SELECTED PHYSICS RESULTS FROM THE HERMES EXPERIMENT

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1. Introduction

The HERMES experiment stopped data taking in 2007. Most of the data were collected using the 27.6 GeV longitudinally polarized positron beam scattered off a hydrogen or deuterium target. A typical beam polarization was about 50 %. The targets were longitudinally or transversely polarized with the polarization close to 90 %. The whole HERMES data set was accumulated at an integrated luminosity of 1505 pb^{-1}.

The HERMES Collaboration studied sum rules for the nucleon spin, quark helicity distributions, polarization of gluons, transverse spin effects, exclusive reactions and GPDs, hyperon polarization, nuclear medium effects. These studies play a key role in better comprehension of the QCD dynamics and spin structure of hadrons.

The PNPI group was involved in the HERMES experiment since its design phase with significant contributions both to the experiment and data analysis. In the data analysis, PNPI takes an active part in several analysis topics such as quark helicity distribution, vector meson electroproduction, polarization of Λ hyperons. Here we present most important results obtained in 2007–2011 years for two analysis topics where the PNPI group plays the leading role.

2. Exclusive electroproduction of vector mesons in deep-inelastic scattering

A study of exclusive electroproduction of vector mesons on nucleons allows for verification of perturbative QCD (pQCD) predictions and gives access to the Generalized Parton Distributions (GPDs) of nucleons. In the one-photon-exchange approximation, the angular distribution of exclusively produced vector-mesons and their decay into final hadrons can be described with the help of the Spin Density Matrix Elements (SDMEs) or, alternatively, in terms of the helicity amplitudes related to the beam/target spin states. The SDME analysis of the ρ^0 meson production studied by the HERMES Collaboration with the help of the HERA polarized positron beam and an unpolarized proton or deuteron target is presented in [1]. The kinematics of the reaction under study was as follows: the photon virtuality $1 < Q^2 < 7$ GeV^2, the centre-of-mass energy of the photon-nucleon scattering $3.0 < W < 6.3$ GeV, the square of the four-momentum transferred to the nucleon $-t < 0.4$ GeV^2. In this experiment, in addition to fifteen unpolarized SDMEs, eight polarized SDMEs were obtained for the first time. The theoretically predicted hierarchy of the SDMEs was observed. The phase difference between the helicity-conserving amplitudes T_{11} and T_{00} was found to be significantly non-zero and Q^2 dependent. It should be noted that the latter observation is in contradiction with the theoretical calculations [2] based on the pQCD with the GPDs of the nucleon well describing the HERA collider data. The kinematic dependences of all 23 SDMEs are measured for both hydrogen and deuterium targets. No significant difference between the proton and deuteron results is seen, which shows that the ρ^0 meson production is dominated by the two-gluon exchange diagrams. On the other hand, the evaluation of certain linear combinations of SDMEs provides an indication that contributions of Unnatural-Parity-Exchange (UPE) amplitudes at not very high energy of the HERMES experiment can be measured. The violation of the *s*-channel helicity is established with high experimental accuracy for the transition of the transverse virtual photon to the longitudinal ρ^0 meson. Contributions of the transitions of the longitudinal photon to the transverse meson and the double spin-flip transition of the transverse photon to the transverse ρ^0 meson also violating the *s*-channel helicity are shown to be small in accordance with theoretical predictions [3, 4].

Any SDME may be expressed through bilinear products of the helicity amplitudes in its numerator and denominator. The numerator contains typically more than one bilinear product. Due to this SDME property it is not easy to understand which amplitude is not well described with theory when the calculated and measured SDMEs disagree. It is not trivial also to interpret the kinematic dependences of SDMEs in terms of the kinematic dependences of the amplitudes and confirm the hierarchy among the amplitudes predicted in [3, 4]. A direct extraction of the amplitude ratios (the measured angular distributions depend on the amplitude ratios rather than on the amplitudes themselves) excludes these shortcomings. This “amplitude” approach allows for a direct comparison of the pQCD predictions and experimental results and for better specification of the reaction mechanism than that using the SDME method. The most important amplitudes are those without the nucleon spin flip when the data on unpolarized targets are studied. They are denoted $T_{\lambda\mu}$ where λ and μ are helicities of the ρ^0 meson and the virtual photon. The results of the amplitude analysis of the same HERMES data sample as in [1] are published in [5, 6]. The ratios of the helicity amplitudes to T_{00} are determined by fitting the measured angular distributions of the final state pions. Given the electron / positron beam is longitudinally polarized, the extraction of both the real and imaginary parts of the ratios of the natural parity exchange amplitudes $T_{\lambda\mu}$ is possible. The modulus of the ratio $|U_{11}/T_{00}|$, where U_{11} denotes the UPE amplitude, can now be directly found. The ratios T_{11} / T_{00}, T_{01} / T_{00}, and $|U_{11}/T_{00}|$ are found to be sizable and their kinematic dependences are parameterized, while all other similar ratios are proved to be small. The real part of T_{11} / T_{00} is found to follow the asymptotic $1/Q$ behaviour predicted by the pQCD [3, 4].

The HERMES data are in agreement with those of the H1 Collaboration [7] as seen in Fig. 1. The imaginary part of T_{11}/T_{00} grows with Q in contradiction with the large-Q asymptotic behaviour expected in the pQCD. The phase difference between T_{11} and T_{00} grows with Q and has a mean value of about 30 degrees in the HERMES kinematic region, which is in agreement with the SDME method [1] but at sharp variance with pQCD based calculations [2]. The behaviour of $\mathrm{Im}(T_{01}/T_{00})$ does not contradict to the asymptotic pQCD behaviour, while $\mathrm{Re}(T_{01} / T_{00})$ is independent of Q, which disagrees with the pQCD. The HERMES result for $\mathrm{Re}(T_{01}/T_{00})$ is close to that of the H1 Collaboration obtained for higher values of Q as can be seen in Fig. 2 where the dependence of the amplitude ratio on the Mandelstam variable t is presented. This comparison shows also that $\mathrm{Re}(T_{01}/T_{00})$ does not depend on Q for the measured values of the photon virtuality. The UPE signal (the non-zero ratio $|U_{11}/T_{00}|$) is seen with a very high significance for both the proton and deuteron data, confirming the existence of the UPE contribution with a higher precision than that obtained with the SDME method. Finally, we would like to stress that the amplitude method permits to study the kinematic dependences and contributions of small amplitudes better than the SDME method with typically smaller statistical uncertainties. This allows for more definite physical conclusions on the QCD dynamics and vector meson production mechanisms.

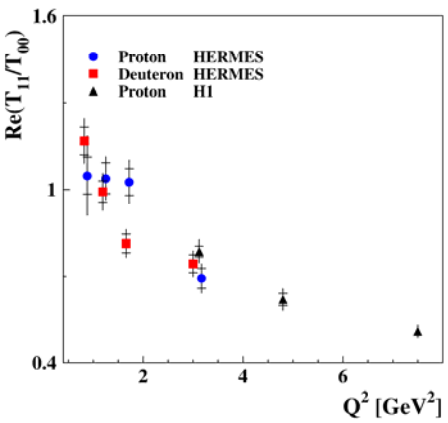

Fig. 1. Q^2 dependence of the helicity amplitude ratio

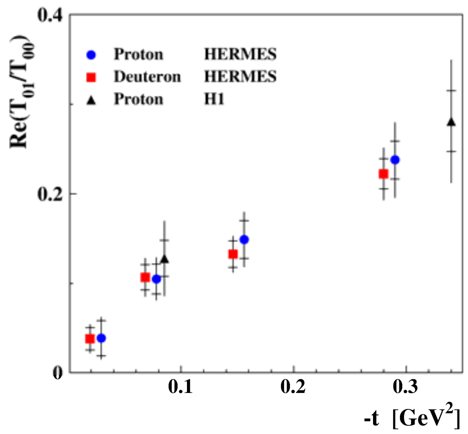

Fig. 2. t dependence of the helicity amplitude ratio

3. Spin transfer to the Λ and $\bar{\Lambda}$ hyperons in semi-inclusive deep-inelastic positron scattering

According to the latest measurements by the HERMES and COMPASS Collaborations, the total quark contribution to the proton spin is found to be $\Delta\Sigma = 0.33 \pm 0.03$ [8]. Using this number and two well-known hyperon β-decay constants ($F = 0.464 \pm 0.008$, $D = 0.806 \pm 0.008$) one can calculate the first moment of the polarized quark distribution $\Delta q_f = q_f^{\uparrow} - q_f^{\downarrow}$ for any SU(6) spin ½ baryon octet state. Here, $f = u, d, s$ is the quark flavour, $q_f^{\uparrow}$, $q_f^{\downarrow}$ is the integrated number density of the quark aligned parallel or anti parallel to the baryon spin, respectively. Thus, for the Λ hyperon one obtains $\Delta q_u^{\Lambda} = \Delta q_d^{\Lambda} = 1/3\ (\Delta\Sigma - D) = -\,0.16 \pm 0.01$ and $\Delta q_s^{\Lambda} = 1/2\ (\Delta\Sigma + D) = 0.57 \pm 0.01$. It is commonly agreed that the Λ spin is preferentially carried by the strange quark, while the contribution from the light quarks, even the sign of this contribution, is still debatable. Thus, in the naïve constituent quark model $\Delta q_u^\Lambda = \Delta q_d^\Lambda = 0$ and $\Delta q_s^\Lambda = 1$ ($\Delta\Sigma = 1$ and $D = 1$ should be taken), *i.e.* the Λ hyperon spin is entirely carried by the *s*-quark, while the light quarks are not polarized. A similar conclusion follows from the lattice-QCD calculations [9]: $\Delta q_u^\Lambda = \Delta q_d^\Lambda = -0.02 \pm 0.04$ and $\Delta q_s^\Lambda = 0.68 \pm 0.04$. Alternatively, it was shown in [10] that the hyperfine interaction responsible for $\Delta - N$ and $\Sigma^0 - \Lambda$ mass splitting results in significantly positive polarized non-strange quark distributions.

Experimental information on the hyperon spin structure can be obtained by measuring the spin transfer to the hyperon produced in the process of polarized quark fragmentation. In the case of $\Lambda(\bar{\Lambda})$, the hyperon polarization (spin transfer) can be measured via the weak decay channel $\Lambda \to p + \pi^-$ ($\bar{\Lambda} \to \bar{p} + \pi^+$) through the angular distribution of the final state particle. It is important that, as compared to other hyperons, the yield of the Λ hyperons is typically high enough to obtain satisfactory statistical precision of the polarization measurements. In the LEP experiments OPAL and ALEPH [11, 12], Λ hyperons were predominantly produced via $Z^0 \to s\bar{s}$ decay, both strange quarks being strongly polarized. The measurements indicate a significant $\Lambda(\bar{\Lambda})$ polarization and positive spin transfer from the strange quark. These experiments confirm high positive polarization of the *s* quark in the Λ hyperon with Δq_s^Λ in the range of 0.6 to 1. In Deep Inelastic Scattering (DIS) of polarized leptons from nucleons, in contrast to Z^0 decay experiments, Λ hyperons are mostly produced due to fragmentation of non-strange polarized *u* and *d* quarks. In the case of Λ hyperons, non-strange quarks also dominate with somewhat larger contributions from $\bar{u}$ and $\bar{s}$ antiquarks.

Here we present the final HERMES results on the spin transfer to the Λ and $\bar{\Lambda}$ hyperons in DIS. They surpass substantially the data sample in [13, 14] in statistical precision. Unlike previous publication, the spin transfer is treated as a vector in the Λ rest frame. Correspondently, a three dimension analysis formalism has been developed in order to reconstruct all three components of this vector.

In the quark parton model, the process of fragmentation of a polarized struck quark to the polarized Λ (or $\bar{\Lambda}$) hyperon can be quantified in terms of the spin dependent (polarized) $\Delta F_f^\Lambda(z)$ and spin independent (unpolarized) $F_f^\Lambda(z)$ fragmentation functions. The partial (for a given flavour *f*) spin transfer $D_f^\Lambda(z)$ can be defined as

$$D_f^\Lambda(z) = \frac{\Delta F_f^\Lambda(z)}{F_f^\Lambda(z)} = \frac{F_{f\uparrow}^{\Lambda\uparrow}(z) - F_{f\uparrow}^{\Lambda\downarrow}(z)}{F_{f\uparrow}^{\Lambda\uparrow}(z) + F_{f\uparrow}^{\Lambda\downarrow}(z)}. \tag{1}$$

Here, $F_{f\uparrow}^{\Lambda\uparrow\downarrow}(z)$ stands for the fragmentation function of a quark (antiquark) of flavour *f* with the positive helicity fragmenting into the Λ hyperon with the positive or negative helicity, $z = E^\Lambda/\nu$ is the fractional energy of the emitted Λ hyperon, ν is the photon energy totally transferred to the struck quark, and E^Λ is the Λ hyperon energy. If the target is unpolarized, the observed Λ polarization reads:

$$P^\Lambda(x, y, z, Q^2) = D^\Lambda(x, z, Q^2) P_b D(y) = \left(\sum_f \omega_f^\Lambda(x, z, Q^2) D_f^\Lambda(z, Q^2) \right) P_b D(y). \tag{2}$$

Here, $D^\Lambda(x, z, Q^2)$ is the total spin transfer, P_b is the beam polarization, $D(y) = [1-(1-y)^2]/[1+(1-y)^2]$ represents the spin transfer from the incident positron to the struck quark (or the depolarization factor of the virtual photon), $y = \nu / E_{\text{beam}}$ is the fractional energy carried by the photon. The Bjorken scaling variable *x* in the target rest frame is given by $x = Q^2/2M_p\nu$, where M_p is the target proton mass and Q^2 is the negative four-momentum transfer squared. It is easy to see that the value $P_b D(y)$ stands for the polarization of the struck quark, $\omega_f^\Lambda(x, z, Q^2)$ represents the purity (fractional probability) for a quark (antiquark) of flavour f to fragment to the Λ hyperon ($\sum_f \omega_f^\Lambda(x, z, Q^2) = 1$). If one assumes that the struck quark f fragmenting to Λ ($\bar{\Lambda}$) preserves its polarization, the partial spin transfer integrated over *z* can be expressed through the first moments of the polarized and unpolarized quark density distributions in the Λ ($\bar{\Lambda}$) hyperon [15]:

$$D_f^{\Lambda}(Q^2) = \frac{\Delta q_f^{\Lambda}(Q^2)}{q_f^{\Lambda}(Q^2)}, \qquad (3)$$

i.e. the partial spin transfer of a quark f to the Λ ($\bar{\Lambda}$) hyperon is given by the average polarization of this quark in Λ ($\bar{\Lambda}$). Despite a number of simplifying assumptions that have been made in deriving Eq. 3, this equation is a useful starting point for qualitative understanding of the spin transfer. Due to the valence quark dominance ($\omega_u^{\Lambda} + \omega_d^{\Lambda} \approx 1$), the measurement of D^{Λ} can provide a realistic measure of the non-strange quark polarization in the Λ hyperon.

The experiment and event selection were described in detail in [13]. The Λ ($\bar{\Lambda}$) hyperons produced in semi-inclusive reactions were detected via $p\pi^-$ ($\bar{p}\pi^+$) weak decay channel. In order to control false asymmetry, a K_s data sample was also accumulated detecting $K_s \to \pi^+\pi^-$ decay. Invariant mass distributions for Λ, $\bar{\Lambda}$ and K_s events are shown in Fig. 3. N_{Λ}, $N_{\bar{\Lambda}}$, N_{K_S} in Fig. 3 are the total number of events after background subtraction, σ is the Λ and $\bar{\Lambda}$ peak resolutions, and (1 – η) is the background contributions.

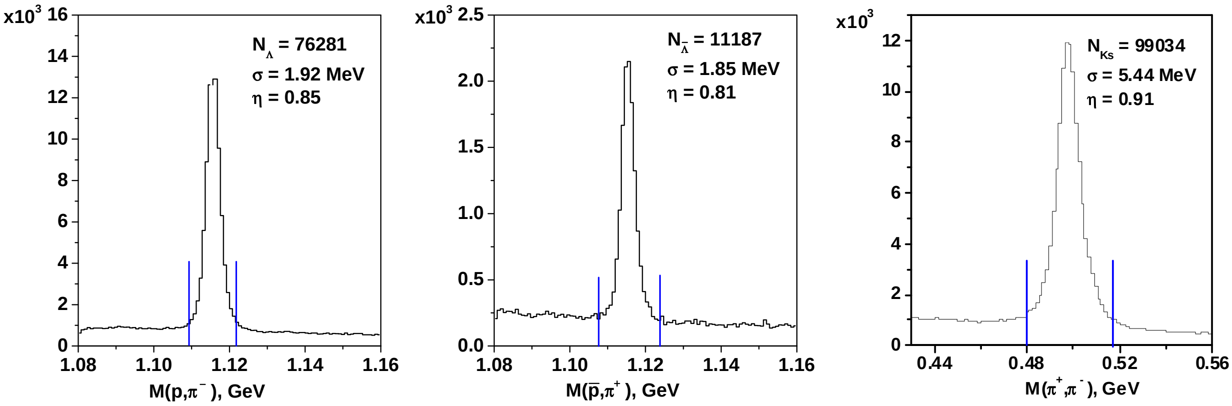

Fig. 3. Invariant mass distributions for Λ, $\bar{\Lambda}$ and K_s events

The spin transfer can be defined in the Λ rest frame as a vector with longitudinal and transverse components both belonging to the production plane formed by the virtual photon momentum $\vec{p}_{\gamma}$ and the Λ momentum $\vec{p}_{\Lambda}$. As the virtual photon is longitudinally polarized (its spin is assumed to direct along the $\vec{p}_{\gamma}$ vector), the component perpendicular to the Λ production plane must be equal to zero because of parity conservation. The coordinate system is defined as follows: the *Z*-axis is taken along the virtual photon momentum $\vec{p}_{\gamma}$ boosted to the Λ rest frame, the *Y*-axis is perpendicular to the production plane, and the *X*-axis is perpendicular to the *YZ* plane.

During the data taking period, the beam polarization was reversed on a month basis such that for the selected data sample the condition $[\![P_b]\!] \approx 0$ was fulfilled. Here, $[\![P_b]\!]$ is the luminosity weighted beam polarization. The extraction of the D_{Li} components is essentially facilitated in this case as no Monte Carlo simulation of the spectrometer acceptance function is needed [13]. Here, the subscript L indicates the direction of the virtual photon spin, i = x, y, z. The spin transfer components for Λ and $\bar{\Lambda}$, integrated over the whole data sample, are presented below:

$$D_{Lx}^{\Lambda} = -0.016 \pm 0.042_{\text{stat}} \pm 0.02_{\text{syst}} \qquad D_{Lx}^{\bar{\Lambda}} = -0.14 \pm 0.11_{\text{stat}} \pm 0.02_{\text{syst}}$$
$$D_{Ly}^{\Lambda} = 0.004 \pm 0.037_{\text{stat}} \pm 0.02_{\text{syst}} \qquad D_{Ly}^{\bar{\Lambda}} = 0.05 \pm 0.10_{\text{stat}} \pm 0.02_{\text{syst}}$$
$$D_{Lz}^{\Lambda} = 0.186 \pm 0.040_{\text{stat}} \pm 0.02_{\text{syst}} \qquad D_{Lz}^{\bar{\Lambda}} = 0.05 \pm 0.10_{\text{stat}} \pm 0.02_{\text{syst}}$$
$$\left|D_{LL'}^{\Lambda}\right| = 0.187 \pm 0.040_{\text{stat}} \pm 0.02_{\text{syst}} \qquad \left|D_{LL'}^{\bar{\Lambda}}\right| = 0.15 \pm 0.11_{\text{stat}} \pm 0.02_{\text{syst}}$$

For both Λ and $\bar{\Lambda}$ hyperons, the D_{Ly} component is found compatible with zero as it should be. For Λ hyperons, the quantization axis is directed practically along the virtual photon momentum (along the Z-axis), the transverse component being correspondently small (compatible with zero), *i.e.* the Λ polarization preserve the spin orientation of the struck quark and $L' = L$, L' being the Λ spin direction. For $\bar{\Lambda}$, the statistical accuracy is not sufficient to come to a similar conclusion.

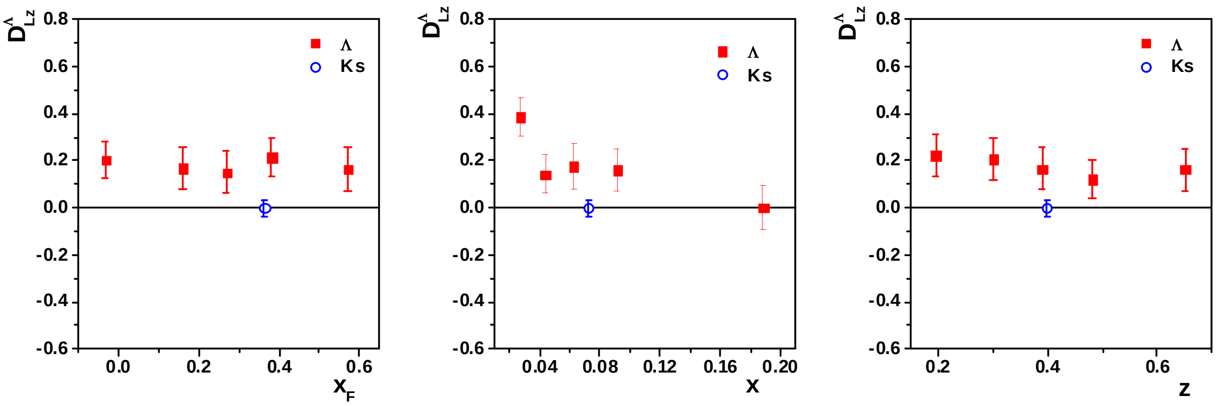

Fig. 4. Dependences of the longitudinal spin transfer to the Λ hyperon on DIS kinematic variables

In Fig. 4, dependences of D^{Λ}_{Lz} on DIS kinematic variables are presented. As seen in Fig. 4, false asymmetries estimated with the K_s data sample are found to be negligibly small and compatible with zero. Comparisons with world data are presented in Fig. 5.

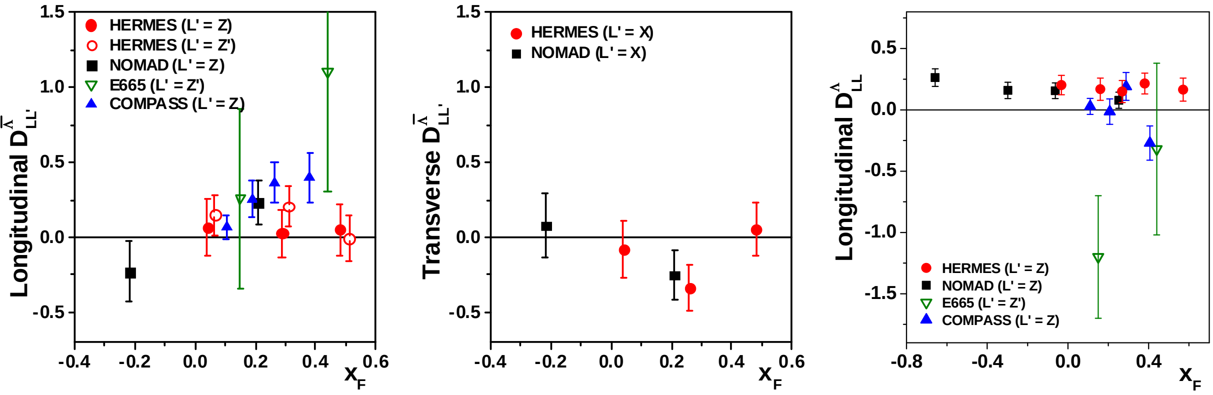

Fig. 5. World data on the longitudinal and transverse spin transfer to the $\bar{\Lambda}$ hyperon and the longitudinal spin transfer to Λ

For Λ hyperons, the obtained results on the longitudinal spin transfer are in good agreement with the NOMAD [16] and recent COMPASS [17] experiments at moderate values of the Feynman scaling variable x_F, while the HERMES and COMPASS results disagree with each other at x_F larger than 0.4. For $\bar{\Lambda}$ hyperons, all D_{Li} components are compatible with zero within statistical error bars of $\pm$ 0.1. Open circles in Fig. 5 (left panel) are the HERMES data with the Z-axis chosen along the momentum of the $\bar{\Lambda}$ hyperon in the laboratory frame.

To conclude, the longitudinal component of the spin transfer to the Λ hyperon is found to be $D^{\Lambda}_{LL} = 0.19 \pm 0.04_{\text{stat}} \pm 0.02_{\text{syst}}$. It is directed along the virtual photon momentum in the Λ rest frame while two other (transverse) components are compatible with zero. A positive and statistically significant value of D^{Λ}_{LL} can be interpreted in favour of a noticeable positive contribution of the light u and d quarks to the Λ spin suggesting $\Delta q^{\Lambda}_{u} = \Delta q^{\Lambda}_{d} \approx 0.2$ in contradiction to the SU(6) prediction based on the value of $\Delta\Sigma = 0.33$, well-established for the proton. A possibility of sizeable SU(6) symmetry breaking in the quark distributions of the Λ hyperon and positive non-strange quark polarization in Λ is discussed in [10, 18].

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