Flavor asymmetry of the polarized sea-quark distributions in the proton

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Abstract

The recent global analysis of helicity parton distributions, which takes into account available data from inclusive and semi-inclusive polarized deep inelastic scattering, as well as from polarized proton-proton scattering at RHIC, appears to offer the first strong evidence that polarized sea-quark distributions are flavor asymmetric, i.e. $\Delta \bar{u}(x) \neq \Delta \bar{d}(x)$. We point out that the flavor symmetry breaking pattern indicated by their analysis, i.e. $\Delta \bar{u}(x) > 0$ and $\Delta \bar{d}(x) < 0$ with the magnitude correlation $|\Delta \bar{u}(x)| < |\Delta \bar{d}(x)|$, is just consistent with our theoretical predictions given several years ago on the basis of the chiral quark soliton model. We also address ourselves to understanding the physics behind this observation.

Undoubtedly, the famous NMC measurement [1], which has established the flavor asymmetry of unpolarized sea-quark distributions, is thought to be one of the most noticeable achievements in the recent studies of nucleon structure functions. The reason is that it gave the first clear evidence for manifestation of nonperturbative chiral dynamics of QCD in high-energy deep-inelastic scattering observables, which was not taken very seriously before this milestone discovery. The NMC observation, i.e. the excess of $\bar{d}$-sea over the $\bar{u}$-sea in the proton, is known to be explained by a variety of models at least qualitatively. (See [2], [3], for review.) They are the meson cloud convolution model including its variants [4] - [9], the chiral quark soliton model (CQSM) [10] - [13], as well as several other models with more phenomenological nature like the statistical parton model [14], [15] and the explanation based on the Pauli exclusion principle [16].

A natural next question is then whether the polarized antiquark sea in the nucleon is also flavor asymmetric or not. Somewhat embarrassingly, existing theoretical answers for this question is fairly dispersed, in remarkable contrast to the unpolarized case. Among others, worthy of special mention is a big difference between the prediction of the meson cloud model

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and that of the CQSM. The CQSM predicts large flavor asymmetry also for the longitudinally polarized sea-quark distributions, i.e. \( \Delta \bar{u}(x) - \Delta \bar{d}(x) > 0 \), whereas the prediction of the meson cloud model for the same quantity is fairly small or slightly positive. (Actually, the meson cloud model contains a lot of parameters and its theoretical predictions are fairly dispersed depending on how many meson-baryon intermediate channels are included in the calculation. Here, we are supposing the prediction of the most elaborate recent calculation by Cao and Signal within the framework of the meson cloud model.) Although it is usually believed that the CQSM yield similar results to those obtained in the meson cloud model or the cloudy bag model as one of such models constructed so as to effectively incorporate the chiral dynamics of Nambu-Goldstone excitations surrounding the nucleon core, it is not necessarily true. Significant differences, if they exist, appears to originate from a unique dynamical ansatz of the CQSM, i.e. the rotating hedgehog. It has been long claimed that this unique feature of the CQSM enables us to explain the celebrated EMC observation, i.e. very small quark spin fraction of the nucleon, quite naturally without introducing any fine tuning. The recently found big difference between the prediction of the CQSM and that of the refined cloudy bag model for the isovector combination of the quark orbital angular momenta \( L^u - L^d \) also appears to be connected with the nontrivial spin-isospin correlation between quark fields embedded in the hedgehog ansatz. Furthermore, the same correlation between spin and isospin is likely to be the cause of the strong correlation existing between the flavor asymmetries of the unpolarized and polarized sea-quark distributions predicted by the CQSM, which dictates that both of \( \bar{u}(x) - \bar{d}(x) \) and \( \Delta \bar{u}(x) - \Delta \bar{d}(x) \) are sizably large in magnitude.

In view of the interesting sensitivity of the flavor asymmetry of the polarized sea-quark distributions to theoretical models, it is of great interest to get direct experimental information on it. Since the separation of the quark and antiquark distributions cannot be done solely from the inclusive measurements, additional information from semi-inclusive measurements is crucial for this separation. The first systematic challenge for aiming at extracting the polarized sea-quark distributions were carried out by the HERMES Collaboration. From semi-inclusive scattering measurements where the final pions and kaons are measured, they extracted the polarized antiquark distributions, thereby concluding that the polarization of each flavor, i.e. \( \Delta \bar{u}(x), \Delta \bar{d}(x), \Delta \bar{s}(x) \), is very small, and compatible with zero, which seems to be consistent with the prediction of the meson cloud model. However, in view of the fact that the mechanism of semi-inclusive scatterings is understood less reliably than that of the inclusive scatterings, and that we have much more precise inclusive data than the semi-inclusive data, it is desirable to perform systematic global analysis, which takes account of all the available information. Such an analysis has recently been done by de Florian et al. Their analysis was performed fully at the next-to-leading order of perturbative QCD, by taking
account of available data from inclusive and semi-inclusive scatterings, as well as from polarized proton-proton scatterings at RHIC. Very interestingly, the result of their analysis appears to offer the first strong evidence in favor of the flavor asymmetry of the polarized sea-quark distributions, i.e. \( \Delta \bar{u}(x) - \Delta \bar{d}(x) > 0 \). Particularly noteworthy here is the observed pattern of flavor symmetry violation in the polarized sea. Their results indicates that \( \Delta \bar{u}(x) > 0 \) and \( \Delta \bar{d}(x) < 0 \) with the interesting magnitude correlation \( |\Delta \bar{u}(x)| < |\Delta \bar{d}(x)| \).

Now, the purpose of the present paper is to point out that the observed pattern of flavor symmetry violation in the polarized sea-quark distribution is just consistent with the parameter-free predictions of the CQSM, which we gave several years ago. We also try to clarify the background physics leading to the observed symmetry breaking pattern of the polarized sea-quark distributions. We shall also make a short remark on their results for the polarized strange-quark distributions in the nucleon from our own viewpoint.

Before showing a comparison of the predictions of the CQSM with the results of the new DSSV analysis, several comments on the model are in order. We have two versions of the CQSM. One is the flavor SU(2) version \[37, 29\], and the other is the flavor SU(3) version \[38, 39\]. The basic parameter common in both models is the dynamically generated quark mass \( M \), which is already fixed to be \( M \simeq 375 \text{ MeV} \) from low energy phenomenology or from the instanton picture of the QCD vacuum, which affords a theoretical foundation of the model \[37\]. The predictions of the SU(2) CQSM for various parton distributions at the model scale is therefore parameter free. The flavor SU(3) version of the CQSM model contains an additional parameter, i.e. the effective mass difference \( \Delta m_s \) between the strange and up-down quarks. We fixed this parameter to be 100 MeV such that the model reproduces the general behavior of the unpolarized strange quark distributions at the high energy scale, \( Q^2 = 4 \text{ GeV}^2 \). (See \[28\], for more detail.) To make a comparison with high energy deep-inelastic-scattering observables, we take the predictions of the CQSM as initial scale distributions at the low energy model scale. The scale dependencies of the distribution functions are taken into account by using the standard evolution equation at the next-to-leading order. The starting energy of this evolution is taken to be \( Q^2 = 0.30 \text{ GeV}^2 \), basically following the strategy of the PDF fits by Glück, Reya and Vogt \[40, 41\].

Now in Fig.1, we show the results of the new DSSV global fit for the isovector distribution \( x (\Delta \bar{u}(x) - \Delta \bar{d}(x)) \) in comparison with the theoretical predictions of the CQSM. Here, the solid and dash-dotted curves are respectively the predictions of the flavor SU(2) and SU(3) versions of the CQSM. As pointed out in \[28\], the flavor asymmetry of the polarized sea-quark distributions is fairly sensitive to the difference of the two versions of the model. (This is not the case for the unpolarized sea-quark distributions. That is, the difference between the predictions of the two models for the distribution \( x (\bar{u}(x) - \bar{d}(x)) \) is fairly small \[28\].) One sees that, with high confidence level, the new DSSV fit shows a strong evidence in favor of the flavor
Figure 1: The predictions of the $SU(2)$ and $SU(3)$ CQSM for the distribution difference $x(\Delta\bar{u}(x) - \Delta\bar{d}(x))$ at $Q^2 = 10$ GeV$^2$, in comparison with the new DSSV global fit with the uncertainty bands for $\Delta\chi^2 = 1$ and $\Delta\chi^2/\chi^2 = 2\%$.

Also very interesting is the flavor separation of the polarized sea-quark distributions. Interestingly, the magnitude of this flavor symmetry violation is fairly close to the prediction of the flavor $SU(3)$ CQSM. It was advocated that sizably large CQSM prediction for $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ is consistent with the large-$N_c$ counting argument [27], which dictates that

$$|\Delta\bar{u}(x) - \Delta\bar{d}(x)| \gg |\bar{u}(x) - \bar{d}(x)|,$$

(1)
since $|\bar{u}(x) - \bar{d}(x)|/|\Delta\bar{u}(x) - \Delta\bar{d}(x)|$ is a $1/N_c$ quantity. In our realistic world, however, $N_c$ is just three, anyway, and the actual numerical predictions might not necessarily obey this general expectation. In fact, in the $SU(3)$ CQSM, we find that the magnitude of $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ is slightly smaller than that of $\bar{u}(x) - \bar{d}(x)$, as shown in Fig.18 of [28]. (Incidentally, our prediction for $x(\Delta\bar{u}(x) - \Delta\bar{d}(x))$ within the $SU(2)$ CQSM is a little smaller than the corresponding prediction of the Bochum group shown in Fig.7 of [36]. The reason of this small discrepancy is not clear, but it may be traced back to the difference of the used soliton profile or the difference of the details of the evolution procedure.)
Figure 2: The predictions of the $SU(2)$ and $SU(3)$ CQSM for the longitudinally polarized sea-quark distribution functions, $x \Delta \bar{u}(x)$ and $x \Delta \bar{d}(x)$ at $Q^2 = 10 \text{ GeV}^2$, in comparison with the DSSV global fit.

A noteworthy feature of the new global fit is the observed pattern of the flavor symmetry breaking. It indicates that $\Delta \bar{u}(x) > 0$ and $\Delta \bar{d}(x) < 0$ with the magnitude correlation $|\Delta \bar{u}(x)| < |\Delta \bar{d}(x)|$. We emphasize that this characteristic of the flavor symmetry breaking pattern of the polarized sea-quark distribution is just what the CQSM predicts [28]. An interesting question is therefore how this unique pattern of symmetry violation arises in the CQSM. Since the physics is basically common in two versions of the CQSM, we explain it in simpler $SU(2)$ CQSM. To this end, we first recall the fact that, within the theoretical framework of the CQSM, the isoscalar and isovector distributions have different theoretical structure due to their different $N_c$-dependence [23, 25, 28], so that the longitudinally polarized distribution functions with each flavor is evaluated as linear combinations of the isoscalar and isovector parts as

$$\Delta \bar{u}(x) = \frac{1}{2} \left[ (\Delta \bar{u}(x) + \Delta \bar{d}(x)) + (\Delta \bar{u}(x) - \Delta \bar{d}(x)) \right], \tag{2}$$

$$\Delta \bar{d}(x) = \frac{1}{2} \left[ (\Delta \bar{u}(x) + \Delta \bar{d}(x)) - (\Delta \bar{u}(x) - \Delta \bar{d}(x)) \right]. \tag{3}$$

Shown in Fig. 3 are the predictions of the $SU(2)$ CQSM for the isoscalar and isovector combinations of the longitudinally polarized quark distribution functions [25]. In this figure, the distribution functions with negative value of $x$ should be interpreted as antiquark distribution.
Figure 3: The predictions of the SU(2) CQSM for the isoscalar and isovector longitudinally polarized distribution functions of the nucleon at the scale of the model. The long-dashed and the dash-dotted curves respectively stand for the contribution of $N_c$ valence quarks and that of the Dirac-sea quarks, while the solid curve represents their sum. The distribution functions $\Delta q(x)$ in the negative $x$ region should be interpreted as antiquark distributions according to the rule: $\Delta \bar{q}(x) = \Delta q(-x)$ with $0 < x < 1$.

according to the rule:

$$\Delta \bar{u}(x) \pm \Delta \bar{d}(x) = \Delta u(-x) \pm \Delta d(-x) \quad (0 < x < 1). \quad (4)$$

The right panel of Fig.3 shows that the vacuum polarization of the Dirac-sea quarks in the hedgehog mean-field plays an important role in generating large flavor asymmetry of the polarized sea-quark distribution. This fact was already emphasized in several previous papers [26], [27]. The physics we are now discussing is connected with another unique feature of the CQSM predictions. As shown in the left panel of Fig.3, it predicts that the isoscalar longitudinally polarized distribution is negative in the small $x$ region including the negative $x$ domain [25], [28], which means that $\Delta \bar{u}(x) + \Delta \bar{d}(x)$ is negative for the physical value of $x$, i.e. for $0 < x < 1$. This observation, combined with the fact that $\Delta \bar{u}(x) - \Delta \bar{d}(x)$ is sizably large and positive for small and negative $x$, leads to an interesting symmetry breaking pattern of the longitudinally polarized sea-quark distributions such that $\Delta \bar{u}(x) > 0$ and $\Delta \bar{d}(x) < 0$ with the magnitude correlation $|\Delta \bar{u}(x)| < |\Delta \bar{d}(x)|$. We emphasize that this feature comes about as a parameter-free prediction of the CQSM. Some years ago, we have pointed out [42] that the negativity of the isoscalar longitudinally polarized quark distribution in the small $x$ region is...
just what is required for reproducing the sign change of the deuteron spin structure function at low $x$ as dictated by the SMC and COMPASS data \([43],[44]\). (Remember that the deuteron spin structure function is roughly proportional to the isoscalar longitudinally polarized distribution function of the nucleon.) This observation then indicates that the flavor symmetry breaking pattern $|\Delta \bar{u}(x)| < |\Delta \bar{d}(x)|$ obtained in the DSSV fit must be strongly influenced by the deuteron structure function data included in their global fit.

Figure 4: The predictions of the SU(2) CQSM for the product of the polarized quark and antiquark distributions, i.e. $\Delta u(x) \times \Delta \bar{u}(x)$ and $\Delta d(x) \times \Delta \bar{d}(x)$ at the model scale. The expectation from the Pauli exclusion principle argument is an approximate equality of these two quantities, i.e. $\Delta u(x) \times \Delta \bar{u}(x) \simeq \Delta d(x) \times \Delta \bar{d}(x)$.

We recall that the flavor asymmetry of the polarized sea-quark distributions is predicted also by some models with more phenomenological nature like the statistical parton model \([14],[15]\) as well as the model based on the Pauli exclusion principle \([16]\). For instance, the analysis by Bhalerao within the statistical model predicts $\Delta \bar{u}(x) > 0$ and $\Delta \bar{d}(x) < 0$ with the magnitude of $|\Delta \bar{d}(x)|$ being larger than that of $|\Delta \bar{u}(x)|$ although slightly \([14]\). Note, however, that this model uses the known empirical information for the magnitudes of $\Delta u + \Delta \bar{u}$, $\Delta d + \Delta \bar{d}$, and $\Delta s + \Delta \bar{s}$, so that its predictions are not of purely theoretical nature. Also interesting is the prediction of the semi-phenomenological model of Gück and Reya based on the Pauli exclusion principle \([16]\). Their model also predicts large flavor asymmetry for both of the unpolarized and polarized sea-quark distributions. Furthermore, this model predicts fairly large asymmetry for
the magnitudes of $\Delta \bar{u}(x)$ and $\Delta \bar{d}(x)$ such that $|\Delta \bar{u}(x)| < |\Delta \bar{d}(x)|$ in conformity with the new DSSV global fit. We point out that the above-mentioned feature comes from the basic ansatz of this semi-phenomenological treatment, which demands that the product

$$\Delta q(x, \mu^2) \Delta \bar{q}(x, \mu^2) \equiv P(x), \quad (5)$$

is universal flavor-independent function $P(x)$ with $\mu$ being an low energy input scale of their evolution program, since the effect of Pauli blocking is only related to the spin of quarks and antiquarks irrespective of their flavor degrees of freedom. Since it is empirically known that $|\Delta u(x)| > |\Delta d(x)|$, it naturally follows that $|\Delta \bar{u}(x)| < |\Delta \bar{d}(x)|$. It may be of some interest to check to what extent the above ansatz holds in our explicit dynamical model predictions. Shown in Fig.4 are the predictions of the SU(2) CQSM for the product of $\Delta u(x)$ and $\Delta \bar{u}(x)$ and that of $\Delta d(x)$ and $\Delta \bar{d}(x)$ at the model energy scale, which we identify with $\mu^2 = 0.30\text{ GeV}^2$. One clearly sees that the ansatz $\Delta u(x) \Delta \bar{u}(x) = \Delta d(x) \Delta \bar{d}(x)$ does not hold good at least in the CQSM. This seems to be an indication that the nontrivial chiral dynamics of QCD besides the Pauli blocking effect plays some important roles in the physics of the flavor asymmetry of sea-quark distributions in the nucleon.

![Figure 5](image-url)

**Figure 5:** The prediction of the $SU(3)$ CQSM for the polarized strange quark distribution $x \Delta s(x)$ in comparison with the DSSV global fit. Here, the solid curve is the prediction of the $SU(3)$ CQSM for the polarized $s$-quark distribution, whereas the long-dashed curve is that for the polarized $\bar{s}$-quark distribution.
Finally, we make a brief comment on the polarized strange quark distributions obtained in the DSSV global analysis. As shown in Fig.5, a remarkable feature of the new DSSV analysis is that a polarized strange quark distribution $\Delta s(x)$ is positive at large or medium $x$, but negative at small $x$, at variance with most of the past PDF fits which use only inclusive DIS (deep-inelastic-scattering) data. This peculiar behavior of $\Delta s(x)$ arises since the (kaon) semi-inclusive DIS data prefer a small and likely positive $\Delta s(x)$ at medium $x$, while inclusive DIS and the constraints from beta-decay demand a negative 1st moment of $\Delta s(x)$ [45], thereby forcing $\Delta s(x)$ to be negative at small $x$. To our knowledge, there is no theoretical model, which predicts such nodal behavior of $\Delta s(x)$. Shown in Fig.5 together with the DSSV fit are the predictions of the SU(3) CQSM for the polarized strange quark distributions. The SU(3) CQSM predicts that both of $\Delta s(x)$ and $\Delta \bar{s}(x)$ are negative in the whole region of $x$, while the magnitude of $\Delta \bar{s}(x)$ is much smaller than $\Delta s(x)$, i.e. $|\Delta \bar{s}(x)| \ll |\Delta s(x)|$. In the DSSV analysis, the equality of the polarized strange quark and antiquark distributions is assumed, because of the reason that the fit is unable to discriminate strange quarks from antiquarks at the present stage. As pointed out by the authors of [36] themselves, however, unlike the spin-averaged case where the distributions of $s(x)$ and $\bar{s}(x)$ are constrained by the conservation law, i.e. $\int_0^1 [s(x) - \bar{s}(x)] \, dx = 0$, there is no absolute need for $\Delta s(x)$ and $\Delta \bar{s}(x)$ to have the same magnitude or even the same sign. Although may not be feasible at the present stage, a possible large asymmetry of the polarized strange sea as suggested by the CQSM should be kept in mind and such possibility is highly desirable to be taken into account in more elaborate global analyses in the future.

To sum up, the recent global analysis of spin-dependent parton distributions appears to offer the first strong evidence in favor of the flavor symmetry violation of the longitudinally polarized sea-quark distributions in the nucleon. We have pointed out that the indicated flavor symmetry breaking pattern, i.e. $\Delta \bar{u}(x) > 0$ and $\Delta \bar{d}(x) < 0$ with the magnitude correlation $|\Delta \bar{u}(x)| \lesssim |\Delta \bar{d}(x)|$, is remarkably consistent with the nearly-parameter-free prediction of the CQSM. An apparent discrepancy remains, however, between their fit for the polarized strange quark distributions in the nucleon and the corresponding prediction of the SU(3) CQSM. To get more definite conclusion on the implication of this discrepancy, we certainly need more and more effort to understand the precise mechanism of semi-inclusive reactions, especially the mechanism of semi-inclusive kaon productions.

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References

[1] NMC Collaboration, P. Amaudruz et al., Phys. Rev. Lett. 66 (1991) 2712.
[2] S. Kumano, Phys. Rep. 303 (1998) 183.
[3] G.T. Garvey and J.C. Peng, Prog. Part. Nucl. Phys. 47 (2001) 203.
[4] J.D. Sullivan, Phys. Rev. D5 (1972) 1732.
[5] A. W. Thomas, Phys. Lett. B126 (1983) 97.
[6] E.M. Henley and G.A. Miller, Phys. Lett. B251 (1990) 453.
[7] S. Kumano, Phys. Rev. D43 (1991) 3067.
[8] W. Melnitchouk and A.W. Thomas, Phys. Rev. D47 (1993) 3794.
[9] H. Holtman, A. Szczurek, and J. Speth, Nucl. Phys. A596 (1996) 631.
[10] M. Wakamatsu, Phys. Rev. D44 (1991) R2631.
[11] M. Wakamatsu, Phys. Rev. D46 (1992) 3762.
[12] M. Wakamatsu and T. Kubota, Phys. Rev. D57 (1998) 5755.
[13] P.V. Pobylitsa, M.V. Polyakov, K. Goeke, T. Watabe, and C. Weiss, Phys. Rev. D59 (1999) 034024.
[14] R.S. Bhalerao, Phys. Rev. C63 (2001) 025208.
[15] C. Bourrely, J. Soffer, and F. Buccella, Eur. Phys. J. C23 (2002) 487.
[16] M. Glück and E. Reya, Mod. Phys. Lett. A15 (2000) 883.
[17] R.J. Fries and A. Schäfer, Phys. Lett. B443 (1998) 40.
[18] K.G. Boreskov, A.B. Kaidalov, Eur. Phys. J. C10 (1999) 143.
[19] F.G. Cao and A.I. Signal, Eur. Phys. J. C21 (2001) 105.
[20] S. Kumano and M. Miyama, Phys. Rev. D65 (2002) 034012.
[21] R.J. Fries, A. Schäfer, and C. Weiss, Eur. Phys. J. A17 (2003) 509.
[22] F.G. Cao and A.I. Signal, Phys. Rev. D68 (2003) 074002.
[23] D.I. Diakonov, V.Yu. Petrov, P.V. Pobyltsa, M.V. Polyakov, and C. Weiss, Nucl. Phys. B480 (1996) 341 ; Phys. Rev. D56 (1997) 4069.
[24] H. Weigel, L. Gamberg, and H. Reinhardt, Mod. Phys. Lett. A11 (1996) 3021 ; Phys. Lett. B399 (1997) 287.
[25] M. Wakamatsu and T. Kubota, Phys. Rev. D60 (1999) 034020.
[26] M. Wakamatsu and T. Watabe, Phys. Rev. D62 (2000) 017506.
[27] B. Dressler, K. Goeke, M.V. Polyakov, and C. Weiss, Eur. Phys. J. C14 (2000) 147.
[28] M. Wakamatsu, Phys. Rev. D67 (2003) 034005 ; Phys. Rev. D67 (2003) 034006.
[29] M. Wakamatsu and H. Yoshiki, Nucl. Phys. A524 (1991) 561.
[30] M. Wakamatsu and T. Watabe, Phys. Rev. D62 (2000) 054009.
[31] M. Wakamatsu, arXiv:0908.0972 [hep-ph].
[32] A.W. Thomas, Phys. Rev. Lett. 101 (2009) 102003.
[33] M. Wakamatsu and H. Tsujimoto, Phys. Rev. D71 (2005) 074001.
[34] M. Wakamatsu and Y. Nakakoji, Phys. Rev. D74 (2006) 054006 ; Phys. Rev. D77 (2008) 074011.
[35] HERMES Collaboration : A. Airapetian et al., Phys. Rev. D71 (2005) 012003 ; Phys. Rev. Lett. 92 (2004) 012005.
[36] D. de Florian, R. Sassot, M. Stratmann, and W. Vogelsang, Phys. Rev. D80 (2009) 034030.
[37] D.I. Diakonov, V.Yu. Petrov, and P.V. Pobylitsa, Nucl. Phys. B306 (1988) 809.
[38] H. Weigel, R.Alkofer, and H. Reinhardt, Nucl. Phys. B387 (1992) 638.
[39] A. Blotz, D.I. Diakonov, K.Goeke, N.W. Park, V.Yu. Petrov, and P.V. Pobylitsa, Nucl. Phys. A555 (1993) 765.
[40] M. Glück, E. Reya, and A. Vogt, Z. Phys. C67 (1995) 433.
[41] M. Glück, E. Reya, M. Stratmann, and A. Vogt, Phys. Rev. D53 (1996) 4775.
[42] M. Wakamatsu, Phys. Lett. B646 (2007) 24.
[43] COMPASS Collaboration, E.S. Ageev et al., Phys. Lett. B612 (2005) 154.
[44] SMC Collaboration, B. Adeva et al., Phys. Rev. D58 (1998) 112001.
[45] E. Leader and D.B. Stamenov, Phys. Rev. D67 (2003) 037503.