Fermi National Accelerator Laboratory

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Hyperons at Fermilab

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Magnetic moment measurements of the baryon octet and decouplet have recently been completed. These measurements illustrate the success as well as the limitations of the simple quark model. Measurements of hyperon production polarizations have shown this to be a rich and complex process. It has forced us to reconsider our basic understanding of hyperon polarization processes.

1. INTRODUCTION

Hyperon magnetic moments and hyperon production polarization are among the most significant experimental results of the Fermilab hyperon program. The magnetic moments measurements are now complete. Final results from completed experiments have been published and no new measurements are in progress or being planned. While these measurements show rough agreement with the simple quark model, their high precision also challenges the existing models and yields insights into the quark structure of the baryons. A great deal of information on hyperon production polarization now exits. Comparisons among the hyperons shows a surprising and baffling complexity and richness. Together with the magnetic moments these results elucidate the limitations of the quark model.

2. MAGNETIC MOMENTS

With the recently published final results[1] on the Ω^- magnetic moment, measurements are available for the moments of all experimentally accessible baryons (lifetimes $\geq 10^{-11}$ s) composed of u, d, and s quarks. These results are shown in Table 1 for both baryons and antibaryons. In Table 1 I show the measured magnetic moment (MM) and its uncertainty (ΔMM) for each particle[1-3]. Also displayed are the quark model prediction, the difference between the model and measurement , its fractional deviation, and σ.

Some comments about the measurements shown in Table 1 are in order. The extreme precision of magnetic resonance techniques place the proton and neutron moment measurements in a class of their own. Measurements of the $\Lambda^\circ, \Sigma^+, \Sigma^-, \Xi^\circ, \Xi^-$, and Ω^- moments were done using Fermilab hyperon

Table 1
Magnetic Moment Comparisons

Baryon	MM ± ΔMM μ_N	ΔMM/MM %	Quark Model μ_N	Difference μ_N	%Dif	σ
p	2.79284739 ± 0.00000006		input			
n	-1.9130428 ± 0.0000005		input			
Λ°	-0.613 ± 0.004	-0.65	input			
Σ^+	2.458 ± 0.010	0.41	2.67	-0.212 ± 0.010	-7.94	-21.20
Σ^-	-1.160 ± 0.025	-2.16	-1.09	-0.07 ± 0.025	6.42	-2.80
$\Sigma^\circ \rightarrow \Lambda^\circ$	-1.61 ± 0.08	-4.97	-1.63	0.02 ± 0.08	-1.23	0.25
Ξ°	-1.253 ± 0.014	-1.12	-1.43	0.177 ± 0.014	-12.38	12.64
Ξ^-	-0.6510 ± 0.0025	-0.38	-0.49	-0.161 ± 0.002	32.85	-65.02
Ω^-	-2.019 ± 0.054	-2.67	-1.84	-0.18 ± 0.05	9.79	-3.33
$\Delta(1232)^{++}$	4.52 ± 0.67	14.81	5.59	-1.06 ± 0.67	-19.00	-1.58
$\bar{p}$	-2.801 ± 0.009	-0.32	-2.793	-0.008 ± 0.009	0.27	-0.85
$\bar{\Sigma}^-$	-2.438 ± 0.037	-1.51	-2.458	0.02 ± 0.04	-0.80	0.53
$\bar{\Xi}^+$	0.657 ± 0.034	5.18	0.651	0.006 ± 0.034	0.93	0.18

beams. Measurements of the Σ^- moment using the hyperfine structure splitting in Σ^- capture in heavy atoms[4] supplement the hyperon beam measurements. A similar technique was used to measure the antiproton magnetic moment. The $\Sigma^\circ \rightarrow \Lambda^\circ \gamma$ transition moment was measured using the Primakoff effect[5] in a Fermilab neutral hyperon beam. The measurements of the two antihyperon moments were done at Fermilab and were made possible by the surprising discovery (discussed later) that these antihyperons could be produced polarized.

I also include in this compilation a measurement of the $\Delta(1232)^{++}$ magnetic moment. This magnetic moment was extracted from a measurement[3] of the pion-proton bremsstrahlung cross section at a total energy corresponding to the $\Delta(1232)^{++}$. This measurement is model dependent and the authors comment: *further improvements in the calculations are needed before the model dependence of the magnetic moment analysis can be fully assessed.* I note the result (and uncertainties) of the authors[3] even though the Particle Data Group[2] estimates a larger uncertainty, (3.7-7.5) μ_N, for the moment. Other than the Ω^-, this is the only decouplet magnetic moment, unsatisfactory as it is, for which we have a measurement.

I compare these measurements with the simple quark model. In this model[6], only valence quarks (described by SU(6) wave functions) contribute to the magnetic moments. I also include the measurement of the $\Sigma^\circ \rightarrow \Lambda^\circ \gamma$ transition moment[2]. The rate for this purely electromagnetic decay is predicted by the same formalism as the magnetic moments. Inputs to this model are the measurements of the proton, neutron, and Λ° moments which fix the intrinsic quark moments.

From Table 1, we note that three of the hyperons have moments measured to a precision >1%, most of the rest to a few % - including the Ω^-. The agreement with the quark model is ≈ 10% except for the Ξ^- which differs by more than 30%. The statistical significance of these deviations is given by the σ shown in the last column. The statistical precision of the data indicates clear disagreements. Figure 1 graphically demonstrates the difference between the measurements and the quark model predictions for each particle. The $\Delta(1232)^{++}$ magnetic moment is not included because of its much larger error.

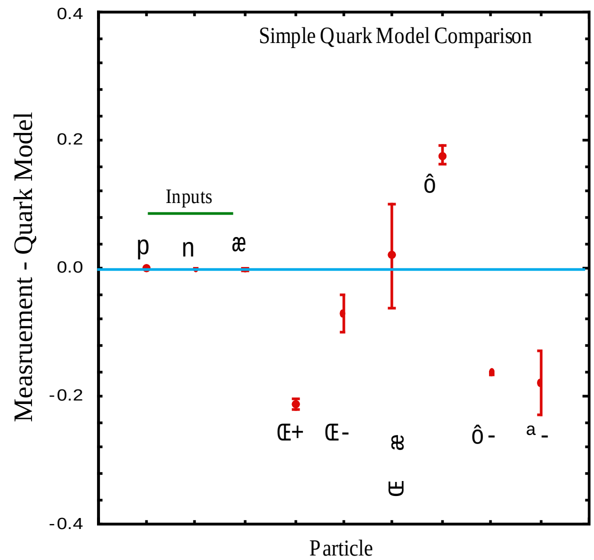

Figure 1. Quark model comparisons

The simple quark model predicts the Ω^- moment to be just three times the Λ° moment. However, the new precision measurement of the Ω^- moment indicates it to be even *larger* by a statistically significant amount. Although the present state of the $\Delta(1232)^{++}$ moment measurements suggests that it is twice the proton moment (as predicted by the simple quark model) it would be interesting to check this with more precise data since this prediction does not involve the s quark.

Should one be surprised by the simple quark model disagreements considering the simplicity (or crudity?) of the model? How can the simple quark model be modified to bring it into better agreement with the data? What does this say about the limitations of the quark model? A recent review by Brekke[7] discusses these questions in much more detail. Are there other approaches which might be useful? The confrontation of lattice gauge theory with these now precise measurements would certainly be of interest.

We have magnetic moment measurements of three octet antibaryons. The CPT theorem requires that they have a magnetic moment of the same magnitude as the corresponding particle but opposite in sign. This indeed seems to be the case as seen in Table 1. The measurement of antihyperon magnetic moments has a certain esoteric appeal but does not present a significant challenge to the CPT theorem at this level of precision.

3. HYPERON POLARIZATIONS

The early discovery that Λ° were produced with significant polarizations at Fermilab energies came as a surprise. Other hyperons were subsequently also found to be polarized. Models which seemed to explain the earlier data became inadequate as more data appeared. As I will show the current picture has taken on an almost Rococo texture.

3.1. Polarization p_t dependence

Significant Λ° polarization was measured in the early Fermilab neutral hyperon beam[8]. Figure 2 shows data[9] for Λ° and $\overline{\Lambda}^\circ$ produced by 400 GeV protons. The polarization is plotted as a function of the transverse momentum, p_t , of the produced hyperon relative to the incident proton momentum. The Λ° polarization was found to be zero in the forward direction and decreased linearly to ≈ -20% at $p_t \approx 1.5$ GeV/c. These early experiments (using Λ°) also indicated that the polarization had little dependence on the initial energy of the proton or the target material.

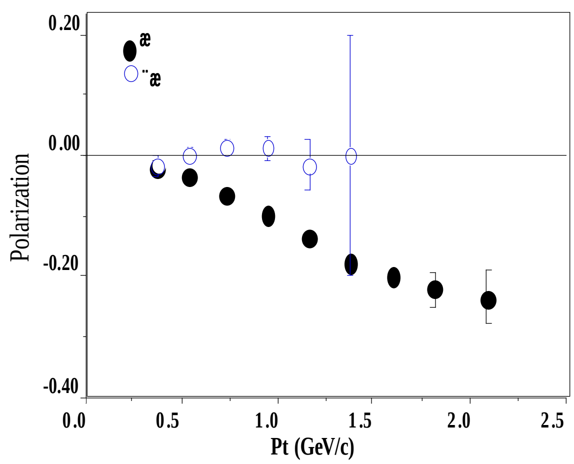

Figure 2. Polarizations of particle Λ° and $\overline{\Lambda}^\circ$

These polarizations have generally been attributed to peripheral mechanisms in which some of the proton valence quarks assimilate a strange quark from the sea to form a polarized hyperon.

The empirical conjecture that the more quarks incorporated from the sea reduces the produced hyperon polarization seemed to be confirmed by measurements of the polarization[10-18], of $\Sigma^\pm$, Ξ^-, and Ξ° hyperons. Figure 3 shows the measured polarizations [19] of some other hyperons. Plotted here is the polarization as a function of the hyperon momentum at a fixed production angle. Since $p_t = P_h \sin\Theta$, where P_h is the hyperon momentum and Θ the production angle, the horizontal axis is proportional to p_t. These are all produced by 400 GeV protons. One sees each of the hyperons being produced with polarization of ≈10-20% at $p_t \approx 1$ GeV/c. Significant polarizations seem to be a general property of hyperon production at high energies.

Figure 3. Polarization of other hyperons

In these interactions, the Λ° is a leading particle and the $\overline{\Lambda}^\circ$ is not. Might this be significant? The fact that early experiments had shown $\overline{\Lambda}^\circ$ to be unpolarized, where in the same kinematic range Λ° was polarized, lent credence to the idea that polarization is a leading particle effect. This was supported by measurements[17] showing the Ω^- to be unpolarized in this same kinematical region. Since the Ω^{--} is composed of three strange valence quarks it contains none of the valence quarks of the incident proton.

However, recent data have cast great doubt on this picture. Figure 4 shows the measurement of the $\overline{\Xi}^+$ polarization by the Fermilab E756 group[20], to be polarized by about the same amount as the Ξ^- .

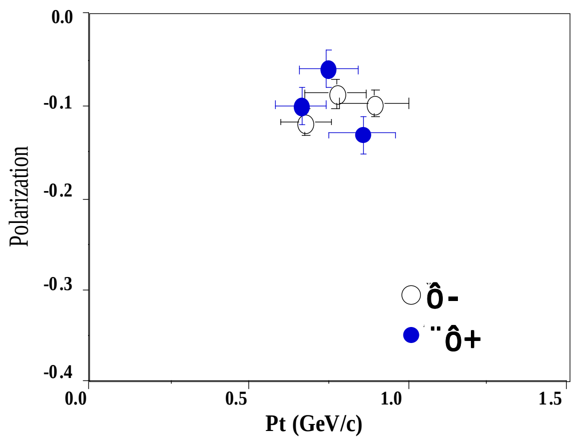

Figure 4. Ξ^- and $\overline{\Xi}^+$ polarization

The Fermilab E761 group[21] have measured the polarization of 375 GeV/c Σ^+ and $\overline{\Sigma}^-$ produced by 800 GeV protons on a Cu target. Figure 5 shows the measured polarizations of Σ^+ and $\overline{\Sigma}^-$ as a function of p_t. In this data one sees that $\overline{\Sigma}^-$ are also produced with ≈ 8% polarization near $p_t \approx 1$ GeV/c.

This Σ^+ data shows that the polarization increases with p_t, goes through a maximum near $p_t = 1$ GeV/c and then decreases. This is the first time this decrease has been clearly observed in a high energy hyperon polarization.

The data of Figure 5 show points taken with both horizontal and vertical targeting for Σ^+ and $\overline{\Sigma}^-$. In horizontal targeting, the incident beam direction is changed in the horizontal (H) plane producing polarization in the same plane (vertical) as the magnetic field of the hyperon magnet Thus there is no spin rotation as the hyperons traverse the magnet. Targeting in the vertical (V) plane produces a polarization in the horizontal plane, perpendicular to the magnet field, thus producing maximum spin rotation as would be desired for measurement of a magnetic moment. This data was used for the Σ^+ and $\overline{\Sigma}^-$ magnetic moment measurements.

Figure 5. Σ^+ and $\overline{\Sigma}^-$ polarization a versus Pt

This experiment demonstrated that $\overline{\Sigma}^-$ hyperons are produced in high energy collisions with polarization of the same sign though of smaller magnitude than that of Σ^+. This observation is similar to the recent Fermilab results [20] which showed that both Ξ^- and $\overline{\Xi}^+$ are polarized with about the same magnitude. This would indicate that the polarization of antihyperons is a common phenomenon, and we should now turn our attention to why the $\overline{\Lambda}^\circ$ are not produced polarized.

3.2. Polarization energy dependence

The early data indicated that there was no strong energy dependence to hyperon polarization. However, recent high statistics data comparing hyperon production at 400 and 800 GeV indicate a much more complex phenomena. Figure 6 shows data from Fermilab E756 comparing Ξ^- production at 400 and 800 GeV [15, 22]. The 400 GeV protons used a 5 mrad production angle whereas the 800 GeV experiment was a 2.5 mrad. Thus the data was matched in both x_F and p_t. One sees that the magnitude of the polarization increases with the incident proton energy.

Figure 6. Comparison of Ξ^- polarization at 400 and 800 GeV.

Figure 7 show the polarization as a function of p_t for Σ^+ at 400 GeV from Fermilab experiments E497[10] and E620 [11] and compares them[21] with E761 at 800 GeV. Note that the E620 data is from production on a Be target. The others use a Cu target. However, at least for Λ° production, the nature of the target material does not seem to have a major effect on hyperon polarization. Pondrom[23] has a good summary of target material dependence of hyperon production and polarization data. All of the Σ^+ data are in a range $0.47 < x_F < 0.53$. This data also shows a clear energy dependence of the Σ^+ polarization. Here, in contrast to the Ξ^- data of Figure 6, the polarization decreases in the same energy range.

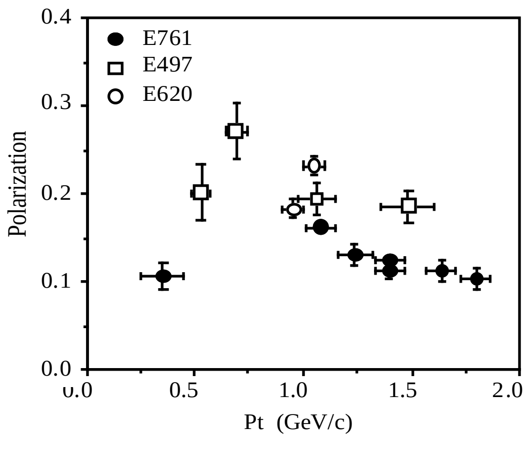

Figure 7. Comparison of Σ^+ polarization at 400 (open points) and 800 GeV (black points).

Fermilab E799, in a recent result[24] used the Λ° contamination in their K° beam to measure the Λ° polarization at 800 GeV. This measurement and the comparison with a previous measurements[25] at 400 GeV is shown in Figure 8. This very nice comparison shows no energy dependence of the polarization!

Figure 8. Comparison of Λ° polarization at 400 and 800 GeV.

We now have good comparisons of the Σ^+, Ξ^-, and Λ° polarizations at 400 and 800 GeV and find the astonishing result that the first decreases, the second increases, and the last remains constant with energy.

3.3 Polarization x_F dependence

A new comparison[26] has been made of the x_F dependence of polarization which contributes yet another dimension to the puzzle. In Figure 9 they displays the x_F dependence of the polarization for two p_t intervals.

Note that for Σ^+ the polarization increases with x_F and is dependent on the p_t interval. For the Λ°, the polarization decreases with x_F and shows no p_t dependence. For the Ξ^- there seems to be neither an x_F or p_t dependence!

Among the many proposed models for hyperon (but not antihyperon) polarization[27-30], let me mention two approaches to the polarization question - both involving similar leading particle effects. One is that

Figure 9. x_F dependence of polarization for two p_t intervals

of the Lund group[31] whose model assumes $q\bar{q}$ pairs are produced from the sea via the breaking of a QCD string but conserving local angular momentum. DeGrand and Miettinen[32] propose two simple rules: quarks which gain longitudinal momentum combine with spins down; quarks which lose longitudinal momentum combine with spins up. This is equivalent to a Thomas precession and a spin orbit coupling. Both models explain much of the hyperon data. The magnitudes of some of the polarizations are at odds with each of the models. Other models are discussed in a review by P. Kroll [33] and is recommended although it was done before the polarizations of the $\overline{\Xi}^+$ and $\overline{\Sigma}^-$ were known. A model using a Regge pole approach[34] gives qualitatively good agreement with Σ^+ polarization data. None of the above models address the polarizations of the antihyperons or the above mentioned hyperon polarization energy dependence.

The only publication[35] that I am aware of that offers an explanation for hyperon (and antihyperon) polarization does so in the framework an optical potential model. In this model the polarization occurs at the surface of the nucleon and the process applies naturally to both hyperons and antihyperons.

The last couple of years have seen a major addition to the available data on the polarization of both hyperons and antihyperons. Clearly the $\Lambda^\circ / \overline{\Lambda}^\circ$, $\Xi^- / \overline{\Xi}^+$, and $\Sigma^+ / \overline{\Sigma}^-$ systems exhibit a rich and challenging set of polarization phenomena that cry out for insightful ideas.

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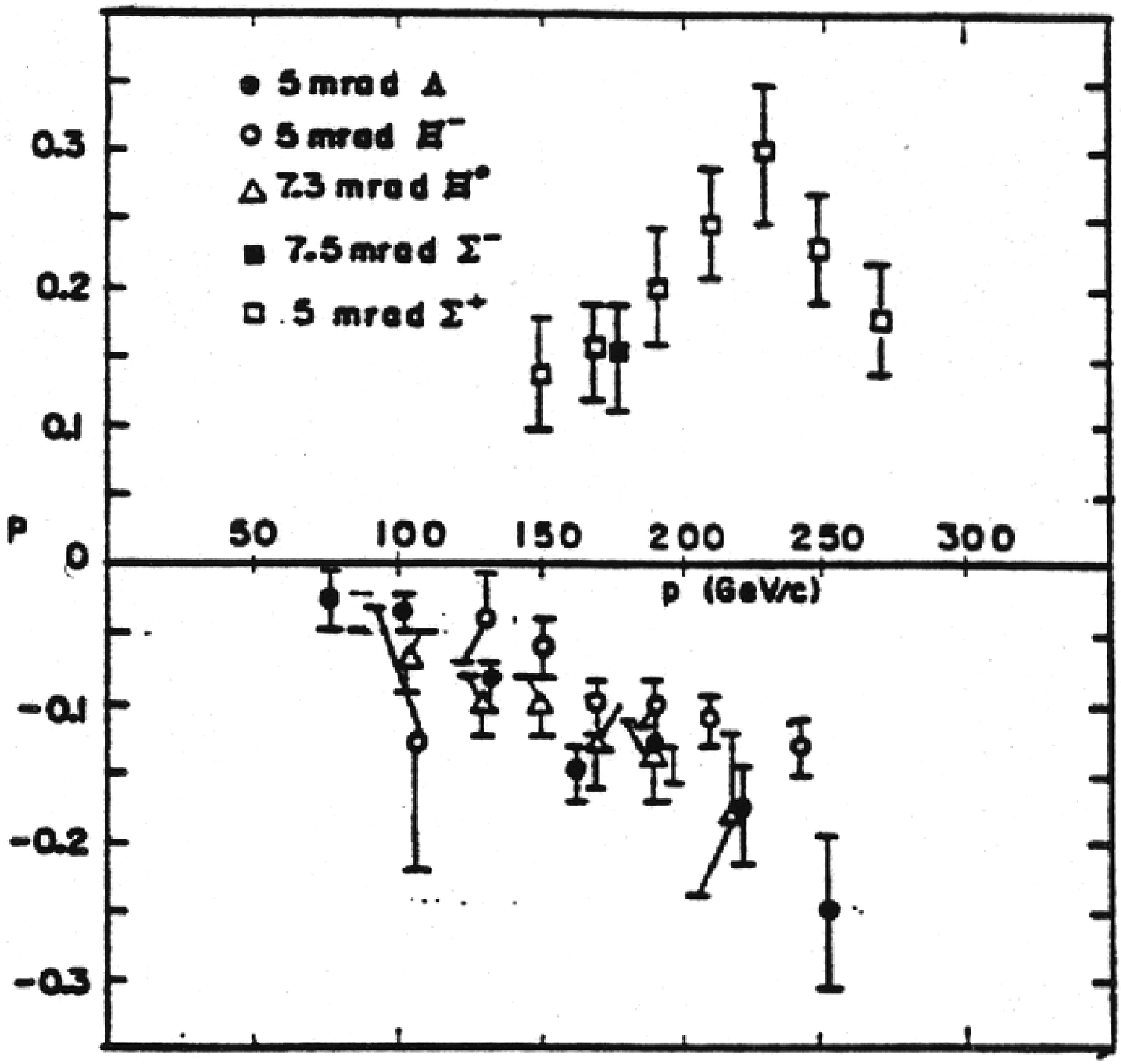

Figure 3. Polarization of other hyperons

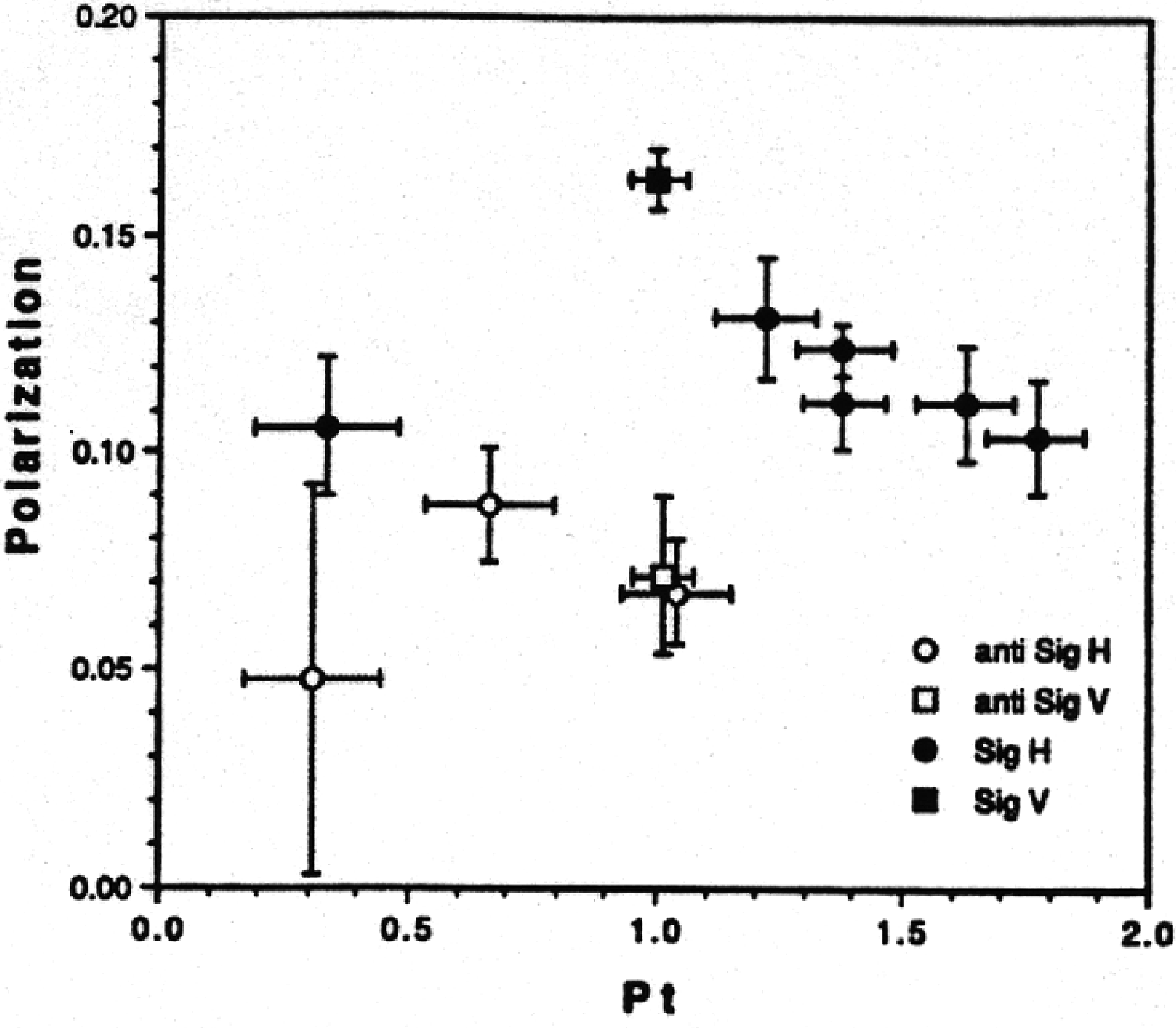

Figure 5. Σ^+ and $\overline{\Sigma}^-$ polarization a versus Pt

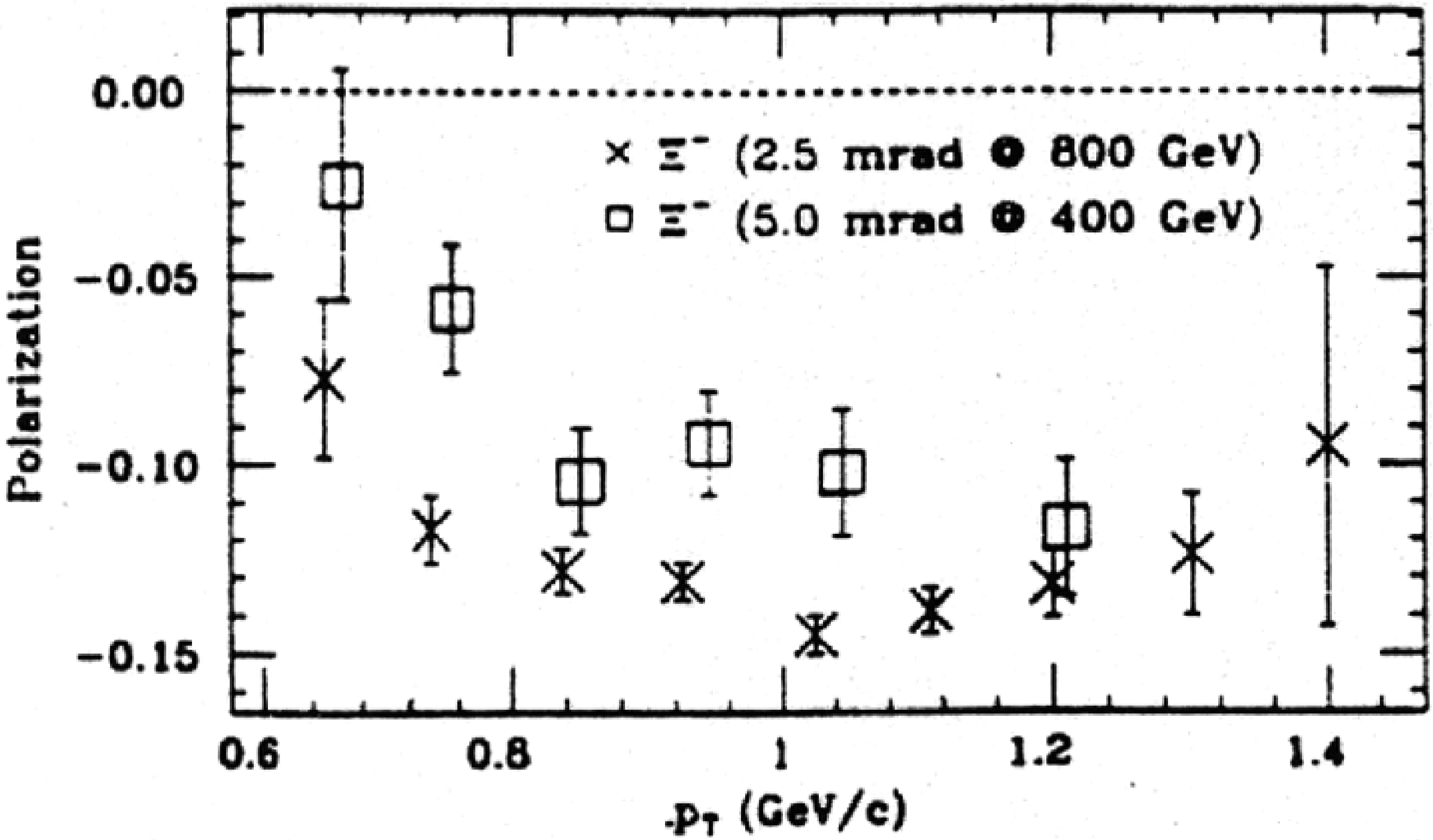

Figure 6. Comparison of Ξ^- polarization at 400 and 800 GeV.

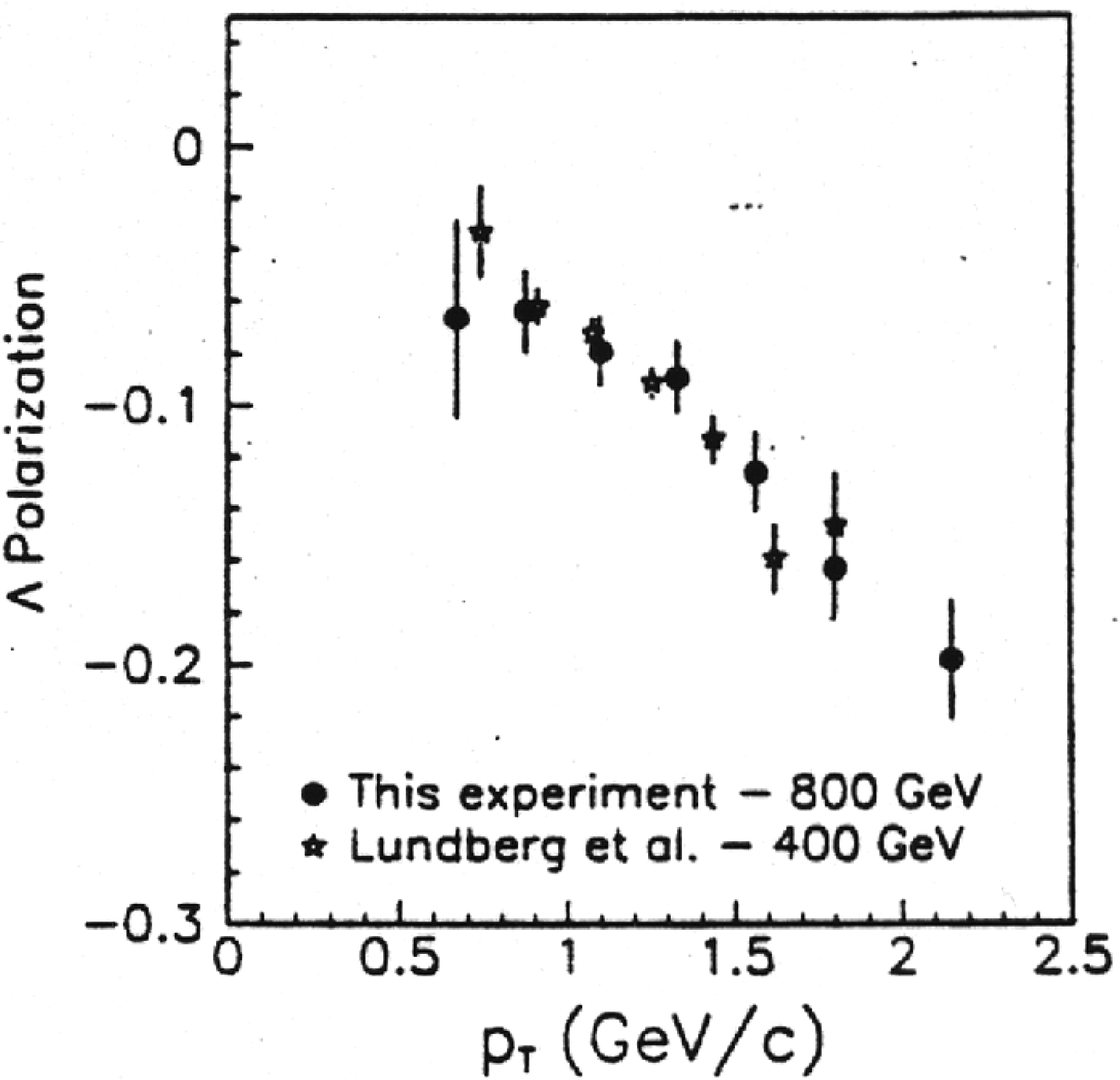

Figure 8. Comparison of Λ° polarization at 400 and 800 GeV.

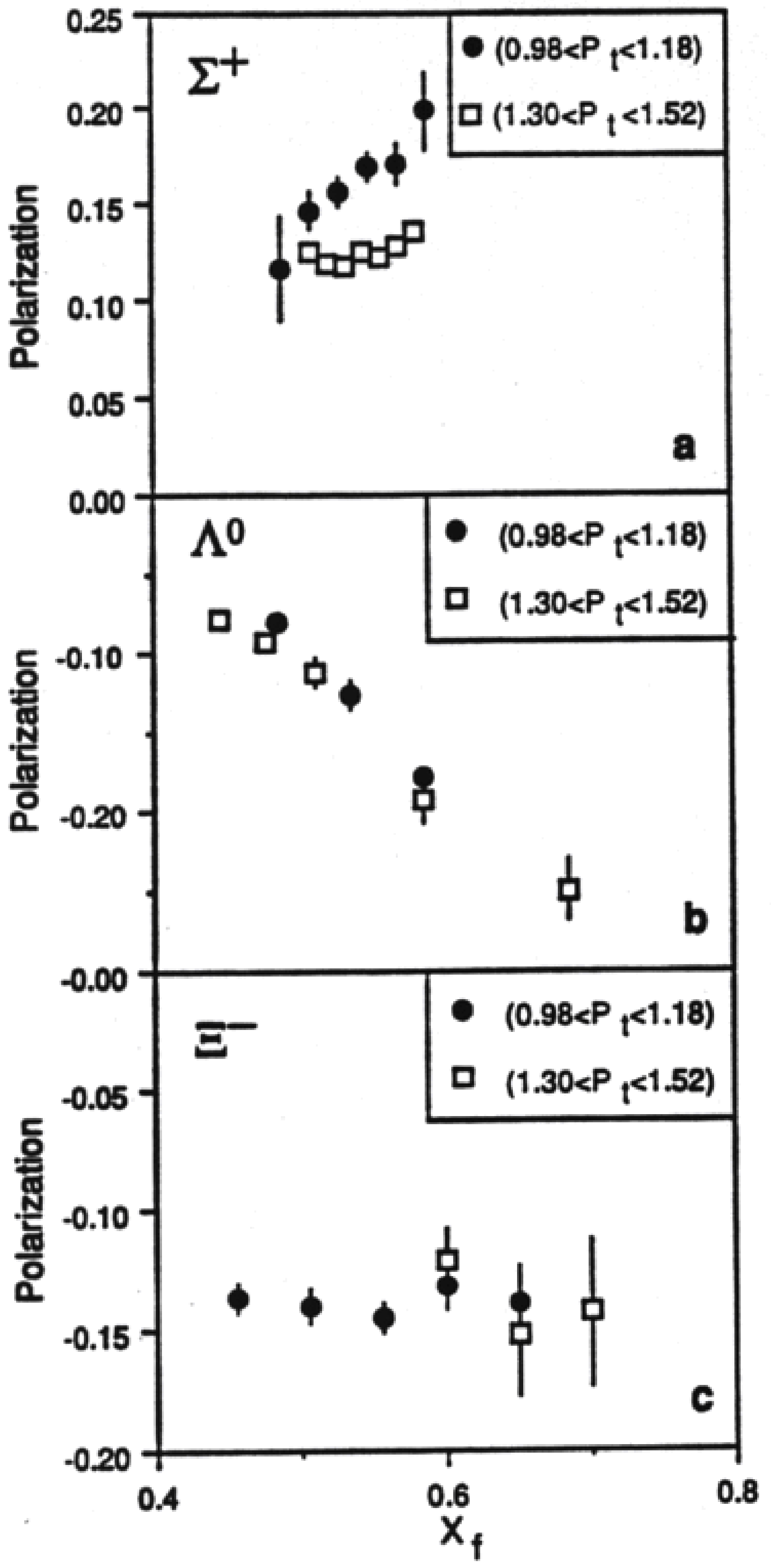

Figure 9. x_F dependence of polarization for two p_t intervals