Nucleon spin structure measurements at Jefferson Lab

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We summarize the measurements investigating the nucleon spin structure done at Jefferson Lab, a multi-GeV continuous electron beam facility located in Newport News, Virginia, USA. After motivating spin structure studies, we explain how Jefferson Lab uniquely contributes to them and describe the experimental program that was achieved with energies up to 6 GeV. We then discuss the continuation of this program at the higher energies now available thanks to the recent 12 GeV upgrade of Jefferson Lab’s accelerator.

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1 Introduction: why study the nucleon spin?

Spin degrees of freedom (d.o.f) in hadron structure studies have been actively used for more than 40 years [1]. Additional d.o.f test comprehensively a theory, as famously expressed by Bjorken [2]: “Polarization data have often been the graveyard of fashionable theories. If theorists had their way, they might well ban such measurements altogether out of self-protection.” In fact, Bjorken’s sum rule [3] played the leading role in establishing that perturbative QCD (pQCD) correctly describes the strong force at high energy, even when spin d.o.f are explicit.

Beside validating pQCD, one also needs to understand QCD at low energy, i.e. in its nonperturbative region. One approach is to study the origin of the nucleon spin, i.e. what values have the quantities in the right side of the nucleon spin sum rule

\[ J = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + \Delta G + L_g, \]  

Equation (1)

as they all have a nonperturbative origins. Here, \( J \) is the nucleon spin, \( \Delta \Sigma/2 \) is the contribution from the quark spins, \( L_q \) the contribution from their orbital angular momenta (OAM), \( \Delta G \) comes from the gluon spins and \( L_g \) from the gluon OAM. The success of the nonrelativistic constituent quark model in 1970s-1980s to describe the unpolarized nucleon structure suggested that only the quark spins were relevant, i.e. \( J \approx \Delta \Sigma/2 \). However, a first measurement yielded \( \Delta \Sigma \approx 0 \) [4] showing that the nucleon spin composition is not as trivial as what the constituent quark model suggested. This complexity signals that interesting information on the nucleon structure and on the strong force nonperturbative aspects are revealed by spin studies. Particularly, information can be gained on quark confinement and the emergence of effective d.o.f (hadrons) from fundamental ones (partons), as discussed in Section 3.

Such gains come from comparing data to nonperturbative calculations obtained using lattice calculations, the Dyson-Schwinger equations [5], or effective approaches like chiral perturbation theory (\( \chi PT \)) [6] or gauge-string duality (AdS/QCD) [7].

Another benefit of nucleon spin studies is that accurate parton distribution functions (PDFs) are needed for high energy research (e.g. for Standard Model tests and searches of new physics) or, on the other side of the energy scale, for atomic physics.

2 The 6 GeV Jefferson Lab nucleon spin program

We will mostly discuss here the inclusive Jefferson Lab (JLab) program. For reports on polarized semi-inclusive deep inelastic scattering (SIDIS) at HERMES and on RHIC-Spin, see the proceeding contributions of B. Seitz, M. Liu and O. Eyser.

The kinematics of JLab at 6 GeV are sketched in Fig. 1 in the energy transfer \( \nu \) and momentum transfer squared \( Q^2 \) space. The relevant d.o.f, which depend on kinematics, are also pictured. In the Bjorken limit \( \nu \to \infty \) and \( Q^2 \to \infty \), with \( x = Q^2/(2M\nu) \) finite (\( M \) is the nucleon mass), quarks are free and are thus the
relevant d.o.f. At high but finite $\nu$ and $Q^2$ (deep inelastic scattering, DIS), gluons appear and also become relevant d.o.f. As $\nu$ and $Q^2$ decrease, gluons increasingly bind the quarks until those react coherently to the probing process. Thus hadronic d.o.f. arise, replacing the partonic ones.

Figure 1: Sketch of the $(Q^2, \nu)$ coverage of JLab at 6 GeV (pink area). The nucleon’s changing aspects and relevant degrees of freedom are also pictured. In the squares are the names of the inclusive polarized experiments. The ellipses indicate their main topics.

Also shown in Fig. 1 are JLab’s polarized inclusive experiments and the main topics they addressed: E94-010 [8] and EG1 [9] chiefly studied sum rules in the parton to hadron transition region. They were continued at lower $Q^2$ ($\chi$PT region) by E97-110, E08-027, and EG4 [10]. E97-103 [11] and E06-014 [12] studied higher twists, i.e. the nonperturbative $1/Q^{2n}$ corrections arising once gluons link the PDF of the struck quark to the PDF of the other partons, which are thus no more spectators to the probing process. RSS [13], EG1dvcs [14], E01-012 [15] and SANE [16] measured the spin structure functions $g_1$ and $g_2$ in the DIS and resonance regions. Finally, E99-117 [17] investigated the high-$x$ region of DIS. Those are the main goals, but high quality ancillary data were also typically provided, e.g. higher twist evaluations from E94-010 and EG1, or high precision high-$x$ DIS data from E06-014.

### 2.1 PDF measurements

Valence quarks dominate in the DIS high-$x$ region, which simplifies the description of the nucleon structure. However, unpolarized PDFs decrease as $x \to 1$, which implies small cross-sections that are further suppressed by kinematic factors varying at first order as $1/x$. The high polarized luminosity of JLab allowed to measure precise spin
asymmetries in this region for the first time. The relative simplicity of the high-$x$ region allows for non-trivial pQCD constraints on the PDFs \cite{18}. Several model predictions also exist, including constituent quark models \cite{19}, the statistical model \cite{20}, hadron-parton duality \cite{21}, a Dyson-Schwinger approach \cite{22}, bag models \cite{23}, and chiral soliton, instanton or covariant quark-diquark models \cite{24}.

Assuming isospin symmetry and no sea quark, the quark polarizations $\Delta_u/u$ and $\Delta d/d$ can be calculated from the high-$x$ spin asymmetry measurements:

$$
\frac{g_1^p}{F_1} = \frac{4\Delta u + \Delta d}{4u + d}, \quad \frac{g_1^n}{F_1} = \frac{\Delta u + 4\Delta d}{u + 4d},
$$

where $F_1$ is the first unpolarized structure function. The quark polarizations are shown in Fig. 2 along with the predictions just listed and the NNPDF \cite{25}, DSSV \cite{26} and JAM \cite{27} global fits. Only the most precise high-$x$ data \cite{9,12,17} are shown. At lower $x$ where sea quarks are significant, SIDIS reactions are needed to separate quark flavors. The low $x$ data in Fig. 2 are from HERMES \cite{28}. A notable result at high $x$ is that $\Delta d/d < 0$, contradicting pQCD unless OAM is present. This suggests that $L_q$ in Eq. (1) is significant.

2.2 Sum rules studies

Another JLab contribution to nucleon spin studies is \textit{via} sum rules. Those usually relate moments of structure functions to global properties of the studied particle. The most famous spin sum rule is Bjorken’s one \cite{3}. It links the isovector part of $g_1$ to
the nucleon axial charge $g_a$:

$$
\Gamma_{1-p-n}(Q^2) \equiv \int_0^{1^-} g_p^a - g_n^a dx = \frac{g_a}{6} \left[ 1 - \frac{\alpha_s}{\pi} - 3.58 \left( \frac{\alpha_s}{\pi} \right)^2 - O(\alpha_s^3) \right] + O(1/Q^2),
$$

(3)

where $\alpha_s$ is QCD’s coupling. The $\alpha_s$-terms are pQCD radiative effects [29]. They vanish for $Q^2 \to \infty$ where the sum rule was originally derived. The $O(1/Q^2)$ terms are higher twists, arising when $Q$ gets close to the confinement scale $\Lambda_s$. The Bjorken sum rule derivation predates QCD and thus is not a QCD prediction. However, its $\alpha_s$-dependence is a pQCD prediction and the sum rule test at high $Q^2$ verified that QCD is correct even when spin d.o.f are explicit.

Another important spin sum rule is that of Gerasimov-Drell-Hearn (GDH) [30]:

$$
\int_{\nu_0}^{\infty} \frac{\sigma_P(\nu) - \sigma_A(\nu)}{\nu} d\nu = \frac{4\pi^2 S\kappa^2}{M^2},
$$

(4)

where $\sigma_P$ and $\sigma_A$ are helicity-dependent photoproduction cross sections, $\nu$ is the probing photon energy, $\nu_0$ the pion production threshold, $S$ the spin of the probed particle, $\kappa$ its anomalous magnetic moment and $\alpha$ is QED’s coupling. Like the Bjorken sum rule, the GDH sum rule was derived in a more general context that of QCD. However, when the studied object is a nucleon or nucleus, QCD can be studied since the validity of Eq. (4) depends on the high-$\nu$ behavior of $\sigma_P - \sigma_A$. Originally derived at $Q^2 = 0$, Eq. (4) was later generalized to $Q^2 > 0$ [31]:

$$
\Gamma_1(Q^2) = \int_0^{x_0} g_1 dx = \frac{Q^2}{2M^2} I_1(Q^2)
$$

(5)

with $I_1$ the first polarized doubly virtual Compton scattering amplitude at $\nu \to 0$.

Both the Bjorken and GDH sum rules involve $\Gamma_1$ and are thus two facets of a sum rule holding at any $Q^2$. This offers a mean to study the transition from hadronic to partonic d.o.f and to test nonperturbative approaches to QCD: $\Gamma_1$ can be measured at different $Q^2$ and then compared to the $I_1$ predicted by the nonperturbative approaches. Data at $Q^2 = 0$ and large $Q^2$ come from BNL, MAMI, DESY, SLAC and CERN [1]. The moderate $Q^2$ range was mapped at JLab [8, 9, 14]. These data are shown on Fig. 3 along with $\chi$PT predictions, the leading-twist pQCD evolution, and several models [32]-[35]. A final $Q^2$ region remained to be mapped: that at low $Q^2$ where $\chi$PT predictions can be reliably tested, typically for $Q^2 \lesssim 0.1$ GeV$^2$. The lowest $Q^2$ points of the experiments [8][9] did reach the $\chi$PT region, but barely or with limited precision. The origin of the disagreement between some of the data and the corresponding $\chi$PT predictions was thus unclear. Hence, new experiments were run to measure $g_1$, $g_2$ and their moments well in the $\chi$PT region: E97110 addressed the neutron, E08-027 measured $g_2$ on the proton, and EG4 measured $g_1$ on the proton and deuteron [10]. The EG4 results on the deuteron are shown in Fig 4.
3 Bridging the hadronic and partonic regions

What does the $Q^2$ mapping of $\Gamma_1$ teach us about the connection between hadronic and partonic d.o.f? At high $Q^2$, higher twists can be extracted and related to confinement [36], the mechanism that makes hadronic d.o.f the relevant ones at low $Q^2$. For example, the twist-4 coefficient $f_{p-n}^2$ was found to be relatively large [37], about half the leading twist contribution at $Q^2 = 1 \text{ GeV}^2$. This agrees with intuition: confinement effects should be large at such $Q^2$. Twist-8 is also large but of opposite sign to that of $f_{p-n}^2$, suppressing the overall higher twist contribution as the observation

Figure 3: Moments $\Gamma_{1p}$ (top left), $\Gamma_{1n}$ (top right), $\Gamma_{p-n}^1$ (lower left) and $\Gamma_2^2$ (lower right).
Figure 4: Left: Deuteron’s truncated moment $\Gamma_1(Q^2)$ compared to models and $\chi$PT calculations. The error bars are statistical. The systematic uncertainty is provided by the horizontal band. Right: truncated generalized spin polarizability $\gamma_d(Q^2)$.

Table 1: Comparison between data and $\chi$PT predictions. Observables for which $\chi$PT was expected to be most robust are in bold. “A” means that data and $\chi$PT agree up to $Q^2 \approx 0.1$ GeV$^2$, “X” means a disagreement and “-” that no prediction was available.

| Ref.          | $\Gamma_p^0$ | $\Gamma_n^0$ | $\Gamma_p^{+n}$ | $\Gamma_n^{+n}$ | $\Gamma_1^{p-n}$ | $\Gamma_1^{n-p}$ | $\Gamma_2^{p-n}$ | $\Gamma_2^{n-p}$ | $\delta_{LT}^{n-p}$ | $d_2^n$ |
|---------------|--------------|--------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|--------|
| Ji 1999 [38, 31] | X            | X            | X               | X               | -               | -               | -               | -               | -               |        |
| Bernard 2002 [39] | X            | X            | A               | X               | X               | X               | X               | X               | X               | -      |
| Kao 2002 [40]    | -            | -            | -               | -               | -               | -               | -               | -               | -               |        |
| Bernard 2012 [41] | X            | X            | A               | X               | A               | X               | X               | X               | X               | -      |
| Lensky 2014 [42]  | X            | A            | A               | A               | A               | X               | X               | X               | $\sim$ A | A      |

of parton-hadron duality requires. Other higher twist studies were done either by fit to moments, direct measurements of $g_2$ and $d_2$, or global analyses [1]. Using Operator Product Expansion, higher twists allow us to apply pQCD to lower $Q^2$ than a leading twist analysis. At lower $Q^2$, $\chi$PT provides an effective theory for nonperturbative QCD. The agreement between data and $\chi$PT predictions [31, 38]-[42] is ambivalent, depending on the observable and the $Q^2$ range on which the comparison is performed. Table 1 summarizes the state of affaires. The observables $\delta_{LT}$ and $I_{\gamma}^{p-n}$ were expected to have robust $\chi$PT predictions because they have suppressed $\Delta_{1232}$ resonance contributions. Furthermore, higher moments like $\delta_{LT}$, $I_\gamma$ or $d_2$ have little contribution from the unmeasured low-$x$ region, and thus no low-$x$ extrapolation uncertainty. Nevertheless, $\chi$PT prediction failed, except for $\Gamma_1^{p-n}$. Recent calculations have however distinctly improved.

In all, the JLab nucleon spin structure data provided a precise mapping of the low and moderate $Q^2$ regions, triggering improvements in $\chi$PT predictions at low $Q^2$ [41, 42], and in perturbative techniques at high $Q^2$ [34]. In particular, $\alpha_s$ obtained from JLab’s $\Gamma_1^{p-n}$ data [43] motivated an AdS/QCD calculation of $\alpha_s$ [44] which lead
to an analytical calculation of the hadron mass spectrum with $\Lambda_s$ as single input parameter \[45\]. The analytic calculation of the hadron masses from $\Lambda_s$ is an ultimate goal of strong force studies. AdS/QCD remains a semi-classical approximation of QCD, but its calculation of masses from $\Lambda_s$ is an encouraging step toward this goal.

4 Perspectives

In the shorter term, the JLab nucleon spin structure program naturally expands to higher energy thanks to the recent 12 GeV upgrade of JLab. Precise polarized PDF measurement will be extended to $x \approx 0.8$. The data will be taken in 2019 \[16\]. In addition to the new insight on $L_q$ given by these data, GPDs and TMDs will constrain it more directly. GPDs and TMDs are a major aspect of the 12 GeV program of Halls A, B and C, with 11 GeV data already taken in Halls A and B. Furthermore, higher $Q^2$ measurements of $g_1$ in Hall B will constraint $\Delta G \[47\]$ with different reactions than that of RHIC and thus be complementary to its $\Delta G$ program.

In the longer term, the Hall A SoLID projet \[48\] will yield GPDs and TMDs with high precision and over extended kinematics, while the EIC \[49\] will measure polarized PDFs, GPDs and TMDs, and thus OAMs, at low $x$. Furthermore, its precise inclusive data measured over the extended $x$ reach will further constrain $\Delta G$.

5 Conclusion

Nucleon spin structure study remains an active field of research. In the pQCD region, JLab provides spin asymmetries at high-$x$, $g_1$ and $g_2$, their various moments, and higher twists. The JLab global analysis JAM determines (un)polarized PDFs and higher twists. Explored at 6 GeV, GPDs and TMDs are a major aspect of the current 12 GeV program.

At lower $Q^2$, JLab data complement the ones from CERN, SLAC and DESY enabling the study of confinement and of the emergence of the effective hadronic degrees of freedom. Most of the moderate $Q^2$ JLab data are now available, as are the low $Q^2$ deuteron data. The low $Q^2$ proton and neutron data are expected for 2019.

Arguably, JLab’s spin sum rule program reached its goal: by providing a precise mapping at low and moderate $Q^2$, it triggered progress in theory, improving the description of the strong force from low $Q^2$ ($\chi$PT), through intermediate $Q^2$ (Schwinger–Dyson equations, AdS/QCD) and to high $Q^2$ (improved perturbative techniques). An example of such progress is the analytic AdS/QCD calculation of the hadron masses from $\Lambda_s$. The 12 GeV upgrade of JLab allows for precision measurements of $g_1$ and $g_2$ at higher $x$ and $Q^2$, as well as higher twist, GPD and TMD extractions. Quark OAM and $\Delta G$ can then be extracted from them. In the longer term, the SoLID detector
will improve GPD and TMD measurements while the EIC will explore the nucleon spin structure at very low $x$.

References

[1] For a review, see A. Deur, S. J. Brodsky, G. F. De Téramond, arXiv:1807.05250
[2] J. D. Bjorken, NATO Sci. Ser. B 197, 1 (1987)
[3] J. D. Bjorken, Phys. Rev. 148, 1467 (1966); Phys. Rev. D 1, 1376 (1970)
[4] J. Ashman et al., Phys. Lett. B 206, 364 (1988)
[5] C. D. Roberts, arXiv:1203.534; A. Bashir, L. Chang, I. C. Cloet, B. El-Bennich, Y. X. Liu, C. D. Roberts and P. C. Tandy, Commun. Theor. Phys. 58, 79 (2012)
[6] V. Bernard and U. G. Meissner, Ann. Rev. Nucl. Part. Sci. 57, 33 (2007)
[7] S. J. Brodsky, G. de Téramond, H. G. Dosch, J. Erlich, Phys. Rep. 584, 1 (2015)
[8] M. Amarian et al., Phys. Rev. Lett. 89, 242301 (2002); Phys. Rev. Lett. 92, 022301 (2004); Phys. Rev. Lett. 93, 152301 (2004), K. Slifer et al., Phys. Rev. Lett. 101, 022303 (2008)
[9] J. Yun et al., Phys. Rev. C 67, 055204 (2003); R. Fatemi et al., Phys. Rev. Lett. 91, 222002 (2003); K. V. Dharmawardane et al., Phys. Lett. B 641, 11 (2006)
N. Guler et al., Phys. Rev. C 92, 5, 055201 (2015) Y. Prok et al., Phys. Lett. B 672, 12 (2009) P. E. Bosted et al., Phys. Rev. C 75, 035203 (2007); R. Fersch et al., Phys. Rev. C 96, 6, 065208 (2017)
[10] K. P. Adhikari et al., Phys. Rev. Lett. 120, 6, 062501 (2018)
[11] K. Kramer et al., Phys. Rev. Lett. 95, 142002 (2005)
[12] M. Posik et al., Phys. Rev. Lett. 113, 2, 022002 (2014) D. Flay et al., Phys. Rev. D 94, 5, 052003 (2016); D. S. Parno et al., Phys. Lett. B 744, 309 (2015)
[13] F. R. Wesselmann et al., Phys. Rev. Lett. 98, 132003 (2007); K. Slifer et al., Phys. Rev. Lett. 105, 101601 (2010)
[14] Y. Prok et al., Phys. Rev. C 90, 2, 025212 (2014)
[15] P. Solvignon et al., Phys. Rev. C 92, 1, 015208 (2015); Phys. Rev. Lett. 101, 182502 (2008)
[16] W. Armstrong et al., arXiv:1805.08835.

[17] X. Zheng et al., Phys. Rev. Lett. 92, 012004 (2004); Phys. Rev. C 70, 065207 (2004)

[18] S. J. Brodsky, M. Burkardt and I. Schmidt, Nucl. Phys. B 441, 197 (1995)
E. Leader, A. V. Sidorov and D. B. Stamenov, Eur. Phys. J. C 23, 479 (2002)
H. Avakian, S. J. Brodsky, A. Deur F. Yuan, Phys. Rev. Lett. 99, 082001 (2007)

[19] N. Isgur, Phys. Rev. D 59, 034013 (1999); H. Dahiya and M. Randhawa, Phys. Rev. D 93, 11, 114030 (2016)
A. I. Signal, Phys. Rev. D 95, 11, 114010 (2017)

[20] C. Bourrely, J. Soffer and F. Buccella, Eur. Phys. J. C 23, 487 (2002)

[21] F. E. Close and W. Melnitchouk, Phys. Rev. C 68, 035210 (2003)

[22] H. L. L. Roberts, et al, Phys. Rev. C 83, 065206 (2011); C. D. Roberts, R. J. Holt and S. M. Schmidt, Phys. Lett. B 727, 249 (2013)

[23] C. Boros and A. W. Thomas, Phys. Rev. D 60, 074017 (1999)

[24] N. I. Kochelev, Phys. Rev. D 57, 5539 (1998); M. Wakamatsu, Phys. Rev. D 67, 034005 (2003); Phys. Rev. D 67, 034006 (2003); H. Weigel, L. P. Gamberg and H. Reinhardt, Phys. Lett. B 399, 287 (1997); Phys. Rev. D 55, 6910 (1997)
O. Schroeder, H. Reinhardt and H. Weigel, Nucl. Phys. A 651, 174 (1999)
I. C. Cloet, W. Bentz and A. W. Thomas, Phys. Lett. B 621, 246 (2005)

[25] E. R. Nocera et al., Nucl. Phys. B 887, 276 (2014)

[26] D. de Florian, R. Sassot, M. Stratmann and W. Vogelsang, Phys. Rev. D 80, 034030 (2009); Phys. Rev. Lett. 101, 072001 (2008)

[27] P. Jimenez-Delgado et al., Phys. Lett. B 738, 263 (2014)

[28] K. Ackerstaff et al., Phys. Lett. B 464, 123 (1999); A. Airapetian et al., Phys. Rev. Lett. 92, 012005 (2004)

[29] A. L. Kataev, Phys. Rev. D 50, 5469 (1994); Mod. Phys. Lett. A 20, 2007 (2005)
P. A. Baikov, K. G. Chetyrkin, J. H. Kuhn, Phys. Rev. Lett. 104, 132004 (2010)

[30] S. B. Gerasimov, Sov. J. Nucl. Phys. 2, 430 (1966) [Yad. Fiz. 2, 598 (1965)];
S. D. Drell and A. C. Hearn, Phys. Rev. Lett. 16, 908 (1966); M. Hosoda and K. Yamamoto Prog. Theor. Phys. 36 (2), 425 (1966)

[31] X. D. Ji and J. Osborne, J. Phys. G 27, 127 (2001); D. Drechsel, B. Pasquini and M. Vanderhaeghen, Phys. Rept. 378, 99 (2003)
[32] V. Burkert and Z. j. Li, Phys. Rev. D 47, 46 (1993)
[33] J. Soffer and O. Teryaev, Phys. Rev. D 70, 116004 (2004)
[34] R. S. Pasechnik, J. Soffer and O. V. Teryaev, Phys. Rev. D 82, 076007 (2010)
    R. S. Pasechnik et al., Phys. Rev. D 81, 016010 (2010)
[35] D. Drechsel et al., Nucl. Phys. A 645, 145 (1999)
[36] M. Burkardt, Phys. Rev. D 88, 114502 (2013)
    M. Abdallah and M. Burkardt, Phys. Rev. D 94, 9, 094040 (2016)
[37] A. Deur et al., Phys. Rev. Lett. 93, 212001 (2004)
    Phys. Rev. D 78, 032001 (2008)
    Phys. Rev. D 90, 1, 012009 (2014)
[38] X. D. Ji, C. W. Kao and J. Osborne, Phys. Lett. B 472, 1 (2000)
[39] V. Bernard, T. R. Hemmert and U. G. Meissner, Phys. Lett. B 545, 105 (2002)
    Phys. Rev. D 67, 076008 (2003)
[40] C. W. Kao, T. Spitzenberg, M. Vanderhaeghen, Phys. Rev. D 67, 016001 (2003)
[41] V. Bernard et al., Phys. Rev. D 87, 5, 054032 (2013)
[42] V. Lensky, J. Alarcon, V. Pascalutsa, Phys. Rev. C 90, 5, 055202 (2014)
    V. Lensky, V. Pascalutsa, M. Vanderhaeghen, Eur. Phys. J. C 77, 2, 119 (2017)
[43] A. Deur, V. Burkert, J. P. Chen and W. Korsch, Phys. Lett. B 665, 349 (2008)
[44] S. J. Brodsky, G. F. de Téramond and A. Deur, Phys. Rev. D 81, 096010 (2010)
[45] A. Deur, S. J. Brodsky and G. F. de Téramond, Phys. Lett. B 750, 528 (2015)
[46] JLab experiments E12-06-109 (S. Kuhn contact), E12-06-110 (X. Zheng contact)
    and E12-06-122 (B. Wojtsekhowski contact)
[47] E. Leader, A. V. Sidorov and D. B. Stamenov, Phys. Rev. D 75, 074027 (2007)
[48] J.-P. Chen et al. SoLID collaboration White Paper.
[49] A. Accardi et al., Eur. Phys. J. A 52, 9, 268 (2016)