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SPIN OBSERVABLES IN THE REACTION $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$

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ABSTRACT

The reaction $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ has been investigated from threshold up to 1.7 GeV/c incident $\bar{p}$ momentum. Large polarizations of Λ and $\bar{\Lambda}$ have been observed even at the lowest energies, and they appear to have a characteristic dependence on the momentum transfer involved. The measured $\Lambda-\bar{\Lambda}$ spin correlations are compatible with the particles being created in a spin-one state. As tests of the fundamental symmetries CPT and CP, the mean lifetimes and the decay asymmetry parameters, respectively, are compared from Λ and $\bar{\Lambda}$ decay distributions.

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1. INTRODUCTION AND MOTIVATION

Although exclusive processes such as $\bar{p}p \to \bar{\Lambda}\Lambda$, $\bar{p}p \to \bar{\Lambda}\Sigma^0 + \Lambda\bar{\Sigma}^0$, and $\bar{p}p \to \bar{\Sigma}\Sigma$ represent only a small fraction of the total $\bar{p}p$ cross-section, they provide a laboratory for detailed studies of specific features of the reactions and, in particular, of the spin dynamics. This paper is restricted to the reaction $\bar{p}p \to \bar{\Lambda}\Lambda$, which is part of an on-going programme in the framework of Experiment PS185 at the CERN Low-Energy Antiproton Ring (LEAR). With an unpolarized beam incident on an unpolarized target, we measure in our experiment the following set of observables: the production cross-section $\sigma(\bar{p}p \to \bar{\Lambda}\Lambda)$, the differential cross-section $d\sigma/d\Omega$, the Λ and $\bar{\Lambda}$ polarizations P, and the $\Lambda - \bar{\Lambda}$ spin-correlation coefficients C_{ij}. The cross-sections are treated in an accompanying paper [1], whereas the spin observables are the subject of this one.

The selectivity of $\bar{p}p \to \bar{\Lambda}\Lambda$ is mainly due to the underlying process of associated strangeness production. This typically involves large momentum transfers of the order of 3 fm^{-1}. The production cross-section is only a small part (10^{-3} to 10^{-4}) of the total $\bar{p}p$ cross-section. With the kinematical threshold at 1.435 GeV/c beam momentum, the range of LEAR momenta used so far translates into a range of about 1 to 100 MeV kinetic energy in the $\bar{\Lambda}\Lambda$ centre-of-mass system. Near the threshold it is expected that only a few partial waves contribute to the production process.

In the static quark model, the Λ hyperon is composed of single u-, d-, and s-quarks in a relative S-state. The u- and d-quarks are coupled to a spin- and isospin-zero pair, so that the spin vector of the s-quark is that of the Λ hyperon itself. The lowest-order quark-line diagram associated with $\bar{p}p \to \bar{\Lambda}\Lambda$ is shown in Fig. 1. The reaction dynamics is determined by the $\bar{u}u$ annihilation and $\bar{s}s$ creation, whilst the ud and $\overline{ud}$ quark pairs are spectators. This makes the process an attractive tool for studying quark–gluon dynamics, and in particular the quantum numbers of the $\bar{s}s$ vertex. If the $\bar{\Lambda}\Lambda$ pairs are produced with pure S-waves, and if the final state is a spin triplet, then the $\bar{s}s$ vertex has the 'gluon quantum numbers' $J^P = 1^-$. In the case of pure P-wave production, and a final-state spin triplet, the vertex has the 'vacuum quantum numbers' $J^P = 0^+$.

It is well known from experiments that hyperons produced in high-energy reactions emerge polarized [2]. Pronounced Λ polarizations of the order of $|P| \approx 0.5$ have been measured in a variety of processes, such as $\gamma p \rightarrow K^+\Lambda$, $\pi^- p \rightarrow K^0\Lambda$, $K^- p \rightarrow \Lambda X$, and $pA \rightarrow \Lambda X$. Such polarization has been observed at transverse momenta of the order of 1 GeV/c, and for a given reaction it seems to be roughly independent of the centre-of-mass energy. Several ideas in the framework of the static quark model have been put forward to explain the observed hyperon polarization. For the case of inclusive Λ production with proton beams, one assumes that s-quarks are produced polarized and then recombine with the incident baryon fragment ('spectator diquark') to form polarized Λ hyperons. The suggested mechanisms for polarizing the s-quarks invoke string breaking [3] or Thomas precession [4]. In a recent experiment [5] with polarized proton beams at BNL, the spin transfer and the analysing power have been measured for $\vec{p}Be \rightarrow \Lambda X$. The Λ polarization appears to be independent of the incident proton polarization. This result is consistent with the idea that the spin of the Λ hyperon is essentially carried by its s-quark. However, it should be noted that the hyperon polarization observed in $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ at low energies results from spin-dependent initial- and final-state interactions rather than from the mechanisms mentioned above.

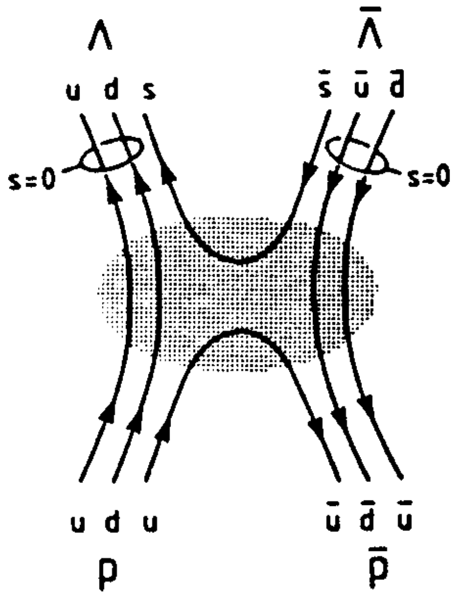

Figure 1: Lowest-order quark-line diagram of the reaction $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$.

2. APPARATUS AND EVENT SIGNATURE

The PS185 apparatus is a non-magnetic forward-decay spectrometer with a large centre-of-mass acceptance. The delayed decays $\bar{\Lambda}\Lambda \rightarrow \bar{p}\pi^{+}p\pi^{-}$ are recorded in a stack of proportional chambers and drift chambers. This chamber stack is sandwiched between devices entering the 'charged − neutral − charged' on-line trigger scheme: a CH_2 target system triggering on the $\bar{p}$ beam and vetoing the production of charged particles, and a scintillator hodoscope triggering on the detection of charged particles from delayed decays. A 0.1 T solenoid with three drift chambers serves to identify Λ and $\bar{\Lambda}$ by means of charge distinction. The detector is described in more detail elsewhere [6].

The events are reconstructed off-line from their tracks recorded in the chamber stack. Those that exhibit a distinctive '2 V^0' signature are kinematically fitted to the hypothesis $\bar{p}p \rightarrow \bar{\Lambda}\Lambda \rightarrow \bar{p}\pi^{+}p\pi^{-}$. With the calculated momenta of the hyperons, the spatial distribution of their decay vertices can be transformed into lifetime distributions. Figure 2 shows Λ and $\bar{\Lambda}$ lifetime distributions for 4063 reconstructed events at 1.546 GeV/c incident $\bar{p}$ momentum [7]. The fitted mean lifetimes of Λ and $\bar{\Lambda}$ agree, within errors, with the world average [8]. From our data we determined the ratio

$$R = (\tau - \bar{\tau})/\langle\tau\rangle = 0.02 \pm 0.05 ,$$

which is consistent with zero as required from CPT invariance. However, our error is smaller than that reported from previous work [8].

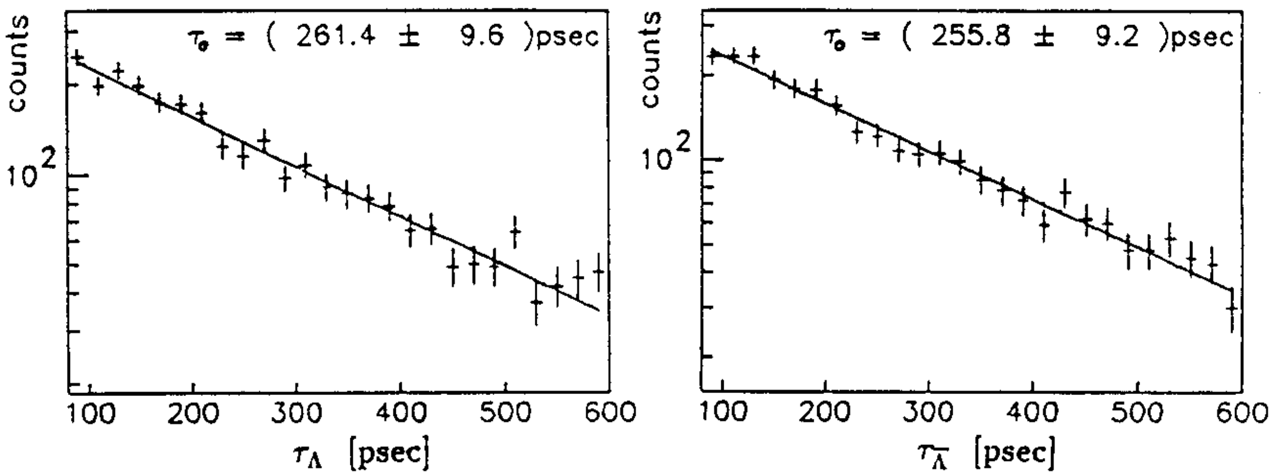

Figure 2: The Λ and $\bar{\Lambda}$ lifetime distributions from $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ at 1.546 GeV/c incident $\bar{p}$ momentum.

3. THE Λ AND $\bar{\Lambda}$ POLARIZATION

Owing to parity conservation in $\bar{p}p \to \bar{\Lambda}\Lambda$, the hyperons can only be polarized transverse to the production plane. The decays $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$ are parity-violating weak decays that are characterized by mixtures of S- and P-wave amplitudes. For a sample of Λ's with polarization P, the angular distribution of the decay protons in the Λ rest frame is given by

$$dN/d(\cos\theta_p) = N(1 + \alpha P\cos\theta_p) ,$$

where θ_p is measured between the normal of the production plane and the proton momentum vector, and $\alpha = 0.642 \pm 0.013$ is the $\Lambda \to p\pi^-$ decay asymmetry parameter. Parity violation in the decays thus manifests itself in an up–down asymmetry of the decay angular distribution with respect to the production plane. The degree of asymmetry in these 'self-analysing' decays is determined by αP.

For the evaluation of αP, the 'method of weighted sums' has been adopted [7]. It requires only a symmetry condition of the detector acceptance function, $\eta(\theta_p) = \eta(180° - \theta_p)$, and no corrections are needed. The condition is well fulfilled in our case. Simulations showed that the method did not bias the polarizations extracted from the real data. The product αP has been evaluated separately for Λ and $\bar{\Lambda}$. However, the polarization distributions can be combined because charge-conjugation invariance in $\bar{p}p \to \bar{\Lambda}\Lambda$ requires the polarizations of the outgoing particles to be equal. In addition, one has $\alpha = -\bar{\alpha}$ if CP conservation is assumed for the decays $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$.

Figure 3 displays a compilation of $\bar{\Lambda}\Lambda$ polarization data obtained with our experiment at incident $\bar{p}$ momenta of 1.445 GeV/c (848 events), 1.477 GeV/c (1185 events), 1.508 GeV/c (1845 events), 1.546 GeV/c (4063 events), and 1.695 GeV/c (11427 events). The polarizations are shown as a function of the four-momentum transfer squared,

$$t = (p_{\bar{p}} - p_{\bar{\Lambda}})^2 = m^2_{\bar{p}} + m^2_{\bar{\Lambda}} - s/2 + \sqrt{(s - 4m^2_{\bar{p}})(s - 4m^2_{\bar{\Lambda}})/4}\, \cos\theta^*_{\bar{\Lambda}} ,$$

which is thus linearly related to $\cos\theta^*_{\bar{\Lambda}}$. The solid curve represents the boundaries t_{min} (at $\theta^*_{\bar{\Lambda}} = 0°$) and t_{max} (at $\theta^*_{\bar{\Lambda}} = 180°$) of the kinematically allowed region for different values of the total centre-of-mass energy $\sqrt{s}$. As in other Λ production experiments, we observe strong polarization for reduced four-momentum transfer squared, $|t'| \geq 0.15$ (GeV/c)^2, where

$$-t' = -(t - t_{min}) = \sqrt{(s - 4m^2_{\bar{p}})(s - 4m^2_{\bar{\Lambda}})/4}\,(1 - \cos\theta^*_{\bar{\Lambda}}) .$$

The polarization distributions for different $\sqrt{s}$ values exhibit a zero-crossing point at the same value of $|t'|$ as indicated by the dashed line. For $|t'| \leq 0.15\ (\mathrm{GeV/c})^2$, we observe positive polarization. Its strength appears to increase with decreasing $\sqrt{s}$. Note that the lowest $\bar{p}$ momentum shown corresponds to only a few MeV kinetic energy in the $\bar{\Lambda}\Lambda$ system.

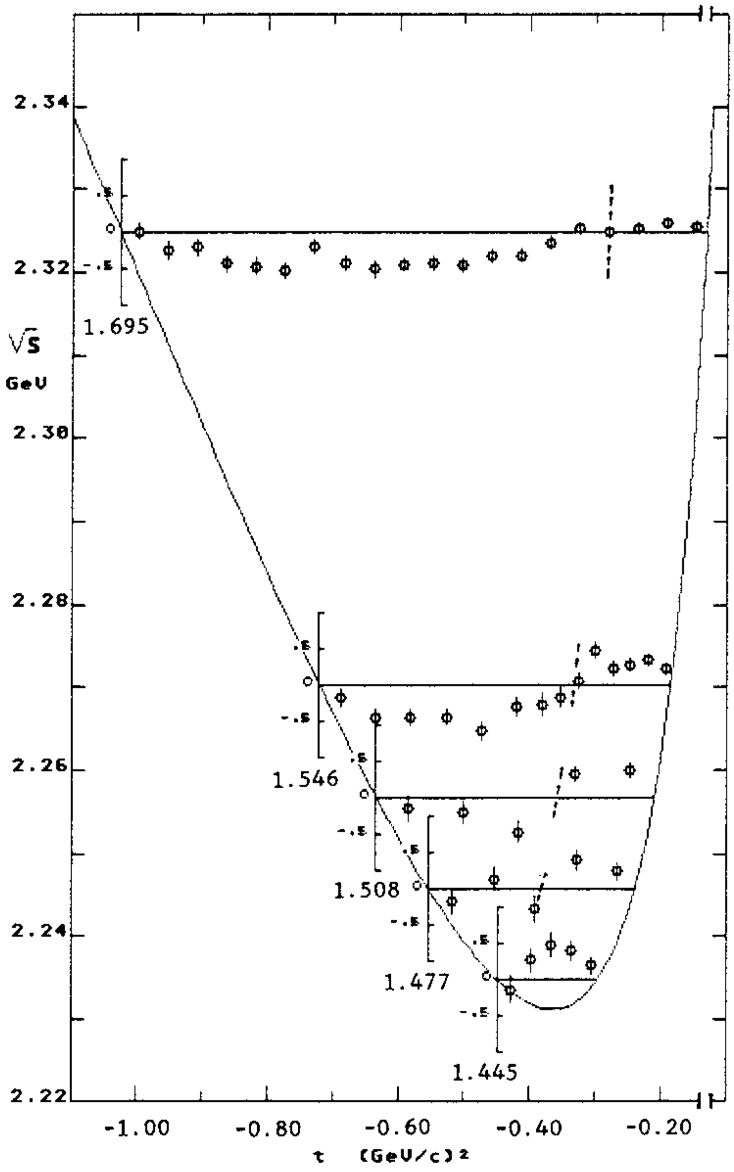

Figure 3: Compilation of hyperon differential polarization data from $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$.

The qualitative features of our polarization data are reproduced by various recent kaon-exchange and 'quark − gluon' calculations. It has been argued [9] that the zero-crossing of the polarization is a consequence of strong P-wave dominance in $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$, which would lead to a pattern with a characteristic $\sin 2\theta^*_{\bar{\Lambda}}$ dependence. It seems, however, that the physical origin for the zero-crossing appearing at constant $|t'|$, and of the trend observed in the positive polarizations, has yet to be explored in more depth.

Because of the invariances discussed above, the polarizations of kinematically correlated Λ and $\bar{\Lambda}$ have been combined to a common distribution for each incident $\bar{p}$ momentum. However, the associated production of $\bar{\Lambda}\Lambda$ pairs and the simultaneous detection of their decays offer the possibility to perform a test of CP conservation in the non-leptonic hyperon decays [10]. The $\bar{p}p$ initial state, and thus also the $\bar{\Lambda}\Lambda$ final state, have a definite CP property, so that final-state interactions cannot generate a misleading signal. There is no $\Lambda - \bar{\Lambda}$ mixing, and therefore any signal constitutes a measure of CP violation with the strangeness changing by one unit.

From the individual Λ and $\bar{\Lambda}$ distributions of αP as a function of the $\bar{\Lambda}$ centre-of-mass angle, one can extract the CP testing ratio $A = (\alpha + \bar{\alpha})/(\alpha - \bar{\alpha})$. The data obtained at 1.546 GeV/c incident $\bar{p}$ momentum yielded the value $A = -0.07 \pm 0.09$ [11]. With the combined statistics of this measurement and another one performed at 1.695 GeV/c incident $\bar{p}$ momentum, corresponding to a total number of nearly 16,000 events, we find

$$\langle A \rangle = \langle (\alpha + \bar{\alpha})/(\alpha - \bar{\alpha}) \rangle = -0.023 \pm 0.057 .$$

The error quoted here is only the statistical one.

With the experimental technique at present used in PS185, a sensitivity on A at the level of 5×10^{-3} could be reached. However, the values of A as predicted in the framework of the Standard Model are of the order of 10^{-4}. Alternative experimental approaches have to be considered in order to reach that level. The three-step reaction $\bar{p}p \rightarrow \bar{\Xi}^+\Xi^- \rightarrow \bar{\Lambda}\pi^+\Lambda\pi^- \rightarrow \bar{p}\pi^+\pi^+p\pi^-\pi^-$ is a unique and promising case [10], because it allows the polarization of the decay baryons −− the Λ's and $\bar{\Lambda}$'s −− to be determined. Such a measurement, which needs a high-intensity $\bar{p}$ beam of about 3.5 GeV/c momentum, could be performed at the FNAL $\bar{p}$ accumulator or at Super-LEAR proposed for CERN.

4. THE $\Lambda - \bar{\Lambda}$ SPIN CORRELATION

If one considers the decays $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$ simultaneously, the double angular distribution of the decay baryons in the respective hyperon rest frames is given by

$$d^2N/[d(\cos\theta_{\bar{p}i})d(\cos\theta_{pj})] = (16\pi^2)^{-1} [1 + \alpha P_\Lambda \cos\theta_{py} + \bar{\alpha} P_{\bar{\Lambda}} \cos\theta_{\bar{p}\bar{y}}$$

$$+ \alpha\bar{\alpha} \Sigma_{ij} (C_{ij} \cos\theta_{\bar{p}i} \cos\theta_{pj})] ,$$

where $\cos\theta_{\bar{p}i}$ ($\cos\theta_{pj}$) is the direction cosine of $\bar{p}$ (p) relative to the i (j) axis, with $i = \bar{x},\bar{y},\bar{z}$ ($j = x,y,z$). In particular, $\bar{y}$ (=y) denotes the direction normal to the $\bar{\Lambda}\Lambda$ production plane. The spin-correlation coefficients C_{ij} are normalized averages of products of three Λ and three $\bar{\Lambda}$ spin components,

$$C_{ij} = 9(\alpha\bar{\alpha})^{-1}\langle\cos\theta_{\bar{p}i} \cos\theta_{pj}\rangle .$$

The nine coefficients are not all independent. Parity conservation in $\bar{p}p \to \bar{\Lambda}\Lambda$ requires $C_{\bar{x}y} = C_{\bar{y}x} = C_{\bar{y}z} = C_{\bar{z}y} = 0$, and, because of charge-conjugation invariance, we have $C_{ij} = C_{ji}$. The only elements of the 3×3 matrix that can be non-zero are $C_{\bar{x}x}$, $C_{\bar{y}y}$, $C_{\bar{z}z}$, and $C_{\bar{x}z}$. These are, however, dependent on the hyperon production angle.

The coefficients have been evaluated [7] adopting the 'method of moments'. Since this method requires an isotropic detector acceptance for the decay baryons, the data had to be corrected correspondingly. Figure 4 displays the $\Lambda - \bar{\Lambda}$ spin-correlation coefficients obtained, as a function of the $\bar{\Lambda}$ centre-of-mass angle, for 1.546 GeV/c incident $\bar{p}$ momentum. The conditions required from invariances mentioned above are fulfilled within experimental errors. The distributions shown correspond to a total number of 4063 events, whereas for $\sigma(C_{ij}) \approx 0.1$ one would need about 5000 events per angular bin.

The spin correlations can be used to calculate the expectation value of the $\bar{\Lambda}\Lambda$ spin-zero projection operator,

$$F_S = 0.25(1 - \langle\vec{\sigma}_{\bar{\Lambda}}\cdot\vec{\sigma}_\Lambda\rangle) = 0.25(1 + C_{\bar{x}x} - C_{\bar{y}y} + C_{\bar{z}z}) .$$

One has $F_S = 0$ for a pure spin-one state, $F_S = 1$ for a pure spin-zero state, and $F_S = 0.25$ for uncorrelated Λ and $\bar{\Lambda}$ spins. From the data shown in Fig. 4, the average value $\langle F_S \rangle = -0.12 \pm 0.07$ has been calculated. This number is somewhat 'unphysical'. However, our Monte Carlo simulations with uncorrelated $\bar{\Lambda}\Lambda$ pairs did not give the expected 0.25 for the singlet fraction, but yielded the value $\langle F_S \rangle_{MC} = 0.17 \pm 0.03$. We therefore conclude from our data that the $\bar{\Lambda}\Lambda$ pairs are produced preferably in a spin-one state. In the context of the static quark model picture, this should then also hold for the embedded $\bar{s}s$ quark pair.

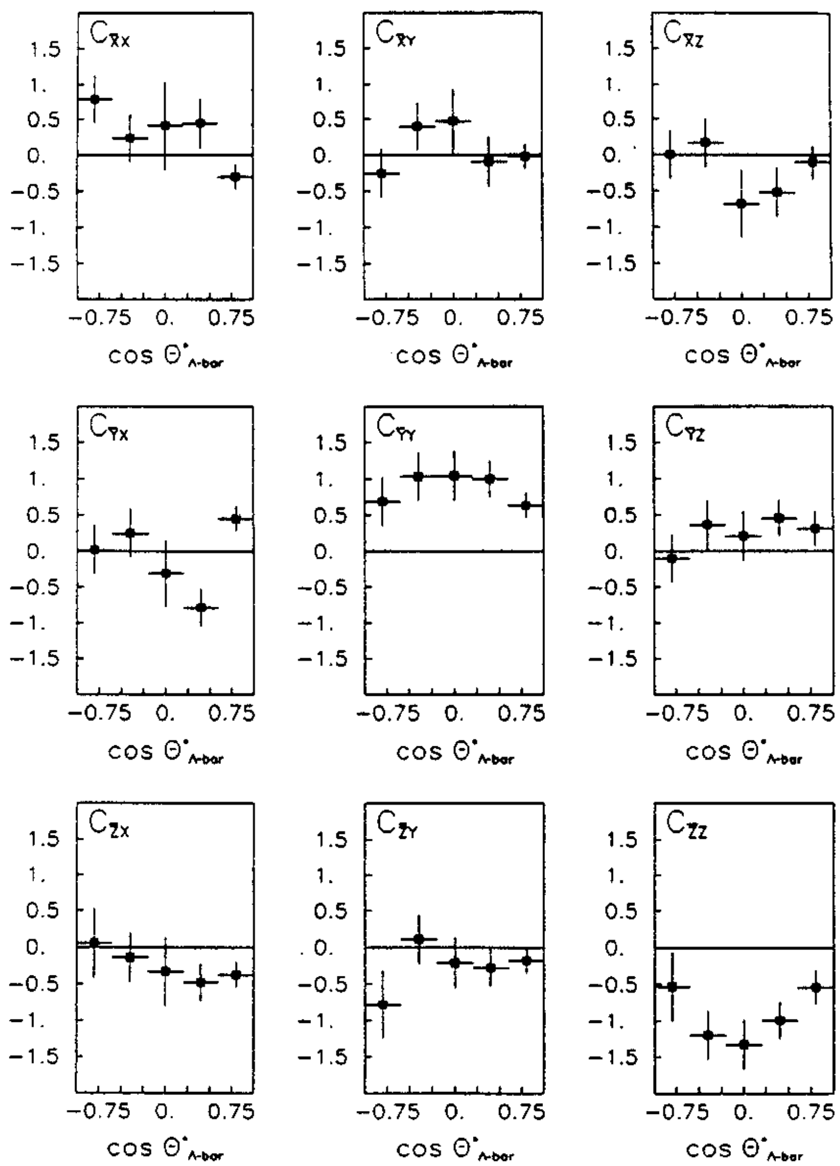

Figure 4: Hyperon spin-correlation coefficients from $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ at 1.546 GeV/c incident $\bar{p}$ momentum.

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