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SIDIS measurements of leading-twist spin azimuthal asymmetries

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Summary. — In this paper an experimental overview of the leading-twist transverse- and longitudinal-spin azimuthal asymmetries measured by SIDIS experiments is given. The recent results from HERMES, COMPASS and JLab experiments are discussed.

PACS 13.60.-r – Photon and charged-lepton interactions with hadrons.
PACS 13.88.+e – Polarization in interactions and scattering.
PACS 13.87.Fh – Fragmentation into hadrons.

1. – Introduction

In the context of the investigation of the nucleon spin structure, the study of transverse-spin and transverse-momentum–dependent (TMD) effects is nowadays attracting much interest. A wide international effort is ongoing in order to enlarge the knowledge on the TMD Parton Distribution Functions (PDF) and Fragmentation Functions (FF), both from the theoretical and from the experimental side.

In line with the experiments that provided the first information on the nucleon spin structure, Deep Inelastic Scattering (DIS) reactions are used or have been used in different laboratories as a simple and powerful tool to investigate TMD effects. For these studies, leptons are scattered off polarised targets, and at least one hadron in the final state is detected (Semi Inclusive reactions — SIDIS). Three laboratories have been involved in this type of measurements till now: DESY (HERMES experiment), CERN (COMPASS experiment) and JLab (CLAS and Hall A Collaboration).

In parallel to the investigation by means of SIDIS, at the Brookheaven National laboratory (RHIC experiments) hard scattering of transversely polarised protons is used to extract information on TMD PDFs. For the future a very promising channel is (polarised) Drell-Yan, for which several projects are being discussed at different laboratories.

In the following only the measurements from SIDIS experiments are discussed.

2. – SIDIS and spin asymmetries

The main advantage of the SIDIS process is that TMD effects are not mixed: at variance with hadroproduction, the TMD effects generate different azimuthal modulations in the SIDIS cross section, which can be separately explored and extracted from the same data. The modulations are the combination of two angles, ϕ_S and ϕ_h, respectively the azimuthal angle of the initial nucleon spin and of the produced hadron momentum. The angles are defined with respect to the direction of the virtual photon, defining the z-axis of the so-called Gamma Nucleon System, in which the xz-plane is defined by the lepton scattering plane. The amplitudes of the modulations are different structure functions, proportional to the convolution of the TMD PDFs and FFs. To access the structure functions appearing in the cross-section part depending on the target polarization, corresponding spin asymmetries are measured comparing the azimuthal distributions of hadrons produced in SIDIS off target with opposite spin orientation. In the following we focus on the leading twist effects, the higher twist effects being discussed in [1]. At leading twist, five spin asymmetries are allowed:

- $A_{UT}^{sin(\phi_h+\phi_S)} \propto h_1 \bigotimes H_1^{\perp}$ (Collins asymmetries),
- $A_{UT,T}^{sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp} \bigotimes D_1$ (Sivers asymmetries),
- $A_{UT}^{sin(3\phi_h-\phi_S)} \propto h_{1T}^{\perp} \bigotimes H_1^{\perp}$,
- $A_{UL}^{sin(2\phi_h)} \propto h_{1L}^{\perp} \bigotimes H_1^{\perp}$,
- $A_{LT}^{cos(\phi_h-\phi_S)} \propto g_{1T} \bigotimes D_1$.

In the labelling of the asymmetries, the first and the second subscripts indicate the beam and target polarization (U: unpolarized, L: longitudinal and T: transverse), the third subscript indicates the virtual photon polarization, and the superscript refers to the azimuthal modulation. As can be seen on the right-hand side of the above equations, each asymmetry gives access to a different PDF, convoluted with the unpolarized FF (D_1) or the Collins FF ($H_1^{\perp}$) describing the correlation between the quark spin and the momentum of the produced hadron.

The PDFs contained in the first 3 asymmmetries, h_1, $f_{1T}^{\perp}$ and $h_{1T}^{\perp}$ are respectively the transversity, the Sivers and the pretzelosity PDFs. They can be accessed experimentally in the same way, using an unpolarized beam impinging on a transversely polarized target. The two PDFs g_{1T} and $h_{1L}^{\perp}$ are usually called "worm-gears": g_{1T} ($h_{1L}^{\perp}$) represents the probability of finding a longitudinally (transversely) polarized quark inside a transversely (longitudinally) polarized nucleon. The way these functions can be accessed experimentally is different: the TMD PDF g_{1T} can be accessed via double spin asymmetries, with a longitudinally polarized beam and a transversely polarized target; $h_{1L}^{\perp}$ can be accessed measuring longitudinal target single spin asymmetries.

3. – The experiments

The features of the SIDIS spin asymmetry measurements common to all the experiments are the use of polarized targets (and polarized beam in case of double spin asymmetries), and of large acceptance spectrometers with particle identification. In particular, the spectrometer has to provide the identification of the scattered lepton and of the produced hadrons, with a large azimuthal angle acceptance.

For a global interpretation of the measurements, the complementarity between different experiments is a key issue. In particular it is important to measure with different target materials (p, n) the asymmetries for different hadrons to allow flavor separation analyses, and thus the extraction of the different TMD PDFs for each quark flavor. Measurements of azimuthal spin asymmetries with on several target materials already exist. To measure on proton and deuterium, HERMES used gaseous targets of hydrogen and deuterium, while COMPASS used solid state targets of NH_3 and ^{6}LiD; an ammonia target was also used by CLAS Collaboration. Finally first handle on the neutron via the use of a ^{3}He gas target has been recently provided by the JLab Hall A Collaboration.

To investigate the kinematic dependence of the asymmetries and disentangle leading and higher twist effects, a large coverage of the kinematical domain is also important. The accessible kinematic variable ranges depend on the luminosity, as well as on the lepton beam energy that is very different at the three laboratories: COMPASS uses a muon beam of 160 GeV/c, HERMES and JLab experiments electron beams of 27.5 GeV/c and 6 GeV/c, respectively. This difference reflects into an almost complementarity range covered for the Bjorken variable x as well as in other correlated variables: the HERMES range is $0.023 < x < 0.4$, while COMPASS allow to access the very low x region ($0.004 < x < 0.3$), and JLab experiments the large x region ($0.14 < x < 0.4$) with high statistics. When comparing the results from the experiments at the same x values, one has to keep in mind that the mean Q^2 values are different. For example, in the region of x around 0.2-0.3, the Q^2 mean value reached by COMPASS is of the order of $20\,(\mathrm{GeV}/c)^2$, a value 6 and 10 times larger than those of HERMES and JLab experiments respectively.

The phase space is also determined by the cuts, that can vary in the different analyses. Usually the cut $Q^2 > 1\,(\mathrm{GeV}/c)^2$ is applied in all the analyses to ensure DIS regime. To avoid resonance regions, a lower limit on W, the hadronic state mass, is imposed, and due to the different W range covered, also this limit is different in the different experiments. Also a lower cut on the relative energy z of each hadron is imposed to avoid the target fragmentation region, the value of the cut depending on W. In some analyses also higher cut on z is used ($z < 0.7$–0.85) to avoid exclusive production, and a further limitation on the relative energy is imposed by the particle identification, since the involved detectors work usually in very precise momentum ranges.

4. – Results on TMD PDFs

4·1. *Transversity*. – In 2005 the HERMES experiment measured for the first time the Collins asymmetries for positive and negative pions on a proton target [2]; the asymmetries were found to be different from zero and provided the first evidence that both the transversity PDF and the Collins FF are different from zero. In parallel first measurement of the Collins asymmetries on a deuterium target were provided by COMPASS [3]; the asymmetries were found compatible with zero within the statistical accuracy, of few percents. The two different results, together with Belle asymmetries [4] in $e^+e^- \to h^+h^-$ reactions, could be described in a single unified picture by a global fit [5, 6]. The first results on the Collins asymmetries were confirmed later with much higher accuracy (errors of the order of 1%) both by HERMES [7] and COMPASS [8, 9]. The final results are shown, respectively, in fig. 1 and 2. All the asymmetries measured by COMPASS on deuteron were found to be zero, also for kaons. The asymmmetries on proton by HERMES show an increasing signal with x, of opposite sign for π^+ and π^-. Very intriguing is the result for K^+, showing a signal larger than that of π^+, hinting for a possible not negligible role of the sea quarks.

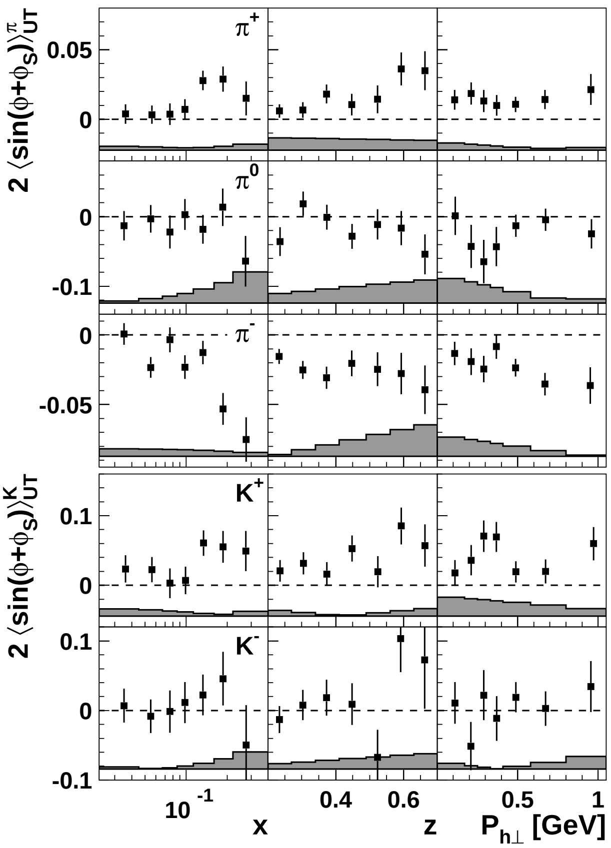

Fig. 1. – Collins asymmetries for pions and kaons on proton measured by HERMES as a function of x, z and hadron transverse momentum.

COMPASS has recently provided also measurements on a proton target [10]. At small x, a region uncovered by HERMES, the asymmetries are compatible with zero. In the valence region, the asymmetries are different from zero and in very good agreement with those of HERMES, a non obvious result because of the different kinematic range covered by the two experiments, implying a negligible Q^2 dependence of the Collins effect. Also preliminary results on asymmetries for kaons [11] have been produced. The K^+ signal seems also in this case larger than that of π^+, but the error bars are too large to draw a definite conclusion. At this workshop, the new results from the 2010 COMPASS data taking with a transversely polarized proton target are shown [12] for the first time. As can be seen in fig. 3, these new results confirm the former results with statistical error bars reduced of about a factor of 2, thus consolidating the overall picture.

First results for the Collins asymmetries on neutron have been recently provided by the JLab Hall A Collaboration [13]. Data on neutron as well as data on deuteron are very important to constrain the d quark PDF. The asymmetries for π^+ and π^-, shown in fig. 4, are compatible with zero, in agreement with expectation from models and fit.

4·2. *Sivers.* – As for the case of the Collins asymmetries, the first information on the Sivers spin asymmetries have been provided in 2005. The Sivers asymmetries were found

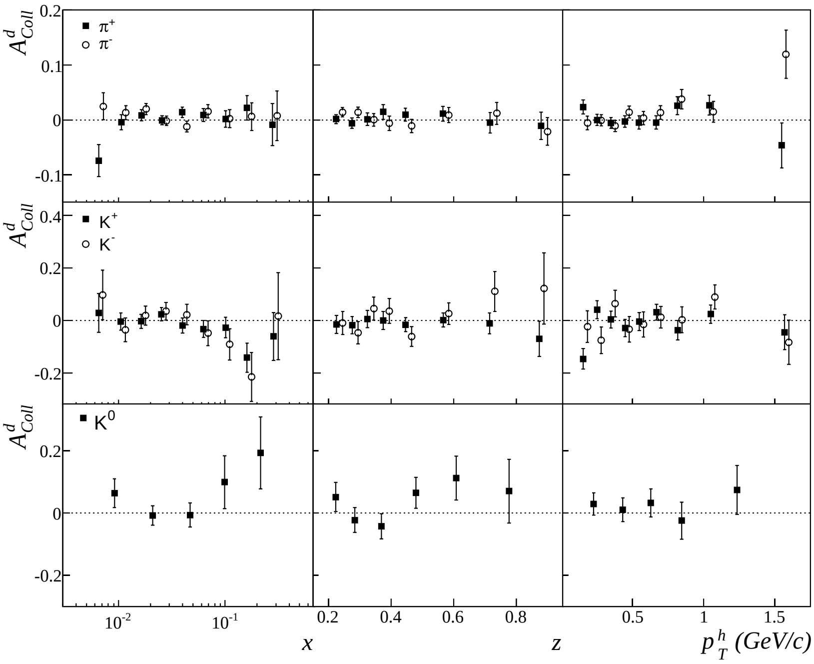

Fig. 2. – Collins asymmetries for pions and kaons on deuteron measured by COMPASS, as a function of x, z and hadron transverse momentum.

compatible with zero for positive and negative hadrons on deuteron by COMPASS [3], while HERMES measured a positive signal for π^+ on proton [2].

The two sets of data were interpreted in a unique framework and allowed for a first extraction of the Sivers PDFs [6, 14], found large and of opposite sign for the u and d quark. The COMPASS result is thus interpreted as a cancellation of the u and d quark contribution in the isoscalar target. Data with improved precision, confirming the previous results, have been produced by COMPASS and HERMES. In particular,

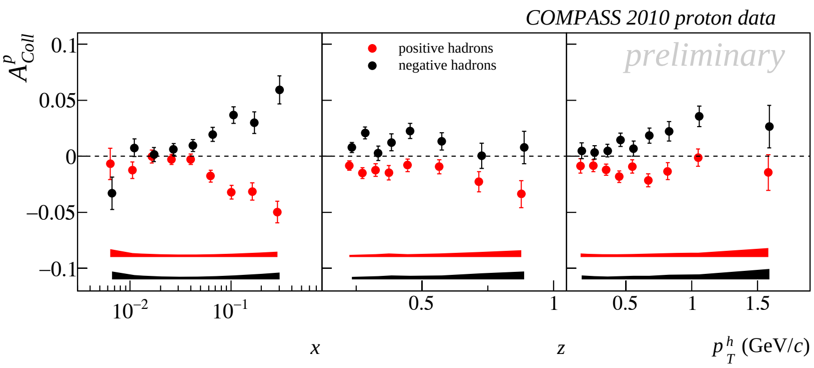

Fig. 3. – Preliminary Collins asymmetries for positive and negative hadrons on proton from 2010 COMPASS data.

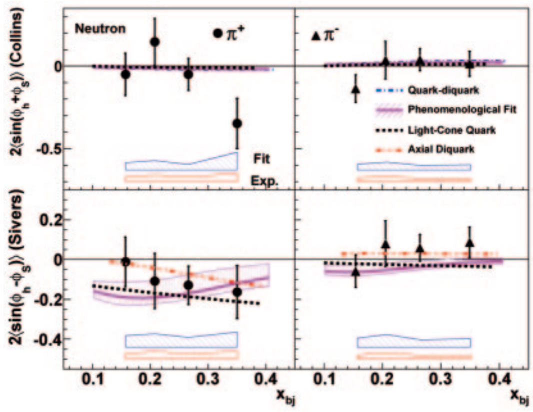

Fig. 4. – Collins and Sivers asymmetries for pions on neutron measured by the JLab Hall A Collaboration.

the results compatible with zero measured by COMPASS on deuteron [8, 9] were confirmed, also on charged and neutral kaons. As visible in fig. 5 HERMES [15] confirmed the non zero asymmetries for π^+ over all the measured x range, at variance with the Collins asymmetries, which go to zero at small x. Interesting are also the trends in other variables: the asymmetries are increasing with z, and increase linearly with the hadron transverse-momentum region up to 0.4 GeV/c, reaching than a plateau for large values. In fig. 5 also the final COMPASS results for a proton target [10] are shown. There is an evidence for a positive signal for positive hadrons extending to the small x region (gray points), in the region not measured by HERMES. In the overlap region between the two

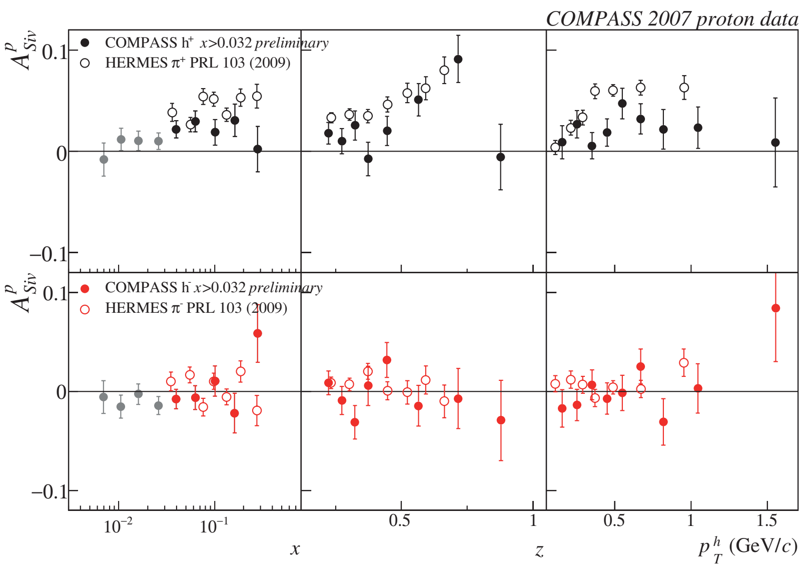

Fig. 5. – Comparison between the HERMES and COMPASS results for the Sivers asymmetry measured on a proton target, as a function of x, z and hadron transverse momentum.

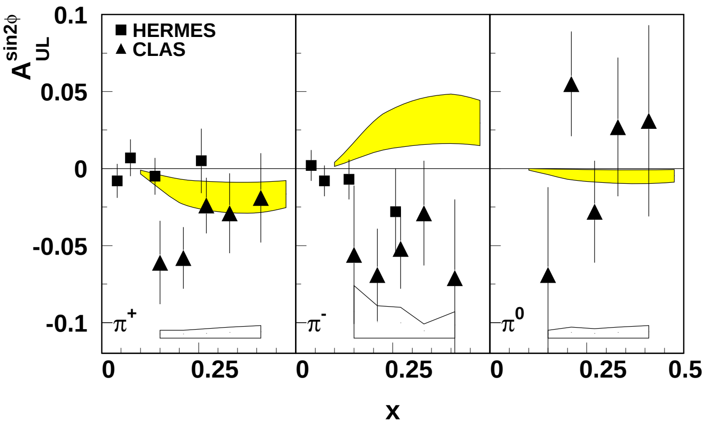

Fig. 6. – Comparison between the HERMES and CLAS results for the $A_{UL}^{sin(2\phi_h)}$ spin asymmetry for pions on proton.

experiments, at large x, the COMPASS asymmetries are smaller by about a factor of two with respect to HERMES's ones. The new COMPASS results on proton presented at this workshop [12] from the 2010 data confirm the older results, with a much better precision (error bars reduced of a factor 2.5), and small systematic uncertainties, at variance with the published results which had a scale error of $\pm 0.01\%$.

The overall picture on the Sivers effect is enriched from the recent results on neutron, from the JLab Hall A Collaboration [13], shown in fig. 4. The asymmetries, compatible with zero for π^- and at slightly negative values for π^+, are in agreement with global fit and prediction from light cone models. Unfortunately, the statistical errors are quite large.

4·3. *Pretzelosity.* – Preliminary results on the $A_{UT}^{sin(3\phi_h-\phi_S)}$ asymmetries have been produced by COMPASS for charged hadrons, both on deuteron [16] and proton [17] targets, and by HERMES for identified hadrons on proton target [18]. All the asymmetries have been found compatible with zero with very high precision. This can be a hint for a small pretzelosity PDF, or for a suppression due to the kinematical factors appearing in the asymmetry expression.

4·4. *Worm gears.* – Preliminary results on the $A_{LT}^{cos(\phi_h-\phi_S)}$ asymmetries, giving access to the g_{1T} PDFs exist from COMPASS, HERMES and JLab. COMPASS has measured the asymmetries for positive and negative hadrons, both on deuteron [16] and proton [17], finding all the asymmetries compatible with zero. HERMES measured the asymmetries for pions and kaons on proton [19], finding an hint for a positive signal, of the order of 2%, on π^-. A small positive signal for π^- was also seen by the JLab Hall A Collaboration, but measuring on the ^{3}He target [20].

COMPASS and HERMES provided results also on the $A_{UL}^{sin(2\phi_h)}$ asymmetry. The results on deuteron for positive and negative hadrons [21] (COMPASS), and for pions and K^+ [22] (HERMES) are compatible with zero. Results for pions on proton target are also available and are shown in fig. 6. HERMES results [23] have been found compatible with zero, while CLAS results [24] show a signal both for π^+ and π^-. Covering the large x range, thus the region of quark u dominance, the CLAS result is of particular interest, since it can allow a first glimpse to worm gear $h_{1L}^{\perp}$. It is also possible that the signal measured at CLAS is due to higher twist effects, or to target fragmentation and more investigation is needed to understand this asymmetry.

5. – Conclusions

It is nowadays clear that transverse-spin and -momentum effects are not negligible at high energies, and give rise to sizeable azimuthal asymmetries in SIDIS reactions. First experimental results have been provided in few past years from different SIDIS experiments, which cover almost complementary phase spaces and use different targets. The measurements provide a consistent picture for Sivers and Collins asymmetries, still with room for improvement on some issues (like Q^2 and hadron transverse-momentum–dependence), as well as first information on other interesting TMD PDFs, like pretzelosity and worm gears. In the near future new data will come from the COMPASS and JLab experiments, but the existing set of data is already quite complete. All these measurements could be used in a unique global fit in order to get a clearer picture of the relevance of the different TMD effects.

REFERENCES

[1] Avakian H., these proceedings.
[2] Airapetian A. *et al.* (HERMES Collaboration), *Phys. Rev. Lett.*, **94** (2005) 012002.
[3] Alexakhin V. Yu. *et al.* (COMPASS Collaboration), *Phys. Rev. Lett.*, **94** (2005) 202002.
[4] Vossen A., these proceedings.
[5] Anselmino M. *et al.*, *Phys. Rev. D*, **75** (2007) 054032.
[6] Melis S., these proceedings.
[7] Airapetian A. *et al.* (HERMES Collaboration), *Phys. Lett. B*, **693** (2010) 11.
[8] Ageev E. S. *et al.* (COMPASS Collaboration), *Nucl. Phys. B*, **765** (2007) 127.
[9] Alekseev M. *et al.* (COMPASS Collaboration), *Phys. Lett. B*, **673** (2009) 127.
[10] Alekseev M. G. *et al.* (COMPASS Collaboration), *Phys. Lett. B*, **692** (2010) 240.
[11] Pesaro G. (COMPASS Collaboration), *J. Phys.: Conf. Ser.*, **295** (2011) 012058.
[12] Bradamante F. (COMPASS Collaboration), these proceedings.
[13] Qian X. *et al.* (Jefferson Lab Hall A Collaboration), *Phys. Rev. Lett.*, **107** (2011) 072003.
[14] Anselmino A. *et al.*, *Proceedings of the Transversity 2005, Como, September 7-10, 2005*, edited by Barone Vincenzo and Ratcliffe Philip G.
[15] Airapetian A. *et al.* (HERMES Collaboration), *Phys. Rev. Lett.*, **103** (2009) 152002.
[16] Parsamyan B. (COMPASS Collaboration), *Eur. Phys. J. ST*, **162** (2008) 89.
[17] Parsamyan B. (COMPASS Collaboration), *J. Phys.: Conf. Ser.*, **295** (2011) 012046.
[18] Pappalardo L. L. (HERMES Collaboration), *Proceedings of the 4th Workshop on Exclusive Reactions at High Momentum Transfer (Exclusive 2010), JLAB, Newport News, Virginia USA, May 18 - 21, 2010.*
[19] Pappalardo L. L. (HERMES Collaboration), *Proceedings of the XIX International Workshop DIS 2011, Newport News, VA USA, April 11-15, 2011* (American Institute of Physics) 2011.
[20] Huang J. *et al.* (Jefferson Lab Hall A Collaboration), *Phys. Rev. Lett.*, **108** (2012) 052001.
[21] Alekseev M. *et al.* (COMPASS Collaboration), *Eur. Phys. J. C*, **70** (2010) 39.
[22] Airapetian A. *et al.* (HERMES Collaboration), *Phys. Lett. B*, **562** (2003) 182.
[23] Airapetian A. *et al.* (HERMES Collaboration), *Phys. Rev. Lett.*, **84** (2000) 4047.
[24] Avakian H. *et al.* (CLAS Collaboration), *Phys. Rev. Lett.*, **105** (2010) 262002.