is in qualitative agreement with the suggestion[2] that the Pomeron couples in a point-like way to individual quarks in a proton (similar to a photon). The results also suggest that, at higher excitation masses, the idea expressed in Refs. [3] is not applicable, namely that the diffractive state exists prior to the interaction as a virtual state which is then realized in the interaction. With such a picture, it would be difficult to understand the observed differences between those final state particles which contain beam proton valence quarks and those that do not.

In the present Letter, we present related results from the same experiment on the diffractive reaction:

$$pp \rightarrow (\Lambda^0 K^+)p \qquad (2)$$

Reaction 2 differs from Reaction 1 in that a single $s\bar{s}$ quark pair is produced in the hadronization of the "stretched" quark-diquark system, compared with the two $s\bar{s}$ pairs produced in Reaction 1.

The larger data sample of more than 10,000 events of Reaction 2 and its relative simplicity compared with Reaction 1 facilitates the study of Λ^0 polarization in some detail. Such polarization is of particular interest for several reasons: (a) the Λ^0 is directly produced in Reaction 2 with negligible background from $\Sigma^* \rightarrow \Lambda\pi$ and a small (controllable) background from $\Sigma^0 \rightarrow \Lambda\gamma$ (these channels dilute inclusively measured Λ^0 polarization); (b) The quark-diquark system, excited in the manner suggested, may allow for a relatively pure realization of the polarization mechanism proposed by Andersson et al.[4]. They have argued that polarization of forward-going Λ^0's is a natural consequence of $s\bar{s}$ pair production in a confining color force field. The characteristic string energy density of 1 GeV/fermi causes the $s\bar{s}$ pair to possess up to one unit of angular momentum, which is balanced by the s and $\bar{s}$ quark spins due to local conservation of angular momentum. Thus, substantially larger Λ^0 polarizations may occur in Reaction 2 than have been observed inclusively in pp interactions. Indeed, in an earlier communication from our group[5], an average Λ^0 polarization of (36 ± 2)% was reported for Reaction 2, compared with the largest inclusively measured Λ^0 polarization[6] of 37%.

The $\Lambda^0 K^+$ system in Reaction 2 enters a forward spectrometer system[7] with its total momentum approximately equal to the beam momentum of 31.4 GeV. During data acquisition, wire chamber hits were used to require a minimum of 3 tracks in the spectrometer. Reaction 2 was selected offline by requiring a (Vee + one track) topology, with the Vee vertex more than 10 cm downstream of the primary vertex. Fig. 1(a) shows the $p\pi^-$ invariant mass, $M(p\pi^-)$, for the Vee's selected in this way. Λ^0's are selected in the interval: $1.106 < M(p\pi^-) < 1.126$ GeV.

A further condition in the data acquisition trigger of Reaction 2 was provided by a set of scintillation counters, some sandwiched with lead, which were used in veto to impose a large rapidity gap between the $\Lambda^0 K^+$ system in the spectrometer (acceptance of ±150 mrad) and the recoiling system in the opposite arm (the veto extended to within 400 mrad of the beam direction in the opposite arm). Although more than two-thirds of the events have a recoil system which is a proton, no attempt was made to detect it since, in soft diffractive processes like Reactions 1 and 2, factorization of the two incident proton interactions results in the properties of the spectrometer system being independent of the identity of the low mass recoiling system[8,10]. Indeed, in the present analysis we find the same polarization properties, but with smaller statistics, when a recoil proton is required (offline) to be collinear with the momentum vector of the tracks in the spectrometer. The absence of a beam-beam interaction signature in the trigger causes negligible background for large cross section processes. The observed multi-track vertex distribution is found to map the beam-beam crossing region and the beam-gas background[8,9] is less than 0.1%.

Fig. 1(b) shows the total momentum of the Λ^0K^+ system, P_{total}, in Reaction 2 for $M(\Lambda K) >$ 2.4 GeV. Simulated P_{total} distributions were generated for the diffractive process $pp \to (\Sigma^0K^+)p \to (\Lambda^0\gamma K^+)p$, where the γ is not seen, and for Reaction 2. A fit was then made to the observed distribution to find the relative amounts of the two processes. The dashed curve in Fig. 1(b) shows the expected shape of background from the Σ^0 reaction and the solid curve shows the sum of the two. It can be seen that the background contribution from the Σ^0K^+ process decreases rapidly with increasing P_{total}. Thus, all further analysis is done with the selection $P_{total} > 31$ GeV, where negligible background remains from the Σ^0 process.

Fig. 1(c) shows the observed distribution of the invariant mass of the diffractive system, $M(\Lambda K)$. Resonance structure is seen in Fig. 1(c) at low mass, although there is none apparent for values above 2.4 GeV or so. The histogram in Fig. 1(c) is a Monte-Carlo simulation of Reaction 2 with events generated according to the parametrization $dN/dM^2 \sim M^{-2}$ and then passed through a software package which simulated the geometrical acceptance and efficiencies of the detector. Although the Monte-Carlo events do not contain the observed resonance structure, they do describe the gross properties of the observed distribution. The losses at low mass in the $M(\Lambda K)$ spectrum in Fig. 1(c) are due to the 23 mrad minimum angle acceptance cut-off of the spectrometer. The fall-off at high mass is dominated by the spectrometer's 150 mrad aperture.

Fig. 1(d) shows the distribution in the squared transverse momentum, P_t^2, to the Λ^0K^+ system for $M(\Lambda K) > 2.4$ GeV. The histogram is for the same Monte-Carlo events used in (c), which also are generated with a simple exponential dependence, $\exp(-4P_t^2)$. Fig. 1(d) shows that there is good acceptance down to $P_t = 0$. This arises because the recoil proton is not detected and because the kinetic energy in the Λ^0K^+ system is sufficient for the particles to be accepted, despite the minimum angle aperture.

Figs. 2(a-c) show the raw (uncorrected) angular distributions of the Λ^0 with respect to the incident beam proton as seen in the (Λ^0K^+) center of mass (Gottfried-Jackson angle Θ), for three ranges of (Λ^0K^+) invariant mass. The histogram on each plot shows the expected shape, if the true distributions were isotropic. A comparison of points and histogram shows that the true distribution is relatively isotropic in the lowest Λ^0K^+ mass region, while a very pronounced forward peak and a weaker backward peak develop with increasing mass. The ratios of the points and histogram values in Figs. 2(a-c) give the corrected distributions shown in Figs. 2(d-f).

The pronounced forward peak for the Λ^0 seen in Fig. 2(f) is similar to that observed[1] for the Λ^0 in Reaction 1, where the effect is interpreted within the framework of the Pomeron exchange model. The Pomeron interacts with a valence u quark and the remaining ud diquark continues in the direction of the beam proton. In the ensuing fragmentation an $s\bar{s}$ pair is created, forming a forward going Λ^0 and a K^+ that moves in the opposite direction. It is interesting to note that the available kinetic energy for the Λ^0 in the highest mass bin in Fig. 2(f), about 1.2 GeV, is very close to that available for the Λ^0 in Reaction 1[1]. Moreover, in the 2-body $\Lambda^0 K^+$ system , cos Θ is equal to Feynman-x_F of the Λ^0 and thus the distribution in Fig. 2(f) may be directly compared with the x_F distribution of Fig. 5 in Ref. [1].

It is quite reasonable to interpret the forward peak of Fig. 2(f) in the same manner as in Ref. 1. The smaller peak observed for backward Λ's in Fig. 2(f) may be evidence for Pomeron-diquark interactions which, from the shape of the distribution in Fig. 2(f) could be as much as a factor of ten weaker than the Pomeron-quark interaction. This interpretation would be consistent with the mounting evidence[11,12] for the significant role of diquarks in high energy interactions.

We turn now to the Λ^0 polarization analysis. In inclusive polarization measurements, the Λ^0 is polarized along the normal to the production plane, $\vec{p}_{beam} \times \vec{p}_\Lambda$. In Reaction 2 a polarization can also be meaningfully defined along $\vec{p}_K \times \vec{p}_\Lambda$ or $\vec{p}_{beam} \times \vec{p}_{\Lambda K}$, where $\vec{p}_{\Lambda K}$ is the total momentum vector of the $\Lambda^0 K^+$ system. We note, however, that because $\vec{p}_{\Lambda K}$ is very nearly parallel to $\vec{p}_{beam}$, all three of these vectors approximately coincide and we therefore use $\vec{p}_{beam} \times \vec{p}_\Lambda$ in our analysis. The polarization, P_Λ, is obtained by fitting the following function to the acceptance corrected decay angular distribution: $dN/d(\cos\theta_p) = 0.5\ (1 + \alpha_\Lambda P_\Lambda \cos\theta_p)$. θ_p is the angle between the proton and the polarization axis in the Λ^0 rest frame and the asymmetry parameter[13], $\alpha_\Lambda = 0.642$.

The Λ polarization (P_Λ) may be measured in Reaction 2 as a function of the longitudinal and transverse momentum of the Λ^0, as was done in Ref. [5], where the acceptance was calculated on a grid in this plane and the procedure was identical to that used in the earlier ISR analyses[6]. However, in order to acceptance-correct an observed distribution in θ_p and measure P_Λ as a function of $M(\Lambda K)$

or Θ, the Monte-Carlo events must model Reaction 2 in all variables, namely P_{total}, P_t, $M(\Lambda K)$, Θ and Φ (the azimuthal angle of Λ^0 in the $\Lambda^0 K^+$ system). Thus the Monte-Carlo events used in Figs. 2 are weighted by the corrected Θ distributions before using them to correct the observed θ_p distributions. There is no detectable dependence on Φ and it is therefore ignored in the analysis.

There are two independent spectrometers, positioned above and below the outgoing beam pipe, which have different acceptance properties. Since their polarization results should agree, there is considerable opportunity for verification of the results. We find average polarizations for Reaction 2 in the lower and upper spectrometers of $(-36.9 \pm 8.3)\%$ and $(-37.6 \pm 7.2)\%$, respectively. There is good agreement between these numbers. The corrected and fitted θ_p distributions are shown in Figs. 3(a,b).

Fig. 4(a) contains the Λ^0 polarization as a function of cos Θ for two bins of diffractive mass. There are two noteworthy effects: (a) P_Λ is significantly larger in magnitude for the higher mass bin; (b) P_Λ depends on Θ. It is positive for $\cos\Theta < -0.5$, becomes negative for $\cos\Theta > -0.5$, reaches a maximum of $(-62 \pm 10)\%$ near $\cos\Theta \approx 0.25$, and decreases again in magnitude for forward going Λ^0's.

In view of the suggestion in Fig. 2(f) that two mechanisms may be contributing to the reaction, Pomeron-quark and Pomeron-diquark interactions, a dependence of P_Λ on Θ of the type observed is not surprising. Combining the languages of Refs. 1 and 4, Fig. 5 illustrates why opposite sign polarization is expected for the forward and backward peaks. In the dominant interaction of a Pomeron with a single quark, the Λ contains the "spectator" ud diquark and continues in the hemisphere of the incident proton. Both s and $\bar{s}$ quark spins are down to balance the orbital angular momentum. Thus the Λ has negative polarization. In the less probable case of a Pomeron-diquark interaction (backward Λ), the same argument leads to positive polarization. In either case, P_Λ is expected to increase with increasing transverse momentum to the Λ^0, as is observed in inclusive measurements[6]. The combination of the two mechanisms could therefore lead to the shape seen in Fig. 4(a). P_Λ is largest in magnitude for $0 < \cos\Theta < +0.5$.

In order to further explore the dependence on $M(\Lambda K)$, Fig. 4(b) shows P_Λ vs. $M(\Lambda K)$ for events with polar angle in the range with largest P_Λ. P_Λ is seen to grow with increasing mass and reaches larger values than have ever been seen in proton-proton interactions. For $2.7 < M(\Lambda K) < 3.0$ GeV,

P_Λ = (62 ± 4)%. Such an increase of P_Λ with M(ΛK) is presumably related to the dynamics of the stretched diquark-quark system. In the language of Ref. [4], higher mass should result in an increased orbital angular momentum of the produced $s\bar{s}$ system and hence larger polarization. It will be very interesting to see if P_Λ increases still further with the much larger values of M(ΛK) which may be accessible in future experiments.

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Figure Captions

1. Raw (uncorrected) distributions: (a) Invariant mass $M(p\pi^-)$ before the Λ^0 selection; (b) Total momentum, P_{total}, of the Λ^0K^+ system for $M(\Lambda K) > 2.4$ GeV (6280 events). Dashed curve in (b) is the background component from diffractive Σ^0K^+ production. Solid curve is the sum of signal and background. (c-d) Invariant Mass, $M(\Lambda K)$, of and squared transverse momentum, P_t^2, to the Λ^0K^+ system when $P_{total} > 31$ GeV (12035 events). Solid histograms in (c,d) are Monte-Carlo events generated according to the parametrization discussed in the text, and passed through detector simulation Monte-Carlo software.
2. Distributions of Λ^0 Gottfried-Jackson angle, Θ, measured in the Λ^0K^+ rest frame with respect to the direction of the incident beam proton for events with $P_{total} > 31$ GeV: (a-c) Points are raw (uncorrected) data for three ranges of $M(\Lambda K)$, 1.7-2.0, 2.0-2.4 and 2.4-3.0 Gev, with 5964, 9060 and 2508 events, respectively. In each case, the histograms are the Monte-Carlo events generated isotropically in Θ and then passed through detector simulation Monte-Carlo software; (d-f) Acceptance corrected versions of (a-c). The solid curve in (f) is a Legendre polynomial fit to the data with $\ell_{max} = 3$.
3. Acceptance corrected Λ^0 decay distribution for Λ^0's with $M(\Lambda K) > 2.6$ GeV and $P_{total} > 31$ GeV; (a) Upper spectrometer, (b) Lower (Down) spectrometer. In each case, θ_p is the angle between the decay proton and the normal to the production plane, $n \approx P_{beam} \times \Lambda^0$. The straight lines are the function: $dn/d(\cos\theta_p) = 0.5\,(1 + \alpha_\Lambda P_\Lambda \cos\theta_p)$ with $P_\Lambda = -37.6\%$ and -36.9%, respectively.
4. Λ^0 polarization when $P_{total} > 31$ GeV: (a) P_Λ vs. Gottfried-Jackson angle of Λ^0 for two ranges of $M(\Lambda K)$; (b) P_Λ vs. $M(\Lambda K)$ for the indicated range of Θ.
5. Diagram showing the two possible outgoing quark and diquark configurations in the Pomeron-proton rest frame, depending on whether the Pomeron has interacted with quark or diquark. In each case the s and $\bar{s}$ spins are pointing into the paper to compensate their orbital angular momentum. As discussed in the text, this leads to negative P_Λ for forward Λ's (along incident p direction) and positive P_Λ for backward Λ's

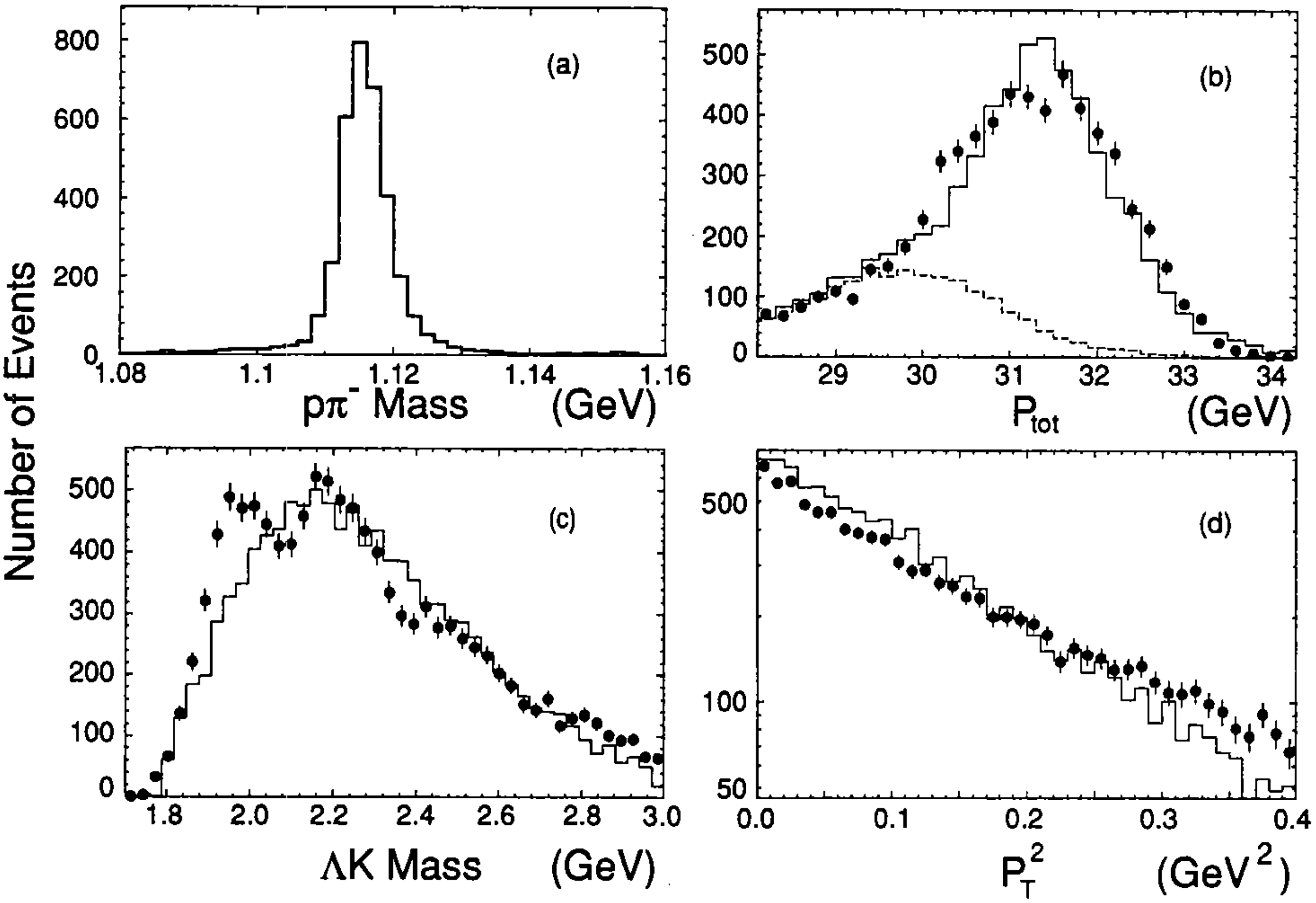

Number of Events
(a)
800
600
400
200
0
1.08
1.1
1.12
1.14
1.16
pπ⁻ Mass (GeV)
(b)
500
400
300
200
100
0
29
30
31
32
33
34
P_tot (GeV)
(c)
500
400
300
200
100
0
1.8
2.0
2.2
2.4
2.6
2.8
3.0
ΛK Mass (GeV)
(d)
500
100
50
0.0
0.1
0.2
0.3
0.4
P_T^2 (GeV^2)

Figure 1

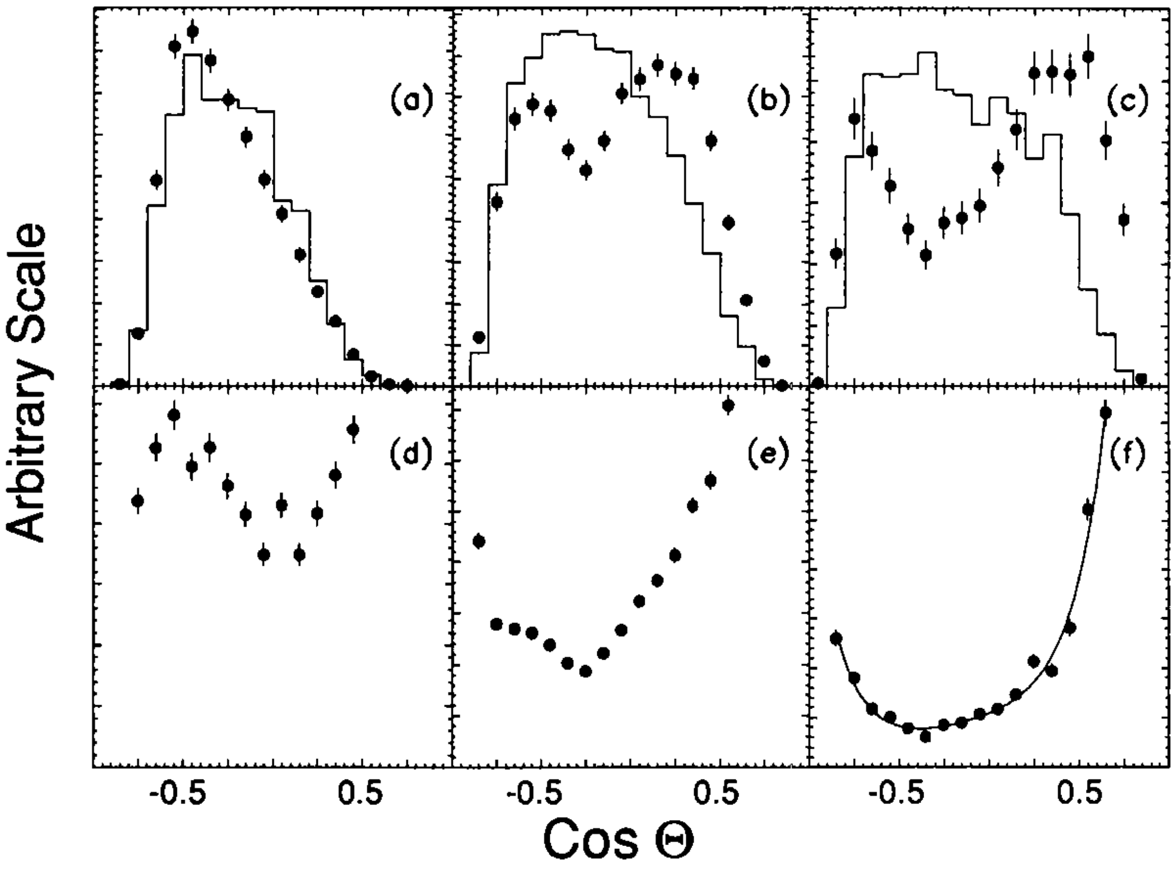
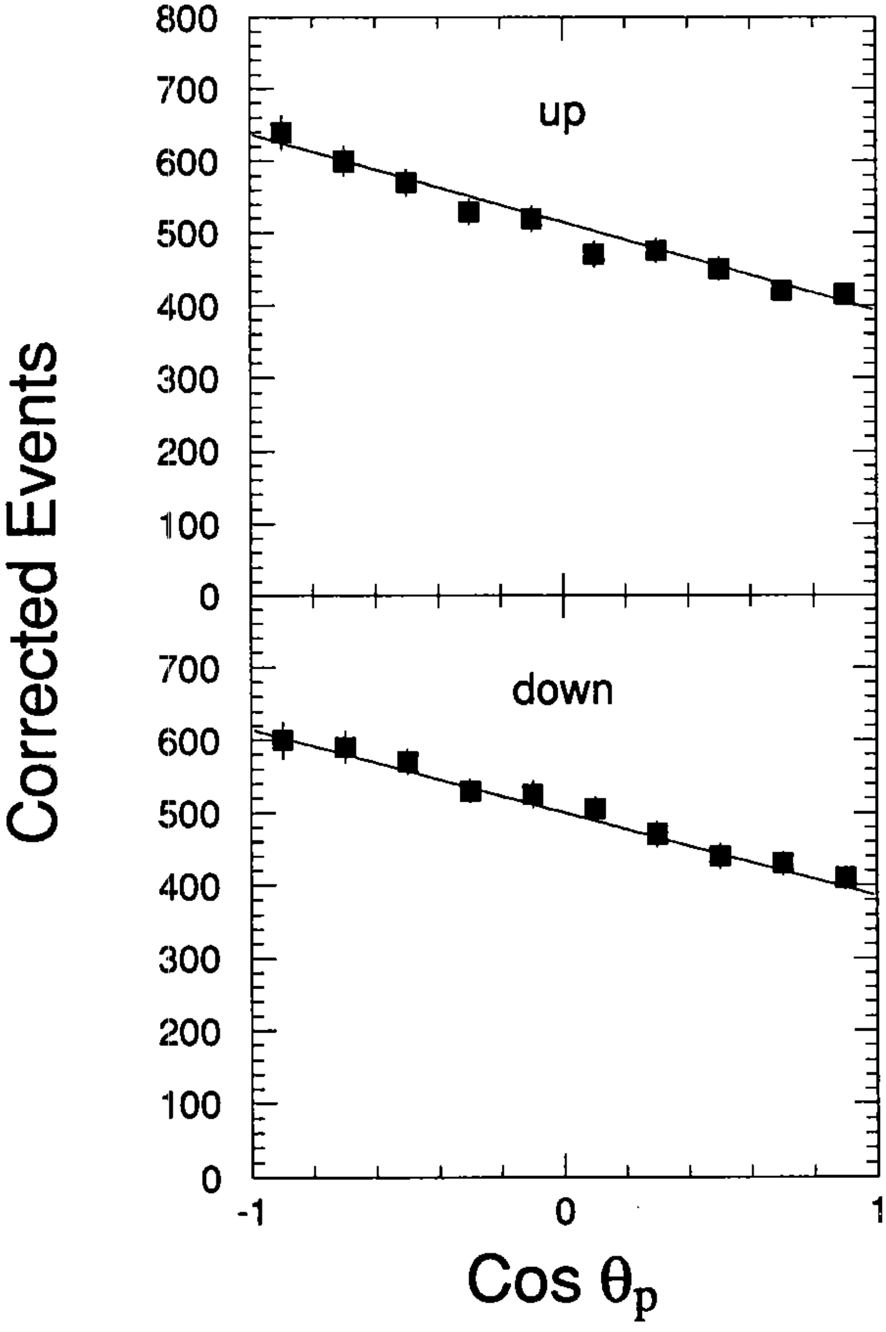


Figure 2



Corrected Events
800
700
600
500
400
300
200
100
0
up
down
-1
0
1
Cos θ_p

Figure 3

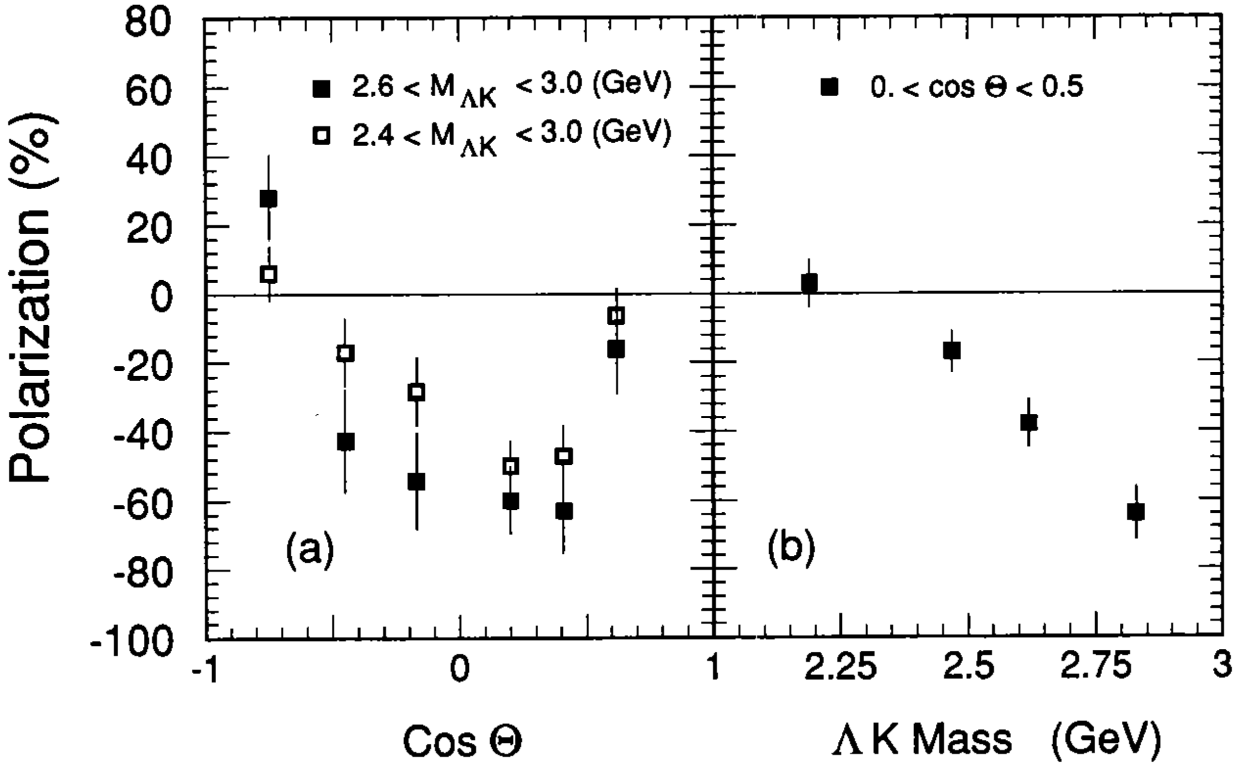

Polarization (%)
80
60
40
20
0
-20
-40
-60
-80
-100
■ 2.6 < M_ΛK < 3.0 (GeV)
□ 2.4 < M_ΛK < 3.0 (GeV)
(a)
-1
0
1
Cos Θ
■ 0. < cos Θ < 0.5
(b)
2.25
2.5
2.75
3
Λ K Mass (GeV)

Figure 4

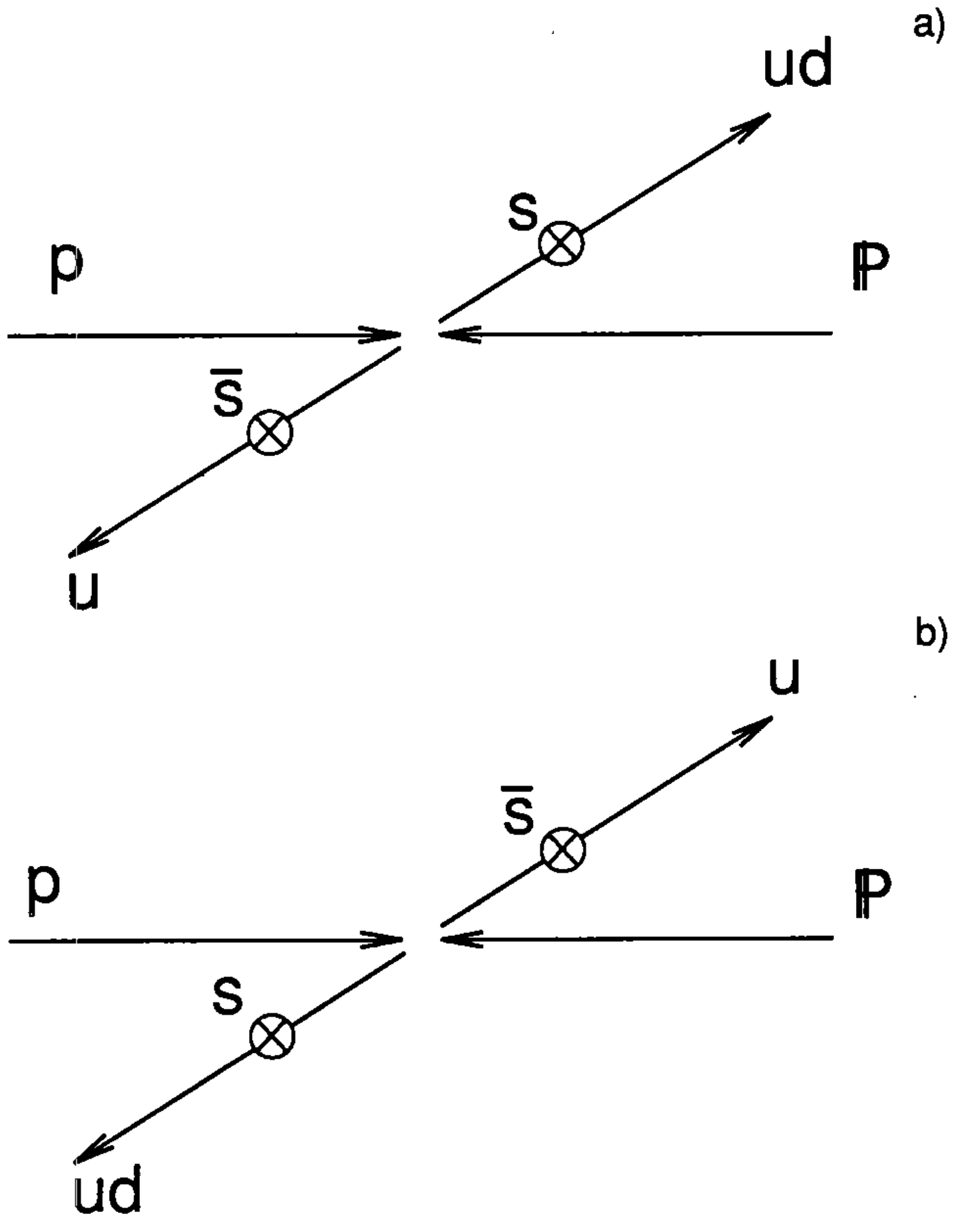


Figure 5