First Simultaneous Extraction of Spin-Dependent Parton Distributions and Fragmentation Functions from a Global QCD Analysis

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First simultaneous extraction of spin-dependent parton distributions and fragmentation functions from a global QCD analysis

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We perform the first global QCD analysis of polarized inclusive and semi-inclusive deep-inelastic scattering and single-inclusive e^+e^- annihilation data, fitting simultaneously the parton distribution and fragmentation functions using the iterative Monte Carlo method. Without imposing SU(3) symmetry relations, we find the strange polarization to be very small, consistent with zero for both inclusive and semi-inclusive data, which provides a resolution to the strange quark polarization puzzle. The combined analysis also allows the direct extraction from data of the isovector and octet axial charges, and is consistent with a small SU(2) flavor asymmetry in the polarized sea.

The decomposition of the proton's spin into its quark and gluon helicity and orbital angular momentum contributions has been one of the defining problems that has engaged the hadron physics community for the better part of three decades [1]. Initial explanations of the small fraction of the proton spin found to be carried by quarks focused on a large gluonic contribution generated through the axial anomaly [2], or a large negative polarization of the strange quark sea. Subsequent experiments failed to find compelling evidence to support either of these scenarios, although recent results from RHIC have provided the first clear indications for a nonzero gluon polarization, Δg [3]. Complementing this has been a growing effort to determine the quark and gluon orbital angular momentum components of the proton spin, through measurements of generalized parton distributions in exclusive processes [4]. Critical to all these endeavors is the necessity to reliably extract from the experimental data the fundamental parton distribution functions (PDFs) that characterize the partons' spin and momentum distributions through global QCD analysis.

Typically, global QCD analyses [5–11] of inclusive deep-inelastic scattering (DIS) and other polarized data extract spin-dependent PDFs using constraints from weak baryon decays under the assumption of SU(3) flavor symmetry. This puts significant restriction on the first moment of the polarized strange PDF, with $\Delta s^+ \equiv \Delta s + \Delta\bar{s} \approx -0.1$. Further assumptions about the behavior of the PDFs at large parton momentum fractions x induces a shape for $\Delta s^+(x)$ with magnitude peaking at $x \sim 0.1$. With the inclusion of semi-inclusive DIS (SIDIS) data, a strikingly different shape for the strange polarization emerges [10, 12], changing sign to become positive at $x \sim 0.1$. This was found, however, to be strongly dependent on the assumed $s \to K$ fragmentation function (FF), which enters in the calculation of the SIDIS cross section [12, 13]. Ideally, an unambiguous determination of the strange quark polarization requires a *simultaneous* QCD analysis of both the PDFs and FFs.

In this paper we report on the first such analysis, using data from inclusive and semi-inclusive DIS and single-inclusive e^+e^- annihilation (SIA) to simultaneously constrain the spin-dependent PDFs and $\pi^\pm$ and $K^\pm$ FFs. To avoid biasing the extraction of Δs^+ by assumptions about SU(3) symmetry, we allow for the combined data sets to determine the octet axial charge directly. This is not feasible in a DIS-only analysis, but becomes viable with the flavor separation capability of SIDIS data. We perform the analysis within the iterative Monte Carlo (IMC) approach [5, 14], which avoids potential bias in single-fit analyses introduced by fixing parameters not well constrained by data, and allows a statistically rigorous determination of PDF and FF uncertainties by an efficient exploration of the parameter space.

In this first combined study of PDFs and FFs, which is performed within collinear factorization at next-to-leading order (NLO) in the $\overline{\rm MS}$ scheme, and referred to as "JAM17", we simplify the analysis by placing cuts on the DIS and SIDIS kinematics to avoid higher twist contributions, with the four-momentum transfer squared $Q^2 > 1$ GeV^2 and hadronic final state mass squared $W^2 > 10$ GeV^2. The higher twists were extracted in a previous IMC analysis [5], with a lower cut $W > 2$ GeV, but did not significantly affect the determination of the leading twist PDFs.

The detailed expressions for DIS and SIA observables can be found Refs. [5] and [14], respectively. For the SIDIS data, the observables measured are the longitudinal double spin asymmetries A_1^h for the production of a hadron h,

$$A_1^h\left(x, z, Q^2\right) = \frac{g_1^h(x, z, Q^2)}{F_1(x, z, Q^2)}, \tag{1}$$

where the semi-inclusive spin-dependent g_1^h and spin-averaged F_1^h structure functions depend on both x and

process	target	$N_{\rm dat}$	χ^2
DIS	$p, d, {}^3$He	854	854.8
SIA ($\pi^\pm$)		459	600.1
SIA ($K^\pm$)		391	397.0
SIDIS ($\pi^\pm$)			
HERMES [50]	d	18	28.1
HERMES [50]	p	18	14.2
COMPASS [51]	d	20	8.0
COMPASS [52]	p	24	18.2
SIDIS ($K^\pm$)			
HERMES [50]	d	27	18.3
COMPASS [51]	d	20	18.7
COMPASS [52]	p	24	12.3
Total:		**1855**	**1969.7**

TABLE I. Summary of χ^2 values and number of data points $N_{\rm dat}$ for the various processes used in this analysis.

the fraction $z = p \cdot p_h / p \cdot q$ of the virtual photon's momentum (q) carried by the hadron (p_h), with p the target momentum.

The polarized g_1^h function in Eq. (1) is defined in terms of the spin-dependent PDFs Δq and FFs D_q^h,

$$g_1^h(x,z,Q^2) = \frac{1}{2}\sum_q e_q^2 \Delta q(x,Q^2) D_q^h(z,Q^2) + \mathcal{O}(\alpha_s), \quad (2)$$

where the $\mathcal{O}(\alpha_s)$ corrections are given in Ref. [15]. The unpolarized structure function F_1^h is defined analogously, with the spin-dependent PDFs replaced by their spin-averaged counterparts.

Following Refs. [5, 14], we parameterize both the polarized PDFs and FFs at the input scale $Q_0^2 = 1$ GeV^2 using template functions of the form

$$\mathrm{T}(x;\boldsymbol{a}) = \frac{M\, x^a (1-x)^b (1+c\sqrt{x})}{B(n+a,1+b) + cB(n+\frac{1}{2}+a,1+b)}, \quad (3)$$

where $\boldsymbol{a} = \{M,a,b,c\}$ are the fitting parameters, and B is the Euler beta function. For the polarized PDFs we set $n=1$ so that M corresponds to the first moment. This template is used for all the fitted polarized PDFs, which we choose to be Δq^+, $\Delta \bar q$ and Δg, for flavors $q = u, d$ and s. The FFs are also given by Eq. (3) (with x replaced by z), setting $c=0$ and $n=2$, so that M corresponds to the average momentum fraction carried by the produced hadron. For the FFs $D_{u^+}^{\pi^+} \equiv D_u^{\pi^+} + D_{\bar u}^{\pi^+} = D_{d^+}^{\pi^+}$, $D_{u^+}^{K^+}$ and $D_{s^+}^{K^+}$, which contain both favored and unfavored distributions, we assign two template functions, while for the remaining unfavored FFs, $D_{\bar u}^{\pi^+} = D_d^{\pi^+}$, $D_s^{\pi^+} = (1/2) D_{s^+}^{\pi^+}$, $D_{\bar u}^{K^+} = (1/2) D_{d^+}^{K^+}$ and $D_s^{K^+}$, along with the heavy quarks and gluons, a single template function is used. Following Ref. [14], we use the zero mass variable flavor scheme and parametrize the heavy quark FFs discontinuously at their mass thresholds.

The resulting χ^2 values for each process fitted in our analysis are presented in Table I. For inclusive DIS we use the data sets from Refs. [16–31], and for SIA from Refs. [32–49]. The SIDIS data sets are from HERMES [50] for $\pi^\pm$ and $K^\pm$ production from the deuteron, and $\pi^\pm$ production from the proton, and from COMPASS with $\pi^\pm$ and $K^\pm$ production from deuterium [51] and hydrogen [52] targets. Overall, the χ^2 per datum for all the SIDIS $\pi^\pm$ data is 68.5/80, and 49.3/71 for the $K^\pm$ data, while the χ^2 per datum for the combined inclusive DIS, SIDIS and SIA data is 1969.7/1855 ≈ 1.06.

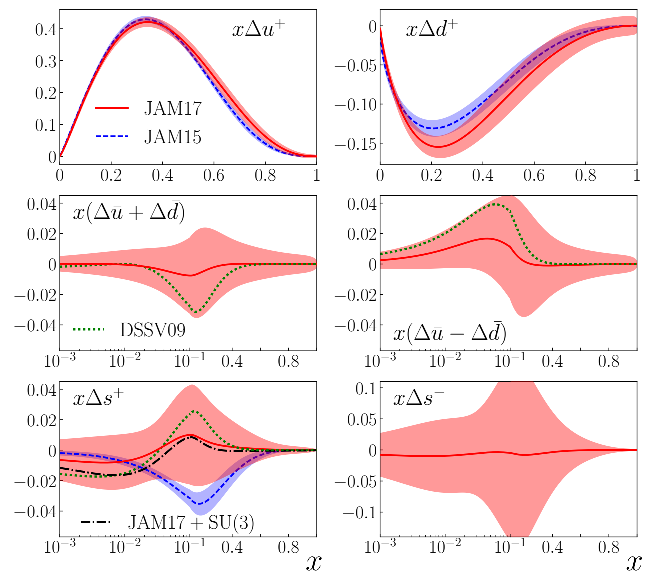

FIG. 1. Spin-dependent PDFs with 1σ uncertainty bands from the JAM17 fit at the input scale $Q_0^2 = 1$ GeV^2. The full results (red solid curves) are compared with the JAM15 Δq^+ PDFs [5] (blue dashed curves) and with the DSSV09 fit [10] for sea quark PDFs (green dotted curves). The Δs^+ PDF is also compared with the JAM17 fit including the SU(3) constraint on the octet axial charge (black dot-dashed curve).

The polarized quark and antiquark PDFs from the combined fit are illustrated in Fig. 1, together with their 1σ uncertainties. (The polarized gluon PDF is essentially unchanged from the earlier JAM15 analysis [5].) For the denominator of the asymmetries A_1^h, we use spin-averaged PDFs from the CJ12 NLO global fit [53]. Using the MMHT14 [54] PDFs instead gives a difference of $\approx 2\% - 5\%$, which is insignificant on the scale of the experimental uncertainties of the asymmetries. The Δu^+ and Δd^+ PDFs, which are determined largely by the inclusive DIS data, are similar to those in the JAM15 analysis [5], giving only marginally harder distributions at large x values. The difference in the magnitudes of Δd^+ at $x \sim 0.2$ arises from anticorrelation with Δs^+; since the latter is less negative, it requires some compensation to describe the DIS observables.

Unlike inclusive DIS, the SIDIS observables can in principle discriminate between different quark and antiquark flavors, and in Fig. 1 we also show the light sea quark polarizations for the isoscalar and isovector combi-

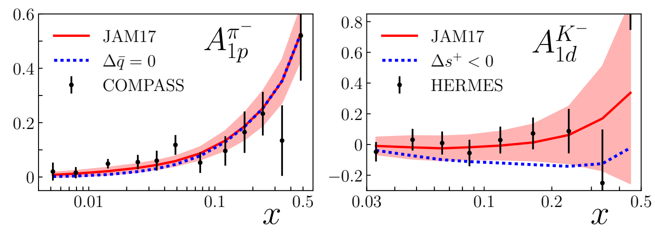

FIG. 2. Semi-inclusive polarization asymmetries $A_{1p}^{\pi^-}$ from COMPASS [52] (left) and $A_{1d}^{K^-}$ from HERMES [50] (right) compared with the full JAM17 fit (red curves and band) and with the result assuming $\Delta\bar{q} \equiv \Delta\bar{u} = \Delta\bar{d} = 0$ (for $A_{1p}^{\pi^-}$) and the (negative) Δs^+ from JAM15 [5] (for $A_{1d}^{K^-}$).

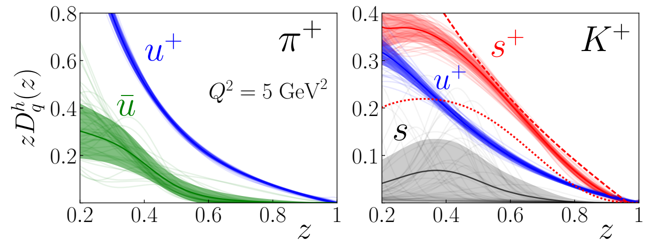

FIG. 3. Fragmentation functions zD_q^h to π^+ (left panel) and K^+ (right panel) for u^+ (blue), $\bar{u}$ (green), s^+ (red) and s (grey) at $Q^2 = 5$ GeV^2 for the JAM17 analysis. Random samples of 50 posteriors are shown with the mean and variance, and compared with the $s^+ \to K^+$ FFs from DSS [62] (dashed) and HKNS [63] (dotted).

nations, $\Delta\bar{u} \pm \Delta\bar{d}$. Our results suggest a slightly positive isovector sea polarization in the range $x \approx 0.01 - 0.1$, with the isoscalar combination more consistent with zero. This is similar to the expectations in some nonperturbative models [55, 56] that predict larger isovector than isoscalar sea polarization, as well as in recent lattice simulations [57, 58]. The signal is relatively weak, however, and can be attributed to several $\pi^\pm$ and $K^\pm$ SIDIS data sets that marginally favor a nonzero sea polarization.

An example of this is illustrated in Fig. 2 for the COMPASS π^- asymmetry [52], which, because of the valence $(\bar{u}d)$ structure of the π^-, is the most sensitive observable to $\bar{u}$ polarization. Comparing the fitted proton $A_{1p}^{\pi^-}$ asymmetry with that obtained by setting $\Delta\bar{u} = \Delta\bar{d} = 0$, the difference is rather small, but noticeable for $x \lesssim 0.1$, where the asymmetry with the unpolarized sea lies at the edge of the 1σ envelope of the full result. Similar effects are found for other SIDIS asymmetries that depend explicitly on $\Delta\bar{u}$ or $\Delta\bar{d}$. The results are also qualitatively similar to those found in the DSSV09 global analysis [10], although the magnitude of the sea quark asymmetries here is somewhat smaller.

For the strange quark polarization, the results in Fig. 1 suggest that Δs^+ is small at all x, albeit within relatively large uncertainties. While consistent with zero within 1σ, there does appear some indication of a positive Δs^+ at $x \approx 0.1$. This can be attributed directly to the HERMES deuteron K^- production data [50], illustrated in Fig. 2. Since Δs is weighted by the (large) favored $D_s^{K^-}$ FF, the $A_{1d}^{K^-}$ asymmetry is most sensitive to strange quark polarization. In contrast, K^+ production, which is sensitive to $\Delta\bar{s}$, is dominated by the much larger Δu PDF weighted by the favored $D_u^{K^+}$.

Compared with the full result, the asymmetry computed with a negative Δs^+, as in the JAM15 analysis of inclusive DIS [5], gives a significantly worse fit to the HERMES $A_{1d}^{K^-}$ data, with χ^2 increasing from 5.7 to 18.5 for 9 data points. A similar effect is seen for the COMPASS K^- data on protons (deuterons), which prefer a non-negative strangeness, with χ^2 increasing from 4.8 to 9.0 (12.0 to 18.5) for 12 (10) data points.

In addition to Δs^+, we also explored the sensitivity to a nonzero strange–antistrange asymmetry, Δs^-. While most global PDF analyses assume $\Delta s = \Delta\bar{s}$, a nonzero asymmetry is expected from chiral symmetry breaking in QCD [59–61]. In principle, the availability of precise $K^\pm$ SIDIS data could discriminate between s and $\bar{s}$ polarization; however, as Fig. 1 illustrates, the current experimental errors render extraction of a nonzero Δs^- signal impractical.

Of course, preference for a positive or negative strangeness depends rather strongly on the FFs used in the evaluation of the asymmetry [6, 12, 13]. The solution to this problem is to simultaneously determine both PDFs and FFs, as we seek to do here. The results for the FFs extracted from the combined fit are displayed in Fig. 3 for the most relevant quark flavors fragmenting to π^+ and K^+, at a scale $Q^2 = 5$ GeV^2 appropriate for the SIDIS data.

For the pion, the $D_{u^+}^{\pi^+}$ FF is relatively well constrained by the SIA data, compared with the unfavored $D_{\bar{u}}^{\pi^+}$. The π^+ FFs are also similar to those from the previous JAM analysis of SIA data [14], as well as from other parametrizations [62, 63]. For kaons, the uncertainties for the favored $D_{u^+}^{K^+}$ and unfavored $D_s^{K^+}$ are generally larger because of the lower precision of the K data.

One of the most important features in Fig. 3 is the difference between the $D_{s^+}^{K^+}$ FF for the various parametrizations, which has profound impact on Δs extraction. Here the JAM17 result is more comparable with the DSS fit [62], while the magnitude of the HKNS [63] result is somewhat smaller. The $D_{s^+}^{K^+}$ FF is also qualitatively similar to the recent NJL–Jet model calculation [64], specifically in the large-z region where $D_{s^+}^{K^+} > D_{u^+}^{K^+}$. The $D_{s^+}^{K^+}$ obtained from the SIA-only analysis [14] is very similar to that in Fig. 3, with the SIDIS data pulling the JAM17 result slightly larger at low z. Recall that the smaller $s^+ \to K^+$ fragmentation in the HKNS fit is what allowed a more negative Δs^+ at $x \sim 0.1$ in the combined DIS and SIDIS analysis of Ref. [13], similar to the shape of Δs^+ in DIS-only analyses such as JAM15 in Fig. 1. The shapes of the heavy quark and gluon FFs are essentially unchanged from Ref. [14].

If it is SIDIS data that restrict the $\Delta s^+(x)$ PDF to be small and positive at intermediate x values, a natural question to ask is what drives Δs^+ to be large and negative in DIS-only analyses? The answer appears to be the imposition of the SU(3) constraint on the octet axial charge, which is related to the lowest moment of the SU(3) nonsinglet combination, $a_8 \equiv \Delta u^+ + \Delta d^+ - 2\Delta s^+$. We have verified that in the absence of this constraint, it is indeed possible to fit the DIS data sets with zero Δs^+ at the input scale, with identical χ^2 values as in a fit with the strange distribution free to vary. This confirms that the sensitivity to Δs^+ from DIS data alone, in combination with Q^2 evolution, is negligible. In contrast, the SU(3) assumption tends to pull the strange PDF to be negative across all x in order to generate a negative moment, $\Delta s^+(Q_0^2) \approx -0.1$.

To understand the origin of the large negative peak in Δs^+ at $x \approx 0.1$ in DIS-only analyses, we examine the behavior of Δs^+ in the absence of low-x DIS data ($x \lesssim 0.02$), where sea quarks are expected to play a greater role. Starting from a shape of $\Delta s^+(x)$ at the input scale that is negative at small x and positive at large x, such as in the DSSV09 fit [10], we find that the strange PDF remains qualitatively unchanged when fitting to the reduced DIS data set. Upon closer examination, around 5 data points at the lowest x bins from the COMPASS deuterium data are found to favor small negative values for Δs^+, which then drives the strange PDF in the intermediate-x region to be more negative in order to satisfy the SU(3) constraint. Finally, the characteristic negative peak at $x \sim 0.1$ observed in most global analyses is generated by fixing the parameter $b \approx 6-10$, as for typical sea quark PDFs. Such a peak is artificial since there is no direct sensitivity to $\Delta s^+(x)$ in current inclusive DIS data.

The "strange quark polarization puzzle" [6, 13] can therefore be understood by simply relaxing the SU(3) constraint, which then produces a strange distribution with shape and magnitude that agree well with DIS and SIDIS asymmetries. While both the (mostly positive) JAM17 and (mostly negative) JAM15 strange PDFs give nearly identical χ^2 for DIS data, the latter will be strongly disfavored by the SIDIS asymmetries. In fact, the positive shape of Δs^+ at $x \sim 0.1$ is obtained even when samples consistent with SU(3) symmetry are selected, as Fig. 1 illustrates. Such samples prefer more negative PDFs at lower x values, $x \lesssim 10^{-2}$, where the shape is not well constrained, and restrict the first moment to $\Delta s^+ \sim -0.1$. In contrast, our new results gives a smaller averaged value, $\Delta s^+(Q_0^2) = -0.03(10)$, but now of course with larger uncertainty. Interestingly, the central value agrees with the recent lattice QCD determination of strangeness polarization, $\Delta s^+_{\rm latt} = -0.02(1)$ at $Q^2 \approx 7$ GeV^2 [65].

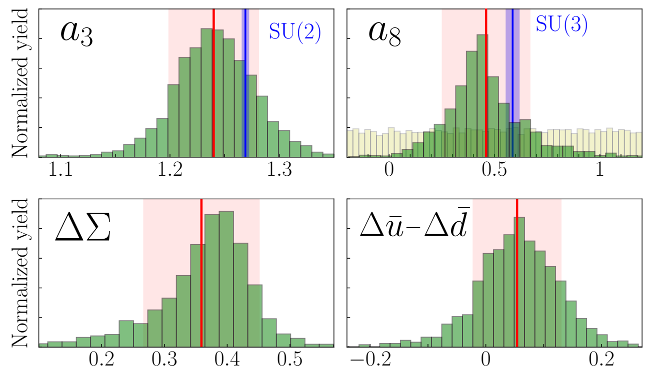

FIG. 4. Normalized yield of the lowest moments of the spin-dependent PDFs for the triplet (a_3), octet (a_8) and singlet ($\Delta\Sigma$) axial charges, and the flavor asymmetry $\Delta\bar{u} - \Delta\bar{d}$, with average values (red vertical lines) and 1σ deviations (pink bands) indicated at the input scale. For the scale invariant a_3 [a_8], the SU(2) [SU(3)] symmetric values are indicated (blue vertical bands), together with the flat prior distributions for a_8 without SU(3) (yellow histograms).

Our result for the strange moment translates to a central value of the octet axial charge $a_8 = 0.46(21)$ that is $\approx 20\%$ smaller than the traditional SU(3) value 0.586(31), as suggested in earlier theoretical studies [66]. Even though the uncertainty is somewhat large, the peaking of the a_8 distribution around ~ 0.5 is entirely data driven, as Fig. 4 illustrates with the comparison of the flat prior distributions sampled in the range $[-0.2, 1.2]$. Future higher precision SIDIS kaon data would be needed to reduce the uncertainty on both the polarized strangeness and test the degree of SU(3) breaking in the octet axial charge.

Another consequence of the more positive value of Δs^+ (smaller a_8) is an $\approx 25\%$ larger total spin carried by quarks and antiquarks in the nucleon [66], $\Delta\Sigma(Q_0^2) = 0.36(9)$. Within the larger uncertainties resulting from the relaxing of the SU(3) constraint in our simultaneous analysis, this is compatible with the singlet charge of 0.28(4) obtained in the JAM15 fit [5]. In fact, the simultaneous fit can also be used to determine the triplet axial charge $a_3 \equiv \Delta u^+ - \Delta d^+$ preferred by the data, without assuming SU(2) symmetry. We find that $a_3 = 1.24(4)$, in good agreement with the standard value $g_A = 1.269(3)$ from neutron weak decay. This is a remarkable empirical confirmation of the equality between a_3 and g_A, and of QCD itself, to almost 2%!

Finally, as suggested in Fig. 1, the antiquark component of the isovector axial charge prefers slightly positive values, $\Delta\bar{u} - \Delta\bar{d} = 0.05(8)$, but is consistent with zero within the uncertainty. The recent polarized pp scattering data from PHENIX [67] on asymmetries from $W^\pm + Z$

decays and from STAR [68] on $W^\pm$ asymmetries also indicate a slightly larger $\Delta\bar{u}$ in the $x \sim 0.16$ range.

In the future, the IMC analysis will be extended to include NNLO [69, 70] and small-x [71, 72] corrections, as well as unpolarized SIDIS data for better determination of the unfavored FFs [73, 74]. Since the unpolarized strange quark PDF is currently not well determined, useful constraints on Δs from these data will necessitate a simultaneous analysis of spin-averaged and spin-dependent PDFs, in addition to FFs. This remains an important challenge for future global QCD analyses.

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[1] C. A. Aidala, S. D. Bass, D. Hasch and G. K. Mallot, Rev. Mod. Phys. **85**, 655 (2013).
[2] G. Altarelli and G. G. Ross, Phys. Lett. B **212**, 391 (1988).
[3] D. de Florian, R. Sassot, M. Stratmann and W. Vogelsang, Phys. Rev. Lett. **113**, 012001 (2014).
[4] M. Diehl, Phys. Rep. **388**, 41 (2003).
[5] N. Sato, W. Melnitchouk, S. E. Kuhn, J. J. Ethier and A. Accardi, Phys. Rev. D **93**, 074005 (2016).
[6] E. Leader, A. V. Sidorov and D. B. Stamenov, Phys. Rev. D **91**, 054017 (2015).
[7] E. R. Nocera *et al.*, Nucl. Phys. **B887**, 276 (2014).
[8] J. Blümlein and H. Böttcher, Nucl. Phys. **B841**, 205 (2010).
[9] M. Hirai and S. Kumano, Nucl. Phys. **B813**, 106 (2009).
[10] D. de Florian, R. Sassot, M. Stratmann and W. Vogelsang, Phys. Rev. D **80**, 034030 (2009).
[11] H. Khanpour, S. T. Monfared and S. Atashbar Tehrani Phys. Rev. D **95**, 074006 (2017)
[12] E. Leader, A. V. Sidorov and D. B. Stamenov, Phys. Rev. D **82**, 114018 (2010).
[13] E. Leader, A. V. Sidorov and D. B. Stamenov, Phys. Rev. D **84**, 014002 (2011).
[14] N. Sato, J. J. Ethier, W. Melnitchouk, M. Hirai, S. Kumano and A. Accardi, Phys. Rev. D **94**, 114004 (2016).
[15] M. Stratmann and W. Vogelsang, Phys. Rev. D **64**, 114007 (2001).
[16] J. Ashman *et al.*, Nucl. Phys. **B328**, 1 (1989).
[17] B. Adeva *et al.*, Phys. Rev. D **58**, 112001 (1998).
[18] B. Adeva *et al.*, Phys. Rev. D **60**, 072004 (1999);
[19] M. G. Alekseev *et al.*, Phys. Lett. B **690**, 466 (2010).
[20] V. Yu. Alexakhin *et al.*, Phys. Lett. B **647**, 8 (2007).
[21] G. Baum *et al.*, Phys. Rev. Lett. **51**, 1135 (1983).
[22] P. L. Anthony *et al.*, Phys. Rev. D **54**, 6620 (1996).
[23] K. Abe *et al.*, Phys. Rev. D **58**, 112003 (1998).
[24] K. Abe *et al.*, Phys. Rev. Lett. **79**, 26 (1997).
[25] P. L. Anthony *et al.*, Phys. Lett. B **493**, 19 (2000).
[26] P. L. Anthony *et al.*, Phys. Lett. B **463**, 339 (1999).
[27] P. L. Anthony *et al.*, Phys. Lett. B **458**, 529 (1999).
[28] P. L. Anthony *et al.*, Phys. Lett. B **553**, 18 (2003).
[29] K. Ackerstaff *et al.*, Phys. Lett. B **404**, 383 (1997).
[30] A. Airapetian *et al.*, Phys. Rev. D **75**, 012007 (2007).
[31] A. Airapetian *et al.*, Eur. Phys. J. C **72**, 1921 (2012).
[32] R. Brandelik *et al.*, Phys. Lett. B **94**, 444 (1980).
[33] M. Althoff *et al.*, Z. Phys. C **17**, 5 (1983).
[34] W. Braunschweig *et al.*, Z. Phys. C **42**, 189 (1989).
[35] H. Albrecht *et al.*, Z. Phys. C **44**, 547 (1989).
[36] H. Aihara *et al.*, Phys. Rev. Lett. **52**, 577 (1984).
[37] X.-Q. Lu, Ph.D. thesis, Johns Hopkins University (1986).
[38] H. Aihara *et al.*, Phys. Rev. Lett. **61**, 1263 (1988).
[39] M. Derrick *et al.*, Phys. Rev. D **35**, 2639 (1987).
[40] K. Abe *et al.*, Phys. Rev. D **69**, 072003 (2004).
[41] R. Akers *et al.*, Z. Phys. C **63**, 181 (1994).
[42] G. Abbiendi *et al.*, Eur. Phys. J. C **16**, 407 (2000).
[43] D. Buskulic *et al.*, Z. Phys. C **66**, 355 (1995).
[44] P. Abreu *et al.*, Nucl. Phys. **B444**, 3 (1995).
[45] P. Abreu *et al.*, Eur. Phys. J. C **5**, 585 (1998).
[46] R. Itoh *et al.*, Phys. Lett. B **345**, 335 (1995).
[47] M. Leitgab *et al.*, Phys. Rev. Lett. **111**, 062002 (2013).
[48] M. Leitgab, Ph.D. thesis, University of Illinois at Urbana-Champaign (2013).
[49] J. P. Lees *et al.*, Phys. Rev. D **88**, 032011 (2013).
[50] A. Airapetian *et al.*, Phys. Rev. D **71**, 012003 (2005).
[51] M. Alekseev *et al.*, Phys. Lett. B **680**, 217 (2009).
[52] M. Alekseev *et al.*, Phys. Lett. B **693**, 227 (2010).
[53] J. F. Owens, A. Accardi and W. Melnitchouk, Phys. Rev. D **87**, 094012 (2013).
[54] L. A. Harland-Lang, A. D. Martin, P. Motylinski and R. S. Thorne, Eur. Phys. J. C **75**, 204 (2015).
[55] A. W. Schreiber, A. I. Signal and A. W. Thomas, Phys. Rev. D **44**, 2653 (1991).
[56] D. Diakonov, V. Petrov, P. Pobylitsa, M. V. Polyakov and C. Weiss, Nucl. Phys. **B480**, 341 (1996).
[57] H. W. Lin, J. W. Chen, S. D. Cohen and X. Ji, Phys. Rev. D **91**, 054510 (2015).
[58] C. Alexandrou *et al.*, arXiv:1610.03689 [hep-lat].
[59] A. I. Signal and A. W. Thomas, Phys. Lett. B **191**, 205 (1987).
[60] W. Melnitchouk and M. Malheiro, Phys. Rev. C **55**, 431 (1997).
[61] A. W. Thomas, W. Melnitchouk and F. M. Steffens, Phys. Rev. Lett. **85**, 2892 (2000).
[62] D. de Florian, R. Sassot and M. Stratmann, Phys. Rev. D **75**, 114010 (2007).
[63] M. Hirai, S. Kumano, T.-H. Nagai and K. Sudoh, Phys. Rev. D **75**, 094009 (2007).
[64] H. H. Matevosyan, A. W. Thomas and W. Bentz, Phys. Rev. D **83**, 114010 (2011).
[65] G. S. Bali *et al.*, Phys. Rev. Lett. **108**, 222001 (2012).
[66] S. D. Bass and A. W. Thomas, Phys. Lett. B **684**, 216 (2010).
[67] A. Adare *et al.*, Phys. Rev. D **93**, 051103 (2016).
[68] L. Adamczyk *et al.*, Phys. Rev. Lett. **113**, 072301 (2014).
[69] D. P. Anderle, F. Ringer and M. Stratmann, Phys. Rev. D **92**, 114017 (2015).
[70] V. Bertone *et al.*, Eur. Phys. J. C **77**, 516 (2017).
[71] Y. V. Kovchegov, D. Pitonyak and M. D. Sievert, Phys. Lett. B **772**, 136 (2017).
[72] Y. V. Kovchegov, D. Pitonyak and M. D. Sievert, arXiv:1706.04236 [nucl-th].
[73] D. de Florian, R. Sassot, M. Epele, R. J. Hernández-Pinto and M. Stratmann, Phys. Rev. D **91**, 014035 (2015).
[74] D. de Florian, M. Epele, R. J. Hernández-Pinto, R. Sas-

sot and M. Stratmann, Phys. Rev. D **95**, 094019 (2017).